Three-dimensional seismic imaging of slow slip zones along the northern Hikurangi margin

Nathan Bangs[1], Harold Tobin[2], Stuart Henrys[3], Dan Barker[3], Philip Barnes[4], Eli Silver[5], Kirk McIntosh[1], David Okaya[6], Rupert Sutherland[3], Greg Moore[7], Shuichi Kodaira[8], Lisa McNeill[9], and Laura Wallace[1]

[1]Univ. Texas, Inst. For Geophysics, [2]Univ. Wisconsin-Madison, [3]GNS Science, New Zealand, [4]NIWA, New Zealand, [5]Univ. Calif.-Santa Cruz, [6]Univ. Southern Calif., [7]Univ. Hawaii-Manoa, [8]JAMSTEC, [9]National Oceanography Centre

nathan@ig.utexas.edu

Subduction margins produce the largest and most destructive earthquakes and tsunami on Earth. Understanding the mechanics of fault slip behaviour on subduction thrust interfaces is critical to understand earthquakes and mitigate seismic hazards. Recent detection of slow slip and its associated seismic phenomena (such as non-volcanic tremor, low-frequency and very-low frequency earthquakes) has transformed our understanding of possible fault slip behaviour (e.g., Ide et al., 2007), which exposes the need to investigate the full range of slip behavior to fully understand deformation mechanisms and rheology on subduction megathrusts.

The mechanisms responsible for slow slip are poorly known, but focus has turned to the role of high-fluid pressure as a controlling factor. Progress in understanding the physical mechanisms behind slow slip will require a combination of detailed seismic imaging, passive seismic monitoring and more direct sampling and measurement of material in the SSE (slow slip earthquake) regions (via ocean drilling) throughout the SSE cycle. However, most well-documented subduction SSEs (Cascadia, southwest Japan, Mexico, Alaska) occur at 25-50 km depth and pose significant challenges for detailed seismic imaging and are impossible for drilling. One notable exception to this lack of access is the northern Hikurangi margin, New Zealand, where SSEs occur approximately every two years at <5-15 km depth, at the down-dip transition from stick-slip to aseismic creep on the Hikurangi subduction thrust. Northern Hikurangi SSEs (see figure) typically last 1-2 weeks and produce slip on the subduction interface equivalent to an Mw 6.3-6.8 earthquake (Wallace and Beavan, 2010). The extremely shallow depth of the northern Hikurangi SSEs permits detailed remote geophysical sensing studies of the physical properties of the interface in the SSE source area, and offers the possibility of calibrating these properties by direct sampling of material in the SSE source area with offshore drilling methods.

In the last couple of years an international group of scientists has assembled to explore and develop strategies to investigate emerging hypotheses about the structures and physical conditions that control a spectrum of slip behaviour along the Hikurangi subduction thrust. The Hikurangi margin exhibits behaviours along the north island of New Zealand that range from regularly repeating slow slip events (SSEs) in the north to full locking and stick-slip in the south. Recent geophysical studies and emerging hypotheses make this a compelling setting to investigate the conditions and processes that control slip behaviour on the subduction thrust. Following a preliminary workshop in May 2010 and a large workshop in Aug. 2011, an international team of scientists has begun planning a broad range of experiments, including IODP drilling, to address slip behaviour along the Hikurangi margin. A description of drilling plans, including riserless drilling and monitoring (781A-Full), and deep riser drilling to ~6 km depth (to be submitted to IODP April 2013) are described in a separate white paper (**Unlocking**

the Secrets of Slow Slip by Scientific Drilling at the Northern Hikurangi Subduction Margin, New Zealand).

A 3D seismic imaging program for the Hikurangi margin

As plans for potential deep drilling evolve, the need to acquire 3D seismic reflection data to further constrain structures and material properties along the Hikurangi margin is evident. These data would allow us to expand hypotheses and develop targets for further investigation. Three-dimensional seismic imaging in the last two decades have demonstrated that is a highly effective tool for mapping fault systems within structurally complex subduction zone settings. Integration of 3D seismic results with ground truthing from drilling is by far the most effective tool for characterizing fault geometry and rock properties that approach the scale of fault slip regions.

We plan to submit proposals to use the R/V Langseth for a 3D survey of the northern Hikurangi margin along the proposed drilling transect. The 3D survey will be designed from existing 2D seismic reflection data in the proposed drilling area. In recent years, a community of largely New Zealand scientists have surveyed the Hikurangi margin extensively with 2D seismics (see figure for location of 2-D seismic lines surveyed at northern Hikurangi in 2005) and swath bathymetry (including SIMRAD multi-beam data) with funding from the New Zealand science funding agencies and government departments. The 2-D MCS data from the offshore northern Hikurangi margin reveal a zone of high-amplitude reflectivity near the subduction interface, 5–15 kilometers below the seafloor, that coincides with geodetically determined SSE source areas (Bell et al., 2010). These high-amplitude reflective zones (HRZs) are interpreted to correspond to fluid-rich sediments, suggesting that high fluid pressures may play an important role in the occurrence of SSEs at the northern Hikurangi margin. In addition to imaging the SSE source area and associated HRZ, the proposed survey also offers an opportunity to image the seamount asperity associated with a 1947 tsunamigenic earthquake on the subduction interface, adjacent to and updip of the SSE source area (see figure). The ability to contrast the properties of the interface in the seamount asperity region (unstable frictional regime) with the surrounding slow slip area (conditionally stable regime) could give important insights into the processes and properties that control the occurrence of earthquakes vs. slow, aseismic slip. Because of both the local interest and the growing international interest in the Hikurangi margin as a setting for this world class problem, we plan to seek funding for the Langseth acquisition from New Zealand, NSF and other international funding agencies.

Survey plans are still preliminary and will not be complete until proposals are submitted, but we envision a 3D survey of ~ 45 days, covering an area of approximately 20 x 50 km, acquired in coordination with another OBS program outlined in a separate white paper. The primary goal would be to image the geometry and reflective properties of the plate boundary fault from the trench across the strongly coupled regions and into the slow-slip patches, to a down dip depth of ~ 10 km. Two-dimensional seismic profiles show high amplitude reflections from the plate interface down to ~10 km. The 3D survey would also map structures and material properties within the overriding plate to examine deformation and the potential plumbing system of the overriding plate. The survey would be centered along the proposed drilling transect as described in the drilling proposal 781A-Full. A 3D seismic survey would be best in the southern summer when the weather in New Zealand is relatively calm.

Summary of plans:

Proposal Type:	"Community" including US and Foreign participants
US Funding Agency:	NSF and other non-US sources
Approx. number of ship days:	60 (but still very uncertain) 3D
Equipment:	3D seismic reflection
Time of year for operations:	Southern summer
Anticipated submission deadline:	Aug 15, 2013 NSF-OCE deadline
Links to other Programs:	IODP and NSF-GeoPRISMS

References

Bell, R., R. Sutherland, D.H.N. Barker, S. Henrys, S. Bannister, L.Wallace, and J. Beavan (2010) Seismic reflection character of the Hikurangi subduction interface, New Zealand, in the region of repeated Gisborne slow slip events, *Geophysical Journal International, 180(1)*, 34-48).

Doser, D.I., and T.H. Webb (2003), Source parameters of large historical (1917-1961) earthquakes, North Island, New Zealand. *Geophys. J. Int.*, *152,* 795-832.

Wallace, L. M., and J. Beavan (2010), Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, J. Geophys Res., 115(B12402), doi:10.1029/2010JB007717.

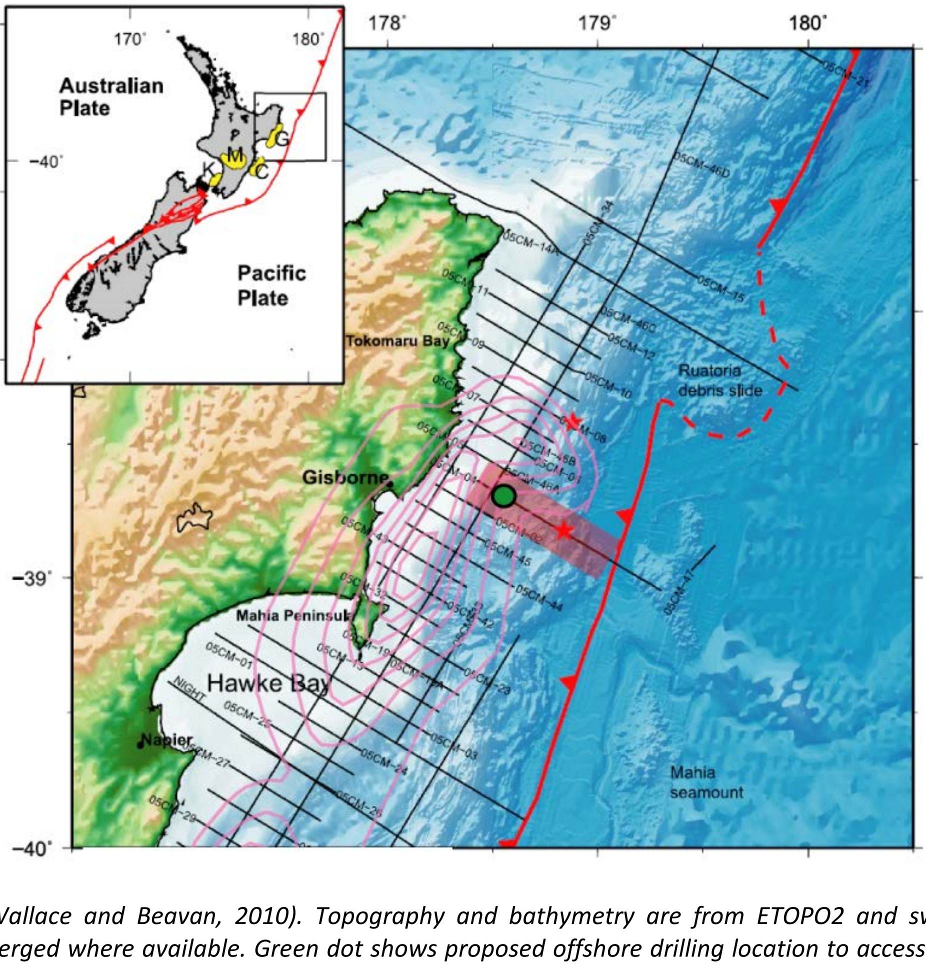


Figure 1. Location of the east coast North Island study region offshore Gisborne modified from Bell et al. (2010). Black lines are most recent 2005 seismic survey lines shot by the NZ Ministry of Econ. Development and consisted of ca. 2800 km of 2-D seismic reflection data including 33 dip and 6 strike profiles. Streamer length varied from 12 km to 4 km, with record lengths of 12 s to 8 s two-way travel time (TWT) and shot intervals of 37.5 m to 25 m using a 4140 cubic inch, 2000 psi air gun source. Pink contours show the areas slow slip since first recorded in 2002 (Wallace and Beavan, 2010). Topography and bathymetry are from ETOPO2 and swath bathymetry has been merged where available. Green dot shows proposed offshore drilling location to access the SSE source area on the interface at ~5 km sub- seafloor. Red toothed line is approximate frontal thrust at accretionary wedge toe and red stars show 1947 tsunami earthquakes locations (Doser and Webb, 2003). Inset is a summary of New Zealand regional tectonics. Yellow patches indicate areas of recorded slow slip (Wallace and Beavan, 2010). K = Kapiti, M = Manawatu, C = Cape Kidnappers and G = Gisborne slow slip events. The red shaded rectangle is the approximate extent of intended 3D MCS survey.

The Active Margin Carbon Cycle

Laurel Childress[1] and Neal Blair[1,2]

[1] *Dept. of Earth and Planetary Sciences, Northwestern University, Evanston, IL;* [2] *Dept. of Civil and Environmental Engineering, Northwestern University, Evanston, IL*

laurel@earth.northwestern.edu

Active Margins and Riverine Systems

Tectonic processes on active margins are intrinsically coupled to the transport of sediment and associated organic matter. Over geologic time scales (>1 Ma), uplift and mass wasting of sedimentary rock from uplifted accretionary wedges inject recycled organic C (e.g. kerogen), along with modern material into the marine environment (Fig. 1). The magnitude and nature of the organic carbon (OC) delivered to the marine realm can also be affected on short time scales due to event based disturbances (e.g. earthquakes, landslides). Hence, tectonic processes in active margins are intrinsically coupled with the transport of sediment and the associated organic matter. River systems located adjacent to active margins are responsible for some of the largest sediment yields on the globe (Milliman and Syvitski 1992). Importantly, those located on active margins discharge a larger percent of sediment directly to deep ocean basins (Milliman and Syvitski 1992).

Current Knowledge of OC on Active Margins

In an active margin system, the recycled pool represents a significant portion of the OC buried in the marine environment (Blair et al., 2004) (Fig. 2). Small mountainous rivers along active margins export particulate organic carbon that is 7-75% fossil C (kerogen) in content, with the remainder derived from modern vegetation and millennial aged soil sources (Leithold et al., 2006; Drenzek et al., 2009; Blair et al., 2010). Recycled C is more inert than younger forms derived from plants and soils, and this inherent recalcitrance should lead to persistence, transit to the deep marine environment, and incorporation into the subduction zone.

Subduction zones are the ultimate sink for sediment and associated OC. To determine global C budgets and volatile production in subduction zones it is necessary to understand the recalcitrance of OC entering these regions. In active margins a significant fraction of OC reaching subduction may be the result of rapid terrestrial erosion by small mountainous rivers. OC from this source which reaches the offshore subduction environment is likely to be recycled C. The relative fates of these organics depend on reactivity and environment.

Unanswered Questions

The fate of recycled C beyond the mid-slope is unknown. Most studies go no further than to describe OC in terms of marine and terrestrial sources and do not consider the presence of fossil material even though the sediments themselves are derived from organic-bearing lithologies. However, the fate of recycled C has significant implications for the global O_2 cycle because the oxidation of fossil C, along with pyrite, is considered to be an important control of pO_2 (Berner and Canfield, 1989). The only known locations for oxidation of recycled C are in subaerial sedimentary rock exposures (Petsch et al., 2000), and soils within large river watersheds on passive margins (Bouchez et al., 2010; Blair and Aller, 2011). To the extent that OC inventories of subduction margins remain approximately constant through time by recycling and reburying fossil C, pO_2 levels would be buffered against rapid changes. The resistance of recycled C to de-volatilization will influence the nature of C incorporated into deep burial and ultimately C budgets for subduction zones.

We know little about the multicycle-C mixture as it moves from the nearshore to the subduction zone. Is the recycled fossil C delivered to the frontal edge of the accretionary wedge to be cycled again and/or subducted? Or is it oxidized and ultimately replaced by marine C during transport offshore? What are the fates of the younger terrestrial and marine OC components? The answers to these questions have significant implications for C-cycle models and the interpretation of the organic geochemical record. The state of our knowledge concerning the nature of sedimentary particulate organic carbon on subduction margins is too primitive to allow us to fully appreciate the importance of these systems to global C and O cycles. Thus, as a prelude to process-based investigations, the primary objective of this research is to begin the assessment of the presence of multicycle OC (fossil plus younger terrestrial material) on subduction margins beyond the mid-slope. The Hikurangi Margin nearshore environment is well studied, and subduction dynamics/sedimentation provides the ideal research site for further investigation of this unexplored portion if the global C-cycle. Preliminary assessment of the nature and distribution of multicycle-C at this site will be important for planning future GeoPRISMS-related studies of C cycling and subduction dynamics.

References:

Berner, R., Canfield, D., 1989. A new model for atmospheric oxygen over Phanerozoic time. *American Journal of Science*, 289(4), 333 - 361.

Blair, N., Aller, R., 2011. The fate of terrestrial organic carbon in the marine environment. *Annual Review of Marine Science*, 4, 401 ‑ 423.

Blair, N., Leithold, E., Brackley, H., Trustrum, N., Page, M., Childress, L., 2010. Terrestrial sources and export of particulate organic carbon in the Waipaoa sedimentary system: Problems, progress and processes. *Marine Geology*, 270, 108 – 118.

Blair, N., Leithold, E., Aller, R., 2004. From bedrock to burial: the evolution of particulate organic carbon across couple watershed-continental margin systems. *Marine Chemistry*, 92, 141 ‑ 156.

Bouchez, J., Beyssac, O., Galy, V., Gaillardet, J., France-Lanord, C., Maurice, L., Moreira-Turcq, P., 2010. Oxidation of petrogenic organic carbon in the Amazon floodplain as a source of atmospheric CO_2. *Geology*, 38(3), 255 - 258.

Drenzek, N., Hughen, K., Montlucon, D., Southon, J., dos Santos, G., Druffel,R., Giosan, L., Eglinton, T., 2009. A new look at old carbon in active margin sediments. *Geology*, 37(3), 239 - 242.

Leithold, E., Blair, N., Perkey, D., 2006. Geomorphic controls on the age of particulate organic carbon from small mountainous and upland rivers. *Global Biogeochemical Cycles*, 20, GB3022.

Milliman J., Syvitski, J., 1992. Geomorphic/Tectonic Control of Sediment Discharge to the Ocean: The Importance of Small Mountainous Rivers. *The Journal of Geology*, 100 (5), 525 – 544.

Petsch, S., Berner, R., Eglinton, T., 2000. A field study of the chemical weathering of ancient sedimentary organic matter. *Organic Geochemistry*, 31(5), 475 - 487.

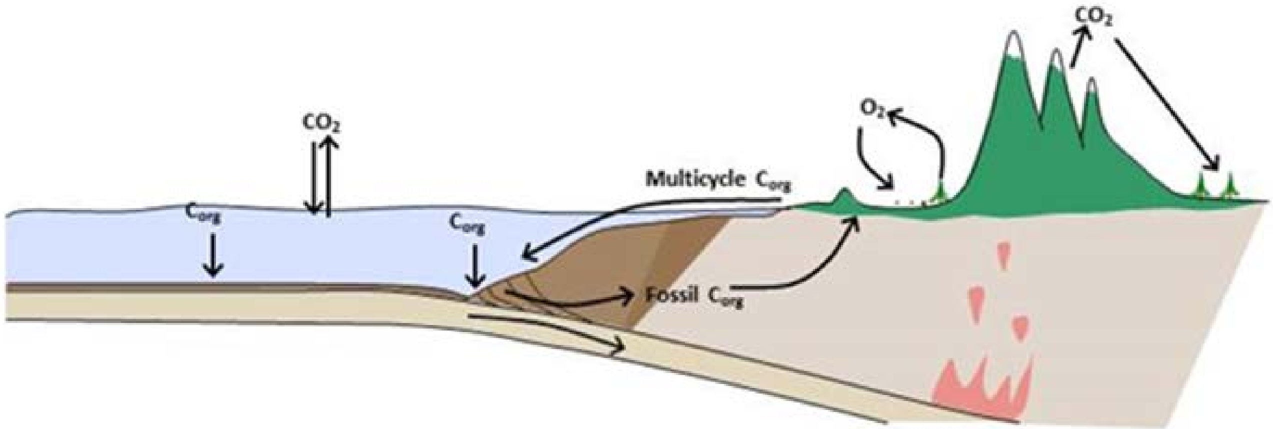


Figure 1. The active margin C-Cycle. Accretion, uplift, and erosion of sedimentary rock on the continent bring previously buried OC to the surface. If mass wasting is sufficiently rapid, as is the norm on these margins, the exposed fossil C is recycled into the sedimentary system thereby avoiding oxidation in subaerial outcrops. The recycled fossil C is blended with younger material as sediments move across the surface.

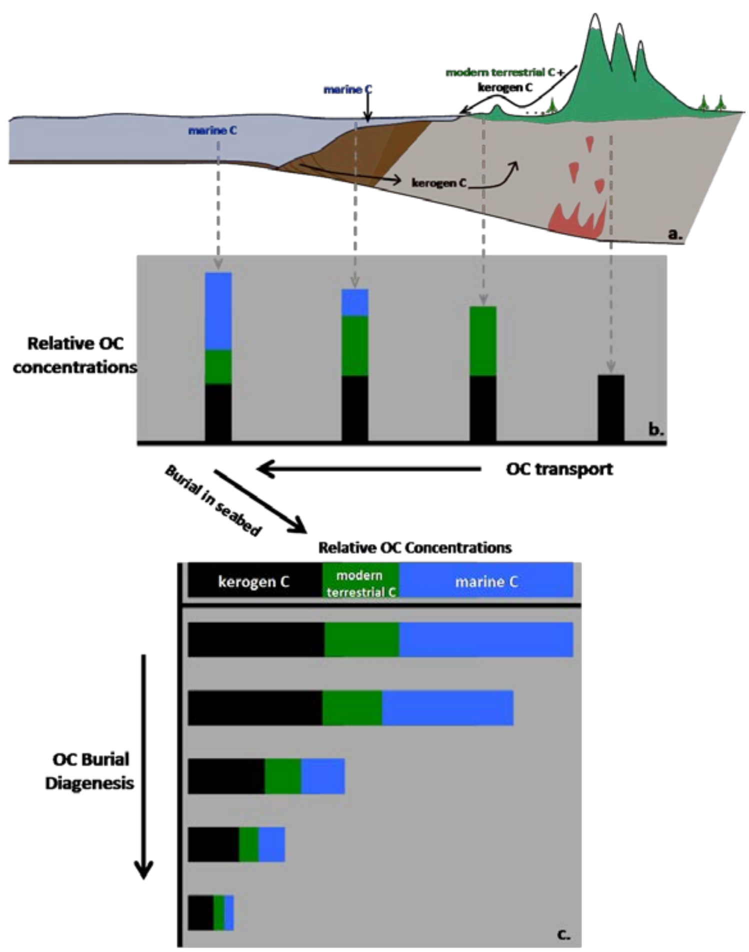


Figure 2. The active margin and accretionary wedge carbon cycle (a). Kerogen formation begins with the diagenesis of organic matter. Tectonically uplifted kerogen will combine with modern terrestrial sources and the mixed pool will be transported by rivers to the marine realm, where the marine pool of organic carbon will be added prior to burial, while terrestrial carbon is concurrently lost (b). During burial and diagenesis marine and modern terrestrial carbon will be lost, while kerogen will be preferentially preserved (c).

Brothers submarine arc volcano: gateway to the sub-arc mantle

Cornel E.J. de Ronde[1] and the Lisbon IODP Working Group

[1] GNS Science: Dept. Marine Geosciences, Lower Hutt 5010, New Zealand

cornel.deronde@gns.cri.nz

The GeoPRISMS Science Program includes two broadly integrated initiatives, distinguished by tectonic setting, with the "Subduction Cycles and Deformation" initiative taking a holistic approach to the deformation processes and *material cycles governed by subduction* (GeoPRISMS draft science plan, 2010). In particular, it studies the properties, mechanisms, and manifestations of strain build-up and release along plate boundaries, and the *transport and release of volatiles such as H_2O and CO_2 through the thrust zone and sub-arc mantle*. One of five Overarching Themes, "Fluids, Magmas and Their Interactions", serves as the basis for integrative studies, with a new focus on *volcanic systems* providing *potential linkages to mining and minerals.* Brothers volcano of the Kermadec Arc, New Zealand, affords an opportunity for such integrative studies.

Volcanic arcs are the surface expression of magmatic systems that result from the subduction of mostly oceanic lithosphere at convergent plate boundaries. Arcs with a submarine component include intraoceanic arcs and island arcs that span almost 22,000 km on Earth's surface, with the vast majority located in the Pacific region. Intraoceanic arcs total almost 7,000 km, thus ensuring a steady supply of dissolved gases and metals to the oceans, and the potential for the formation of polymetallic mineral deposits.

Most mineralization along intraoceanic arcs is dominated by mineral assemblages representing high-sulfidation conditions, including elemental sulfur, polymorphs of silica, alunite and lesser pyrite. This mineralizaton is typically associated with relatively low temperature (≤120°), diffuse, acidic (pH <3), metal-poor but gas-rich emissions from seafloor hydrothermal systems. Less common are focused, relatively high temperature (~300°C), metal-rich fluids where Fe-Cu-(±Au)-Zn sulfides and barite/anhydrite predominate. Both types of venting show evidence for contributions from magmatic sources. These two types of venting represent end-members of a continuum that spans magmatic-hydrothermal to water/rock dominated systems, respectively. More mature vent fields are better able to deliver and accumulate metals at the seafloor.

The ~1,220 km long Kermadec arc is host to ~40 large volcanoes of which 80% are hydrothermally active, making it the most active arc in the world. Hydrothermal activity associated with these arc volcanoes, including both caldera- and cone-types, is dominated by the discharge of magmatic volatiles. This hydrothermal magmatic signature(s), including high concentrations of S and C species gases together with high Fe contents, coupled with the shallow depths (~1800-120 m below sea level) of these volcanoes, greatly influences the chemistry of the venting fluids, the mineralization that results from these fluids, and more than likely has important consequences for the biota associated with these systems. Given the high metal contents and very acidic fluids, these hydrothermal systems are thought to be important analogues of the porphyry copper and epithermal gold rich deposits exploited on land today.

Brothers volcano of the Kermadec arc is host to a hydrothermal system unique among seafloor hydrothermal systems. It has two distinct vent fields, known as the NW Caldera and Cone sites, whose geology, permeability, vent fluid compositions, mineralogy and ore forming conditions are in stark contrast to each other. The NW Caldera site strikes for ~600 m in a SW-NE direction with chimneys occurring over a ~145 m depth interval, between ~1690 and 1545 m. At least 100 dead and active sulfide chimney spires up to 7 m tall occur in this field, whose ages fall broadly into three groups: < 4 years, 23 and 35 years old. Two main types of chimney predominate: Cu-rich (up to 28.5 wt.% Cu) and more commonly, Zn-rich (up to 43.8 wt.% Zn). Vent fluids here are focused, hot (≤302°C) and metal-rich, with moderate gas contents.

The Cone site comprises the Upper Cone site atop the summit of the recent (main) dacite cone, and the Lower Cone site that straddles the summit of an older, smaller, more degraded dacite cone on the NE flank of the main cone. Huge volumes of diffuse venting are seen at the Lower Cone site, in contrast to venting at both the Upper Cone and NW Caldera sites. Individual vents are marked by low relief (≤0.5 m) mounds comprised predominately of native sulfur with bacterial mats. Vent fluids are very acid (pH 1.9) and gas-rich, though metal-poor. The NW Caldera and Cone sites are considered to represent water/rock and magmatic-hydrothermal dominated end-members, respectively. Drilling Brothers would provide an exciting opportunity to understand subseafloor volcanic architecture, hydrology, polymetallic ore deposition formation and the deep biosphere of intraoceanic arc volcanoes associated with convergent plate margins.

References:

de Ronde, C.E.J., Massoth, G.J., Butterfield, D.A., Christenson, B.W., Ishibashi, J., Ditchburn, R.G., Hannington, M.D., Brathwaite, R.L., Lupton, J.E., Kamenetsky, V.S., Graham, I.J., Zellmer, G.F., Dziak, R.P., Embley, R.W., Dekov, V.M., Munnik, F., Lahr, J., Evans, L.J. and Takai, K., 2011, Submarine hydrothermal activity and gold-rich mineralization at Brothers volcano, Kermadec arc, New Zealand. Mineralium Deposita 46: 541-584, DOI 10.1007/s00126-011-0345-8.

GeoPRISMS Draft Science Plan, 2010, http://www.geoprisms.org/science-plan.html

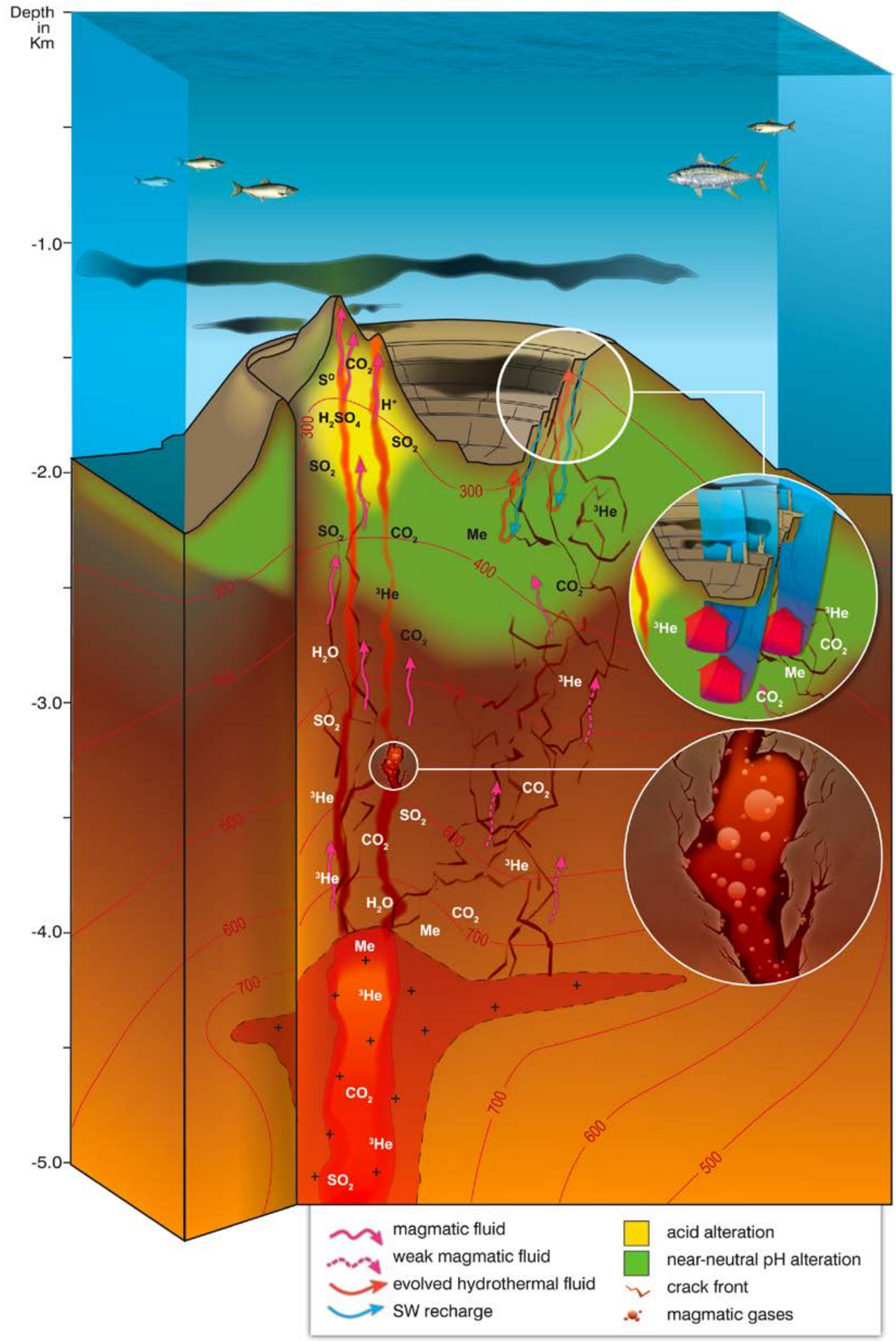


Figure 1. High resolution, AUV-derived data of seafloor geology, structure, geophysics and vent distribution, plus submersible sampling of rocks, mineralization, biology and vent fluids, has enabled a first-order model of the hydrothermal system at Brothers to be constructed (from de Ronde et al., 2011).

Exterra: Understanding Convergent Margin Processes Through Studies of Exhumed Terranes – GeoPRISMS New Zealand Focus Site

Besan Dragovic[1*], S. Penniston-Dorland[2], M. Feineman[3], M. Caddick[1], H. Stowell[4], A. Tulloch[5], J. Schwartz[6], N. Mortimer[5], J. Barnes[7], S. Gordon[8], I. Wada[9], E. Syracuse[10],J. Ague[11], E. Baxter[12], B. Hacker[13], G. Bebout[14]

[1]Virginia Tech, [2]U. Maryland, [3]Penn State, [4]U. Alabama, [5]GNS Science, [6]Cal. State U. Northridge, [7]U.T. Austin, [8]U. Nevada-Reno, [9]Tohoku University, [10]U. Wisconsin-Madison, [11]Yale University, [12]Boston University, [13]U.C. Santa Barbara, [14]Lehigh University.

dragovic@vt.edu

The GeoPRISMS SCD Science Plan identified the study of exhumed terranes as an important component of subduction zone research. Exhumed rocks from the accretionary wedge, forearc, subducted slab and middle to lower arc crust can illuminate the role of volatiles, fluids and melts, and geochemical cycling during subduction, leading to a better understanding of continental crust formation and evolution. Also, analysis of exhumed terranes has the unique ability to inform studies of active subduction by testing the assumptions required by models, experiments, and interpretive geophysics and geochemistry.

New Zealand Focus Sites

***1) Otago Schist (OS),* Fig. 1a:** Investigation of exposed accretionary wedge rocks, such as the *OS*, allows the disentanglement of mixing and material transport processes occurring within and above the subducting slab. The *OS* is a >150 km wide belt of deformed and metamorphosed greywacke, basalt, shale, and chert [1-4]. This unit is considered to represent the exhumed section of a Late Paleozoic-Mesozoic accretionary prism, formed by subduction under the Paleo-Pacific Gondwana margin [5-8]. Peak temperatures of the central greenschist facies unit are estimated to have reached 350-400°C [1, 3]. The *OS* displays extensive vein formation and associated metasomatism, exhibiting evidence for subduction-related reactive fluid flow [6, 9].

***2) Fiordland Block (FB),* Fig. 1b:** A major limitation in understanding the magmatic evolution of continental margin-arc systems is our limited knowledge of magmatic, metamorphic and deformational processes that occur in the deep crust. Well-exposed middle and lower arc crustal terranes (e.g. the *FB*), can provide key spatial and temporal constraints on the evolution of arc magmas that *cannot be addressed directly through studies of erupted lavas*. This helps us to construct a 4-D geologic perspective of a continental margin-arc system that relates field-based petrologic observations to those derived from deep-crustal seismic reflection imaging and laboratory-based partial melting experiments. The *FB* exposes >3,000 km^2 of Mesozoic middle and lower crust that records a history of mafic-intermediate arc magmatism, lower crustal melting, and high-grade metamorphism [10, 11]. Eclogite, granulite, and amphibolite facies rocks of the *FB* constrain metamorphic depth and temperature [12-15]. Garnet Sm-Nd and zircon U-Pb ages indicate that high temperature metamorphism closely followed magmatism in parts of Fiordland [14, 16-17] providing an opportunity to test ties between arc magmatism, high temperature metamorphism, exhumation, and partial melting in the crust.

Key questions addressed by the study of exhumed terranes *(and relevant proposed study site)*

*What is the composition of slab-derived fluids? How do processes in the forearc and accretionary wedge affect the overall subduction zone elemental budget? (**OS**)* Knowledge of the composition of slab-derived fluids is largely derived indirectly from elemental variations in arc lavas [18, 19], experiments [20, 21], or theoretical calculations [22]. The *OS* offers field evidence for extensive fluid flow and elemental mobility [6, 9, 23, 24]. Fluid flow in accretionary prisms is driven mainly by expulsion of pore waters from sediments, devolatilization from (meta)sedimentary rocks, and dehydration of the subducting slab and/or forearc mantle wedge. Mineral scale data from these locales are needed to test and ground-truth existing experiments that constrain the solubility of minerals and elemental partitioning between minerals and fluids, placing these within the context of a dynamic subduction environment.

*What are the pathways, fluxes, and timescales of fluid release in the slab? What is its thermal evolution? (**OS**)* Models of fluid production based on thermodynamic equilibrium [25, 26] can predict volumes of fluid released during subduction. Patterns of fluid release during *OS* evolution can be quantified using thermo-petrologic models [27,28]. Geospeedometry suggests rapid timescales of fluid release on the order of hundreds of years [29, 30], while geochronology has the potential to constrain timescales and fluxes [28] on the order of hundreds of thousands of years. The *OS* provides insight into the mechanisms of fluid transport, paths, and fluxes in the accretionary wedge [6, 9]. Geochronology combined with thermodynamic modeling can yield petrologically-derived *P-T-t* paths, providing constraints for geodynamical models of subduction zones.

*What are the geochemical products of subduction that influence the formation and evolution of continental crust? (**FB**)* The FB contains Mesozoic tonalite-trondjhemite-granodiorite (TTG)-like plutons [11, 31]. Modern analogs of TTGs are believed to form by partial melting of underplated basaltic materials at the base of the arc crust [32] (and/or high pressure garnet fractionation). This demonstrates that contributions to the long-term growth and evolution of continental crust come not only from mantle-derived melts that erupt at continental arcs, but also from more evolved plutons that form within the deep crust. The *FB* provides the opportunity to investigate the structure and chemistry of these plutons directly in a relatively intact crustal sequence.

*What are the fluxes into and out of the crust over time? (**FB**)* Mantle and slab-derived melts (and possible sediment relamination onto the base of the arc) provide fluxes into the crust, while delamination and erosion represent mass loss from the crust [33, 34]. Petrologic and geochronologic evidence for rapid heating and exhumation may provide supporting evidence for delamination and links to possible vertical movement [35]. Interdisciplinary studies of the *FB* will address the relationships between crustal melt generation and metamorphism, including: i) *Is magmatism steady state or punctuated?* ii) *How do timescales of arc magmatism and thermal perturbations associated with magmatic advection relate to granulite-facies metamorphism and lower crustal cooling?* iii) *What role does high-pressure mineral fractionation play in the intracrustal differentiation of arc magmas and the possible foundering of ultramafic cumulates?*
How variable is the composition, fabric, melt/fluid content, and thermal structure of the arc crust, and how might these properties affect seismic velocity profiles? (***FB***) Models for lateral and vertical crustal flow (that have previously been developed for collisional orogenic belts) [36, 37] can be tested in the *FB*, providing an opportunity to study how flow and ductile deformation

affect the rheological evolution of an arc. Interpretation of seismic velocity data requires knowledge of physical properties of the low velocity middle to lower arc crust. *FB* offers an opportunity to directly observe the stratified petrology that contributes to the horizontal complexity of the crust.

Data and sample management

An integrated database and sample archive will allow field geologists to connect with users requiring samples (including experimentalists, petrologists, geochemists, or researchers who cannot participate in fieldwork due to health, time, or cost limitations). Samples collected during targeted field expeditions and seminars will be archived, magnifying the scope and impact of the field mission by making samples available to the wider research and education community. PETLAB (http://pet.gns.cri.nz/) was developed by GNS Science to manage and archive samples and associated analytical data. It allows immediate dissemination of data that enables its timely use, and currently holds a diverse collection of records on 185,000 samples of which 50,000 have geochemical, geochronological and/or thermochronological analytical data. ExTerra will work with the US-based Integrated Earth Data Applications (IEDA) facility to develop an interface with PETLAB. PETLAB should be added to the GeoPRISMS Data Portal, and could then be systematically encouraged for use by all GeoPRISMS projects working on the NZ primary site.

References:

1. Fagereng, A, Cooper, A., 2010. J. Metamorph. Geol., 28, 935-954.
2. Mortimer, N., 2000. Int. J. Earth Sci., 89, 295-306.
3. Mortimer, N., McLaren, S., Dunlap, W.J., 2012. Tectonics, 31, 1-15.
4. Turnbull, I., Mortimer, N., Craw, D., 2001. New Zeal. J. Geol. Geophys., 44, 171-183.
5. Fagereng, A., Cooper, A., 2010. New Zeal. J. Geol. Geophys., 53, 57-70.
6. Breeding, C., Ague, J., 2002. Geology, 30, 499-502.
7. Mortimer, N. 1993. Tectonics, 12, 237-244.
8. Coombs, D., Landis, C., Norris, R., et al., 1976. Am. J. Sci., 276, 561-603.
9. Qiu, L., Rudnick, R., Ague, J., McDonough, W., 2011. Earth Planet. Sci. Lett., 301, 213-221.
10. Klepeis, K.. Clarke, G. Rushmer, T., 2003. GSA Today, 13, 4-11.
11. Allibone, A., Jongens, R., Scott, J., et al., 2009. New Zeal. J. Geol. Geophys., 52, 379-415.
12. Klepeis, K., Clarke, G., Gehrels, G., Vervoort, J., 2004. New Zeal. J. Struct. Geol., 26, 765-791.
13. DePaoli, M., Clarke, G., Klepeis, K., et al.,, 2009. J. Petrol., 50, 2307-2343.
14. Stowell, H., Parker, K., Gatewood, M., 2010. Geochim. Cosmochim. Acta, 74, A997.
15. Stowell, H., Tulloch, A., Zuluaga, C., Koenig, A., 2010. Chem. Geol., 273, 91-110.
16. Parker, K., 2010. M.S. Thesis U. Ala.
17. Parker, K., Stowell, H., Gatewood, M., 2010. GSA Abstr. w. Progr., 42.
18. McCulloch , M., Gamble, J., 1991. Earth Planet. Sci. Lett., 102, 358-374.
19. Class, C., Miller, D., Goldstein, S., Langmuir, C., 2000, Geochem. Geophys. Geosyst., 1, DOI:10.1029/1999GC000010.
20. Kessel, R., Schmidt, M., Ulmer, P., Pettke, T., 2005. Nature, 437, 724-727.
21. Feineman, M., Ryerson. F., DePaolo, D., Plank, T., 2007. Chem. Geol., 239, OI:10.1016/j.chemgeo.2007.01.008.
22. Manning, C., 1998. SMPM, 78, 225-242.
23. Galvez, M., Beyssac, O., Benzerera, K., et al., 2012. Contrib. Mineral. Petrol., 164, 895-914.
24. de Ronde, C., Faure, K., Bray, C., Whitford, D., 2000. Econ. Geol., 95, 1025-1048.
25. Schmidt, M., Poli, S., 1998. Earth Planet. Sci. Lett., 163, 361-379.
26. Hacker, B., 2008. Geochem. Geophys. Geosyst., 9, DOI:10.1029/2007GC001707.
27. Wada, I., Behn, M., Shaw, A., 2012. Earth Planet. Sci. Lett., 353-354, 60-71.
28. Dragovic, B., Samanta, L., Baxter, E., Selverstone, J., 2012. Chem. Geol. 314-317, 9-22.

29. Penniston-Dorland, S., Sorensen, S., Ash, R., Khadke, S., 2010. Earth Planet. Sci. Lett., 292, 181-190.
30. John, T., Gussone, N., Podlachikov, Y., et al., 2012. Nature Geosci., doi:10.1038/NGEO1482, 489-492.
31. Tulloch, A., Kimbrough, D., 2003. Geol. Soc. Am. Sp. Paper, 374, 275-295.
32. Jackson, M., Gallagher, K., Petford, N., Cheadle, M., 2005. Lithos, 79, DOI:10.1016/j.lithos.2004.05.004.
33. Hacker, B., Kelemen, P., Behn, M., 2011. Earth Planet, Sci. Lett., 307, 501-516.
34. Lee, C., Morton, D., Little, M., et al., 2008. PNAS, 105, 4981-4986.
35. Massone, H., 2006. Mineral. Petrol., 86, 177-202.
36. Patterson, S., Miller, R., 1998. Tectonics, 17, 571-586.
37. Gordon, S., Bowring, S., Whitney, D., et al., 2010. Geol. Soc. Bull., 122, 1308-1330.

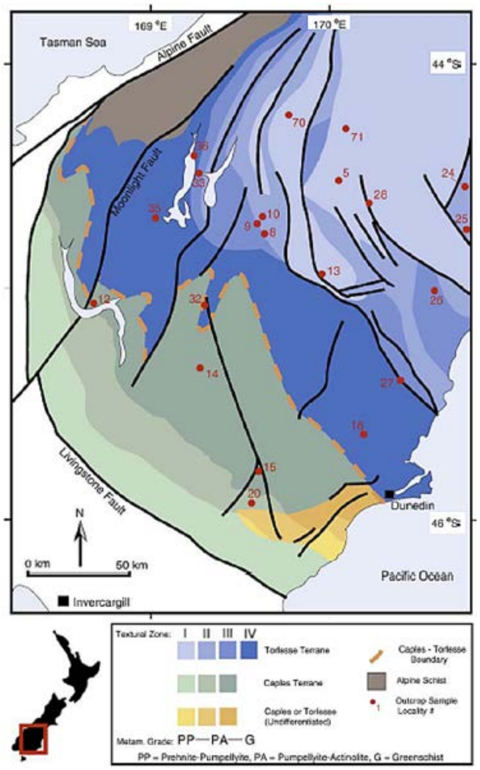


Figure 1A. Geologic map of the Otago Schist. [9].

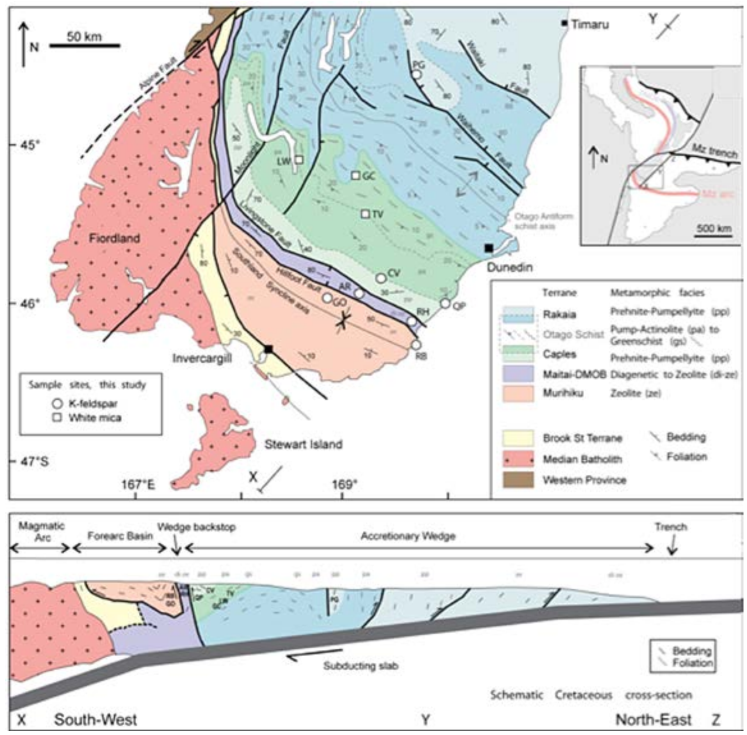


Figure 1B. Geol. map of the basement rock of NZ south. South Island. [3].

Linking fluid chemistry to mechanics and geophysical structure along the Hikurangi Margin

Susan Ellis[1], Dan Barker[1], Philip Barnes[2], Ake Fagereng[3], Francesca Ghisetti[4], Agnes Reyes[1], Demian Saffer[5], Laura Wallace[6], Achim Kopf[7], Jens Greinert[8], Ingo Pecher[9], Charles Williams[1], Katrina Marson-Pidgeon[1], Stuart Henrys[1], Andreia Plaza[1], Rachel Lauer[5], Rupert Sutherland[1], Martha Savage[10], John Townend[10],Tim Stern[10]

[1]GNS Science, L. Hutt, New Zealand; [2]NIWA, Wellington, New Zealand; [3]U. Cape Town, South Africa; [4]TerraGeologica, New Zealand; [5]Penn State U., USA; [6]U. Texas, Austin, USA; [7]MARUM Research Centre, University Bremen, Bremen, Germany; [8]GEOMAR Research Centre, Kiel, Germany; [9]School of Environment, U. Auckland, Auckland, New Zealand; [10]Victoria University, Wellington, New Zealand.

s.ellis@gns.cri.nz

GPS studies of elastic strain accumulation in the North Island show that the Hikurangi megathrust has a sharp along-strike depth transition from a shallow (<15 km) to deep (~35 km) downdip termination of interseismic locking from north to south [e.g., *Wallace et al., 2004; 2009*]. This transition accompanies other along-strike changes, including the depth of slow-slip events (SSEs) [see summary in *Wallace et al., 2009*], and a significant change in fluid residence times and mantle input from north to south [*Reyes et al., 2010; Figure 1a*]. The strongly locked southern Hikurangi margin is adjacent to a rapidly growing, gently sloping accretionary wedge, in comparison to the narrow, steep wedge in the north [e.g., *Barker et al., 2009; Figure 1b-c*].

To understand how these changes relate to each other, observations at different timescales from geophysics, geochemistry, and geology need to be integrated into models of subduction dynamics and fluid flow [*Figure 1d*]. There are several projects currently underway that attempt this type of model, including a Marsden that has been studying the effect of high fluid pressures around a seamount on frictional behaviour of the interface [*Williams et al., in prep*.] and a newly-funded 3-year Marsden grant using coupled fluid-mechanical models to investigate the cause of abrupt changes in locking depth along the Hikurangi margin.

A critical input for such models is an estimate of fluid budgets, which requires accurate estimates of fluid sources within subducting sediment and crust [see *Pecher et al., 2010*]. Up to 30 new samples of fluid chemistry from onshore springs and seeps are planned as part of one of the Marsden projects mentioned above. Such samples provide information on fluid residence times in the crust and fluid sources, which can be used to constrain fluid/mechanical models. There are also plans to measure changes in fluid chemistry and fluid pressure on slow-slip timescales as part of the proposed IODP riserless drilling project [*Saffer et al., 2011*]. Finally, plans are underway for the German RV SONNE and the MeBo seafloor drill to install flowmeters and osmo-samplers along the Hikurangi margin, and sample key locations (landslide scars, mud volcanoes and seeps) offshore. This will provide information on in situ flow rates and hence some idea about permeability, as well as a long-term record of fluid geochemical variations with time. When tied to proxies that work as geothermometers (e.g. B and its isotopes, which has been partly incorporated with hydrogeological models of accretionary wedges [e.g. *Saffer & Kopf, 2006*]), we can estimate the depth of fluid source origin and how rapidly these fluids migrate upward.

A key question when linking fluid-flow to mechanical models is: which fluid pressure variations along the Hikurangi margin are compatible with observed changes in fluid chemistry, wedge morphology, and locking depth along-strike? For example, there are two competing hypotheses to explain the along-strike locking depth change, which have clear and opposite predictions for fluid pressure variations: (1) permeability and upper plate tectonic stresses modulate the transition from locked to stable sliding by changing the depth at which brittle give way to viscous processes along the interface; and/or (2) high fluid pressures caused by subduction of fluid-rich sediments (possibly mediated by changes in interface roughness and/or rock properties [e.g., *Bell et al., 2010*]) reduce effective normal stress, promoting stable frictional slip. Hypothesis (1) is consistent with observed along-strike variations in fluid residence times and wedge morphology, but predicts less fluid overpressure to the north, which contradicts other geophysical observations [*e.g., Heise et al., 2012*].

As well as fluid budgets, the present-day geophysical structure [e.g., the recently acquired Sahke transect in the south; *Henrys et al., submitted*], thermal structure [e.g., *Harris et al., this volume*] and the thickness and mechanical properties of subducting sediments provide important constraints to model long-term wedge evolution along the Hikurangi Margin [e.g., *Underwood et al., this volume*]. Models of 2D and 3D wedge evolution in the past few million years can be constrained by decompacting and restoring tied seismic sections to create a time series of geological cross-sections. Key questions include: Which variations in fluid pressure along-strike are consistent with long-term wedge morphology and fluid chemistry? Is fluid pressure an important parameter to control wedge stability through time? Can sufficiently variable fluid pressure within and above the interface be created and sustained over long enough time periods to explain changes in wedge taper along-strike? On shorter time scales, questions to be addressed are: Are the fluid pressure transients or changes in fluid geochemical composition a precursor to seismic events? Does permeability change measurably during seismic events, and how do these changes evolve over time?

References:

Barker, D., Sutherland, R., Henrys, S., Bannister, S. 2009. Geometry of the Hikurangi subduction thrust and upper plate, North Island. New Zealand. *G-cubed*, *10*: Q02007.

Bell, R., Sutherland, R., Barker, D., Henrys, S., Bannister, S., Wallace, L., Beavan, J. 2010. Seismic reflection character of the Hikurangi subduction interface, New Zealand, in the region of repeated Gisborne slow slip events. *Geophysics Journal International, 180*(1): 34-48.

Harris, R., Trehu, A., Ellis, S., Henrys, S., Joshu Mountjoy, J., Barnes, P.,Pecher, I., Townend, J., and Wada, I., Heat Flow along the Hikurangi Margin, *Geoprisms White Paper*, this volume.

Heise, W.; Caldwell, T.; Hill, G.; Bennie, S.; Wallin, E.; Bertrand, E., 2012. Magnetotelluric imaging of fluid processes at the subduction interface of the Hikurangi Margin, New Zealand. *GRL*, *39*: doi:10.1029/2011GL050150.

Henrys, S. et al., submitted. SAHKE geophysical transect reveals crustal and subduction zone structure at the southern Hikurangi margin, New Zealand.

Reyes, A., Christenson, B., Faure, K., 2010. Sources of solutes and heat in low enthalpy mineral waters and their relation to tectonic setting: New Zealand, *J. Vol. Geoth. Res., 192*, 117–141.

Saffer, D.M., Kopf, A., 2006. Quantifying the source regions of observed pore water B and δ^{11}B signatures at shallow depths in forearcs. *EOS, Trans. AGU (Supplement).*

Saffer, D.M. et al., 2011. Unlocking the secrets of slow slip by drilling at the northern Hikurangi subduction margin, New Zealand: Riserless drilling to sample and monitor the forearc and subducting plate. IODP full propsl #781A.

Wallace, L., 20 others, 2009. Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand, *Geochem. Geophys. Geosyst., 10*, Q10006, doi:10.1029/2009GC002610.

Williams, C., Eberhart-Phillips, D., Bannister, S., Barker, D., Henrys, S., Reyners, M., Sutherland, R., submitted. Revised Interface Geometry for the Hikurangi Subduction Zone, New Zealand, submitted to *SRL*.
Williams, C., Ellis, S., Marson-Pidgeon, K., Henrys, S., Barker, D., in prep. The effect of pore fluid pressure variations on slip stability around seamounts: numerical models of slow slip along the northern Hikurangi subduction.
Underwood, M., Barnes, P., Mountjoy, J., Wallace, L., Saffer, D., Henrys, S., Ito, Y., Tobin, H., Kodaira, S., Bangs, N., Fagereng, A., Savage, H., Ellis, S., Torres, M.,Marsaglia, K., Drilling subduction inputs to the northern Hikurangi margin, New Zealand, *Geoprisms White Paper,* this volume.

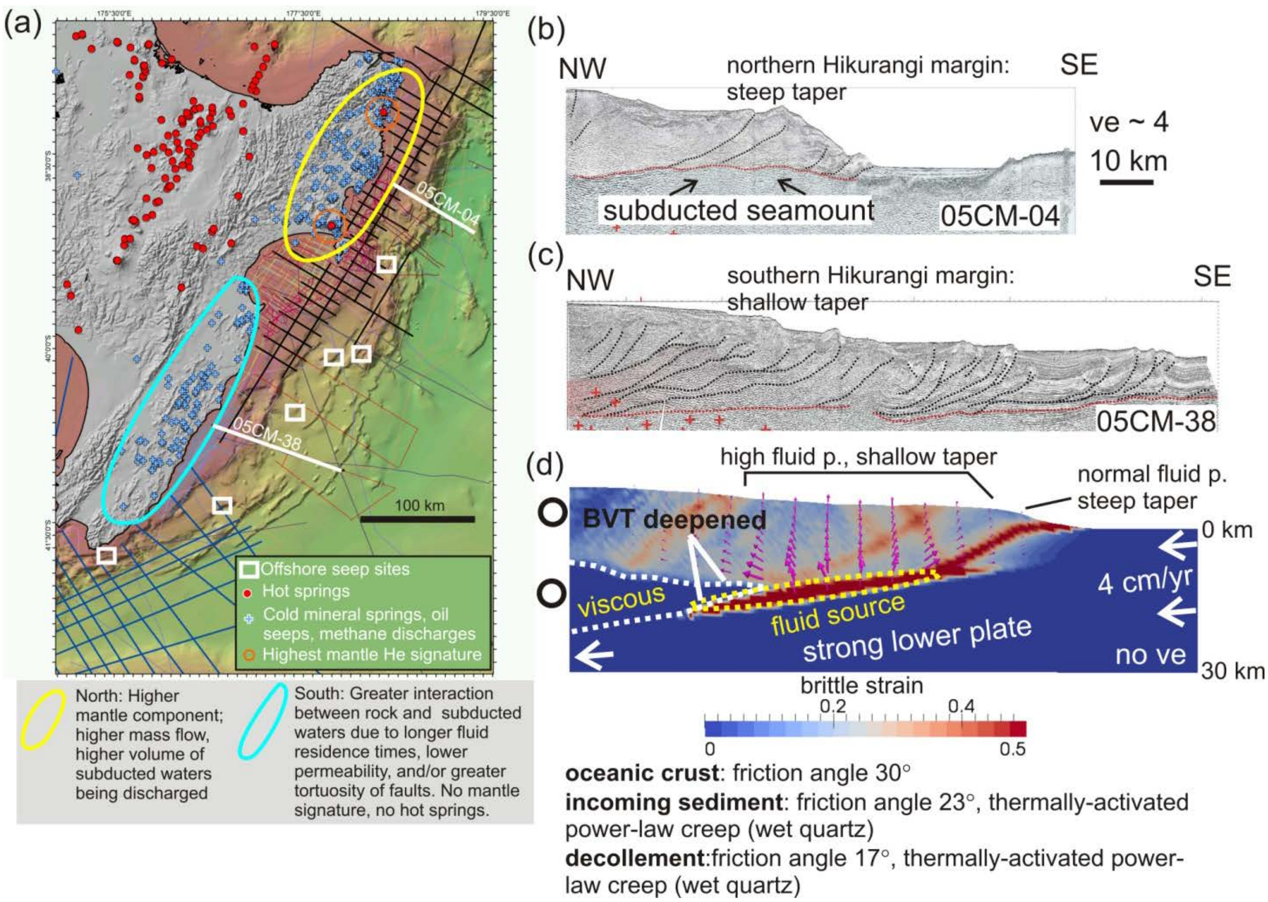


Figure 1.

GeoPRISMS Data Portal: New Zealand Primary Site

Andrew Goodwillie, and the GeoPRISMS Portal team

Lamont-Doherty Earth Observatory, Palisades, NY, 10960

andrewg@LDEO.columbia.edu

1) Introduction

The GeoPRISMS Data Portal of the Marine Geoscience Data System is funded by NSF as part of the IEDA Facility to provide data services to the GeoPRISMS community. For each GeoPRISMS primary site, the data portal has been populated with a range of existing high-priority terrestrial and marine data sets. For the New Zealand area, this includes, for example, links to the SAHKE and various Ewing/Rig Seismic multi-channel experiments. The portal offers tailored searches for GeoPRISMS-related data, and the GeoPRISMS bibliography seamlessly links papers to data sets and to funding awards.

GeoMapApp, Virtual Ocean and EarthObserver are map-based tools that provide rich data exploration, analysis and visualisation functionality (Figures 1 and 3).

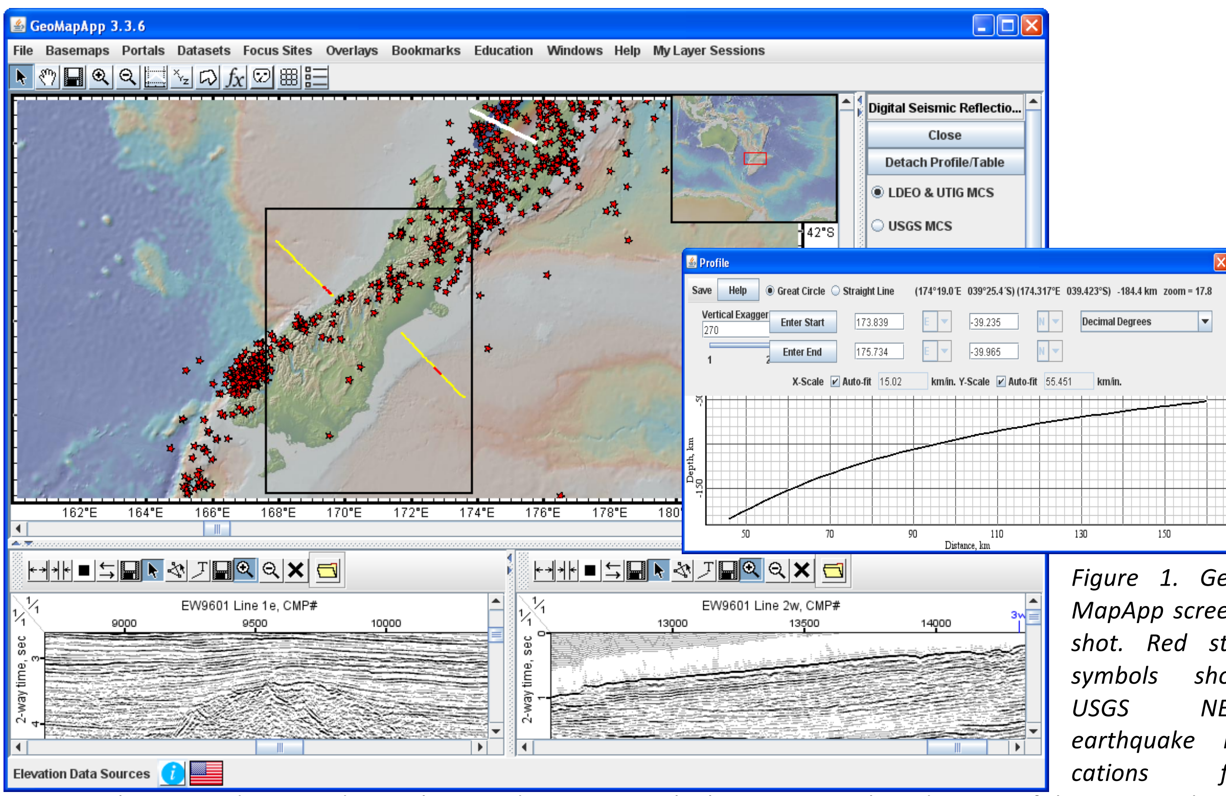


Figure 1. GeoMapApp screenshot. Red star symbols show USGS NEIC earthquake locations for events with magnitudes > 4.5 during the period 1973-2009. The locations are plotted on top of the 30m-resolution joint Japanese-US ASTER land elevation grid and the 100m Global Multi-Resolution Topography synthesis grid of the oceans. Yellow lines indicate positions of the two MCS profiles shown in the lower panes, for Ewing cruise EW9601, legs 1e and 2w. The white line near the top of the map shows the location of the profile shown right of centre giving depth to the top of the subducting interface, from Syracuse and Abers (2006). GeoMapApp images can be saved in various formats and users are able to import their own data sets such as grids and spreadsheets.

2) Services

- **Data Portal**

The GeoPRISMS data portal, like the predecessor MARGINS portal, is integrated with the wider Lamont database system and offers a compilation of pre-existing data sets of interest to the community. Links are provided to New Zealand-related projects such as the Seismic Array Hikurangi Experiment (SAHKE), and a simple search function, described below, provides user access to the data. The portal team will work with PIs, members of the community and the GeoPRISMS Office to ensure appropriate capture of marine and terrestrial field program information and derived data products.
http://www.marine-geo.org/portals/geoprisms/

- **Search for Data**

Data can be found (Figure 2) by searching on key words such as data or device type, name of field program or investigator, by geographic location, and even by award numbers. Filtered searches and auto-complete technology help speed users towards data.
http://www.marine-geo.org/tools/new_search/index.php?initiative=GeoPRISMS

Expedition/ Compilation	Platform Name	Start/Stop Date	Lead Investigator	References
NewZealand:SAHKE ▶Data Set(s)	Not Supplied	2009-11-01 2011-12-31	Stern	Henrys et al., 2010 Sutherland et al., 2010 Mochizuki et al., 2010
EW0001 ▶Data Set(s)	*Maurice Ewing*	2000-01-09 2000-01-28	Fulthorpe	▼Program References Lu, 2004 Lu et al., 2003
EW9601 ▶Data Set(s)	*Maurice Ewing*	1996-02-07 1996-03-13	Henyey	▼Program References Greenroyd et al., 2003 Davey et al., 1998 Harrison, 1999 Okaya et al., 2002

Figure 2. Example of data portal search results listing. Links at left take users to data sets in the IRIS and Lamont-UTIG databases and to information about the field programs. Links at right allow users to view publications tied with the data sets.

- **Data Visualisation and Exploration**

GeoMapApp and Virtual Ocean offer a rich variety of options for users to plot, analyse and visualise their data in a geographical setting (Figures 1 and 3). EarthObserver, a recently-released app for the iPad™, iPod Touch™ and iPhone™ offers instant mobile access to a large range of built-in data sets.
http://www.geomapapp.org/, http://www.virtualocean.org/, http://www.earth-observer.org/

- **Bibliography**

  The integrated, searchable GeoPRISMS bibliography contains all references from the GeoPRISMS Science Plan, bringing the total citations to more than 600, with papers tied to associated data sets and to funding awards. Searching can be done by primary site, paper title, author, year, and journal. The lists of publications can also be exported to EndNote™. To help grow the number of relevant citations, community members can submit reference information using a handy web form linked to the bibliography web page.
  http://www.marine-geo.org/portals/geoprisms/references.php

- **Data Management Plan Tool**

  To help investigators with their NSF proposal submission, the on-line data management plan form can be quickly filled in, printed in PDF format and attached to a proposal. http://www.iedadata.org/compliance/plan

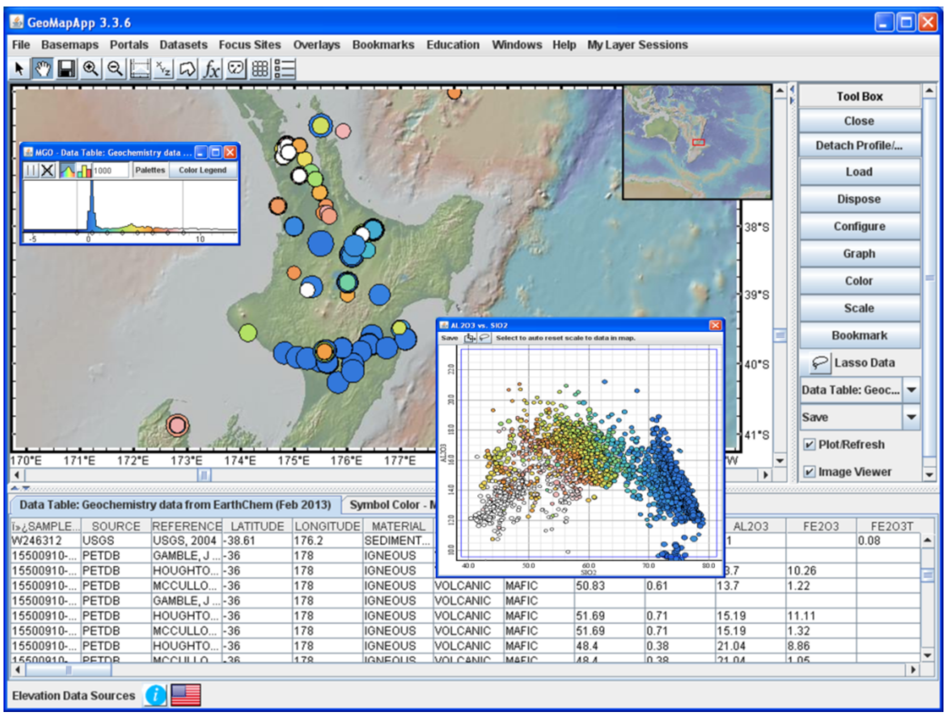


Figure 3. Geochemical analytical data of New Zealand North Island volcanic rock samples from the EarthChem database, as of February 2013. Symbols are coloured on MgO content, scaled on K_2O, and the inset graph shows Al_2O_3 plotted against SiO_2. A lasso tool allows records to be captured and saved.

3) Data Policy

Led by Susan Schwartz, the GeoPRISMS data policy was compiled by a sub-committee of the GeoPRISMS Steering and Oversight Committee, with input from NSF and the database group. http://www.geoprisms.org/data-policy.html

4) Community Outreach and Accountability

A representative from the database group attends most GeoPRISMS meetings to act as a community liaison, to increase awareness about the data portal services, and to solicit feedback and advice on products and resources. A report on database activities appears in the GeoPRISMS twice-yearly newsletter, and, at each GeoPRISMS Steering and Oversight Committee meeting, a report is given and data-related discussions held.

The GeoPRISMS data manager, Andrew Goodwillie, and the database team are keen to help the community with questions related to data, analysis tools or the GeoPRISMS bibliography.

5) References

GeoPRISMS Data Portal Status Report, *GeoPRISMS Newsletter*, Fall 2012, vol 29, page 18. http://www.geoprisms.org/images/stories/documents/newsletters/Issue%2029.pdf

Syracuse, E.M. and G. A. Abers (2006), Global compilation of variations in slab depth beneath arc volcanoes and implications. *Geochem. Geophys. Geosyst*., **7**(5), doi: 10.1029/2005GC001045.

Resolving Fundamental Questions of Subduction Initiation in New Zealand

Mᡅᢙŝ Gurnis[1], RdzLJŜǋǘ Sutherland[2], SŜl·ƴ S. Gulick[3], Hl·ǋϒ J. Van Avendonk[3], JdzfᡅŜƴ /ƻffƻǘ[4], Fǋl·ƴœƻᡅă Bache[2], PᡅŜǋǋᡅŎᢙ Rouillard[5] Ǝ and Jƻl·ƴƴ M. Stock[1]

[1]*Seismological Laboratory, Caltech, Pasadena, CA;* [2]*GNS, Wellington, NZ;* [3]*UTIG, University of Texas, Austin, TX;* [4]*DIMENC, Nouméa, New Caledonia;* [5]*ADECAL, Nouméa, New Caledonia*
gurnis@caltech.edu

Resolving fundamental questions on the nature, history and dynamics of subduction initiation (SI) is a central theme of the *GeoPrisms* and *IODP* science plans. New Zealand has two of only a handful of well-preserved examples of SI – a nascent subduction to the south (Puysegur-Fiordland), and a fully developed system intimately related to a global change in plate motion to the North (Tonga-Kermadec). Targeted observations in each region will constrain geodynamic parameters and provide insights that will underpin new types of models.

Subduction Initiation. Initiation of subduction and changes in plate motion are linked, as the largest driving and resisting forces associated with plate tectonics occur within subduction zones. By far the largest change in Pacific plate (PAC) kinematics since 80 Ma is manifest as a bend in the Emperor-Hawaii seamount chain. A westward swerve in Pacific plate motion occurred at about the time subduction zones initiated throughout the western Pacific. It follows that clarifying what happened in the western Pacific during Eocene time is likely to lead to fundamental insights into SI and the general physics of plate tectonics. There are two widely held views: either subduction initiates spontaneously or it has to be induced (Stern, 2004; Gurnis et al, 2004). In the spontaneous model, oceanic lithosphere ages, thickens, increases in density, and eventually sinks into the mantle under its own weight. In the induced model, externally applied compressive stresses are necessary to overcome the strength of the lithosphere and pre-existing faults before subduction can be induced.

Geochronology shows that the bend in the Emperor-Hawaii seamount chain started at ~50 Ma and may have occurred over a period of ~8 Myr (Sharp and Clague, 2006). The onset of plate motion change corresponds with the timing of Pacific-Farallon plate boundary rearrangement and termination of spreading in the Tasman Sea. This reorganization was followed by a change in direction and rapid increase in rate of Australia (AUS)-Antarctic spreading with consequent northward acceleration of Australia and initiation of Australia-Pacific spreading southwest of New Zealand. Reconfiguration of plate boundaries in Antarctica, the Indian Ocean, and Asia reveal the truly global nature of this phase of tectonic change.

Most work on SI has focused on initiation of Izu-Bonin-Mariana (IBM) subduction, which was synchronous with the change in Pacific Plate motion at ca. 50 Ma. The early arc was dominated by boninitic volcanism, which requires a high degree of partial melting of a source depleted in major elements but enriched in volatiles (Stern and Bloomer, 1992). Samples recovered from the Mariana forearc and ~1,500 km farther north near the Bonin islands reveals a volcanic stratigraphy containing basalts, similar to mid-ocean ridge basalt (MORB), that were the first to erupt in the nascent arc (52-49 Ma), which were then quickly followed by boninites (49-45 Ma), and then by normal arc lavas within several million years (Reagan *et al*., 2010; Ishizuka *et al*., 2011). IBM is a natural laboratory to constrain models of SI and distinguishing between spontaneous and induced models is a central goal of upcoming IODP Expedition 351. However, there are limitations of the IBM example. First, the relative motion between the Philippine Sea Plate and PAC during the Eocene is unknown. Second, because the subduction zone has long transitioned from nascent to self-sustaining SI, we do not know the mechanics and structural evolution of the Pacific plate as it first started to subduct. Third, the intra-oceanic deep-water setting of IBM results in a highly-condensed sedimentary record of events. These issues are minimized around New Zealand, and indeed the Tonga-Kermadec example is part of the same 50 Ma SI event as IBM.

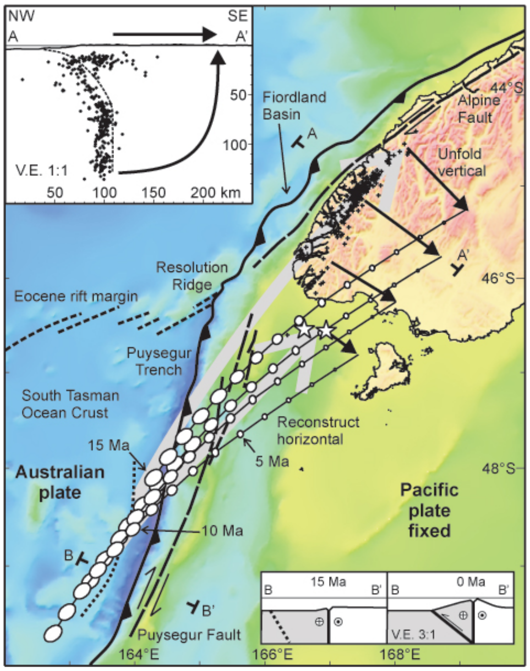
Puysegur-Fiordland. The Puysegur-Fiordland subduction zone forms the northern extremity of the transpressional AUS-PAC plate margin south of New Zealand. Although juvenile, and potentially not yet a self-sustaining subduction zone, the margin is characterized by convergence, a trench (gravitationally and bathymetrically), a Benioff zone (down to 170 km depth, Fig. 1 inset), and sparse, young calc-alkaline volcanism on the overriding Pacific plate. Previous geophysical surveys demonstrate that the morphology of Puysegur Ridge, a bathymetric high on the overriding Pacific plate, immediately east of the trench, shows a characteristic change from uplift to subsidence with increasing AUS-PAC convergence. This proximal change in vertical motion precedes the change in overall dynamic state of the incipient subduction zone. The segment associated with greatest convergence (≈ 200 km) is associated with a highly-anomalous gravity signal. An approximately -100 mGal free air anomaly is associated with a relative bathymetric high and suggests that there is a strong vertical force pulling downward on the Puysegur Ridge, consistent with the history inferred from geomorphology. Comparison of these features with geodynamic models, strongly suggests that the margin is making a transition from forced to a self-sustaining subduction. No other subduction zone is in this critical state; this area thus presents us with a unique observational target to measure parameters that are fundamental to the geodynamics. These key parameters could be obtained with a well-designed geophysics cruise involving seismic reflection & refraction, bathymetry, gravity and magnetics. Understanding the force balance along Puysegur Ridge and how the slab-pull force is coupled into the over-riding plate requires a refined gravity and mechanical model, and hence measurement of the crustal thickness and the geometry of the slab. We hypothesize that a strengthening of the slab-pull force causes subsidence along the ridge. Existing, but low-resolution seismic-reflection data suggest that the region is relatively transparent for a subduction zone and indicates that modern MCS and refraction data would easily detect subducting oceanic crust. Forward modeling of well-designed seismic source-receiver configurations shows that one would be able be able to measure the dip and other features of the slab (Fig. 2). We know of no other comparable region where such a set of measurements could be made at this critical phase of SI.

Tonga-Kermadec (TK). Records of SI are rarely well preserved, because of subsequent tectonic and volcanic disruption, but TK SI occurred near the margin of thinned continental crust (Norfolk Ridge, Lord Howe Rise) that was tectonically isolated by subsequent backarc spreading. Persistent Cenozoic submarine conditions led to continuous sedimentation in many places. Cessation of spreading in the Tasman Sea at 52-50 Ma and deformation of New Caledonia with a peak of high-pressure metamorphism at 44 Ma provides a direct temporal link between southwest Pacific events, IBM, and the Emperor-Hawaii bend. Australia-Pacific plate motions are precisely known since 44 Ma (Fig. 3) from ocean crust created at the southern end of the boundary, and via plate closure calculation (Cande and Stock, 2004; Sutherland, 1995). Eocene convergence rates varied from <1 cm/yr in New Zealand to 10 cm/yr near New Caledonia.

Seismic-reflection data (Fig. 4) reveal stratal records of Eocene change, including evidence for distal (>300 km) km) minor compression and >1 km of uplift-subsidence, and proximal uplift-subsidence of Norfolk Ridge and deep-water sedimentary basin formation in the New Caledonia Trough. The stratigraphic records of compression and vertical motions provide a unique opportunity to understand with high precision the temporal and spatial context of large-scale SI through geophysical surveys tied to IODP drilling. New seismic-reflection lines are needed to supplement a large recently-released dataset and hence define drilling targets, and transects of boreholes are needed to understand along-strike and proximal-distal relationships. These would be achieved through cruise TECTA (Tectonic Event of the Cenozoic in the Tasman Area) and the dredging cruise VESPA (Volcanic Evolution of the South Pacific), both currently ranked priority 1 by the French National Oceanographic Fleet Committee for 2014 / 2015. The primary goals of the seismic, dredging and drilling would be: to establish the regional timing and magnitude of deformation, uplift, and subsidence, to constrain the SI process; and to relate TK and IBM events to global plate motion changes and the evolution of global plate-driving forces.

References:

Cande, S. C., and Stock, J.M., 2004, GJI, 157, 399-414; Gurnis, M. et al. 2004, G^3, 5, doi:10.1029/2003GC000681; Ishizuka, O et al., 2011, EPSL 306, 229-240; Reagan, M. K., et al., 2010, G^3 11, Q03X12, doi:10.1029/2009GC002871; Sharp, W.D., and Clague, D.A., 2006, Science, 313, doi: DOI: 10.1126/science.1128489; Steinberger, B., et al., 2004, Nature, v. 430, p. 167-173. Stern, R. J. and Bloomer, S. H., 1992, Geol. Soc. Am. Bull. 104, 1621-1636. R. Stern, 2004 , EPSL 226, 275-292; Sutherland, R., 1995, Tectonics, 14, p. 819-831; Sutherland et al. 2009.Geosphere 5, 409–425; Sutherland, R., et al., 2010, Tectonics, 29 doi: Tc200410.1029/2009tc002476.



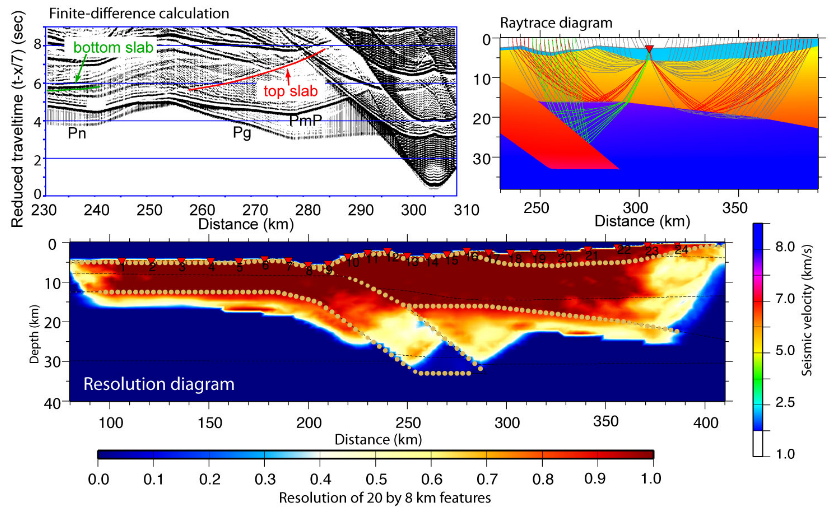
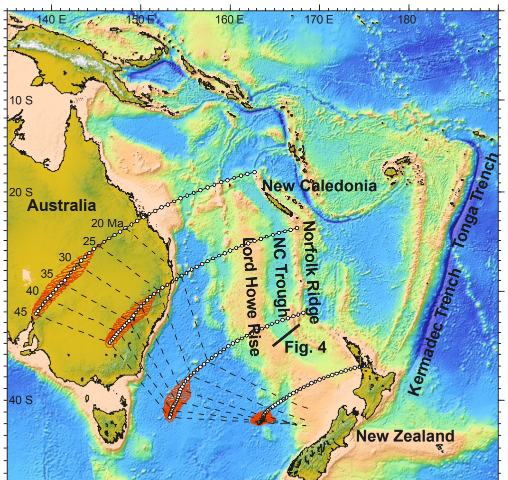


Figure 1. (above left) Unfolding and reconstructing Fiordland subduction. Crosses on the map are epicentres of earthquakes with hypocentral depth >50 km. Crosses on section A-A' are earthquake hypocentres within 40 km of section A-A'. Stars show young volcanic features, inferred to be sourced from near the top of the subducted slab at c.70 km depth. Bold arrows represent the effect of unfolding the subducted plate, restoring it to the Earth's surface with down-dip line length preserved. Sequential ellipses are the reconstructed point interpolated every 1 Ma using AUS-PAC motion. From Sutherland et al. (2009)

Figure 2. (above right) Proposed OBS array across Puysegur Trench and Puysegur Ridge. Finite-difference simulation shows turning waves (Pg and Pn), reflections from Moho, and top and bottom of oceanic crust in the subducting slab should be visible in data east of the trench. Resolution test for refracted and reflected phases between airgun and 24 OBS locations confirms that a subducting slab could be detected using OBS travel time inversion.



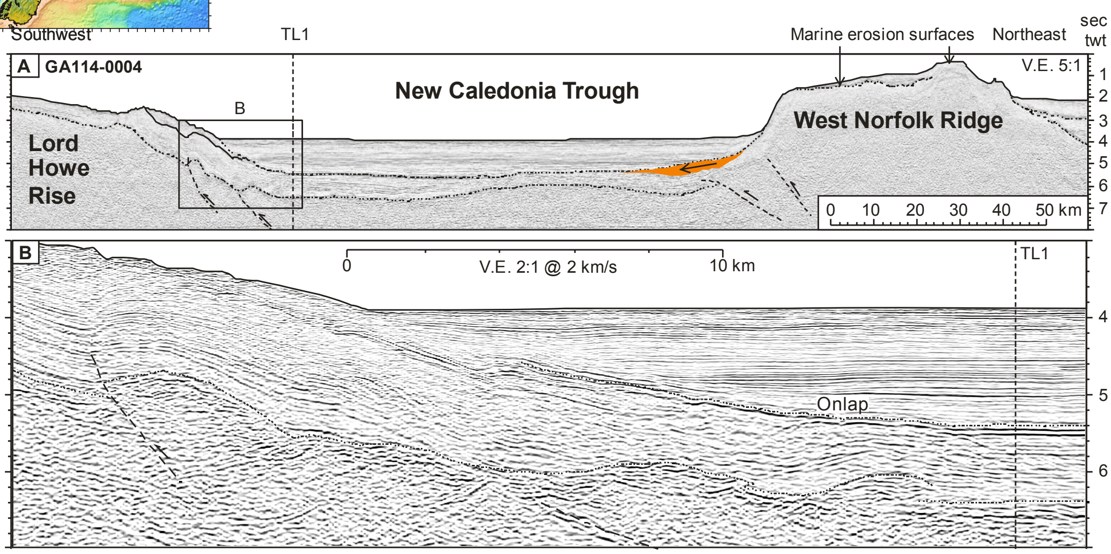


Figure 3. (above) Reconstruction of selected Australian plate points relative to a fixed Pacific plate. Note much higher convergence rates near New Caledonia (NC) shortly after subduction initiation (45-25 Ma). **Figure 4.** (right) Seismic section showing deformation, uplift of Norfolk Ridge (marine planation), with subsequent subsidence, and infilling of the New Caledonia Trough.

Heat Flow along the Hikurangi Margin

Robert N. Harris[1], Anne M. Trehu[1], Susan M. Ellis[2], Stuart Henrys[2], Joshu Mountjoy[3], Philip Barnes[3], Ingo Pecher[4], John Townend[5,] and Ikuko Wada[6]

[1] College of Earth, Oceanic, and Atmospheric Sciences, Oregon State Univ. Corvallis, Oregon, USA; [2]GNS Science, Lower Hutt, New Zealand; [3]NIWA, Wellington, New Zealand; [4]School of Environment, University of Auckland, New Zealand; [5]School of Geography, Environment and Earth Sciences, Victoria Univ. Wellington, New Zealand; [6]International Research Institute of Disaster Science, Tohoku University

rharris@coas.oregonstate.edu

The thermal regime and hydrology of convergent margins play an important role in the evolution, structure and deformation of the margin, the nature of the seismogenic zone and for the generation of slow slip events (SSEs). Over the past few decades New Zealand Earth scientists have collected a vast quantity of data focusing on the Hikurangi margin and subduction zone (Figure 1). These data demonstrate the presence of significant along-strike variations in the seismogenic zone, distribution of SSEs, interseismic coupling, offshore margin structure, seismic velocity and attenuation structure, and geochemistry of fluids emerging at the surface among other properties (Figure 1c) [e.g., *Wallace et al.*, 2009; *Reyners et al.*, 2006; *Wallace & Beavan*, 2010; *Reyes et al*., 2010]. Currently, our understanding of the Hikurangi margin and its along strike variations is fundamentally limited by a lack of knowledge of the thermal regime. No systematic heat flow measurements to understand the tectonics of this margin have been made. Observations of seafloor heat flow are needed to provide direct constraints on subseafloor thermal conditions, and on model constraints to estimate the temperature structure along the subduction fault, pathways and vigor of fluid flow, and a wide range of geophysical, geochemical, and petrologic processes at depth.

We are proposing to collect heat flow measurements and additional seismic reflection data in the northern and southern Hikurangi margin segments to understand differences in the distribution and styles of deformation (Figure 1). The northern area is associated with an aseismic creep-dominated subduction interface and is the site of repeated shallow (< 15 km depth) SSEs [*Wallace & Beavan*, 2010], and historic tsunami earthquakes that nucleated near the trench (Ms 7.0-7.2 in March and May, 1947 [*Doser & Webb*, 2003]). Additionally this area is the focus of a proposed IODP drilling transect with the primary objective of intersecting the source area of SSEs, and is also within a proposed OBS array.

The southern Hikurangi field area contrasts strongly with the northern field area. Here SSEs are deep (> 40 km) and geodetic studies indicate deep interseismic coupling on the plate interface. Heat flow transects can be collected along the passive and controlled source onshore-offshore Seismic Array HiKurangi Experiment (SAHKE [*Henrys et al., 2010*]) designed to image the forearc structure and understand physical processes controlling locking along this portion of the Australian-Pacific plate boundary and along the wide-angle multi-channel Pegasus line 023 [*Geotrace*, 2010] designed to detect hydrocarbons.

Global databases of heat flow show only two measurements offshore the Hikurangi margin. Eleven measurements of heat flow exist onshore. North of Hawke Bay heat flow values are between 80 and 50 mW m^{-2} and south of Hawke Bay heat flow values are somewhat lower at 40-45 mW m^{-2}. Heat flow has been estimated from bottom simulating reflectors (BSRs) which are widely observed along the margin [*Townend*, 1997a; *Henrys et al*., 2003]. These analysis show that, in general, heat flow is nearly constant along strike, ranging between about 40 and 50 mW m^{-2} and decreasing landward consistent with the downward advection of heat and thickening of the margin. In a local methane hydrate study, marine probe values of heat flow were collected offshore the south coast of the North Island [*Schwalenberg et al.*, 2010]. These probe values of heat flow vary between 35 and 50 mW m^{-2} and are generally 5-10 mW m^{-2} higher than the BSR values of heat flow. Discrepancies between these analyses may be due to the use of empirical margin-wide velocity traveltime functions, uncertainties in thermal conductivity [*Pecher et al*., 2010] and/or the impact of sedimentation.

References:

Doser, D. I., and Webb, T. H., 2003. Source parameters of large historical (1917 – 1961) earthquakes, North Island, *New Zealand, Geophys. J. Int., 152*, 795 – 832, doi:10.1046/j.1365-246X.2003.01895.x.

Geotrace, 2010. Peagus, Bounty Trough, Great South Basin and Sahke Processing Report. Ministry of Economic Development New Zealand Unpublished Petroleum Report PR4279Rep.

Henrys, S. A., Ellis, S., and Uruski, C., 2003. Conductive heat flow variations from bottom-simulating reflectors on the Hikurangi margin, *New Zealand, Geophys. Res. Lett. 30*, doi:10.1029/2002GL015772.

Henrys, S., Sutherland, R., Seward, A., Henderson, M., et al., 2010. The 2009-10 SAHKE Experiment: Acquisition and Preliminary Results Across the Interseismically Locked Southern Hikurangi Margin, New Zealand, in Abstract T51D-2078, 2010 Fall Meeting, edited, AGU, San Francisco, Calif., 13-17 Dec.

Pecher, I. A., Henrys, S. A., Wood, W. T., Kukowski, N., et al., 2010. Focused fluid flow on the Hikurangi Margin, New Zealand - evidence from possible local upwarping of the base of gas hydrate stability. *Mar. Geol. 272*, 99–113, doi:10.1016/j.margeo.2009.10.006.

Reyes, A. G., Christenson, B. W., and Faure, K., 2010. Sources of solutes and heat in low enthalpy mineral waters and their relation to tectonic setting: New Zealand, *J. Vol. Geotherm. Res., 192*, 117–141, doi:10.1016/j.jvolgeores.2010.02.015.

Reyners, M., Eberhart-Phillips, D., Stuart, G., and Nishimura Y., 2006. Imaging subduction from the trench to 300 km depth beneath the central North island, New Zealand, with Vp and Vp/Vs, *Geophys. J. Int., 165*, 565–583, doi:10.1111/j.1365-246X.2006.02897.x.

Schwalenberg, K., Wood, W., Pecher, I., Hamdan, L., et al., 2010. Preliminary interpretation of electromagnetic, heat flow, seismic, and geochemical data for gas hydrate distribution across the Porangahau Ridge, New Zealand, *Mar. Geo., 272*, 98-98, doi:10.1016/j.margeo.2009.10.024.

Townend, J., 1997. Estimates of conductive heat flow through bottom-simulating reflectors on the Hikurangi Margin and southwest Fiordland, New Zealand, *Mar. Geol., 141*, 209–220.

Wallace, L. M., and Beavan, R. J., 2006. A large slow slip event on the central Hikurangi subduction interface beneath the Manawatu region, North Island, New Zealand, *Geophys. Res. Lett., 33*, L11301, doi:10.1029/2006GL026009.

Wallace, L. M., Reyners, M., Cochran, U., S. Bannister, Barnes, P. M., et al., 2009. Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand, *Geochem. Geophys. Geosyst., 10*, Q10006, doi:10.1029/2009GC002610.

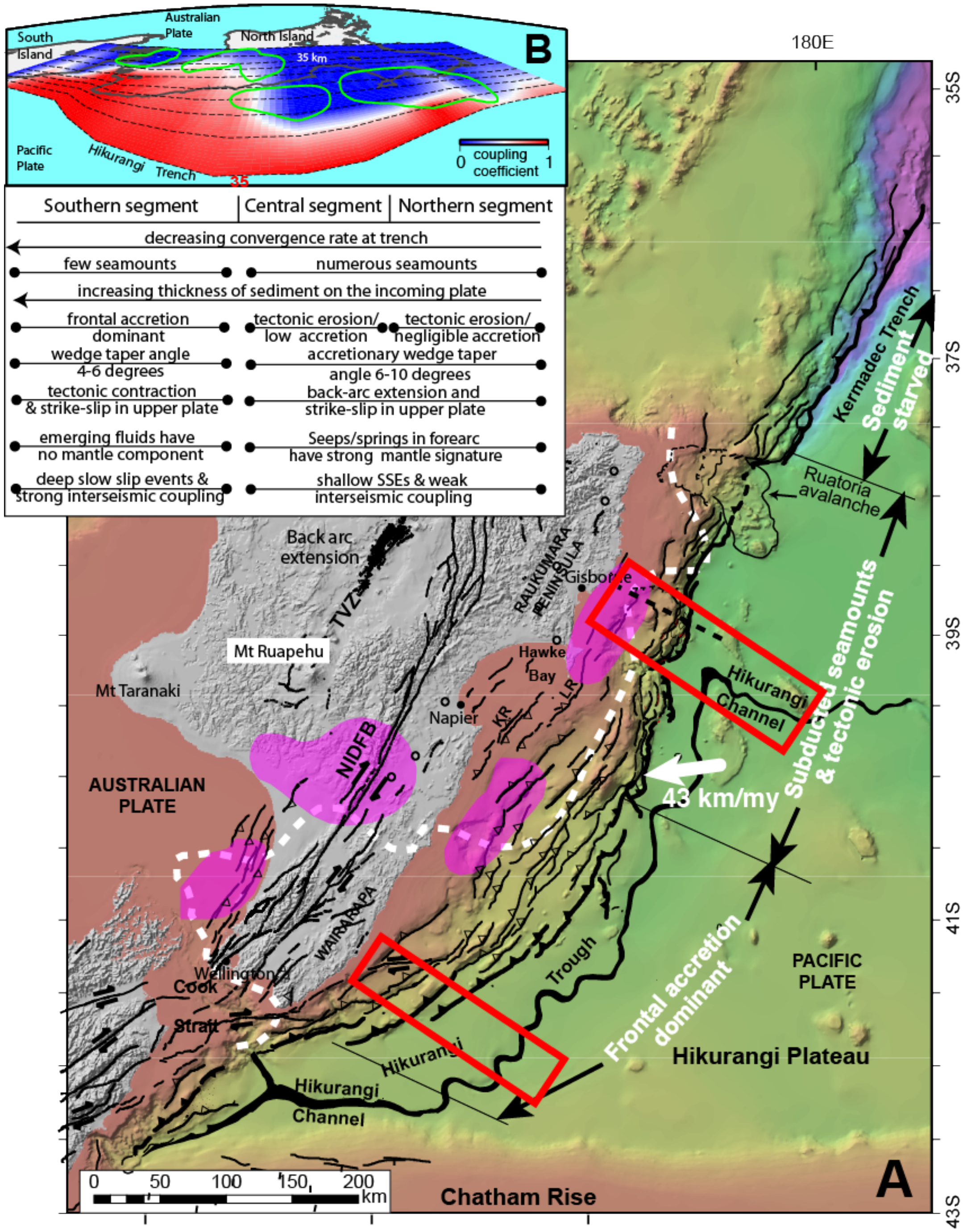


Figure 1. Overview and tectonic setting of the Hikurangi margin, New Zealand [modified from Barnes et al., 2010]. A) Bathymetry, topography, and active faulting of the onshore and offshore margin. White arrow shows plate converge rate and azimuth. Bold white dashed line shows position 20 mm yr^{-1} slip deficit [Wallace et al., 2004]. Magenta areas show region of observed slow slip events. The position of strong coupling is between this contour and the deformation front. Red rectangles show proposed north and south heat flow areas. B) Perspective view of Hikurangi margin [modified from Wallace and Beavan, 2010] illustrating the portions of the subduction interface that undergo stick-slip and aseismic slip in terms of the coupling coefficient. Coupling coefficients of one indicate locked areas and coefficients near zero indicate regions of steady aseismic slip. Green contours show areas slow slip events since 2002. Along strike variations in convergent margin properties are summarized below the plot.

Imaging the Southern Hikurangi Margin locked subduction interface and upper plate by passive and active seismic and magnetotelluric arrays

Stuart Henrys[1], David Okaya[2], Hiroshi Sato[4], Tim Stern[3], Marth Savage[3], John Townend[3], Grant Caldwell[1], Wiebke Heise[1], Stephen Bannister[1], Bill Fry[1], Rupert Sutherland[1], Aaron Wech[1]

[1]GNS Science, Lower Hutt, New Zealand; [2]University of Southern California; [3]Victoria University of Wellington; [4]Earthquake Research Institute, University of Tokyo

s.henrys@gns.cri.nz

Subduction zones produce the largest earthquakes and tsunamis on Earth, as evidenced by the 2011 Tohoku Mw 9.0 earthquake (Simons et al., 2011) and 2004 Sumatra Mw 9.3 earthquake (Ammon et al., 2005; Lay et al., 2005). The fault slip behaviour on subduction thrust faults varies greatly between subduction zones, and along-strike at the same subduction zone. The Hikurangi subduction system in North Island, New Zealand, has not experienced a M8+ megathrust earthquake in historical times but, exhibits a range of slip conditions, from aseismic to strongly coupled, with strain release by coseismic, slow slip, and repeating microseismic events (Wallace et al., 2010). Multi-disciplinary studies reveal the complex interplay between upper and lower plate structure, subducting sediment, thermal effects, regional tectonic stress regime, and fluid pressures all contribute to interface behaviour (Wallace et al., 2010). The fact that the locked part of the interface is under land makes this region an ideal location to target a range of geophysical observations to determine physical parameters that control locking on the Hikurangi plate interface and to determine geometrical relationships with upper crustal faults.

We undertook a controlled-source and passive (earthquake) seismic imaging experiment in the Wellington region in 2009-2011 (Henrys et al., submitted). The Seismic Array HiKurangi Experiment (SAHKE, Fig. 1) imaged the plate interface beneath southern North Island with onshore-offshore marine active-source seismic data from three sides, onshore shots, and local and teleseismic earthquakes. Onshore-offshore wide-angle seismic-reflection and refraction data constrain a detailed 2D tomographic model of P-wave structure across a transect of the southern Hikurangi margin orthogonal to the Australia/Pacific plate boundary. This model places constraints on key parameters such as Moho geometry, subducting slab geometry and forearc structure, which may modulate the location of plate coupling. Furthermore recent magnetotelluric (MT) data shows that an electrically conductive layer of underplated sediment is present at the interface in the weakly coupled region (Heise et al., 2012) but may be absent in the locked region.

The relationship of locked zone properties to upper crustal structures and seismicity together with the relationship to slow slip events that occur down dip of the locked zone, however, remain unknown. The existing SAHKE data were not designed to capture this level of detail nor is the regional GeoNET seismic networks capable of detecting seismicity associated with SSEs. Specifically we advocate complimentary seismic and MT observations (Fig) that include: **(1)** Reoccupying the temporary SAHKE transect 3C stations for a 12 -18 month period comprising 300 stations spaced 300 m apart; **(2)** augmenting this 2D array with small 3D (100 m spacing) and large regional (10 km spacing) arrays; **(3)** instrument some of the 50 m SAHKE shot holes with borehole seismographs; **(4)** complete E-W MT profile co-located with the SAHKE transect and collect lines perpendicular to the subduction margin; **(5)** acquire high-resolution seismic reflection lines across accessible parts of the lower North Island that cross Wellington and Wairarapa Faults .

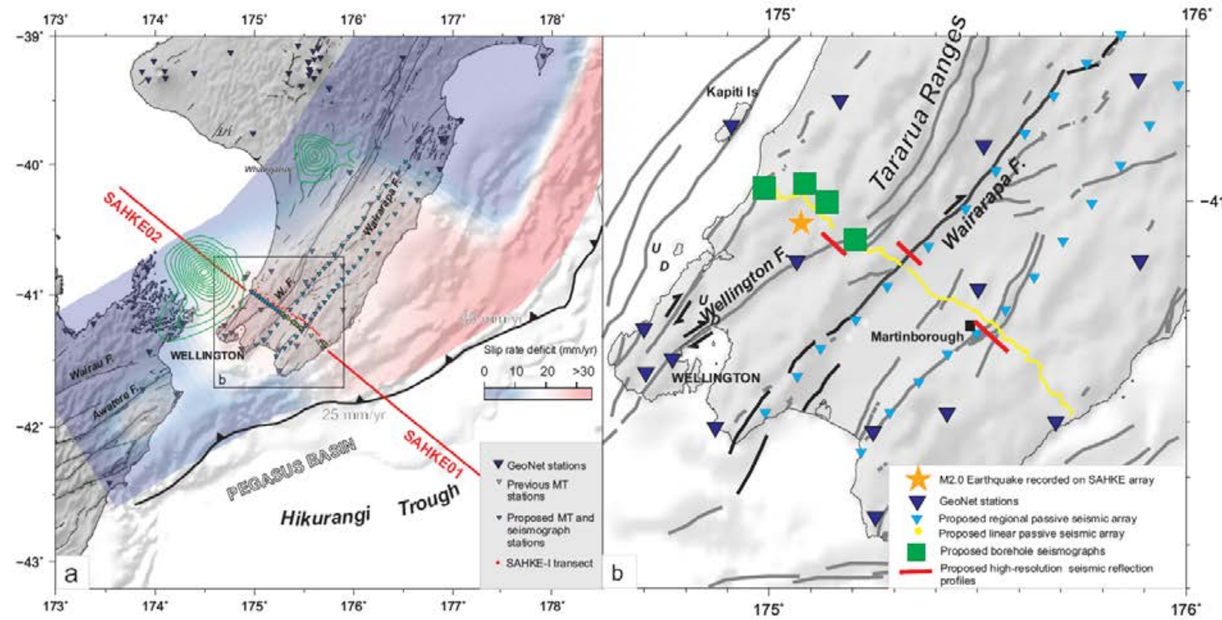


*Figure 1. Tectonic setting showing major active faults of the southern North Island of New Zealand and location of SAHKE experiments. (**a**) Slip rate deficit distribution at the plate interface (Wallace et al., 2012). Green contours show cumulative slip (mm) in slow-slip events (SSEs) during 2002-2010. Red regions are where the plate interfaced is locked.. SAHKE01 and SAHKE02 (red lines) recorded onshore by the transect deployment (red dots). Inverted blue triangles indicate the locations of permanent National Network and Wellington regional network monitored by GeoNet. Thin black lines denote active faults: W.F.=Wellington fault. previous MT stations (green inverted triangles) and proposed (blue) together with regional passive seismograph. Numbers indicate convergence rate at the Hikurangi Trough (in mm/yr) (Wallace et al., 2012). (**b**) Location of proposed linear passive seismometer array (yellow points; space 300 m apart) co-located with stations deployed during SAHKE. Green filled boxes show the locations of the 4 borehole seismographs. Blue inverted triangles proposed regional seismograph array and MT stations. Orange star is location of M2.0 earthquake located at 26 km depth and recorded on SAHKE array (Fig. 2).*

The closely spaced seismic arrays will allow passive imaging array techniques to be applied to the earthquake data and enable us to explore down dip variation in fault properties. For example a M2.0 located at 26 km depth beneath the SAHKE array is shown in Fig. 2. The hypocenter is just above the slab interface and the array has successfully captured reflected P and S-wave slab phases. The regional seismic array will allow us to investigate the along strike changes in seismicity and whether this relates to the transition from locked to unlocked part of the plate interface. Borehole seismometers should allow us to improve detection threshold of local earthquakes, improve our chances of finding and locating micro-seismicity and tremor, and potentially provide information on the relationship of SSEs and seismicity. High resolution seismic reflection data will be integrated with SAHKE data to improve knowledge of the geometry of upper crustal faults that splay from the subduction interface. Finally MT data will be used to construct a 3D conductivity image of the locked plate interface and compared to the P-wave velocity and seismic images.

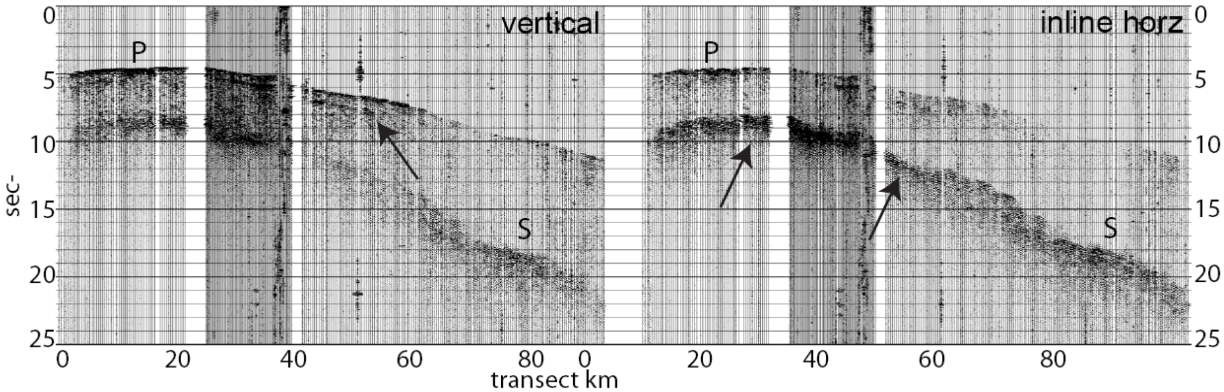


Figure 2. Local earthquake collected into SAHKE transect. 3-C stations have 300 m spacing with 150 m densification in the middle. Magnitude 2.0 earthquake is at 26 km depth, just above the slab interface. Sharp secondary P event may be associated with interface or subduction-related structure at base of overlying plate. S-waves exhibit lateral variation in first and secondary (coda) waveform character. Heterogeneity in overlying plate affects arrival times.

References:

Ammon, C.J., Ji, C., Thio, H.-K., Robinson, D., Ni, S., Hjorleifsdottir, V., Kanamori, H., Lay, T., Das, S., Helmberger, D., Ichinose, G., Polet, J., and Wald, D., 2005, Rupture Process of the 2004 Sumatra-Andaman Earthquake: Science, v. 308, p. 1133-1139.

Heise, W., Caldwell, T.G., Hill, G.J., Bennie, S.L., Wallin, E., and Bertrand, E.A., 2012, Magnetotelluric imaging of fluid processes at the subduction interface of the Hikurangi margin, New Zealand: Geophys. Res. Lett., v. 39, p. L04308.

Henrys, S., Wech, A.G., Sutherland, R., Stern, T., Savage, M., Sato, H., Mochizuki, K., Iwasaki, T., Okaya, D., Seward, A., Tozer, B., Townend, J., Kurashimo, E., Iidaka, T., and Ishiyama, T., submitted, SAHKE geophysical transect reveals crustal and subduction zone structure at the southern Hikurangi margin, New Zealand: Geochem. Geophys. Geosyst.

Lay, T., Kanamori, H., Ammon, C.J., Nettles, M., Ward, S.N., Aster, R.C., Beck, S.L., Bilek, S.L., Brudzinski, M.R., Butler, R., DeShon, H.R., Ekstrom, G., Satake, K., and Sipkin, S., 2005, The Great Sumatra-Andaman Earthquake of 26 December 2004: Science, v. 308, p. 1127-1133.

Simons, M., Minson, S.E., Sladen, A., Ortega, F., Jiang, J., Owen, S.E., Meng, L., Ampuero, J.-P., Wei, S., Chu, R., Helmberger, D.V., Kanamori, H., Hetland, E., Moore, A.W., and Webb, F.H., 2011, The 2011 Magnitude 9.0 Tohoku-Oki Earthquake: Mosaicking the Megathrust from Seconds to Centuries: Science, v. 332, p. 1421-1425.

Wallace, L., Bell, R., Townend, J., Ellis, S., Bannister, S., Henrys, S., Sutherland, R., and Barnes, P.M., 2010, Subduction Systems Revealed: Studies of the Hikurangi Margin: EOS Transactions, American Geophysical Union, v. 91, p. 417-428.

Wallace, L.M., Barnes, P., Beavan, J., Van Dissen, R., Litchfield, N., Mountjoy, J., Langridge, R., Lamarche, G., and Pondard, N., 2012, The kinematics of a transition from subduction to strike-slip: An example from the central New Zealand plate boundary: J. Geophys. Res., v. 117, p. B02405.

Why do some subduction zones have M9 earthquakes and others less than M7.5?
Composition and state variations on the subduction thrust

Roy Hyndman

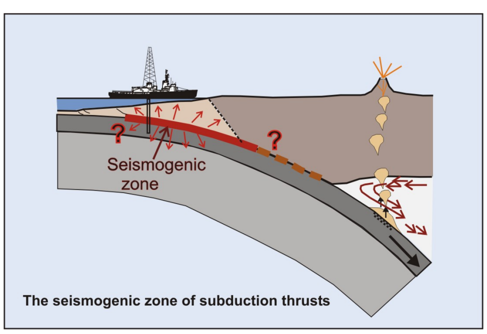
Pacific Geoscience Centre, Geological Survey of Canada & Earth and Ocean Sciences University of Victoria.

rhyndman@nrcan.gc.ca

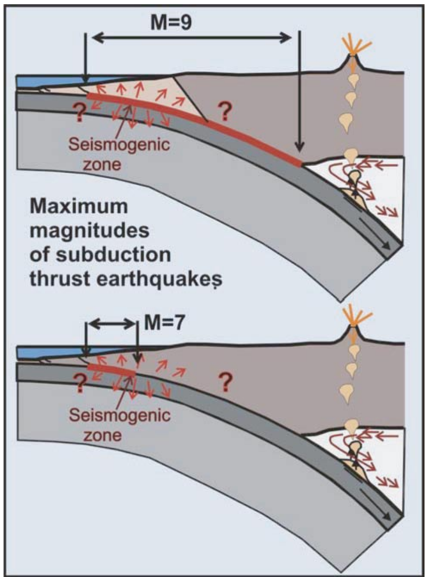
The maximum size of subduction earthquakes is an important scientific question and a critical earthquake hazard issue. Some subduction zones have had M~9 earthquakes, NE Japan, Chile, Sumatra, etc. and some M<7.5 such as the Mariana and several other west Pacific island arcs. Of course we need to be cautious a M7.5 maximum (Mx) based on known past events since M9 earthquakes can have return times of over 600 yrs (i.e, recent NE Japan megathrust). We could be more confident if we are able to identify a physical explanation for the two Mx types. With this caution I will assume that the estimates of maximum magnitude difference are valid. At the end I give a few notes on addressing this question by drilling, seismic surveys, and other studies off New Zealand, Cascadia, and elsewhere. This topic addresses GeoPRISMS objectives of: societal impacts, and under Subduction Cycles and Deformation, "strain buildup and release along the plate boundary" and "release of volatiles such as H_2O and CO_2".

Seismic Coupling and Seismic Efficiency

Two expressions are closely related to maximum magnitude, "seismic coupling ratio" or seismic efficiency, and the downdip extent of the seismogenic zone. Seismic coupling (see Wang and Dixon, 2004 EOS) here is defined as the fraction of the plate convergence that is accommodated by thrust earthquakes (i.e., seismic moment) compared to aseismic motion (the degree of "locking" is another sometimes confusing expression). I note the problem of tsunami earthquakes, where rupture is too slow for much seismic energy but that can generate large tsunamis. The coupling ratio involves a down-dip seismogenic width, sometimes taken to be from the trench to a common observed limit of 30-40 km. In fact, the seismogenic width can vary considerably (discussion below) and a low coupling ratio can simply be the result of a very shallow downdip limit. The main other way of viewing a low seismic coupling is that there are patches on the thrust that are seismic and areas that move aseismically. For lower coupling subduction zones, there are several suggestions for variable seismic and aseismic patches. There may be slippery material like serpentinite/talc on the thrust (discussed below) with "coupled" patches such as subducted seamounts (see Wang and Bilek, 2011, Geology; Kodaira et al., 2000, Science), or there may be areas of higher and lower pore pressure. The subduction zone stress regime also has been suggested as an important factor. However, it is now recognized that most if not all subduction thrusts are very weak, similar to San Andreas fault, so regional tectonic stress variations are unlikely to be a critical factor.



The seismogenic zone of subduction thrusts

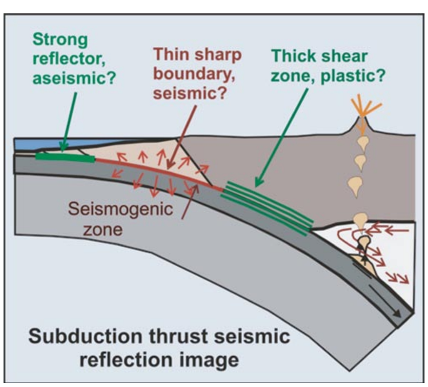


GPS and other geodetic data are now giving us some indication of "coupling" for the landward parts of an increasing number of subduction zones. The majority of margins that have had M9 earthquakes appear to be mainly "fully coupled", although there are interesting exceptions. For example the central part of the M9 1964 Alaska earthquake that had less slip than adjacent areas has less inferred "coupling" based on GPS data. Unfortunately, most west Pacific island arcs like the Mariana where there have been only <M7.5 earthquakes have backarc spreading and it is difficult to separate steady spreading motion from elastic strain buildup in the GPS signal. However, it should be possible to separate the two signals with careful analysis of land data; this is well worth pursuing. Difficult seafloor GPS is the sure way to allow the separation of the two signals.

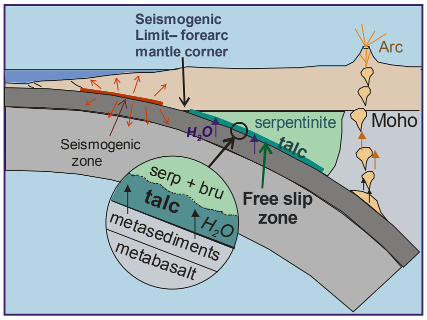
Updip and Downdip Limits of Seismogenic Zone

The updip and downdip limits of the seismogenic zone are an important control of maximum magnitude. Also, the downdip limit represents the closest approach of the seismic source and therefore the ground motion and earthquake hazard at near coastal cities. The updip limit strongly affects the tsunami generation. Most subduction zones that have had M9 earthquakes appear to have a deep downdip limit, 30-40 km, whereas the Mariana and other island arcs with Mx<7.5 appear to have shallow maximum depth thrust events, less than 10 km for Mariana (see Pacheco et al., 1993, JGR). If the downdip limit is so shallow that it approachs or overlaps the updip limit, very large thrust earthquakes are not possible. This is one explanation for the small maximum magnitude of these island arc subduction zones (see Hyndman,Yamano, Oleskevich, 2006, Island Arc).

The updip limit of great earthquake rupture (usually defined by aftershocks) is commonly some 10's of km landward of the trench. The first reasonable explanation was that the accretionary prism may be aseismic, but it is now recognized that some great earthquakes occur completely under the accretionary prisms. The second explanation was that the limit was controlled by the smectite-illite clay transition, but this too has been discounted (e.g. Saffer and Marone, 2003, EPSL). So we still do not have a satisfactory explanation but downdip temperature-dependent physical and chemical changes are likely the origin of this limit.



For the downdip limit, there are a number of possibilities, several are: (1) Maximum temperature for seismic behaviour in felsic rocks of about 350C from laboratory data. This temperature seems to apply for the San Andreas and other continental faults. The temperature is reached at great depth for most subduction zones with the exception of those that are subducting young and hot oceanic plates such as SW Japan, Cascadia, Mexico, etc. where it is at 20-30 km depth. For these, it is probably the controlling mechanism. For one area of Cascadia there appears to be a change in thrust character from thin seismic to thick ductile (Nedimovic et al., 2003, Science), as sometimes observed at the thermally controlled "brittle-ductile" transition in exposed continental faults. Bell et al., (2009, GJI) examined the reflection character of the Hikurangi thrust and found substantial spatial variations. However, the Cascadia-type downdip transition is not expected in this cool subduction zone.



(2) The forearc mantle corner. At this point the thrust is overlain by forearc mantle that is expected to be serpentinized by fluids being driven off the downgoing plate by increasing heat and pressure (e.g., Peacock and Hyndman, 1999, GRL). The structure of serpentinite suggests that it is aseismic, but this is still debated. However, the rising fluids also should be silica saturated resulting in talc on the thrust; talc is exceptionally weak and is unlikely to be able to support elastic strain build-up and earthquake rupture. An important observation has been serpentinite and talc on the San Andreas fault, notably in the SAFOD borehole where the fault is creeping.The forearc mantle corner is usually poorly determined but generally is at a depth of 30-40 km, a common maximum depth for great thrust earthquake rupture. Several subduction zones appear to have seismic behaviour to slightly greater depths but it is not clear if this is due to structural complexity or areas such as subducted seamounts were there is not serpentinite/talc on the thrust. There is now some evidence that the updip limit of ETS slow slip occurs at the forearc mantle corner. The slow slip therefore may be associated with the serpentinite/talc.

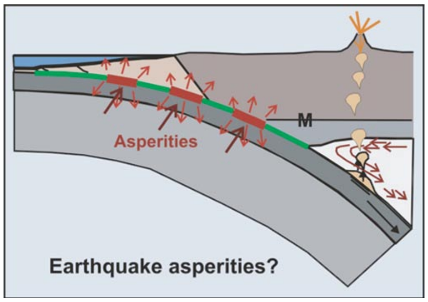
In west Pacific subduction zones like Mariana where the maximum magnitude if often less than M7.5, it has been argued that the updip limit and downdip limit may overlap so there is a minimal seismogenic zone (e.g., Hyndman et al., 2006, Island Arc). This is because these may have oceanic crust in the forearc (perhaps thickened) only 5-10 km thick, so the forearc mantle corner may be this shallow and the downdip seismogenic limit very shallow. An important observation in several of these subduction zones is serpentinite diapirs reaching the surface a few 10's km from the trench. They may be over the shallow forearc mantle corner. In any case, their occurrence indicates the likelihood of serpentinite/talc on the thrust only a short distance downdip landward from the trench. With a common width updip aseismic zone, the seismogenic zone is very narrow and only small maximum magnitudes are possible.

Short Margin-Parallel Extent for Subduction Thrust Earthquakes

The maximum magnitude of subduction thrust earthquakes is limited by the along-margin extent. Some margins have events that extend long distances along the margin (Cascadia is a good example) whereas others have short lateral extents not much more than the downdip extent. Some possibilities for the difference are stress concentrators due to roughness of the incoming plate, seamounts, normal faulting structures, aseismic ridges, etc. (see Wang and Bilek, 2011, Geology; Kodaira et al., 2000, Science). Large accretionary sedimentary prisms may provide a smooth thrust surface with few stress concentrators that start and stop rupture.

Patchy Seismic and Aseismic Zones on the Subduction Thrust

The other way that small maximum magnitudes may be explained is through patchy seismic and aseismic zones on the subduction thrust. The "patchy" locked and rupture areas may be small fraction of total area that is mainly aseismic. Sheared off seamounts are one type of localization. Subducted sediments also may isolate the thrust from aseismic mantle serpentinite/talc. One possibility is that the incoming oceanic crust contains substantial serpentinite that may be in the footwall of the subduction thrust and that is smeared out along the thrust making it largely aseismic. Peridotite and serpentinite are surprisingly common in DSDP/ODP/IODP ocean crustal core samples. Only a few small special areas then may be seismic, rather like the situation of the creeping section of the San Andreas fault which exhibits numerous small earthquakes.



For a previous relevant discussion see: Hyndman, 2007, The seismogenic zone of subduction thrust faults: What we know and don't know, Columbia Univ. Press.

New Zealand Tests of Hypotheses for Maximum Magnitude Controls.

1. 3D multichannel seismic reflection surveys to map in detail variations in thrust interface character associated with inferred seismic ("locked") and aseismic areas (creeping?) (extension of Bell et al., 2009, GJI, Hikurangi thrust reflection character study).

2. Drilling of subduction thrust to see if serpentinite/talc is present in aseismic area, as found for creeping section of San Andreas fault (in SAFOD borehole; Moore and Rymer,2007, *Nature* **448**, 795-797)) compared to inferred locked Hikurangi area.

3. Detailed mapping and sampling of the incoming oceanic plate to see if there are occurrences of serpentinite in the crust.

4. Detailed mapping of location of forearc mantle corner, compared to landward limit of GPS-inferred locked zone.

Developing an effective community response to the next "Great East Coast Subduction Zone Earthquake and Tsunami"

David Johnston[1], Stuart Fraser[1], Graham Leonard[1], Wendy Saunders[1], Kim Wright[1]

[1] *Joint Centre for Disaster Research, Massey University – GNS Science, Wellington*

David.Johnston@gns.cri.nz

Major subduction zone earthquake and tsunami, such as in the Indian Ocean (2004) and Japan (2011), have focused attention on the potential impact of a tsunami of similar size and extent occurring locally to New Zealand. The New Zealand scientific and emergency management communities have directed attention towards the risk from an earthquake and tsunami being generated at the Hikurangi subduction margin, off the east coast of the North Island. Many local emergency management agencies are reviewing their existing arrangements based on observations from Japan and our knowledge of risk reduction options is leading to innovative policy and practice. However, much still remains to be done to reduce the risk to a future "Great East Coast Subduction Zone Earthquake and Tsunami".

Knowledge of the potential for significant earthquakes at the Hikurangi subduction margin has been developed over several years through studies of background seismicity and plate motion (e.g. Wallace et al., 2009). Paleoseismic and paleotsunami studies demonstrate the past occurrence of significant earthquake and tsunami at the Hikurangi subduction margin (Cochran et al., 2006). Previous numerical simulation of tsunami due to various earthquakes sources at the Hikurangi margin has demonstrated the potential for at-shore wave heights of 5m or more, and run-up to double that (Power et al., 2008). Development of a probabilistic tsunami model for New Zealand and high-resolution simulation of the onshore effects of local subduction zone tsunami are underway, as is development of a framework for detailed simulation of evacuation from local tsunami. Much of our understanding of the subduction hazard, particularly regarding frequency, remains uncertain but a significant local earthquake and tsunami is known to be a very real prospect.

Tsunami awareness in New Zealand has evolved over the last 50 years since the 1960 Chilean tsunami, which struck New Zealand without official warning and caused significant damage, despite occurring at low tide (Johnston et al., 2008). From 1960 to 2004 various measures were put in place, such as becoming part of the Pacific Tsunami Warning System, which led to improvements in official warning mechanisms. However, in surveys in 2003 public understanding of risk and correct warning-response action was shown to be limited (Webb, 2005). Following the 2004 Indian Ocean tsunami the New Zealand government initiated an extensive review of tsunami hazard, risk and preparedness (Berryman, 2005; Webb, 2005), which ranked tsunami risk to property potentially on par with that of earthquake and risk to life an order of magnitude greater. The Ministry of Civil Defence & Emergency Management (MCDEM) subsequently developed guidance for tsunami signage, development of evacuation zones and dissemination of warnings (MCDEM, 2008a, 2008b, 2010), and GNS Science produced guidance on how to incorporate tsunami modeling into land use planning (Saunders et al. 2011). These initiatives represent significant steps forward in our preparedness for a subduction zone earthquake and tsunami, but there is a long way to go to ensure adequate awareness and preparedness of individuals and communities. Arguably the greatest priority is to increase public understanding that local tsunami will not be preceded by official warnings, and that immediate self-evacuation is the best way to preserve life-safety.

References:

Berryman, K. (compiler), 2005. Review of tsunami hazard and risk in New Zealand, Institute of Geological and Nuclear Sciences client report 2005/104.

Cochran, U.A., Berryman, K.R., Zachariasen, J., et al., 2006. Paleoecological insights into subduction zone earthquake occurrence, eastern North Island, New Zealand. Geological Society of America Bulletin. 118 (9-10). pp. 1051-1074.

Johnston, D.M., Pettersson, R., Downes G., et al., 2008. Developing an effective tsunami warning system: lessons from the 1960 Chile earthquake tsunami for New Zealand coastal communities. Kotuitui: New Zealand Journal of Social Sciences Online. 3 (2) p. 105-120.

MCDEM, 2008a. National Tsunami Signage Technical Standard for the CDEM Sector [TS 01/08]. Wellington, New Zealand.

MCDEM, 2008b. Tsunami Evacuation Zones. Director's Guideline for Civil Defence Emergency Management Groups [DGL 08/08]. Wellington, New Zealand.

MCDEM,2010. Tsunami Advisory and Warning Plan. Supporting Plan [SP01/09] Revised October 2010. Wellington, New Zealand.

Power, W.L., Reyners, M. & Wallace, L.M. (2008). Tsunami hazard posed by earthquakes on the Hikurangi subduction zone interface. GNS Consultancy Report 2008/40. Lower Hutt, New Zealand. 58p.

Saunders, W. S. A., Prasetya, G., & Leonard, G. (2011). New Zealand's Next Top Model: incorporating tsunami inundation modelling into land use planning. Lower Hutt: GNS Science.

Wallace, L.M., Reyners, M., Cochran, U.A., et al.., 2009. Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand. Geochemistry Geophysics Geosystems. 10(10). p. 32.

Webb, T. (compiler), 2005. Review of New Zealand's preparedness tsunami hazard, comparison to risk and recommendations for treatment, Institute of Geological and Nuclear Sciences client report 2005/162.

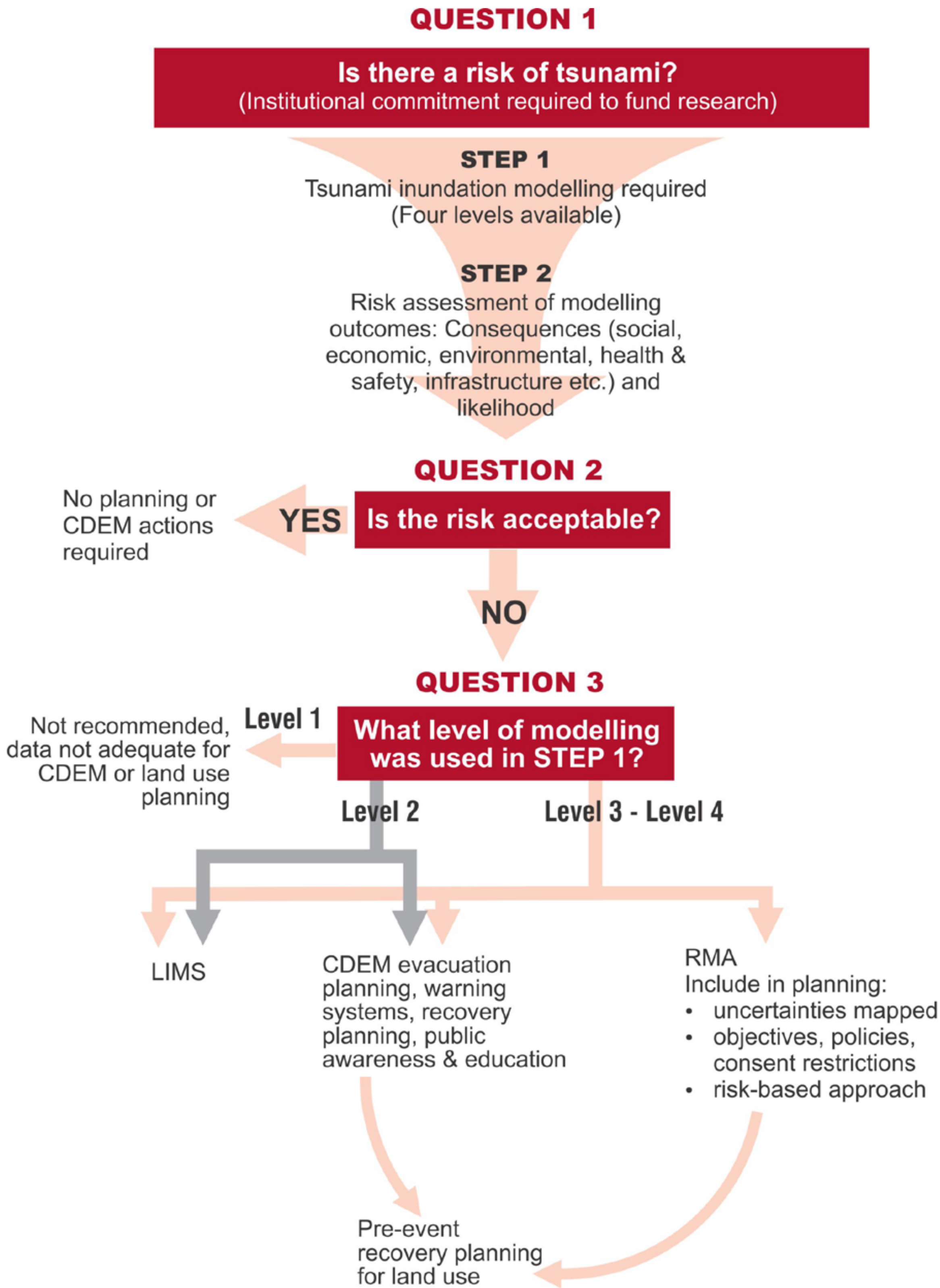


Figure 1. Decision tree for including tsunami risk into hazard mitigation strategies (Saunders et al, 2011)

Constrains on the thermal history of crystal-rich magmas from crystal residence timescales

Adam Kent[1] and Kari Cooper[2]

[1] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, 97331; [2] Department of Geology, University of California, Davis, CA 95616

adam.kent@geo.oregonstate.edu

Many intermediate and silicic composition volcanic rocks, including some of the largest known eruptions, involve remobilization of magma or crystal-rich mush that has been stored with the crust for significant time periods. Developing a better understanding of the thermal and chemical evolution of magmas within crustal reservoirs has implications for the longevity and mechanisms of generation of chemically diverse magmas and for the mechanisms that mobilize this material for eventual eruption. The physical and thermal states of the system are intimately linked, going from mostly liquid to mushy to potentially solid or almost-solid systems primarily as a function of temperature. Crystal-scale records provide evidence of long-term storage and recycling of crystals within a reservoir system, but the extent to which storage occurs in mostly-liquid vs. mostly-solid or solid bodies is unclear. Numerical models can provide insights into thermal histories at a reservoir scale, and crystal and liquid thermometry can provide insights into the thermal state of the crystals at snapshots in time, but developing thermal histories from the record in erupted products has been elusive.

We have developed an approach for quantifying the thermal histories of magma bodies by combining information about crystal residence times from multiple sources. U-series crystal ages provide the total time since crystals grew (albeit averaged over all crystals/zones in a bulk separate). In contrast, trace-element zoning provides an upper limit to the duration of storage at high temperatures, and crystal sizes and CSDs provide insights into the total growth time of crystals. By combining information from all of these sources, we can link the crystal growth and diffusion ages to thermal states and therefore constrain thermal histories. We use recent eruptive products at Mt Hood as a case study, building off of previous ^{238}U-^{230}Th-^{226}Ra crystal age, CSD, and diffusion modeling results. ^{230}Th-^{226}Ra ages of crystals from the silicic endmember of the two most recent Mt Hood eruptions both have average ages of >4.5 ka and have cores with ages >10 ka. Diffusion of Sr in plagioclase limits the time spent at temperatures >850-900 °C to less than a few decades. Crystal sizes and CSDs constrain the total duration of crystal growth and allow identification of multiple crystal populations in the samples. Collectively, these data constrain models of crystal growth and dissolution as a function of thermal histories, showing that only a small fraction of the total time that the crystals were present could have been spent at temperatures significantly above the solidus, and an even smaller fraction of that time could have been spent at temperatures high enough for trace-element diffusion to be significant. These observations suggest that the state of the reservoir in which crystals at Mt Hood are stored was at near- or sub-solidus temperatures for most of its history, with brief excursions to higher temperature likely related to recharge and eruption (and which may have resulted in some minor dissolution of crystals).

Although Mount Hood is the only system for which a complete data set is available, a summary of data (Figure 1) shows that the general features we observe are a global feature of crustal magmatic systems. Given that the thermal history of magmas is important for understanding a variety of magmatic and eruptive processes the widespread application of the approach detailed herein to magmas produced in different tectonic environments and to systems of different overall size and flux is likely to provide important insight into volcanic processes.

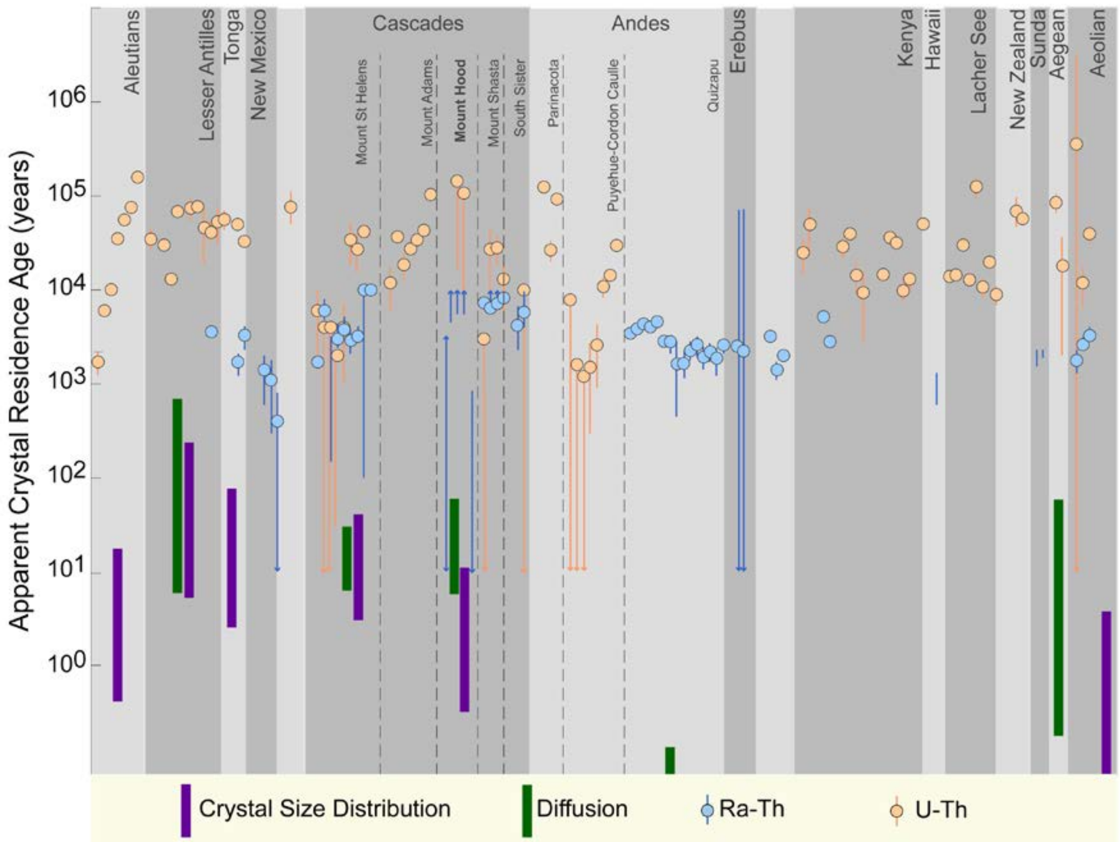


Figure 1. Global summary of U-Th-Ra, diffusion, and crystal size distribution estimates of crystal residence ages in magmas.

How do subduction zones end?

Simon Lamb[1], Martha Savage[1], Tim Stern[1], John Townend[1], Paul Denys[2]—other collaborators also welcome

[1] Institute of Geophysic, Victoria University of Wellington, Wellington, New Zealand;
[2] School of Surveying, University of Otago, Dunedin, New Zealand

Simon.Lamb@vuw.ac.nz

Subduction is a fundamental part of plate tectonics that accommodates most of the plate convergence required by motion on a planet with a constant size. Theoretical models show that the large forces required for initiation of subduction zones are difficult to sustain on a real Earth. Thus, most subduction zones are likely to form by lateral propagation at their ends. In addition, the ends of subduction zones often exhibit complex tectonic, as well as being the places where large subduction thrust earthquakes initiate or terminate.
The New Zealand plate-boundary is unique in containing two ends of subduction zones, as well as a rapidly rotating hinge where one segment of a subduction system is rotating relative to another (Fig. 1)[1]. All these features lie beneath, or are exposed, onshore. Thus, the northern edge of the subducted Australian plate, along the Puysegur subduction zone, occurs beneath southern South Island, whereas the southern edge of the subducted Pacific plate lies beneath northern South Island. A hinge between the rapidly rotating Hikurangi subducting margin and the more stable Tonga-Kermadec subduction zone cuts through Northeastern North Island. Finally, deep Benioff zones beneath all these regions provide an excellent geometry for seismic probing of the overlying lithosphere with passive source seismology (Fig. 1). The fundamental problem here is the difference in behaviour of oceanic and continental lithosphere in zones of plate convergence. Thus, the along strike end of a subduction zone usually occurs at a transition between negatively buoyant oceanic and buoyant continental lithosphere. These transitions are likely candidates for regions where continental crust can be locally subducted to great depth, ultimately to rise rapidly to the surface giving rise to ultra-high pressure rocks in some core complexes.

We propose using New Zealand as a natural laboratory to study the dynamics and kinematics of subduction termination, and its implications for subduction propagation and initiation. Such a study would focus on the detailed deep lithospheric structure of these regions, in the context of the active surface kinematics and longer term geological and plate tectonic evolution.

The shape of the New Zealand landmass and it position relative to the subduction zone make it a favourable place to carrying out deep geophysical imaging of subduction. There have been a number of deep crustal transects across the width of the plate boundary zone, both in the parts where there is subduction (NIGHT[2], SAHKE[3]) and continental convergence (SIGHT[4]). There have also been some arrays of passive broadband seismometers at the ends of the South Island. (e.g., Marlborough[5], Fiordland[6], triggered instruments only), but none of these deployments has targeted or overlapped much with the transition areas between subduction and transpression. There is a dense array of permanent seismic and GPS stations (GeoNet) in

North Island, but these stations are more sparse in South Island (Fig. 2). We propose capitalizing on the existing seismic work, augmenting it with extra deep lithospheric soundings to form 3-D lithospheric arrays in three critical regions across where there will be major changes in lithospheric structure. We refer to these as the Puysegur Array (PA), Marlborough Array (MA), and Raukumara Array (RA). They will cover their respective regions with two-dimensional arrays as densely as can be managed within likely funding constraints (e.g., approximately 100 broadband seismometers each), such as the piggy-back arrays operating on the US Earthscope arrays. Joint international proposals should be prepared to carry out the projects, likely to be run in stages to allow results of earlier studies to inform the planning of the later ones.
The project would include:

- Deep crustal and mantle probing using seismic and other geophysical stations spanning the edges of the Puysegur and Hikurangi margins (PA and MA), using active and passive source seismology.
- In addition to determining the velocity structure, there would be detailed studies of microseismicity and anisotropy and resistivity.
- Densification of continuous GPS in these regions to monitor crustal motions and slow earthquakes and tremor activity. A dense array on the Alpine Fault near the PA array has found tremor[7], however no cGPS is available yet to see if slow slip is occurring nearby.
- Dynamical modeling of the evolution of the edges of subduction zones

References:

1 Cande, S. C. & Stock, J. M. Pacific-Antarctic-Australia motion and the formation of the Macquarie Plate. *Geophys. J. Int.* **157**, 399-414 doi:310.1111/j.1365-1246X.2004.02224.x. (2004).

2 Stern, T. *et al.* Crust-mantle structure of the central North Island, New Zealand, based on seismological observations. *Journal of Volcanology and Geothermal Research* **190**, 58-74 (2010).

3 Henrys, S. *et al.* SAHKE geophysical transect reveals crustal and subduction zone structure at the southern Hikurangi margin, New Zealand. *G-cubed* **submitted** (2013).

4 Okaya, D. A., Henrys, S. & Stern, T. Double-sided ohshore-offshore seismic imaging of a plate boundary: "super-gathers" across South Island, New Zealand. *Tectonophysics* **355**, 247-263 (2002).

5 Wilson, C. K., Jones, C. H., Molnar, P., Sheehan, A. F. & Boyd, O. S. Distributed deformation in the lower crust and upper mantle beneath a continental strike-slip fault zone; Marlborough fault system, South Island, New Zealand. *Geology* **32**, 837-840 (2004).

6 Gledhill, K. R. & Savage, M. K. Seismic anisotropy above the Fiordland subduction zone, New Zealand *Seismological Research Letters* **73**, 222 (2002).

7 Wech, A. G., Boese, C. M., Stern, T. A. & Townend, J. Tectonic tremor and deep slow slip on the Alpine Fault. *Geophys. Res. Lett.* **39**, doi:10.1029/2012gl051751 (2012).

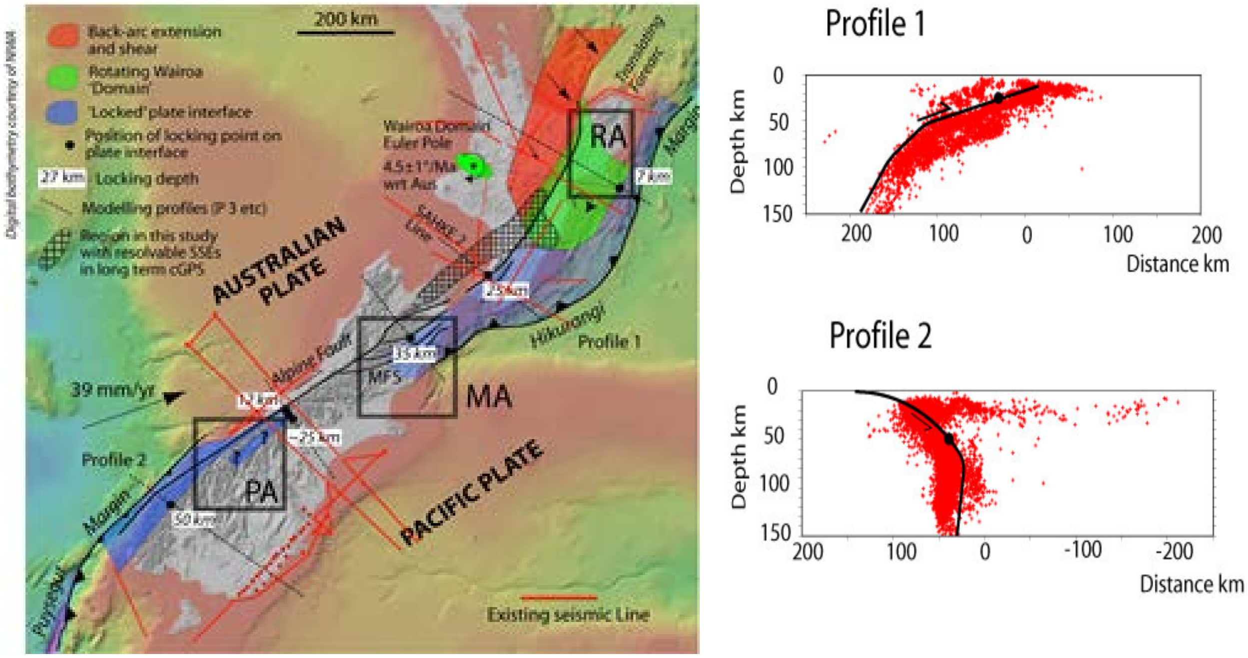


Figure 1. Left : Bathymetric map of the New Zealand plate boundary zone, showing the main edges of the locked portions of the plate interface and also the rapidly rotating 'Wairoa Domain' in the northern part, as well existing deep seismic lines/transects. Boxes show areas of deep geophysical arrays (PA, MA, RA, see text) spanning regions where subduction changes markedly or terminates. Right : Profiles 1 and 2 show geometry of subducted slab in the Hikurangi and Puysegur subduction zones.

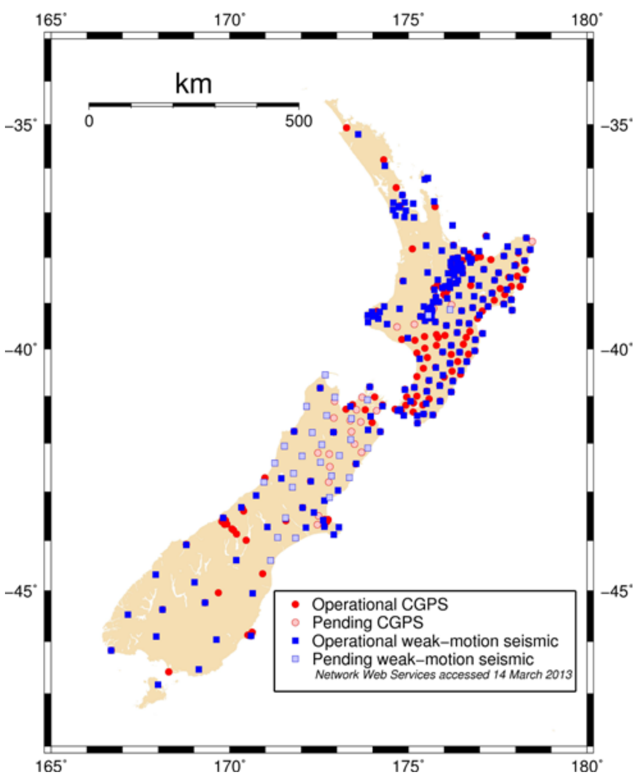


Figure 2. Operating and proposed permanent GeoNet cGPS and seismic stations in New Zealand.

Constraining melt transport, storage, and chemical modification in monogenetic vents: Focus on the Auckland Volcanic Field

John C. Lassiter[1], Jaime D. Barnes[1], Marc Hesse[1]

[1]*Dept. of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, USA*

lassiter1@jsg.utexas.edu

Monogenetic vent fields are a major type of volcanism at many subduction settings (e.g., New Zealand, Cascadia, Trans-Mexican Volcanic Belt), and the dominant type of continental basaltic volcanism. Many monogenetic vent sequences display systematic stratigraphic variations in chemical and isotopic composition that may derive from time-variant magma generation and extraction processes (c.f., *Reiners*, 2002), or from varying degrees of crustal contamination (c.f., Paricutin Volcano; *McBirney & Taylor*, 1987). Understanding the origin and significance of temporal trends in monogenetic vents is central to several GeoPrisms themes, including "How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?" and "What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?" (GeoPrisms Draft Science Plan). In addition, several young, potentially active monogenetic vent fields are located in or near high-population-density areas (Auckland, Mexico City), and thus represent a significant but poorly characterized volcanic hazard. For example, several recent studies have examined volcanic hazards posed by the Auckland Volcanic Field (*Sandri et al.,* 2012), and challenges associated with monitoring this field using both ground deformation (*Kereszturi et al.*, 2012) and seismic monitoring (*Ashenden et al.*, 2011).

The Auckland Volcanic Field (AVF) contains approximately 50 late Pleistocene to recent eruptive centers scattered within and surrounding the Auckland metropolitan area (*Kermode*, 1992; *Allen & Smith*, 1994). Most of the volcanic cones are small (<0.05 km^3), but a few recent eruptions such as at Rangitotu volcano have been much greater in size (up to 2 km^3). Many AVF eruptive products are porphyritic and contain large phenocrysts of olivine with lesser clinopyroxene and plagioclase. Fractional crystallization thus appears to have played a important role in the evolution of some AVF lavas, with both shallow fractionation of olivine and deeper fractionation of clinopyroxene potentially generating much of the compositional variations observed in individual monogenetic vents (c.f., *Smith et al*., 2008). However, recent U-Th-Ra studies suggest that mixing of melts from distinct mantle sources is also important (*McGee et al.*, 2011). Pronounced ^{226}Ra excesses in eruptive products from Rangitoto volcano (~500 BP, AVF) also constrain the maximum duration of crustal melt storage prior to eruption.

Because of the large population of the Auckland metropolitan area (~1.46 million inhabitants), volcanism within the AVF presents a significant volcanic hazard (c.f., *Sandri et al*., 2012). Understanding the conditions of magma storage preceding AFV vent eruptions can aid the development of methods for detecting magma ascent or injection that precedes volcanic eruptions within the field. For example, if sill emplacement shortly precedes the eruption of many monogenetic vents, then possible loci of future eruptions might be determined through remote sensing of land surface deformation that would accompany this emplacement (*Kereszturi et al.*, 2012). However, the magnitude and spatial distribution of surface deformation will be strongly influenced by the depth of magma injection and the volume of stored melt.

We propose that a more complete understanding of the processes of melt generation, transport, and pre-eruptive storage leading to monogenetic vent eruptions can be gained by integrating ongoing geochemical studies of temporal geochemical variations in individual monogenetic vent sequences with numerical modeling of melt transport and sill injection/deflation processes and focused geophysical investigation of the structure of the mantle and crust beneath the AVF. Several questions regarding melt generation and transport that have implications for not only our understanding of melt generation and evolution, but also for assessment and monitoring of volcanic hazards, include:

1) Do systematic compositional variations in monogenetic vent sequences primarily reflect variable melt/crust interaction, or mixing of discrete parental melts derived from heterogeneous mantle?
2) What are the pre-eruptive volatile contents of monogenetic vent magmas, and how do these influence eruptive style?
3) What is the spatial and temporal distribution of melt in the mantle and crust beneath active monogenetic vent fields?
4) Where and for how long are monogenetic vent magmas stored in the crust prior to eruption?
5) How can insights gained from geochemical and geophysical studies on the processes of melt generation, transport, and storage related to monogenetic vents be utilized to improve volcanic risk assessment and monitoring of active or potentially active monogenetic vent fields?

Community efforts that could be coordinated to address these questions include: FTIR study of melt inclusions and phenocryst phases to constrain pre-eruptive volatile contents and depths of magma storage; numerical modeling of ground response to magma emplacement at depths appropriate for the AVF; constraints on the duration of crustal melt storage from crystal size distributions and U-Th-Ra disequilibria; optimized seismic studies designed to constrain spatial (and temporal?) variation in melt fraction within the mantle and crust beneath the AVF; utilization of temporal geochemical variations in monogenetic vent sequences to constrain quantitative models of melt migration and storage.

References:

Ashenden, CL, JM Lindsay, S Sherburn, et al. (2011), Some challenges of monitoring a potentially active volcanic field in a large urban area: Auckland volcanic field, New Zealand. *Natr. Hazards* 59, 507-527.

Kereszturi, G, J Procter, SJ Cronin, et al. (2012), LiDAR-based quantification og lava flow susceptibility in the city of Auckland (New Zealand. *Remote Sens. Env.* 125, 198-213.

McBirney, A.R., H.P. Taylor, R.L. Armstrong, Paricutin re-examined: a classic example of crustal assimilation in calc-alkaline magma. *Contrib. Mineral. Petrol.*, 95, 4-20, 1987Needham

McGee, L.E., C. Beier, I.E.M. Smith, S.P. Turner (2011), Dynamics of melting beneath a small-scale basaltic system: a U-Th-Ra study from Rangitoto volcano, Auckland volcanic field, New Zealand, *Contrib. Mineral. Petrol.* 162, 547-563.

Reiners, P.W. (2002), Temporal-compositional trends in intraplate basalt eruptions: Implications for mantle heterogeneity and melting processes. *Geochem. Geophys. Geosys.*, 3, d.o.i.: 10.1029/2001GC000250.

Sandri, L, G Jolly, J Lindsay, T Howe, W Marzocchi, Combining long- and short-term probabilistic volcanic hazard assessment with cost-benefit analysis to support decision making in a volcanic crisis from the Auckland Volcanic Field, New Zealand. *Bull. Volcan.* 74, 705-723, 2012.

Smith, I.E.M., S. Blake, C.J.N. Wilson, B.F. Houghton (2008), Deep-seated fractionation during the rise of a small-volume basalt magma batch: Crater Hill, Auckland, New Zealand. *Contrib. Mineral. Petrol.*, 155, 511-527.

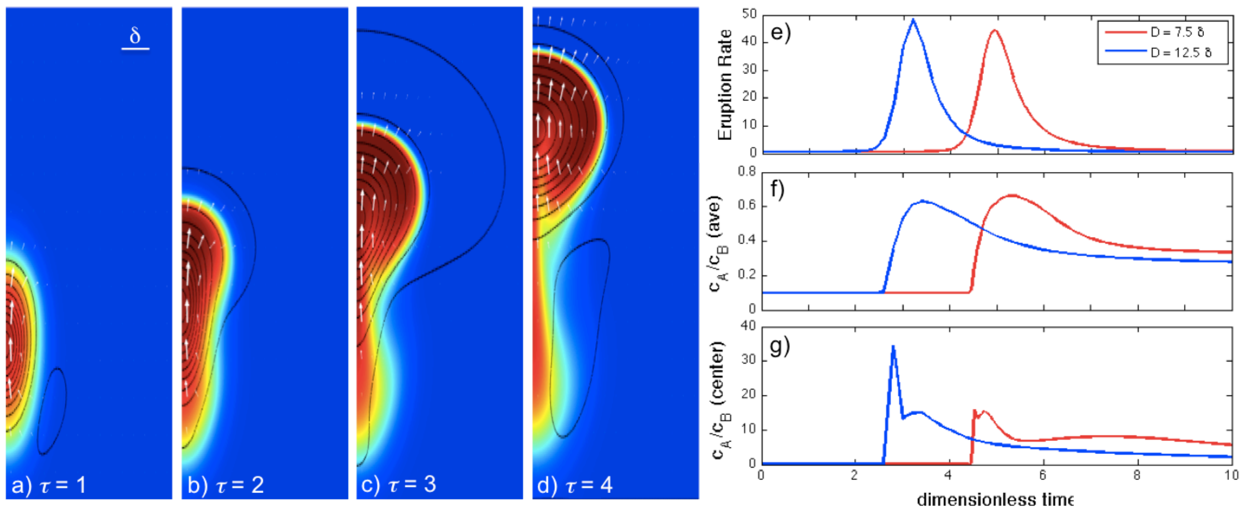


Figure 1. (a to d) Numerical simulations of an isolated pool of melt (left boundary is a symmetry axis), due to localized melting of a fertile heterogeneity, rising through an ambient mantle at very low melt fraction in a domain of 6 by 20 compaction length, δ. The black contours show the porosity normalized to the background, white arrows indicate melt velocity, and the color indicates the concentration of a tracer A introduced with the melt pool. (e to g) Evolution of the magma at the surface (top of simulation domain) for melting at two different depths. The melt composition in (f) is averaged over the entire top of the domain while (g) shows the more extreme variability at the center of the rising pool, i.e. the top left corner of the domain.

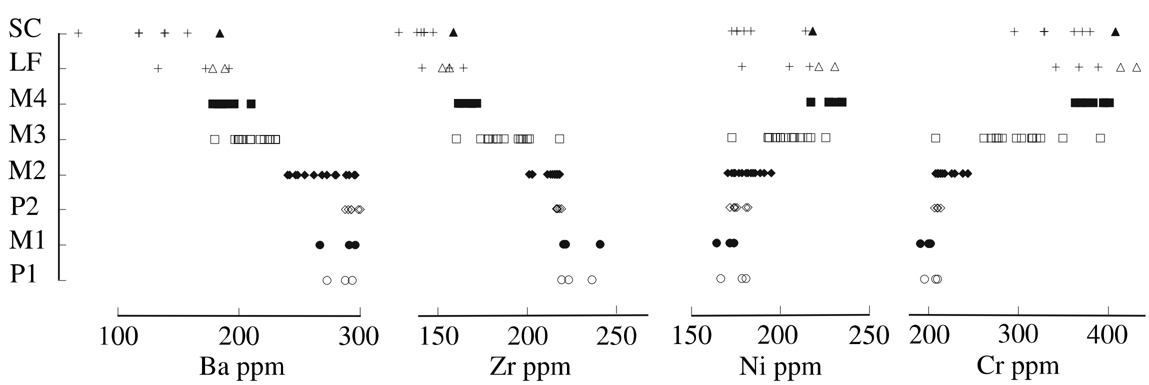


Figure 2. Stratigraphic variation in trace element abundance variations in the Crater Hill monogenetic vent sequence, Auckland Volcanic Field. From Smith et al. (2008). Similar chemical trends are observed in AVF vent sequences. Smith et al. (2008) argued for significant high-pressure clinopyroxene fractionation as a potential source of the chemical variations observed at Crater Hill. However, McGee et al. (2011) suggested mixing of eclogite- and peridotite derived melts generated the chemical variations observed at Motukorea Volcano, AVF.

GeoPRISMS Science Goals in the Havre Trough Back-Arc Basin

Fernando Martinez[1] and Robert A Dunn[2]

[1] Hawaii Institute of Geophysics and Planetology; [2] Department of Geology and Geophysics, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI 96822, USA

fernando@hawaii.edu; dunnr@hawaii.edu

The Havre Trough is an ultra-slow opening (~15-20 mm/yr, *Ruellan et al.*, 2003) back-arc basin undergoing active extension in a broad zone proximal to the arc volcanic front. This appears to be a distinct style of seafloor spreading specific to back-arc basins. We suggest that it facilitates the study of intrinsic melt generation and chemical patterns in the mantle wedge by minimizing 2-D plate-driven advection components while sampling mantle wedge melts over a broad zone. These conditions make the Havre Trough well suited to address GeoPRISMS science objectives:

How do volatile release and transfer affect the rheology and dynamics of the plate interface, from the incoming plate and trench through to the arc and back-arc? At mid-ocean ridges the extraction of water from the mantle by melting has been proposed to greatly strengthen the residual mantle leading to the formation of a strong anhydrous "compositional" lithosphere [*Hirth and Kohlstedt*, 1996; *Phipps Morgan*, 1997] and perhaps helps focus deformation and volcanism to narrow plate boundary zones [*Macdonald*, 1982]. At back-arc basins, mantle water content increases by over an order of magnitude as the volcanic arc is approached [*Kelley et al.*, 2006] resulting in a several orders of magnitude weakening of mantle material [*Hirth and Kohlstedt*, 2003]. Near the arc, lithospheric mantle may not be able to dehydrate because the subducting slab is a continual source of new water and because melts produced near the volcanic front are so hydrous that residual mantle in equilibrium with these melts retains appreciable water [*Hirth and Kohlstedt*, 2003]. Thus, the plate boundary zone at arc-proximal back-arc spreading centers may be exceptionally weak and broad relative to mid-ocean ridges. Observations at the southern end of the Lau basin [*Martinez and Taylor*, 2006; *Watanabe et al.*, 2010; Fig 1] show a pronounced change in character of the plate boundary zone: a narrow zone of volcanic crustal accretion abruptly transitions to a broad, deep zone of volcanic extension consisting of small volcanic cones and ridges. This morphology continues into the Havre Trough for ~1500 km to New Zealand (Fig. 2). Originally, this narrow-to-broad plate boundary transition was interpreted as organized magmatic spreading replacing tectonic "rifting" [*Parson and Wright*, 1996], but more recent observations indicate both stages are fundamentally magmatic [*Martinez and Taylor*, 2006; *Wysoczanski et al.*, 2010]. If this interpretation is correct then the Lau-Havre Trough transition exhibits a fundamental change in the nature of seafloor spreading from a mid-ocean ridge-type, with a narrow plate boundary zone, to a back-arc style of a broad plate boundary zone, probably linked to high water content and its effects on mantle wedge and lithospheric rheology.

How are volatiles, fluids, and melts stored, transferred and released though the subduction system? The ultra-slow opening rates of the Havre Trough permit the pattern of melt generation in the mantle wedge to be expressed in crustal volcanism (Fig.2). The Havre Trough exhibits contemporaneous volcanism in distinct bands extending basinward along slab trajectories from arc volcanoes [*Wright et al.*, 1996; *Wysoczanski et al.*, 2010]. These volcanic bands appear to be surface expressions of mantle wedge "hot fingers" postulated by *Tamura et al.* [2002]. We suggest that ultra-slow extension facilitates the volcanic expression of melt generation in the mantle wedge by minimizing the 2-D mantle advection components imposed by plate spreading. Unlike ultra-slow spreading at mid-ocean ridges, where mantle is commonly exhumed, in arc-proximal back-arc settings the crust appears to be fully magmatic, but modulated in volume in cross-trending patterns. This probably reflects the higher water content in back-arc settings compared to mid-ocean systems, facilitating mantle melting even at ultra-slow opening rates.

What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust? Arc-proximal back-arc spreading centers generate thick felsic crust [*Martinez and Taylor*, 2002; *Dunn and Martinez*, 2010] (Fig. 3) at greater rates than the volcanic arc itself. In the Lau Basin, abrupt changes in the architecture and chemistry of back-arc crust have been documented [*Dunn and Martinez*, 2010] and similar changes are suggested in the Havre Trough. However, unlike the spreading-parallel crustal domains in the intermediate to fast spreading Lau Basin (Fig. 3), the ultra-slow spreading Havre Trough exhibits crustal domains in across-basin bands (Fig. 2), perhaps reflecting the inherent chemical and melt generation patterns in the mantle wedge. These felsic back-arc components suggest significant possible contributions to continental crust formation beyond the volcanic arc itself.

References:

Dunn, R. A., and F. Martinez (2011), Contrasting crustal production and rapid mantle transitions beneath back-arc ridges, *Nature*, *469*(7329), 198-202.

Hirth, G., and Kohlstedt, D. L. (1996), Water in the oceanic upper mantle: implications for rheology, melt extraction and the evolution of the lithosphere, *Earth and Planetary Science Letters*, *144*, 93-108.

Hirth, G., and Kohlstedt, D. (2003), Rheology of the upper mantle and the mantle wedge: A view from the experimentalists, in *Inside the Subduction Factory*, edited by J. Eiler, pp. 83-105, American Geophysical Union, Washington DC.

Kelley, K. A., Plank, T., Grove, T. L., Stolper, E. M., Newman, S., and Hauri, E. (2006), Mantle melting as a function of water content beneath back-arc basins, *Journal of Geophysical Research*, *111*, B09208.

Macdonald, K. C. (1982), Mid-ocean ridges: Fine scale tectonic, volcanic and hydrothermal processes within the plate boundary zone, *Annual Review of Earth and Planetary Science*, *10*, 155-190.

Martinez, F., and Taylor, B. (2002), Mantle wedge control on back-arc crustal accretion, *Nature*, *416*(6879), 417-420.

Martinez, F., and Taylor, B. (2006), Modes of crustal accretion in back-arc basins: Inferences from the Lau Basin, in *Back-Arc Spreading Systems: Geological, Biological, Chemical and Physical Interactions, Geophyscial Monograph 166*, edited by D. M. Christie, C. R. Fisher, S.-M. Lee and S. Givens, pp. 5-30, American Geophysical Union, Washington, DC.

Parson, L. M., and Wright, I. C. (1996), The Lau-Havre-Taupo back-arc basin: A southward-propagating, multi-stage evolution from rifting to spreading, *Tectonophysics*, *263*, 1-22.

Phipps Morgan, J. (1997), The generation of a compositional lithosphere by mid-ocean ridge melting and its effect on subsequent off-axis hotspot upwelling and melting, *Earth and Planetary Science Letters*, *146*, 213-232.

Ruellan, E., Delteil, J., Wright, I., and Matsumoto, T. (2003), From rifting to active spreading in the Lau Basin--Havre Trough backarc system (SW Pacific): Locking/unlocking induced by seamount chain subduction, *Geochemistry, Geophysics, Geosystems*, *4*, doi: 10.1029/2001GC000261.

Tamura, Y., Tatsumi, Y., Zhao, D., Kido, Y., and Shukuno, H. (2002), Hot fingers in the mantle wedge: new insights into magma genesis in subduction zones, *Earth and Planetary Science Letters*, *197*(1-2), 105-116.

Watanabe, M., Okino, K., and Kodera, T. (2010), Rifting to spreading in the southern Lau Basin: Variations within the transition zone, *Tectonophysics*, *494*(3-4), 226-234.

Wright, I. C., Parson, L. M., and Gamble, J. A. (1996), Evolution and interaction of migrating cross arc volcanism and back-arc rifting: An example from the southern Havre Trough (35°20'-37°S), *Journal of Geophysical Research*, *101*(B10), 22,071-022,086.

Wysoczanski, R. J., Todd, E., Wright, I. C., Leybourne, M. I., Hergt, J. M., Adam, C., and Mackay, K. (2010), Backarc rifting, constructional volcanism and nascent disorganised spreading in the southern Havre Trough backarc rifts (SW Pacific), *J Volcanol Geoth Res*, *190*(1-2), 39-57.

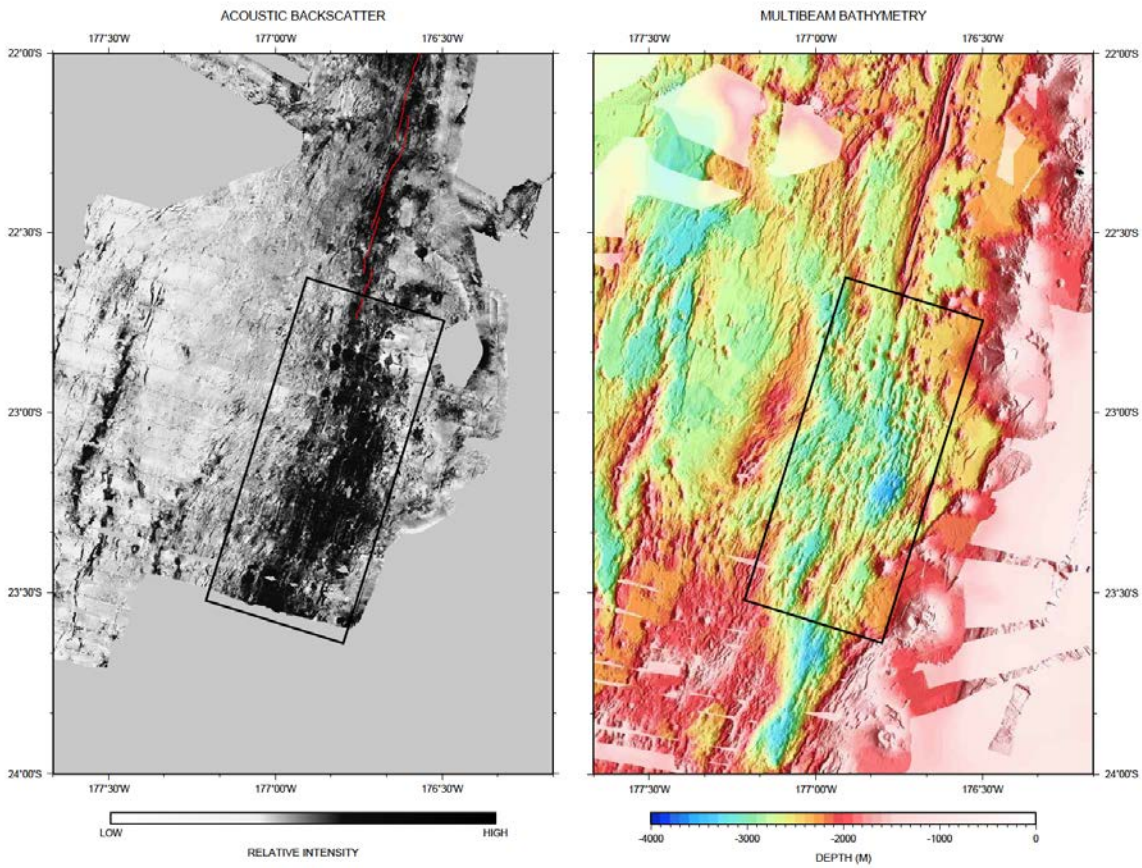


Figure 1. Change in character of the plate boundary zone in the southern Lau Basin. (Left) Acoustic backscatter imagery shows broad distribution of recent volcanism south of the Valu Fa ridge axis (red line). Dark shades = high backscatter. (Right) Bathymetry shows change from peaked narrow Valu Fa Ridge (red line) to deeper and broader terrain consisting of small volcanic cones and ridges. This volcanic morphology of ridges and cones separated along-strike by deeper basins continues in the Havre Trough for 1500 km to New Zealand. It appears to represent a new type of broad plate boundary associated with arc-proximal spreading at slow to ultra-slow rates. Data contributed by K. Okino, U. Tokyo [Watanabe et al., 2010].

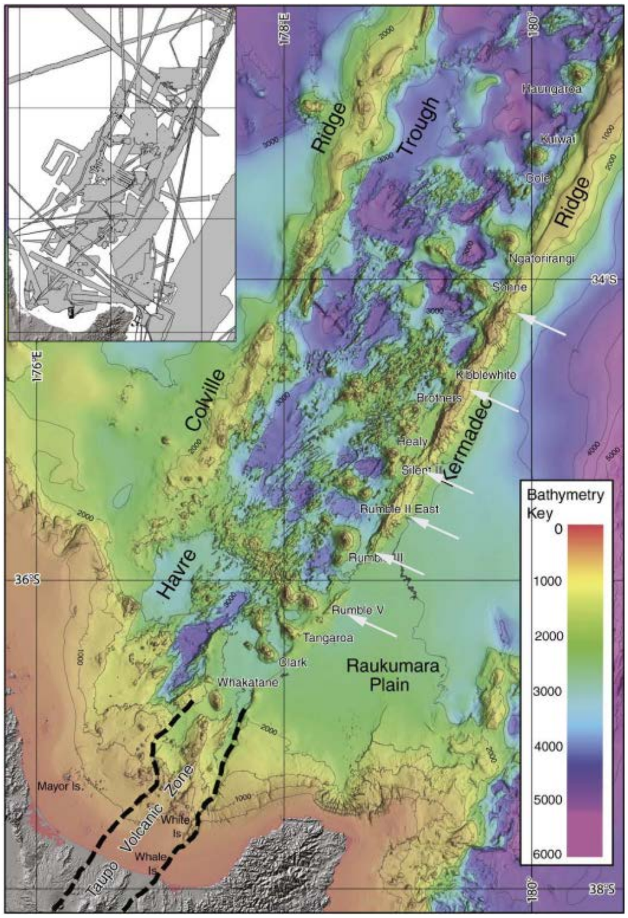
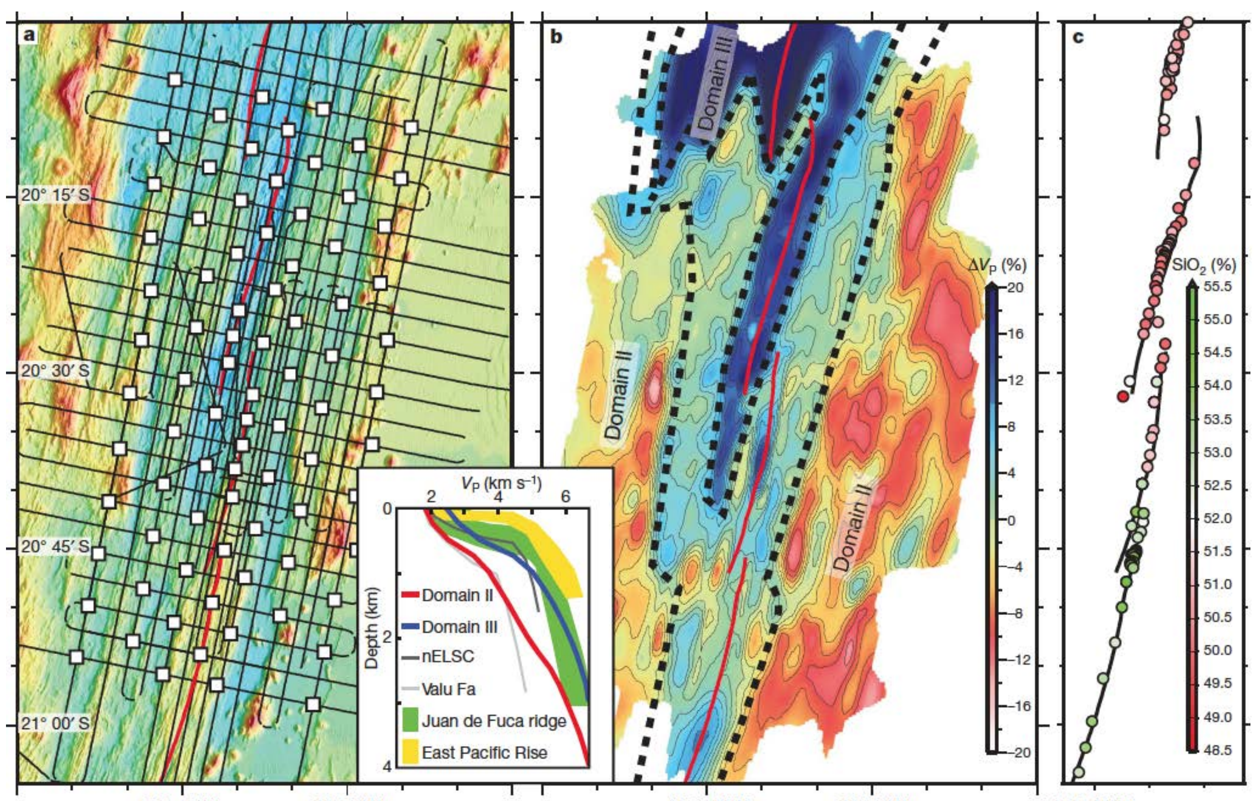


Figure 2. Left) Bathymetry of the Havre Trough showing pattern of crustal accretion. Cross-trending volcanic zones (arrows) are separated by deeper basins suggesting analogies to mantle wedge "hot fingers" postulated by Tamura et al., [2002] . The volcanic terrain may reflect the pattern of melt generation in the mantle wedge more clearly than in other back-arc basins due to the ultra-slow opening rates which minimize plate-driven mantle upwelling and melting components. Figure from Wysoczanski et al., [2010].

Figure 3. Below) Seismic tomography results in the Lau Basin showing large abrupt changes in crustal properties forming distinct domains of thick andesitic crust (Domain II) and thinner basaltic crust (Domain III) with arc separation. A) bathymetry and experiment layout. B) seismic velocity structure. C) silica content of lavas. Havre Trough may reflect similar crustal domains but oriented across-basin due to more pronounced expression of inherent mantle wedge character as a result of ultra-slow opening rates. Figure from Dunn & Martinez [2011].



Testing induced vs spontaneous subduction initiation mechanisms in the SW Pacific

Nick Mortimer[1], Christian Timm[1], Kaj Hoernle[2], Ian Smith[3], Kathie Marsaglia[4]

[1] GNS Science, Dunedin and Lower Hutt, New Zealand ; [2] GEOMAR, Kiel, Germany; [3] Auckland University, New Zealand, [4] California State University Northridge, USA

n.mortimer@gns.cri.nz

Most of this white paper summarizes a 2013 proposal to the Marsden Fund (a New Zealand equivalent of NSF); we also mention related sedimentary basin work that is underway and a planned research cruise. We welcome comment, and invite contributions of additional cross-disciplinary work.

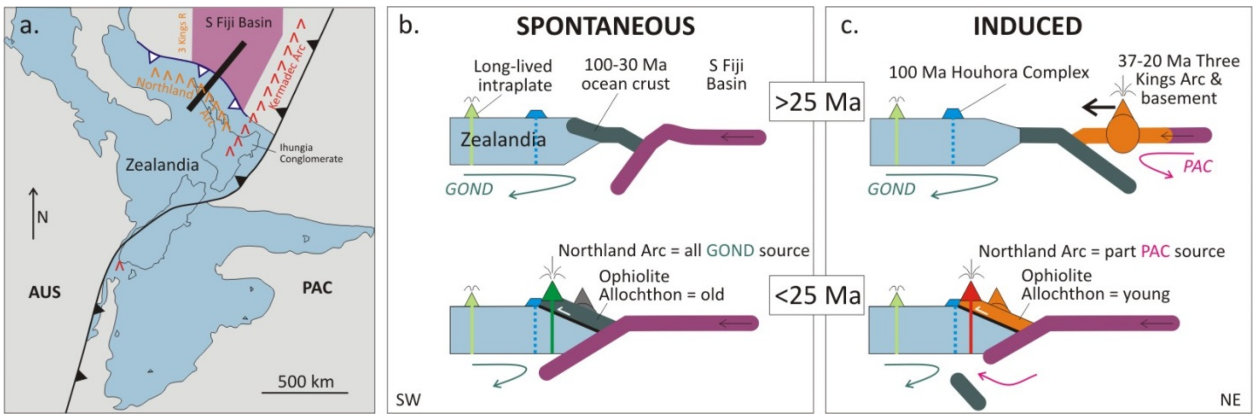


Figure 1. (a) Location map thick black line is cross section line; (b), (c) contrasting options for c. 25 Ma (Early Miocene) subduction initiation in Northland, New Zealand[3]. Green-blue-grey=lavas with Gondwana mantle source, red-orange-purple=Pacific mantle source lavas.

A critical but little-investigated aspect of subduction is how it starts. Conceptual geodynamic models of subduction initiation can be classified as either spontaneous (e.g. subduction triggered by density instabilities) or induced (e.g. arc-continent collision followed by subduction flip)[1,2]. However there are relatively few actual situations in which these models can be empirically tested as subduction initiation is, by definition, a transitory and spatially restricted process. Modern examples are rare and its recognition in the geological record can be controversial and ambiguous (Fig. 1)[3,4].

The Izu-Bonin-Marianas volcanic arc of the western Pacific is often cited in papers on *intra-oceanic* subduction initation. The arc system of the SW Pacific is ideally suited for testing subduction initiation processes at a *continent-ocean boundary* (Fig. 1). This region underwent a convergent to passive margin transition in the Late Cretaceous, with re-establishment of subduction in the Oligocene, eventually evolving into the modern Hikurangi-Kermadec subduction zone. The Miocene Northland volcanic arc (Fig. 1) is known to have erupted through and onto in situ Zealandia continental crust and faulted oceanic ophiolite allochthon in the interval 23-16 Ma [4-6].

When, how and why did SW Pacific subduction initiate adjacent to Northland (white teeth in Fig. 1a)? We propose novel empirical geochemical and geochronological tests of this longstanding SW Pacific tectonic problem using basalt lava geochemical, Sr, Nd, Pb and Hf isotope and Ar-Ar age data. If subduction was induced spontaneously then all Northland lavas, including those in the Allochthon, will have isotopically distinct Gondwana (a.k.a. Indian) mantle sources (Fig. 1b). However if subduction was induced by subduction flip following collision of an older arc (cf. models of New Caledonia) then some lavas with a Pacific mantle source will be present in the Northland Arc and Allochthon (Fig. 1c). Ar-Ar dating is a critical part of our programme as resolving the disputed Cretaceous (old) vs Oligocene (young) age of parts of the Northland Allochthon will provide a separate but related test of the subduction initiation mode. identifciation and direct dating of compositionally distinct rocks relevant to subduction polarity e.g. boninites, adakites, shoshonites will also be important.

The advantages of investigating continent-ocean subduction initiation models in the Zealandia-SW Pacific area are that (i) established isotopically distinctive end-member Indian and Pacific mantle sources in the region permit our innovative approach[7,8]; (ii) onland geology is well characterised and a long-baseline volcanic record can be sampled[4-6]; (iii) alternative local tectonic models are mature and clearly defined[9-12].

Our results will indicate if continent-ocean subduction initiation off Northland was spontaneous or induced. Induced initiation will demonstrate the applicability of New Caledonia-style collisional models to New Zealand (Fig. 1b) and demand a major overhaul of conventional local tectonic models. Spontaneous initiation will require a new, globally-applicable model of ophiolite emplacement (obduction), unrelated to collision and subduction flip (Fig. 1c).

Related to Oligocene sub duction initiation, but separate from the Marsden Fund proposal, are two other projects:

(1) planned acquisition of samples from the Three-Kings Loyalty Ridge. This is the submarine continuation of the Northland Arc, and is possibly an older feature. The **VESPA** cruise proposal, coordinated by an IFREMER-UBO-GNS group, has been rated P1 (highest) but is not yet scheduled.

(2) CSUN-GNS study of the post-allochthon Ihungia Conglomerate which contains ophiolitic clasts. The sedimentary basin response adjacent to the ophiolite allochthon will help constrain the tectonic geometry of subduction initiation[13,14].

References:

1. Stern, R.J. 2004. Subduction initiation: spontaneous and induced. Earth and Planetary Science Letters 226: 275–292.

2.Gurnis, M., Hall, C. & Lavier, L. 2003. Evolving force balance during incipient subduction. Geochemistry, Geophysics, Geosystems 5: Q07001, doi:10.1029/2003GC000681

3.Wakabayashi, J. & Shervais, J.W. 2012. Initiation and termination of subduction: rock record, geodynamic models, and modern plate boundaries. Lithosphere 4: 467–468.

4.Malpas, J., Sporli, K.B., Black, P.M. & Smith, I.E.M. 1992. Northland ophiolite, New Zealand, and implications for plate-tectonic evolution of the southwest Pacific. Geology 20: 149–152.

5.Booden, M.A., Smith, I.E.M., Black, P.M. & Mauk, J.L. 2011. Geochemistry of the early Miocene volcanic succession of Northland, New Zealand, and implications for the evolution of subduction in the Southwest Pacific. Journal of Volcanology and Geothermal Research 199: 25–37.

6.Mortimer, N., Gans, P.B., Palin, J.M., Meffre, S., Herzer, R.H. & Skinner, D.N.B. 2010. Location and migration of Miocene-Quaternary volcanic arcs in the SW Pacific region. Journal of Volcanology and Geothermal Research 190: 1-10.

7. Crawford, A.J., Briqueu, L., Laporte, C. & Hasenaka, T. 1995. Coexistence of Indian and Pacific oceanic upper mantle reservoirs beneath the central New Hebrides Island Arc. American Geophysical Union Monograph 88: 199–217.
8. Pearce, J. A., Kempton, P.D. & Gill, J.B. 2007. Hf-Nd evidence for the origin and distribution of mantle domains in the SW Pacific, Earth and Planetary Science Letters 260: 98–114.
9.Mortimer, N., Herzer, R.H., Gans, P.B., Laporte-Magoni, C., Calvert, A.T. & Bosch, D. 2007. Oligocene-Miocene tectonic evolution of the South Fiji Basin and Northland Plateau, SW Pacific Ocean: evidence from petrology and dating of dredged rocks. Marine Geology 237: 1–24.
10. Crawford, A.J., Meffre, S. & Symonds, P.A. 2003. 120 to 0 Ma tectonic evolution of the southwest Pacific and analogous geological evolution of the 600 to 220 Ma Tasman Fold Belt System. Geological Society of America Special Paper 372: 383–403.
11.Schellart, W.P., 2007. North-eastward subduction followed by slab detachment to explain ophiolite obduction and Early Miocene volcanism in Northland, New Zealand. Terra Nova 19: 211–218.
12. Whattam, S.A., Malpas, J., Smith, I.E.M. & Ali, J.R. 2006. Link between SSZ ophiolite formation, emplacement and arc inception, Northland, New Zealand : U-Pb SHRIMP constraints: Cenozoic SW Pacific tectonic implications. Earth and Planetary Science Letters 250: 606–632.
13.Marsaglia, KM, Rains, J, Bender, C, Mortimer, N, 2010. Sedimentary signatures and paleogreographic implications of subduction inception: two Pacific margin examples. Geological Society of America Abstracts with Programs, 42, 5, 678.
14.Gurnis, M, 1992. Rapid continental subsidence following the initiation and evolution of subduction. Science, 255, 1556-1558.

Seafloor instability processes and products on the active Hikurangi margin

Joshu Mountjoy[1], Ingo Pecher[2,3], Katrin Huhn[4], William Power[2], Sebastian Krastel[5], Alan Orpin[1], Philip Barnes[1], Hugo Pouderoux[6], Stuart Henrys[2], Gareth Crutchley[2], Geoffroy Lamarche[1], Clark Alexander[7], Joerg Bialas[8], Emily Lane[1], Christof Mueller[2]

[1] NIWA, Wellington, New Zealand; [2] GNS Science, Lower Hutt, New Zealand; [3] University of Auckland, New Zealand, [4] Marum, Bremen, Germany; [5] University of Kiel, Germany; [6] University of Calgary, Canada; [7] Skidaway Institute of Oceanography, USA; [8] Geomar, Kiel, Germany.

Joshu.Mountjoy@niwa.co.nz

Submarine landslide complexes and mass-transport deposits (MTD's) occur widely across active margins affected by many forcing factors including earthquakes; sediment loading; gas hydrates; tectonic deformation and slope undercutting. The Hikurangi Margin is no exception, reflecting the tectonically dynamic nature of the margin and a voluminous terrigenous sediment supply during both glacial and interglacial stages. Documented slope failures range in size from the margin scale Ruatoria collapse at 10^{12} m^3, widespread failures in submarine canyons with volumes as low as 10^5 m^3, to discrete earthquake-triggered turbidites only centimetres in thickness. The products of submarine slope failures – MTD's – are widely preserved in slope basins imaged with seismic reflection data.

Landslides have a role in margin evolution, influencing canyon development, cross-slope sediment transfer activity and accretionary processes. Studies indicate that landslides pose a potential hazard to New Zealand coastal populations, particularly where submarine canyons encroach across the shelf to within close proximity of the coastline. Current seafloor instability research addresses key aspects of the spectrum of global questions relating to submarine landslides. 1) What are fundamental processes that control slope mass movements? 2) What is the hazard to coastal populations from submarine landslides? 3) What information can the downslope deposits from submarine landslides (turbidites) contribute to the paleoseismic record?

Analysis of submarine landslides and related processes link to the *New Zealand Primary Site GeoPRISMS Implementation Plan* directly in terms of *Section 2.4.4/D* for paleoseismic studies, and indirectly in terms of the wider efforts to understand upper plate stratigraphy and climate influences. Seafloor instability processes are likely to be a significant ancillary topic based on datasets collected for other purposes (e.g. 3D multichannel seismic reflection data to image the Hikurangi subduction thrust). In the following paragraphs we outline ongoing research that links with several active and proposed international initiatives.

To address process controls on mass movements, a comprehensive effort is in motion to understand the role of gas hydrate in slow moving or creep slope failures – a new mechanism of submarine slope instability as yet only identified on the Hikurangi Margin. Downslope creep-deformation of ice-sediment mixes occurs widely on earth as rock glaciers, and has been proposed for other planets. In the submarine environment such processes are unknown, and to date few examples of slowly-deforming sediment bodies have been documented; however there is strong evidence that gas hydrates cause "creeping" in a well imaged, slowly deforming submarine landslide off the east coast of New Zealand's North Island (Figure 1). This constitutes a fundamental shift for the role of gas hydrates in seafloor stability as hydrates are directly weakening the seafloor on short timescales, as oppose to the widely cited model of temperature controlled dissociation causing failure on a glacial-interglacial time frame. To investigate this mechanism several field campaigns are proposed. 1) 3D P-Cable seismic reflection data across the landslides in collaboration with Geomar and the University of Kiel. 2) Coring using Marum's MeBo robotic drilling technology to sample and analyse landslide debris and adjacent sediments. 3) An APL to IODP proposal 781A (which is proposed adjacent to this landslide complex) will be submitted to collect in-situ hydrate samples from the landslides, and to undertake LWD to characterize the failed sequence.

Towards the southern margin, two initiatives are currently underway focused on landslide-generated tsunami hazards. In the Cook Strait, a multi-year project is focused on quantifying the probabilistic landslide tsunami hazard from landslides within the shelf indenting canyon to the coastal areas of central New Zealand. Initial modeling of previous events shows that landslide-tsunami can generate waves up to 5 m in populated coastal areas. This work addresses major questions related to the hazard from landslides in complex submarine terrain. Whereas many landslide-tsunami models allow landslide debris to run down an infinite slope, our results show that interaction with opposing canyon walls significantly affects tsunami generation and focusing. Submarine canyons are the principal means by which large scale seafloor slopes approach the coast around the globe – Cook Strait's Nicholson Canyon occurs 10 km off Wellington airport and drops from 100 to 500 m water depth. To the south, Kaikoura Canyon is another major canyon system which is incised to c. 0.5 km from the coast. A 0.25 km^3 incipient earthquake-triggered failure in this canyon head has been modeled to generate waves up to 13 m high and, with a very high littoral zone sediment input, may reoccur on c. 200 yr timeframe. Work is currently in progress applying state-of-the-art geophysical and sediment analysis techniques to understanding the actual nature of the unstable sediment. Depending on these results, proposed future work includes in-situ geotechnical analysis, stability modeling and a re-evaluation of the tsunami hazard and risk related to the sediment failure scenario.

At many active continental margins, off-fault submarine paleoseismic records have been interpreted from turbidite sequences recovered in cores. The application of turbidite paleoseismology techniques is ideally suited to continental margins where turbidites have been emplaced into a steadily depositing background sequence of hemipelagic or pelagic sediment, and where tests can be drawn for regional event synchronicity, sedimentology, and correlation with existing earthquake records. Identification of turbidites from high-resolution stratigraphic records, their chronology and provenance allows tectonic and climate signals to be deciphered. For the eastern North Island, there are no paleo-earthquake records unambiguously originating from a rupture along the Hikurangi subduction zone, but paleotsunami deposits and co-seismic uplifts associated with upper plate earthquakes have been recognised. On the Poverty continental margin, 67 synchronous turbidites were described by Pouderoux et al. (2012) that span the last 18,000 yrs resulting from earthquakes, with a mean return time of ~230 yr, with a 90% probability range from 10–570 yr. The earthquake chronology indicates cycles of progressively decreasing earthquake return times, from ~400 yr to ~150 yr at 0– 7 kyr, 8.2–13.5 kyr, 14.7–18 kyr. The two 1.2 kyr-long intervals in between (7–8.2 kyr and 13.5–14.7 kyr) correspond to basin-wide reorganisation of the Poverty slope seascape, reflecting the emplacement of two large MTD's. These and other buried MTD's form the greater percentage of mid-slope basin fill at this location highlighting the important role mass failure processes have in margin building and large scale cross-slope mass flux.

The Hikurangi margin exhibits a hugely varied range of mass-transport and seafloor instability processes and large scope exists for increasing understanding of globally relevant fundamental landslide processes and hazard implications. There is significant scope to develop new collaborative projects, and also to integrate with complementary proposals that will collect data relevant to landslide, MTD and turbidite-paleoseismicity research.

References:

Mountjoy, J. J., Pecher, I., Henrys, S., Barnes, P. M., and Plaza-Faverola, A., in review: Creeping deformation mechanisms for mixed hydrate-sediment submarine landslides. *Geology*.

Pouderoux, H., Lamarche, G., and Proust, J. N., 2012, Building an 18 000-year-long paleo-earthquake record from detailed deep-sea turbidite characterisation in Poverty Bay, New Zealand: *Natural Hazards and Earth System Sciences*, v. 12, no. 6, p. 2077-2101.

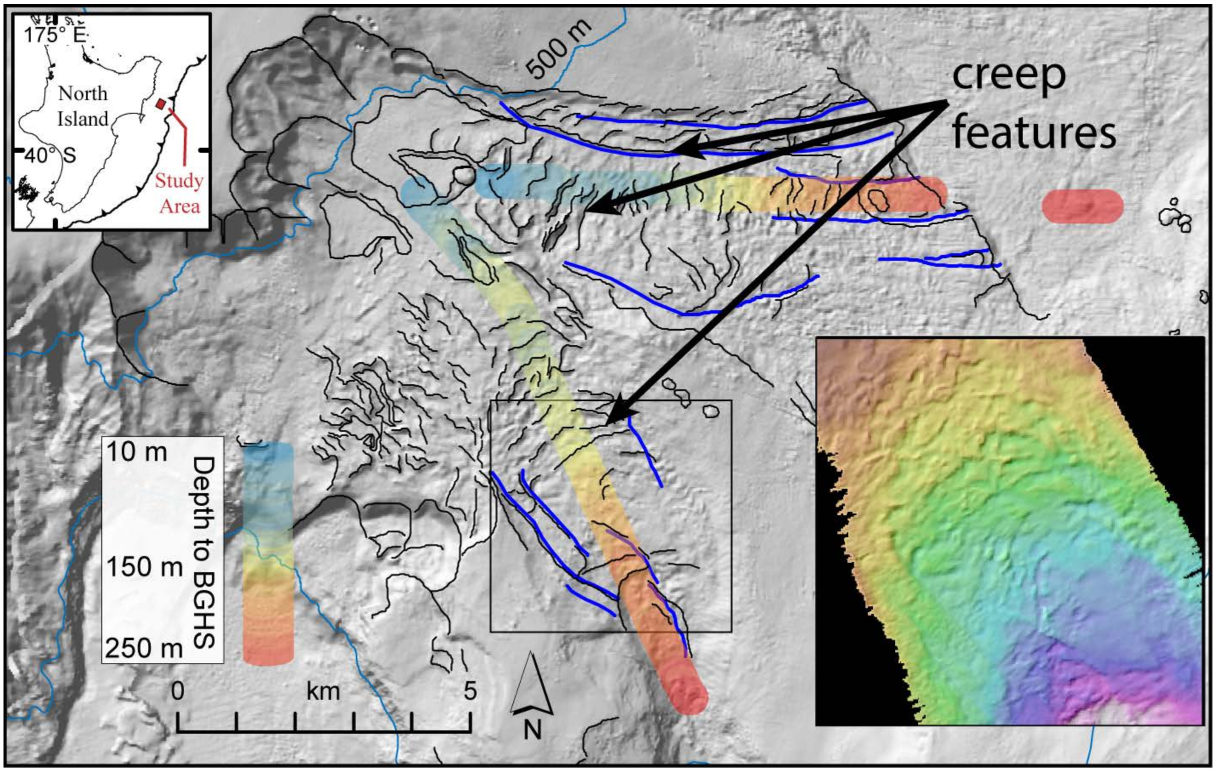


Figure 1. Creeping slope instability complex on New Zealand's East Coast. The slow deformation of this landslide is proposed to be controlled by gas hydrate occurring within the landslide debris. After Mountjoy et al. (in review).

Characterization of structure and properties of the northern Hikurangi margin using OBS seismology for studies of slow slip and along-strike variations in plate interface coupling

OBS working group (alphabetical): Stuart Henrys[1], Shinichi Kodaira[2], Kirk McIntosh[3], Kimi Mochizuki[4], David Okaya[5], Tim Stern[6], Harm van Avendonk[3]

[1]GNS Science, Lower Hutt, NZ, [2]JAMSTEC, Japan; [3]Univ. Texas/IG, USA; [4]Univ. Tokyo/ERI, Japan; [5]Univ Southern California, USA; [6]Victoria Univ. Wellington, NZ.

okaya@usc.edu

The Hikurangi subduction system exhibits a range of slip conditions, from aseismic to strongly coupled, with strain release by coseismic, slow slip, and repeating microseismic events. Multi-disciplinary studies as summarized in Wallace et al. (2009) point to a number of factors which affect frictional properties and stress along the Hikurangi plate interface. These factors are identified as also important in other subduction systems and include the presence of fluids and accretionary sediments, serpentinization and other hydration processes in the slab and plate interface, shear localization and stress buildup, temperature, lower plate morphology (seamounts, plateaus), and aseismic slip processes. Slow slip earthquakes (SSE) are still not well understood, but studies consider conditionally stable frictional regimes, in the transition zone between velocity strengthening (e.g., aseismic slip) and velocity-weakening (e.g., stick-slip) behavior on the interface (e.g. Scholz 1998; Schwartz and Rokosky 2007). Many workers also suggest that fluids play a major role in the occurrence of slow slip events and associated non-volcanic tremor (e.g., Obara et al., 2002; Liu and Rice, 2007).

The New Zealand continuous GPS and seismic national networks have led to the identification of slow slip events at the Hikurangi subduction margin. The northern Hikurangi margin SSEs are shallow (<15 km depth), occur more frequently, have shorter durations (1 week up to 2 months) and smaller equivalent moment release (~6.5-6.8) and possibly associated with subducted fluid-rich sediment (Bell et al., 2010). In contrast, the Southern Segment SSE events (e.g., Fig. 1) are deep, (35-50 km depth), characterized by long durations (1-1.5 years) and larger equivalent moment release (> Mw 7.0). Relevant scientific questions include how do the physical properties of the interface change in the downward transition from strong coupling to slow slip? Do SSE occur in regions of locally elevated fluid pressures? If so, how does this fluid pressure evolve along the interface and within the overlying plate during an SSE cycle? Will substantial fluid migration occur, influencing SSE behavior and nearby seismicity? Integrated, multi-disciplinary studies are required and are direct targets for the proposed series of IODP boreholes (as summarized in IODP slow slip event workshop; Bell et al., 2012). These Hikurangi source areas are accessible for geophysical observations that will aid in the assessment of the physical controls on SSE behavior.

Three major regions of along-strike coupling conditions have been identified by Wallace et al (2009) and listed in Fig. 2. The areal extent of strong coupling is much broader in the south than for the Northern and Central Segments, suggesting conditions for a future large magnitude megathrust event. Seismic transects are now established in the Central and Southern Segments (NIGHT and SAHKE projects, respectively; Henrys et al., 2006; Henrys et al., submitted). The proposed IODP drillhole transect nicely forms a baseline for a broader seismic transect of the Northern Segment subduction margin. Such a transect would allow for direct comparison of these three major along-strike zones.

We propose OBS-based studies at different scales that target high resolution images of the proposed borehole region and also provide the broader regional context of the subduction system for the net drillhole transect. At a broader scale, a pair of refraction-wide angle reflection transects are proposed (Fig 3): (a) an OBS-portable land instrument onshore-offshore seismic profile through the drillhole sites extending landward in the slab downdip direction and (b) an OBS-only strikeline that will examine local lateral variations in the plate interface, overlying and subducting plates. Seismic airgun sources will be used. These transects will provide seismic velocities and possible direct waveform images of major structures such as overlying plate internal structure and downdip Moho, the plate interface, Hikurangi plate structure (sedimentary basins, plateau/oceanic crust) and sub-Moho lithospheric mantle. They also will contribute information to the inferences of elastic and other material properties. The regional transects to the south offer indications of seismic opportunities; the SAHKE transect observes subduction channel reflections tracking downdip well beneath the land portion of the overlying plate (Henrys et al., submitted). Because of the major community focus on the offshore SSE region, these wide-angle transects can be designed with locally densified instrumentation to provide even higher spatial resolution along the borehole transect within the broader regional context. The transects will complement the 3D MCS survey that is being proposed by others.

In addition to the transects, within our working group we propose smaller-scale targeted OBS studies that examine the plate interface near the boreholes. An example includes several-km long crossing linear arrays centered on a major borehole with dense (100m) spacing to obtain seismic proxies for physical properties. Other targets include detailed imaging of plate interface structures (roughness). Discussions among our international working group members will continue with a goal to develop an implementation plan that includes science teams, time frames, and strategies for instrumentation, vessels for sources and deployments, proposals, and alignment of international funding periods.

References:

Bell, R., R. Sutherland, D.H.N. Barker, S. Henrys, S. Bannister, L.Wallace, J. Beavan, Seismic reflection character of the Hikurangi subduction interface, New Zealand, in the region of repeated Gisborne slow slip events, Geophys. J. Int., 180, 34-48, 2010.

Henrys, S., M. Reyners, I. Pecher, S. Bannister, Y. Nishimura, and G. Maslen, Kinking of the subducting slab by escalator normal faulting beneath the North Island of New Zealand, Geology, 34, 777-780, 2006. Liu, Y. and Rice, R., Spontaneous and triggered aseismic deformation transients in a subduction fault model, J. Geophys. Res., 112, B09404, doi:10.1029/2007JB004930, 2007.

Henrys, S., Wech, A.G., Sutherland, R., Stern, T., Savage, M., Sato, H., Mochizuki, K., Iwasaki, T., Okaya, D., Seward, A., Tozer, B., Townend, J., Kurashimo, E., Iidaka, T., submitted, SAHKE geophysical transect reveals crustal and subduction zone structure at the southern Hikurangi margin, New Zealand: G-Cubed.

Obara, K., Nonvolcanic deep tremor associated with subduction in southwest Japan, Science, 296, 1679-1681, doi:10.1126/science.1070378, 2002.

Scholz, C.H., Earthquakes and friction laws, Nature, 391, 37-42, 1998.

Schwartz, S.Y. and J.M. Rokosky, Slow slip events and seismic tremor at circum-Pacific subduction zones, Rev. of Geophys, 45, RG3004, doi:10.1029/2006RG000208, 2007.

Wallace, L., Bell, R., Townend, J., Ellis, S., Bannister, S., Henrys, S., Sutherland, R., and Barnes, P.M., 2010, Subduction Systems Revealed: Studies of the Hikurangi Margin: EOS Trans., AGU, v. 91, p. 417-428.

Wallace, L. M., M. Reyners, U. Cochran, S. Bannister, P.M. Barnes, K. Berryman, G. Downes, D. Eberhart-Phillips, A. Fagereng, S. Ellis, A. Nicol, R. McCaffrey, R.J. Beavan, S. Henrys, R. Sutherland, D.H.N. Barker, N. Litchfield, J. Townend, R. Robinson, R. Bell, K. Wilson, and W. Power, Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand, Geochem. Geophys. Geosyst., 10, Q10006, doi: 10.1029/2009GC002610, 2009.].

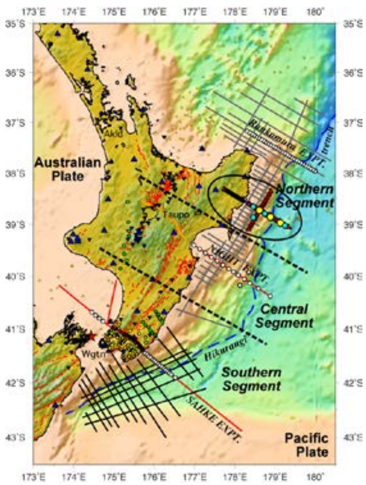


Figure 1 (left). Hikurangi subduction system, North Island, NZ. System varies along-strike (three segments). Seismic transects exist in southern two segments; we propose one in north. Proposed IODP wells (blue, yellow circles).

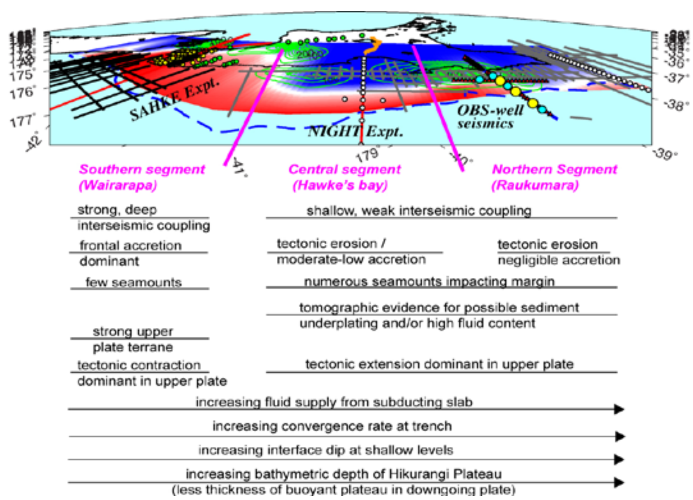


Figure 2. (right) North Island oblique view illustrating degree of coupling and list of properties/conditions that vary along-strike. Green contours denote SSE. Modified from Wallace et al (2010).

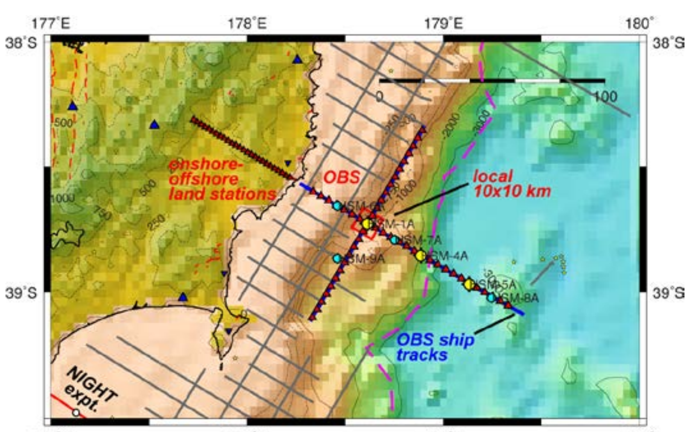
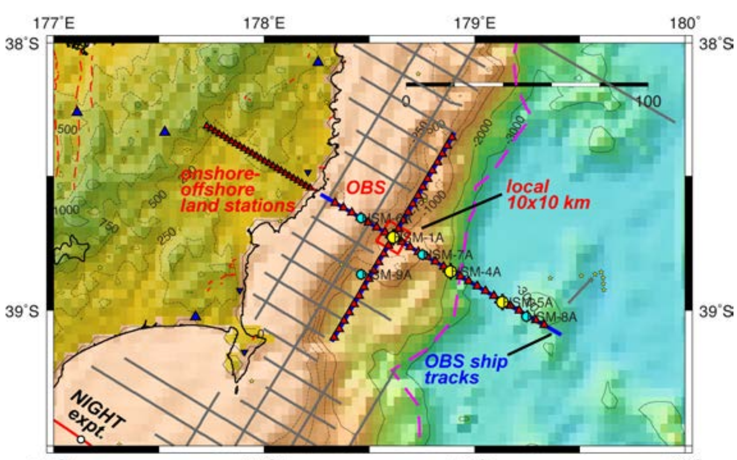


Figure 3. (left) OBS-based seismic transects coincident with proposed IODP borehole transect (blue-yellow circles). OBS (red triangles) will record airgun sources along ship tracks. OBS spacing will be finer based on instrument numbers. Densification will target main boreholes. Red box denotes possible site of focused higher resolution OBS seismic studies.


177°E
178°E
179°E
180°
38°S
39°S
0
100
500
1000
750
500
250
onshore-
offshore
land stations
OBS
local
10x10 km
-2000
-3000
-1000
SM-1A
ISM-7A
SM-4A
SM-9A
ISM-5A
SM-8A
OBS ship
tracks
NIGHT
expt.

Gas Hydrates in New Zealand

Ingo A. Pecher[1,2], Stuart Henrys[2], Joshu Mountjoy[3], Philip Barnes[3], Andrew Gorman[4], Jörg Bialas[5], Gareth Crutchley[5,2], Andreia Plaza-Flaverola[2], Jens Greinert[5], Katrin Huhn[6], Nina Kukowski[7], Marta Torres[8], Richard Coffin[9], Michael Riedel[10]

[1]School of Environment, University of Auckland, New Zealand; [2]GNS Science, Lower Hutt, New Zealand; [3]NIWA, Wellington, New Zealand; [4]Department of Geology, University of Otago, Dunedin, New Zealand; [5]Geomar, Kiel, Germany; [6]MARUM, Bremen, Germany, [7]University of Jena, Germany; [8]Oregon State University, Corvallis, OR, USA; [9]Naval Research Laboratory, Washington, DC, USA; [10]Natural Resources Canada, Sidney, BC, Canada

i.pecher@auckland.ac.nz

Gas hydrates have been studied extensively in the past two decades with significant government and industry interest in gas hydrates as a possible natural-gas resource (e.g., Boswell, 2009) and as a potential geohazard for deep-water infrastructure (e.g., McConnell et al., 2012). While strong progress has been made addressing these objectives, many fundamental questions related to gas hydrates are still unresolved, in particular their role in the global carbon cycle and climate change (e.g., Dickens, 2003) as well as their effect on seafloor stability (e.g., Bangs et al., 2010; Mountjoy et al., submitted). Furthermore, many questions related to the distribution of gas hydrates have yet to be answered, such as sources of gas, gas-supply for hydrate formation, and emplacement of gas hydrates in sediments.

Gas Hydrates offshore New Zealand: The Hikurangi Margin (Figure A) is the only area offshore New Zealand in which gas hydrates have been sampled (e.g., Bialas et al., 2007). Indirect evidence for gas hydrates is provided by the presence of bottom simulating reflections (BSRs) on the Fiordland-Puysegur Margin (Townend, 1997) and indications for gas within the hydrate stability zone in the Northland and Taranaki Basins (Ogebule and Pecher, 2010). Pockmarks on the Chatham Rise may be caused by gas hydrate dissociation during glacial sealevel lowstands (Davy et al., 2010). The New Zealand government is funding a program to assess gas hydrates as a possible energy resource, focusing on the Hikurangi Margin. Drilling is now required to calibrate geophysical reservoir characterisation, perhaps as part of a government-backed Complementary Project Proposal to IODP. The economic case for gas hydrates in New Zealand is unique because of the depletion of known conventional gas fields, New Zealand's remoteness resulting in high cost for LNG import, and relatively small rates of gas consumption suggesting hydrates could provide New Zealand with gas for several decades. New Zealand's gas hydrate deposits are also ideally suited to address several key basic-science questions.

Seafloor Stability: Studies of the effect of gas hydrates on seafloor failure have generally focused on gas hydrate dissociation, assuming that solid gas hydrates strengthen sediments. Observations on the Hikurangi Margin may now lead to a paradigm shift: the gas hydrate zone itself may be a region of sediment weakness. Creeping of submarine landslides and seafloor erosion appear to be linked to a thin zone of gas hydrates. Seafloor weakening could be caused either by elevated pore pressures transmitted through hydrofractures into the hydrate zone

(Crutchley et al., 2010) or by plastic deformation of ice-like gas hydrates similar to rock glaciers (Mountjoy et al., submitted) (Figure B). Remote drilling off the R/V *Sonne* is now planned to sample sediments from the creeping landslides. Acquisition of 3-D seismic data has been proposed to extend results from remote drilling. Ultimately, drilling through the entire creeping slide mass, collection of pressure cores, and borehole logging are needed to confirm the presence of hydrates, investigate their pore-scale distribution, and quantify their effect on sediment physical properties. The D/V *JOIDES Resolution* is ideally suited for these investigations which has led to plans for the submission of an Ancillary Program Letter to the proposed IODP leg in the study area (proposal 781A).

Cold seeps, link to fluid migration, and gas hydrate emplacement: Fluid migration into and through the gas hydrate stability zone on the Hikurangi Margin is thought to be highly focused with vigorous gas expulsion at cold seeps (Coffin et al., submitted; Greinert et al., 2010) and pronounced local thermal anomalies marked by upwarping of BSRs (Pecher et al., 2010). Seismic reflection profiles show that known seep sites are closely associated with major thrust faults through the accretionary wedge. It has been proposed that gas hydrate formation may be caused by cooling of gas-bearing sediments following a decrease of fluid advection, a novel model of hydrate emplacement in sediments (Toulmin et al., 2010). Furthermore, a strong link between BSR occurrence and fluid migration from underthrusted sediments has been shown and it has been suggested that this link is caused by enhanced rates of microbial and possibly thermogenic methane transport into the hydrate stability field in addition to in-situ generation of methane (Plaza-Faverola et al., 2012). Deep sediment cores in those areas may help to unravel the methane generation process, as well as the transport mechanism of free gas through the gas hydrate stability field. A study has recently been proposed to design coring and drilling programs aimed at investigating focused fluid flow on the Hikurangi Margin and its effect on the local gas hydrate system near sites of fluid expulsion. Answering these questions will provide new insights into the mechanisms that control gas hydrate formation as well as more globally, methane cycling in subduction zones.

Response of gas hydrates to sealevel lowering: Seafloor pockmarks have been detected over a >20,000 km^2 area on the Chatham Rise (Davy et al., 2010). These pockmarks appear to be controlled by bathymetry and are situated in a seafloor-depth range that is predicted to have moved out of hydrate stability during glacial-stage sealevel lowstands. Buried pockmarks in seismic data are present at reflections that appear to mark sealevel lowstands (Figure C). It has therefore been suggested the pockmarks formed following gas hydrate dissociation during glacial sealevel lowering. Because of a bathymetric locking of currents, parts of the Chatham Rise are thought to not have experienced any significant bottom-water temperature changes during glacial cycles, making the study area ideally suited to investigate the effect of sealevel-lowering on gas hydrate-bearing sediments. Evaluation of data acquired during a recent seismic and coring survey of the R/V *Sonne* is expected to shed more light onto these findings.

With the very recent success of offshore production testing off Japan, hydrates may become a promising gas resource. However, many basic-science aspects related to gas hydrates have yet to be resolved. New Zealand offers excellent opportunities for gas hydrate research, which will ultimately require ocean drilling.

References

Bangs, N. L., Hornbach, M. J., Moore, G. F., and Park, J.-O., 2010, Massive methane release triggered by seafloor erosion offshore southwestern Japan: Geology, v. 38, p. 1019-1022.

Bialas, J., Greinert, J., Linke, P., and Pfannkuche, O., 2007, FS Sonne Fahrtbericht / Cruise Report SO 191 New Vents, Volume 9: Kiel, IFM-GEOMAR, p. 186.

Boswell, R., 2009, Is gas hydrate energy within reach?: Science, v. 325, p. 957-958.

Coffin, R. B., Hamdan, L. J., Plummer, R. E., Smith, J. P., Osburn, C. L., Yoza, B., Pecher, I., Rose, P. S., and Montgomery, M. T., submitted, Plate convergence forcing influence on shallow sediment carbon cycling: Porangahau Rige, Hikurangi Margin, New Zealand: Mar. and Petrol. Geol.

Crutchley, G. J., Geiger, S., Pecher , I. A., Gorman, A. R., Zhu, H., and Henrys, S. A., 2010, The potential influence of shallow gas and gas hydrates on seafloor erosion of Rock Garden, an uplifted ridge offshore of New Zealand: Geo Mar. Lett., v. 30, no. 3-4, p. 283-303.

Davy, B., Pecher, I. A., Wood, R., Carter, L., and Gohl, K., 2010, Gas Escape Features off New Zealand – Evidence for a Massive Release of Methane from Hydrates?: Geophys. Res. Lett., v. 37, p. L21309.

Dickens, G. R., 2003, Rethinking the global carbon cycle with a large, dynamic and microbially mediated gas hydrate capacitor: Earth Planet. Sci. Lett., v. 213, p. 169-183.

Greinert, J., Lewis, K. B., Bialas, J., Pecher , I. A., Rowden, A., Bowden, D. A., De Batist, M., and Linke, P., 2010, Methane seepage along the Hikurangi Margin, New Zealand: Overview of studies in 2006 and 2007 and new evidence from visual, bathymetric and hydroacoustic investigations: Mar. Geol., v. 272, no. 1-4, p. 6-25.

McConnell, D. R., Zhang, Z., and Boswell, R., 2012, Review of progress in evaluating gas hydrate drilling hazards: Mar. and Petrol. Geol., v. 34, p. 209-223.

Mountjoy, J. J., Pecher , I., Henrys, S., Barnes, P. M., and Plaza-Faverola, A., submitted, Creeping deformation mechanisms for mixed hydrate-sediment submarine landslides.: Geology.

Ogebule, O. Y., and Pecher, I. A., 2010, Possible gas hydrates in the Northland and northern Taranaki Basins – indirect evidence from seismic data: N. Z. J. Geol. Geophys., v. 53, no. 4, p. 369-373.

Pecher , I. A., Henrys, S. A., Kukowski, N., Crutchley, G. J., Gorman, A. R., Wood, W. T., Coffin, R., Greinert, J., Faure, K., and CHARMNZ Working Group, 2010, Focussing of fluid expulsion on the Hikurangi margin, New Zealand, based on evidence for free gas in the regional gas hydrate stability zone: Mar. Geol., v. 272, p. 99-113.

Plaza-Faverola, A., Klaeschen, D., Barnes, P., Pecher , I., Henrys, S., and Mountjoy, J., 2012, Evolution of fluid expulsion and controls on hydrate formation across the southern Hikurangi subduction Margin, New Zealand: Geochem. Geophys. Geosyst., v. 13, no. 8, p. Q08018.

Toulmin, S. J., Schwalenberg, K., Pecher , I. A., Crutchley, G., Gorman, A. R., and Wood, W. T., 2010, Gas hydrate formation on the Porangahau Ridge offshore New Zealand - evidence from seismic, heatflow, and electromagnetic data, 7th International Workshop on Methane Hydrate R&D: Wellington, New Zealand.

Townend, J., 1997, Estimates of conductive heat flow through bottom-simulating reflectors on the Hikurangi margin and southwest Fiordland, New Zealand: Mar. Geol., v. 141, p. 209-220.

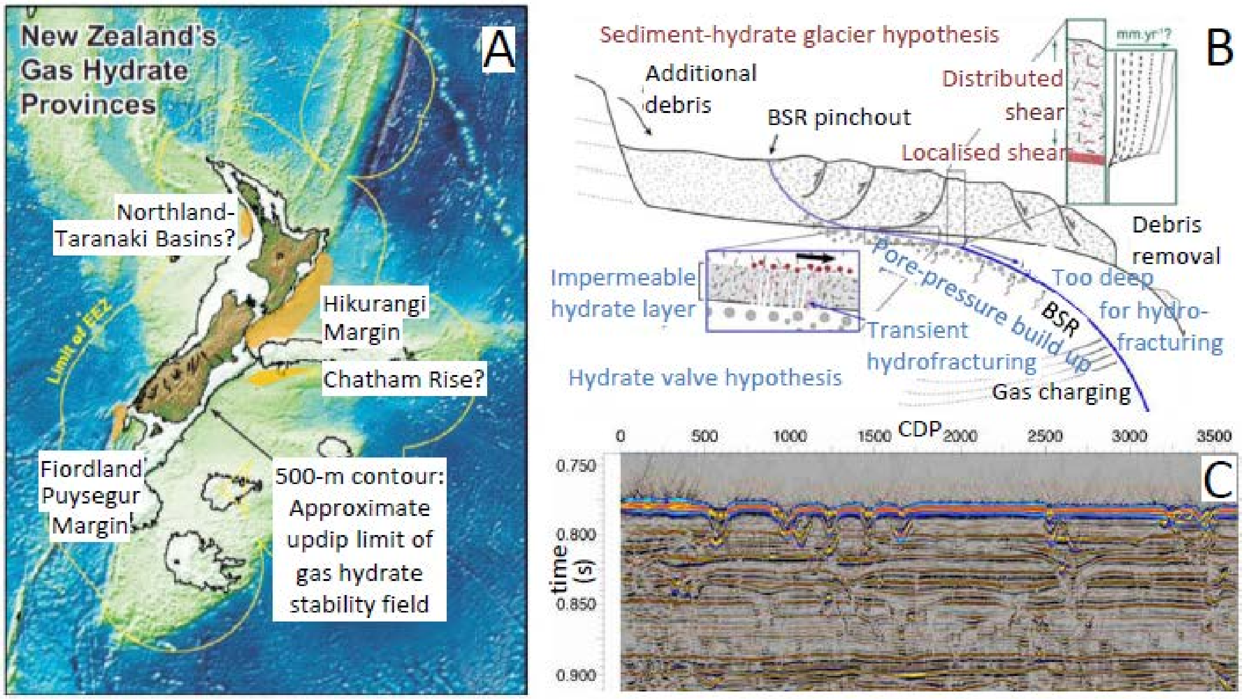


Figure A. Gas hydrate provinces offshore New Zealand. Figure B. Hypotheses for gas-hydrate-related creeping of sediments (after Mountjoy et al., submitted). Figure C. Seismic images of seafloor and buried pockmarks on the Chatham Rise (R/V Sonne voyage SO-226)

Paleoseismology at the Hikurangi Margin

Jessica Pilarczyk[1], Ursula Cochran[2], Nicola Litchfield[2], Kate Clark[2], Bruce Hayward[3], Geoffroy Lamarche[4], Benjamin Horton[1]

[1]Department of Earth & Environmental Science, University of Pennsylvania, Philadelphia, PA; [2]Natural Hazards Group, GNS Science, Lower Hutt, New Zealand; [3]Geomarine Research, Auckland, New Zealand; [4]National Institute of Water & Atmospheric Research, Wellington, New Zealand

jpilar@sas.upenn.edu

Paleoseismology along Hikurangi Margin coastlines contributes to two questions guiding the GeoPrisms SCD initiative:

1. What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?
2. How does deformation across the subduction plate boundary evolve in space and time through the seismic cycle and beyond?

Coastal paleoseismology can address amounts and rates of Hikurangi megathrust deformation throughout complete earthquake cycles over periods of hundreds to thousands of years. We aim to measure subduction-zone strain accumulation and release indirectly by inferring coastal land-level changes from small (<2m) changes in relative sea level (RSL) that occur both instantaneously (coseismic) and gradually (interseismic). Measuring the magnitude and timing of Hikurangi plate boundary deformation improves assessments of earthquake and tsunami hazards in New Zealand as well as far field locations.

Marshes and tidal inlets from NE New Zealand contain an extensive sedimentary archive of Holocene earthquakes and tsunamis originating from the Hikurangi Margin (Cochran et al., 2005; 2006; Hayward et al., 2006). Multiple cycles of tectonic subsidence have been preserved in the sedimentary record. As inferred from couplets of interbedded organic and silty sediment beneath coastal wetlands, the Hawke's Bay coastal stratigraphy may record up to six great earthquakes over the last 7100 years (Hayward et al., 2006). This is similar to Holocene sedimentary sequences of coseismic and interseismic land-level changes at several other subduction zones such as Cascadia. Here, the sedimentary record has validated a 3-D elastic dislocation model for the Cascadia margin that allows the slip to vary both along strike and in the dip direction (Wang et al., in press). In contrast, other subduction zones (e.g. south-central Chile) have only fragmentary evidence for earthquake-induced land-level movements because of falling sea level since 6 ka combined with probable near complete postseismic recovery following great earthquakes.

An improved paleoseismic record of the Hikurangi Margin is valuable to the GeoPrisms SCD initiative because it will aid in defining the source for paleoearthquakes. This would involve investigations of new sites along the Hikurangi Margin and increasing the resolution of radiocarbon age control for known events from new and existing sites (e.g. Cochran et al., 2005; 2006). An improved record will also quantify the vertical resolution of land-level changes throughout a seismic cycle. Statistical transfer functions will be developed to infer tidal elevations from microfossils (e.g. diatoms, foraminifera, pollen; e.g. Sawai et al., 2004). Existing studies of the history of Hikurangi Margin earthquakes and tsunamis indicate that a complicated pattern of land-level changes occur over short distances (Cochran et al., 2005). One of the most precise ways to resolve these patterns is to apply high resolution, microfossil-based, sea level reconstructions to Hikurangi coastal sediments. These reconstructions can then be compared with the well established northern Hikurangi turbidite record, which provides a continuous paleoearthquake history over the last 18 ka (Pouderoux et al., 2012).

Defining the extent of paleoearthquakes and quantifying the vertical land-level motion throughout multiple earthquake cycles will: (1) begin to clarify the relationship between upper plate fault movement and movement on the subduction thrust; (2) yield more precise measurements of coseismic and interseismic deformation over timescales of decades to centuries; (3) test hypothetical rupture segmentation boundaries; (4) provide more extensive measurements of post-earthquake vertical deformation for prehistoric earthquakes; (5) examine evidence for or against precursory deformation just prior to great earthquakes; (6) help constrain regional slip models of Hikurangi megathrust rupture for tsunami simulations; and (7) test hypotheses of slip-predictable, time-predictable, and slip-time-unpredictable strain accumulation.

References:

Cochran, U., Berryman, K., Mildenhall, D., Hayward, B., Southall, K., Hollis, C., 2005. Towards a record of Holocene tsunami and storms for Northern Hawke's Bay, New Zealand. New Zealand Journal of Geology and Geophysics, 48, 507-515.

Cochran, U., Berryman, K., Zachariasen, J., Mildenhall, D., Hayward, B., Southall, K., Hollis, C., Barker, P., Wallace, L., Alloway, B., Wilson, K., 2006. Paleoecological insights into subduction zone earthquake occurrence, eastern North Island, New Zealand. GSA Bulletin, 118(9/10), 1051-1074.

Hayward, B., Grenfell, H., Sabaa, A., Carter, R., Cochran, U., Lipps, J., Shane, P., Morely, M., 2006. Micropaleontological evidence of large earthquakes in the past 7200 years in southern Hawkes's Bay, New Zealand. Quaternary Science Reviews, 25(11/12), 1186-1207.

Pouderoux, H., Lamarche, G., Proust, J., 2012. Building a 18,000 year-long paleo-earthquake record from detailed deep sea turbidite characterization in Poverty Bay, New Zealand. Natural Hazard and Earth System Processes, 12, 1-25.

Sawai, Y., Satake, K., Takanobu, K., Nasu, H., Shishikura, M., Atwater, B., Horton, B., Kelsey, H., Nagumo, T., Yamaguchi, M., 2004. Transient uplift after a 17th-century earthquake along the Kuril subduction zone. Science, 306, 1918-1920.

Wang, P., Engelhart, S., Wang, K., Hawkes, A., Horton, B., Nelson, A., Witter, R., in press. Heterogeneous rupture in the great Cascadia earthquake of 1700 inferred from coastal subsidence estimates. Journal of Geophysical Research – Solid Earth.

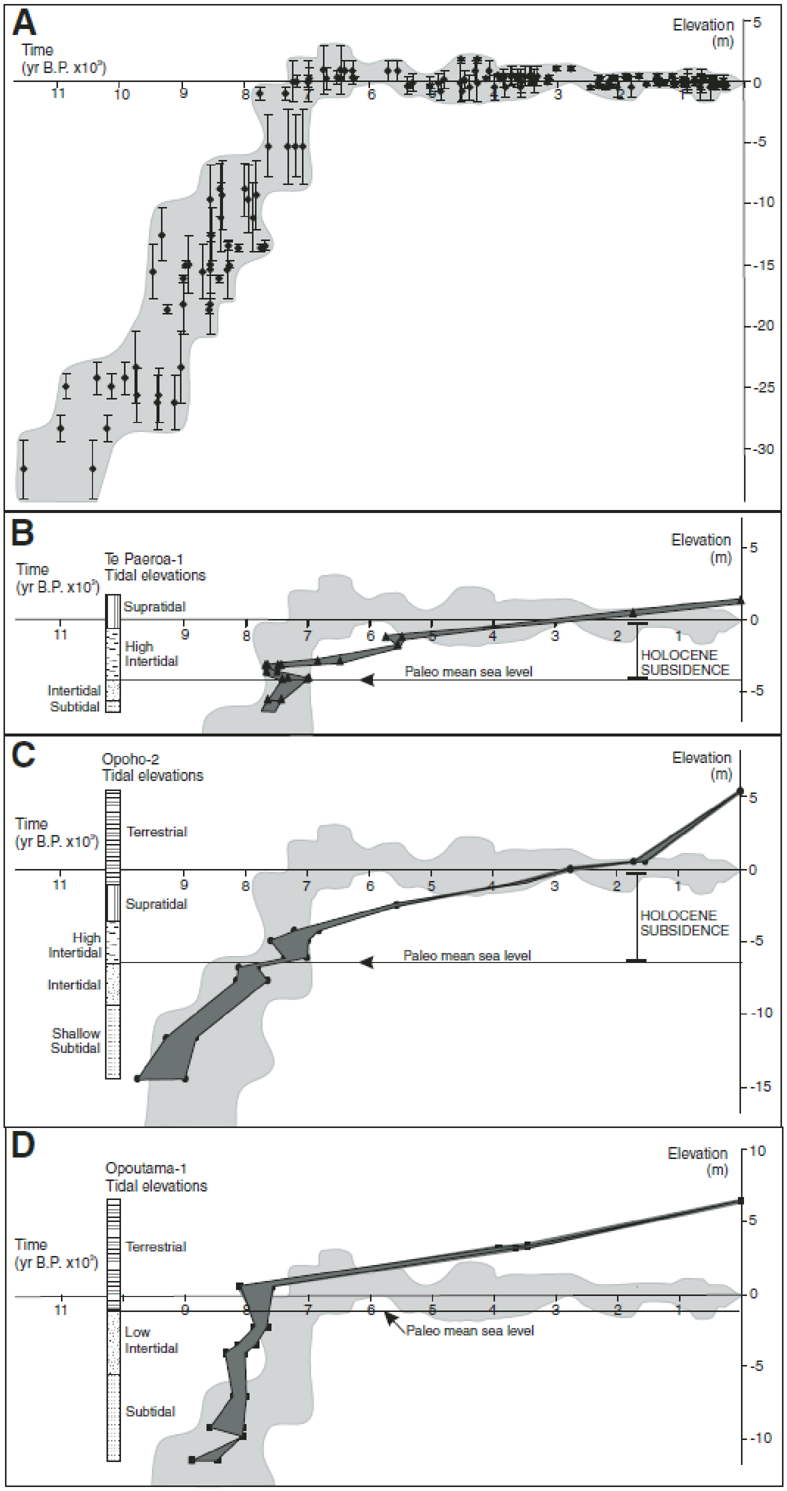


Figure 1: Using sea level reconstructions to estimate vertical land-level changes throughout a seismic cycle. (A) Holocene eustatic sea level curve for New Zealand. (B, C, D) Age-depth curves for select cores taken from Hawke's Bay, compared to Gibb's (1986) New Zealand sea level curve (shown in grey). Tidal elevations inferred from paleoenvironmental reconstructions are shown at left and indicate the position of paleo mean sea level. The inferred net Holocene subsidence is shown at right (Cochran et al., 2006).

Integrating Current Research on Subduction Processes and Records into Learning and Teaching: Potential for GeoPRISMS Knowledge Transfer

Kate Pound[1], Lee Schmitt[2], Megan Jones[3], Kerry Swanson[4], Maree Hemmingsen[4], Kathleen Marsaglia[5]

[1] Atmospheric & Hydrologic Sciences, St. Cloud State University, St. Cloud, Minnesota, USA; [2] School of Education, Hamline University, Saint Paul, Minnesota, USA; [3] North Hennepin Community College, Brooklyn Park, Minnesota, USA; [4] Department of Geological Sciences, University of Canterbury, Christchurch, New Zealand. [5] Department of Geological Sciences, California State University, Northridge, California, USA

kspound@stcloudstate.edu

Exactly how should we attempt to transfer the knowledge gained through cutting-edge geosciences research to undergraduates, K-12 students and their teachers, and the general public? What parts of this new knowledge should we attempt to transfer? How can we transfer it effectively to engage non-scientists and communicate the value of the broader scientific endeavor? What has society in general got to gain from improved understanding of science in general, and subduction processes specifically?

The need for a citizenry that understands the importance of science in democratic decision-making processes has been demonstrated (AAAS, 1993; NRC, 1996), but a more challenging task is effectively communicating exactly why we as geoscientists continue to conduct research, how we do it, and how it will benefit society. An additional challenge is engaging science-phobic students and communities in science. Even though the focus of GeoPRISMS is the study of subduction processes, the excitement of new research results can only be communicated if recipients are engaged by, and have an understanding of, the overall context and relevance. For this reason, GeoPRISMS outreach and education programs can simultaneously (a) piggy-back on already existing materials (e.g. plate tectonics; SERC http://serc.carleton.edu/teachearth/index.html ; discovering plate boundaries, http://plateboundary.rice.edu/), (b) leverage general interest in natural hazards, and (c) use GeoPRISMS-specific themes (e.g. the tectonics-sediment-climate interactions theme) to engage its various audiences and build their understanding of the scientific process through aspects that are immediately relevant to them. Below, we present three approaches that could be used, targeting a spectrum of levels and situations.

(1) What specific suggestions do we have for transferring knowledge and connecting Undergraduate Educators to GeoPRISMS?

Research conducted under MARGINS has been transferred into a variety of 'mini-lessons' available through SERC, Earthscope http://www.earthscope.org/eno/handouts, and IRIS http://www.iris.edu/hq/programs/education_and_outreach/resources . We suggest that from this start, a series of scaffolded teaching exercises, based on real research results and focused on tectonic processes and their relevance to society, could be developed for use in the undergraduate classroom. A model for such exercises is those developed for *Reconstructing*

Earth's Climate History: Inquiry-based Exercises for Lab and Class (St. John et al., 2012). Initial identification of core skills and specific content knowledge, use of backward design (Wiggins & McTighe, 2006), and recognition of how we learn (NRC, 2005) incorporated with initial identification of student misconceptions are integral parts of effective lesson design. Dissemination of teaching materials (together with 'plug-and-play' answer-keys) to undergraduate and graduate educators is only effectively accomplished through hands-on workshops.

(2) How can cutting-edge GeoPRISMS research be translated for use in K-12 classrooms?
Effective transfer of knowledge and skills, associated with cutting-edge research into the K-12 classroom, requires a complex partnership and filters. It is essential that teachers are familiar and comfortable with the teaching materials they are using, and that the materials fulfill their curricular needs at an appropriate level. A majority of teachers teaching earth science do not have dedicated training in earth science. We suggest an approach modeled by TIMES (Teaching Inquiry-based Minnesota Earth Science) (Schmitt, 2012), in which a group of middle- and high-school teachers spend two weeks in the field learning fundamental aspects of geology, facilitated by education specialists who act as go-betweens, connecting content to curriculum and teaching; in this instance it would be in New Zealand, and in the context of subduction. Teachers would build their knowledge of geology, how geoscientists *do* science, and as a consequence build their confidence so they can better incorporate geology-related research and topics into their teaching. Mediated access to both research geoscientists and educators assist the teachers in translation of their overall experience into directed, purpose-built teaching materials that are place based (Semken & Brandt, 2010; Pound et al., 2011), address topics relevant to their curricula, and support the Next Generation Science Standards (NRC, 2012). An essential aspect is the continued support of teachers as they implement the materials that they design (Loucks-Horsley et al., 2010); this is provided through online discussions and follow-up sessions attached to regional or national meetings.

(3) How can Indigenous Knowledge (*Mataranga Maorii*) be used to engage science-phobic students to empower them and their communities (*Runanga, hapu and iwi on Marae*)?
Model programs 'Te Ru Tauira' and 'Te Pu Tautahi' are after-school programs established through collaboration between Maori, low-decile high schools and school communities, and the University of Canterbury; the ultimate aim of the program is to engage, encourage and support Maori secondary students to move on to University education, and connect them to careers that will help them become future leaders in their communities. This is accomplished through first building connections and trust with the Marae; then, based on the requests from the Marae, and existing curriculum, a series of Lab-type activities focused on 'The Arrival' (Nga Tapuae o Kupe) are undertaken. These activities are structured around the Indigenous Peoples' skills and knowledge of the natural world. In the context of GeoPRISMS the broad topics of earthquakes, tsunami, and volcanic eruptions would be ideal topics. Activities are designed so that students learn experientially what their ancestors had learned or already knew (Traditional Knowledge), and in so doing they experience 'doing science'. This program provides resources for the students and their teachers, allows them to consider science as a non-threatening

extension of their own culture, using a collaborative approach that values both Mataranga Maori and western science, providing a pathway to higher education.

This model is complementary to the approach used in (2) above. In the context of GeoPRISMS we suggest that this model (a) be further developed and supported for use with the Marae, (b) a similar approach be developed and implemented in the context of Indigenous people of the Pacific Northwest and Alaska, and (c) that collaborations or exchanges between Indigenous peoples of both New Zealand and North America focused on connecting Indigenous Knowledge with Science be supported; similar initiatives have been supported by local Indigenous people in Aotearoa New Zealand.

References:

American Association for the Advancement of Science. (1993). *Science for all Americans.* Washington DC: National Academy Press.

Kristen St. John, R. Mark Leckie, Kate Pound, Megan Jones, and Lawrence Krissek. (2012). Reconstructing earth's Climate History: Inquiry-based Exercises for Lab and Class. Wiley-Blackwell, 528p.

Loucks-Horsley, S., Stiles, K., Mundry, S., Love, N. Hewson, P. (2010). *Designing professional development for teachers of science and mathematics*. Thousand Oaks, CA: Corwin Press, Inc.

National Research Council. (2005). *How students learn*. Washinton, DC: National Academies Press.

National Research Council. (2012). *A framework for k-12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: National Academies Press.

Pound, K., Campbell, K., & Schmitt, L. (2011). *Archean to Anthropocene: Field guides to the geology of the Mid-continent of North America.* An examination of the bedrock geology and Mississippi River valley in the Twin Cities: Pedagogical strategies for introductory geology field trips. Boulder, CO: Geological Society of America. Field Guide 24.

Schmitt, L. (2012). *Teaching inquiry-based Minnesota earth science (TIMES): A study of the long-range effects of the TIMES professional development program on teacher practice.* Capstone dissertation. St. Paul, MN: Hamline University.

Semken, S., & Brandt, E. (2010). Implications of sense of place and place-based education for ecological integrity and cultural sustainability in contested places. In D. Tippins, M. Mueller, M. van Eijck, & J. Adams (Eds.), *Cultural studies and environmentalism: The confluence of ecojustice, place-based (science) education, and indigenous knowledge systems* (pp. 287-302). New York: Springer.

Wiggins, G. & McTighe, J. (2006). *Understanding by design*. Arlington, VA: Association for Supervision and Curriculum Development, p. 24.

Cambrian Rocks of the Takaka Terrane, the Foundation of Zealandia: A Complex Record of Subduction Initiation and Arc Development Exposed in the Nelson Area of the South Island

Kate Pound[1], John Bradshaw[2], Margaret Bradshaw[2], Richard Jongens[3], Carsten Munker[4], Kari Bassett[2], Kathleen Marsaglia[5]

[1] Atmospheric & Hydrologic Sciences, St. Cloud State University, St. Cloud, Minnesota, USA; [2] Department of Geological Sciences, University of Canterbury, Christchurch, New Zealand; [3] Anatoki Rocks Consulting, Dunedin, New Zealand; [4] Institut für Geologie und Mineralogie, Universität zu Köln, Cologne, Germany; [5]Department of Geological Sciences, California State University, Northridge, California, USA.

kspound@stcloudstate.edu

The Takaka, Buller and their correlative terranes in Fiordland (Fig. 1) constitute the Western Province of New Zealand and the foundation of the Zealandia microcontinent (Rattenbury et al., 1998 and references therein). Some of the oldest, Middle Cambrian, rocks in the Takaka Terrane are the exhumed products of a marginal arc that can be linked to rocks of similar age and tectonic affinity in Antarctica, SE Australia, and Tasmania (e.g., Cooper and Tulloch, 1992; Munker & Crawford, 2000; Squire & Wilson, 2005; Gutjahr et al., 2006).

The Takaka Terrane (Fig. 2) includes an extensive record of arc-related low-K to high-K calc-alkaline volcanics (Devil River Volcanics Group, DRVG). A record of pre-DRVG arc sedimentary rocks (Junction Formation and the poorly-understood Heath Creek beds) and back-arc volcanic rocks (Mataki Volcanics, range from MORB to low-K arc; similar to modern back-arc tholeiites), are intruded by the boninitic Cobb Igneous Complex (Munker & Cooper, 1999). Boninitic clast-bearing conglomerates of the Heath Creek beds indicate a complex pre-DRVG history involving subduction. The DRVG is overlain by epiclastic volcanic and siliciclastic sedimentary rocks of the Haupiri Group (Pound, 1993). The Takaka Terrane units are now preserved in a series of fault-bounded slices where the bounding faults probably initiated as thrusts, but record a complex history of multi-phase reactivation (Pound, 1993; Munker & Cooper, 1999; Jongens, 2003; Jongens, 2006). The upper Middle Cambrian Lockett Conglomerate (Pound, 1993; Pound et al., 1993) was deposited across an evolving accretionary prism that included broken formation and diapiric intrusion of the Balloon Melange. All of the Cambrian units in the Takaka Terrane are present within the Balloon Mélange, which continued to evolve during the tectonic transition to passive margin sedimentation in the overlying Late Cambrian to Ordovician units.

What Aspects of the Evolution of the Early Paleozoic Part of the Zealandia Microcontinent are relevant to GeoPRISMS?

1. INSIGHTS INTO PROCESS OF SUBDUCTION INCEPTION AND TERMINATION - The oldest successions in the Takaka Terrane may provide a stratigraphic record of subduction inception, as well as arc and back-arc basin development. Sandstones of the Junction Formation and Heath Creek beds may be the detrital hallmark of rapid uplift and erosion associated with induced subduction similar to what has been predicted by geodynamic modeling and/or observed elsewhere in nascent forearc successions (e.g., Marsaglia, 2012; Rains et al., 2012).

There is potential for U-Pb and Lu-Hf work (detrital and tephra zircon dating) that will better define the relations between stratigraphic successions within the fault-bounded packages, as well as potential to constrain arc termination through evaluation of Haupiri Group conglomerates.

2. INSIGHTS INTO THE MAGMATIC/GEOCHEMICAL EVOLUTION OF ARC/BACKARC – New insights into the early history of pre-Devil River Arc evolution could be gained through use of analytical tools including the Lu-Hf system and systematic Pb isotope measurements, which could be used to address the origins and implications of the unusually radiogenic Pb compositions (Munker, 2000; Wombacher & Munker, 2000) of Takaka terrane rocks and arcs in general, and serve as a tool in paleogeographic reconstructions.

3. LARGER, GLOBAL IMPLICATIONS - PALEOGEOGRAPHIC RECONSTRUCTIONS OF LARGE/LONG-LIVED ACTIVE MARGINS – Insights into the temporal and and spatial variability in subduction-related segments at convergent margins can be gained at the Cambrian margin of Gondwana. The largely volcanic/sedimentary record of the Takaka Terrane has been linked to sequences in Tasmania and Antarctica, and a variety of plate models have been presented (Gutjahr et al, 2006; Munker & Crawford, 2000; Squire and Wilson, 2005), none of which have accommodated all of the geochemical, sedimentologic, stratigraphic and structural data available. Bradshaw et al. (2009) present a model correlating the Bowers Terrane of Northern Victoria Land with Takaka terrane rocks. Extensive work on Bowers Terrane rocks (references in Bradshaw et al., 2009) provides insights into Cambrian subduction-related processes at the Gondwana margin. There is potential for mapping, stratigraphic, sedimentologic, and geochemical work within poorly-understood units (e.g. Anatoki Formation; Christmas Conglomerate; Heath Creek beds) of the Takaka Terrane in order to better constrain correlations and models, and build understanding of Middle Cambrian subduction-related processes at the Gondwana margin.

4. INSIGHTS INTO THE LONGEVITY AND ROLE THAT FAULTS INITIATED DURING SUBDUCTION MAY HAVE HAD DURING SUBSEQUENT EVENTS – Faults initiated during subduction and arc development record multiple phases and senses of movement. Exhumed Takaka Terrane rocks provide a window into the partitioning of strain, and the evolution of fault geometries over time, including their role during the transition from subduction to extension. There is potential for further examination of these faults.

References

Bradshaw, J. D., , Gutjahr, M., Weaver,S. D., Bassett, K. N., 2009. Cambrian intra-oceanic arc accretion to the austral Gondwana margin: constraints on the location of proto-New Zealand. Australian Journal of Earth Sciences 56: 587-594.

Gutjahr, M., Bradshaw, J.D., Weaver, S., Münker, C., Ireland, T., 2006. Provenance of Cambrian Conglomerates from New Zealand: implications for the tectonomagmatic evolution of the SE Gondwana margin. Journal of the Geological Society 163: 997-1010.

Jongens, R., 2003. Structure of the Buller and Takaka Terrane rocks adjacent to the Anatoki Fault, northwest Nelson, New Zealand. New Zealand Journal of geology and geophysics, 49:4, 443-461.

Jongens, R., Bradshaw, J.D., Fowler, A.P., 2006. The Balloon Melange, Northwest Nelson: Origin, structure, and emplacement. New Zealand Journal of Geology and Geophysics, 46:3, 437-448.

Marsaglia, K.M., 2012. Sedimentation at Plate Boundaries in Transition: Recent Advances in the Tectonics of Sedimentary Basins, Busby, C. and Pérez, A., eds., Blackwell, p. 291-309.

Munker, C, Cooper, R.A., 1999. The Cambrian arc complex of the Takaka terrane, new Zealand: An integrated stratigraphical, paleontological and geochemical approach. New Zealand Journal of Geology and Geophysics 42:3, 415-445.

Münker, C. ,2000. Pb-Nd isotopes indicate the origin of island arc terranes in the Early Paleozoic Pacific. Journal of Geology 108 (2): 233-242.

Münker, C. and Crawford, A.J., 2000. Cambrian arc evolution along the SE-Gondwana active margin: a synthesis from Australia-New Zealand-Antarctica correlations. Tectonics 19 (3): 415-432.

Pound, K.S., 1993. Geology of the Lower Paleozoic haupiri group rocks, Cobb Valley area, Northwest Nelson, New Zealand. Unpublished PhD thesis, University of Otago, Dunedin, New Zealand, 366 p.

Pound, K.S., Cooper, R.A., Grapes, R.H., Stedman, H., 1993. Northwest Nelson-basement geology. *In* Grapes, R.H., Little, T., Campbell, H.J., *eds.* Conference Field Trip Guides, Geological Society of New Zealand Miscellaneous Publication 79B: 75-136.

Rains, J., Marsaglia, K.M., Dunne, G. ,2012. The stratigraphic and petrologic record of Permian subduction inception along the North American margin. Lithosphere, 4, 533-552.

Rattenbury, M.S., Cooper, R.A., Johnston, M.R. (compilers), 1998. Geology of the Nelson area. Institute of Geological and Nuclear Sciences 1;250 000 geological map 9. 1 sheet + 67 p. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Limited.

Squire, R.J., Wilson, C.J.L., 2005. Interaction between collisional orogenesis and convergent-margin processes: evolution of the Cambrian proto-Pacific margin of East Gondwana. Journal of the Geological Society, 162, 749-761.

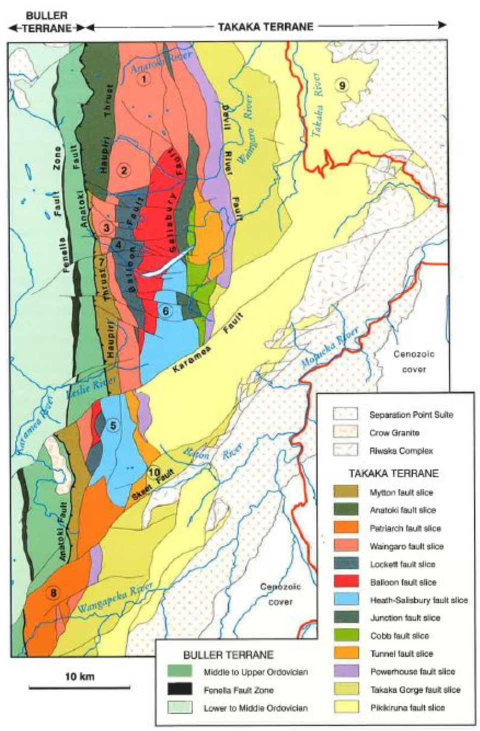


Figure 1

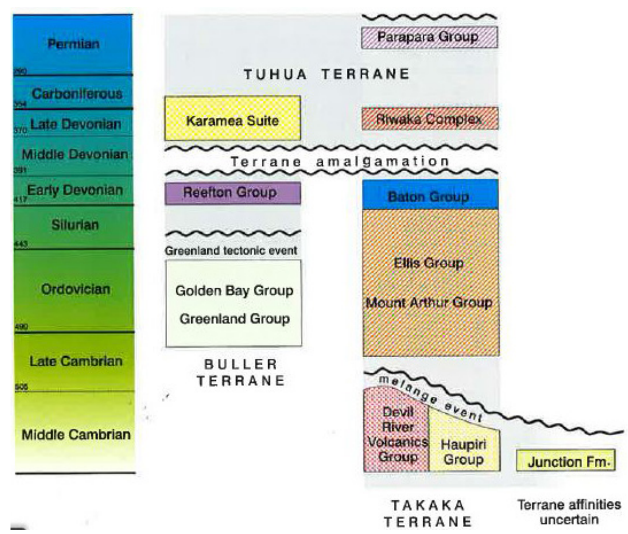


Figure 2

Figure 1. Map of northwest Nelson, showing distribution of Buller and Takaka Terrane rocks within fault-bounded slices (from Rattenbury et al., 1998, Fig. 16)

Figure 2. Major rock units of the Buller and Takaka Terranes of northwest Nelson (from Rattenbury et al., 1998, Fig. 10)

Look before it leaps: the interplay of magmatism, tectonism and basement structural inheritance in a migrating rifting arc

Julie Rowland[1], Colin Wilson[2], Cindy Ebinger[3]

[1] School of Environment, University of Auckland, New Zealand, State; [2] Victoria University of Wellington, New Zealand; [3] Rochester University, New York, USA.

j.rowland@auckland.ac.nz

The <2 Ma Taupo Volcanic Zone (TVZ) is but the current manifestation of >15 My of continental arc magmatism, volcanism and extension linked to subduction of the Pacific Plate beneath the North Island of New Zealand (Figure 1). The evolution of this system in response to roll-back of the subduction hinge is recorded in surface and subsurface geology (Mauk et al., 2011; Rowland et al., 2010, 2012 and references therein). The age distribution of volcanoes, epithermal mineral deposits and their active geothermal analogues, and fault-bounded volcaniclastic basins is consistent with a punctuated southeastward migration of the loci of heat and mass flux, and extensional strain. Three aspects make this system worthy of attention in relation to Geoprisms Draft Science Plan 5. Rift initiation and evolution (RIE).

1) The TVZ represents a highly active arc-related rift. It is subaerial and occurs where a complex interplay of lateral and perpendicular structural features offer unique insights into structural and magmatic controls on continental rifting processes. Much of our understanding of continental break-up comes from places where the mantle flux of heat and mass is pinned to the locus of rifting in the continent (Ebinger et al., in press). Notable exceptions are Yellowstone, where the plate is overriding the plume (Hannan et al., 2008 and references therein) and western Pacific back-arc basins, incipient and developed. The opening and closing of backarc basins is a critical process, setting in place structural and stratigraphic architecture that exerts a major control on hazards and resources in such settings. However, we do not know whether the lengths and timescales of rifting and magmatism in migrating rifting arcs is unique or similar to those described elsewhere (Ebinger et al., in press).
2) The central TVZ is anomalous with respect to its rhyolitic volcanic productivity, which is inextricably linked to tectonic processes (Allan et al., 2012; Rowland et al., 2010). The apparent rapidity with which large (>100 km^3) magma volumes accumulate within the crust is astonishing (Allan et al., 2013).
3) Oblique convergence of the Pacific and Australian plates is partitioned within the overriding plate into strike-slip along the North Island Fault System (NIFS) and extension within the Taupo Volcanic Zone. Within central TVZ, extension is considered to be localized within the densely-faulted Taupo Fault Belt (Villamor & Berryman, 2001). However, the TFB is one of two parallel depocenters that run between the active calderas (Okataina and Taupo). Each is subsiding at a rate of about 4 mm/yr. Currently, the greatest heat and mass transfer is localized within the active calderas and the intervening Taupo-Reporoa Basin (TRB) – the eastern depocenter that abuts the Kaingaroa Plateau, an enigmatic feature that separates the TVZ from the NIFS. Despite its high heat output (>2000MW_{th}) and subsidence the TRB

has subdued relief, a feature interpreted to indicate little active tectonism. However, the kinematics of the TRB and whether it is an incipient rift-jump are unknown.

A consortium approach involving cGPS, borehole seismology, InSAR, LiDAR, and other geological and geophysical methods is required to: 1) develop a high-fidelity model of rheology as moderated by magma storage and compositional alteration throughout central TVZ and surrounds; 2) image pre-rift and rift fabrics; and 3) evaluate and understand controls on strain partitioning within the TVZ and surrounds.

References:

Allan, A, Wilson, C, Millet, M, Wysoczanski, R, 2012. The invisible hand: tectonic triggering and modulation of a rhyolitic super eruption. Geology 40, 563-566.

Allan, A, Morgan, D, Wilson, C, Millet, M, 2013. From mush to eruption in centuries: assembly of the super-sized Oruanui magma body. Contributions to Mineralogy and Petrology (in press: doi:10.1007/s00410-013-0869-2).

Ebinger, C, van Wijk, J, Keir, D, In Press. The time scales of continental rifting: implications for global processes. GSA 125th Special Volume.

Hannan, B, Shervais, J, Vetter, S, 2008. Yellowstone plume-continental lithosphere interaction beneath the Snake River plain. Geology 36, 51-54.

Mauk, J, Hall, C, Chesley, J, Barra, F, 2011. Punctuated evolution of a large epithermal province: The Hauraki Goldfield, New Zealand. Economic Geology, 106, 921-943.

Mouslopoulou, V, Nicol, A, Little, T.A, Walsh, J.J, 2007. Displacement transfer between intersecting regional strike-slip and extensional fault systems. J. Struct. Geol. 29, 100-116.

Rowland, J. V, Bardsley, C, Downs, D, Sepulveda, F, Simmons, S, Scholz, C, 2012. Tectonic controls on hydrothermal fluid flow in a rifting and migrating arc, Taupo Volcanic Zone, New Zealand. 34th NZ Geothermal Conference.

Rowland, J, Simmons, S, 2012a. Hydrologic, magmatic and tectonic controls on hydrothermal flow, Taupo Volcanic Zone, New Zealand: Implications for the formation of epithermal vein deposits. Economic Geology, 107, 427-457.

Rowland, J, Wilson, C, Gravley, 2010. Spatial and temporal variations in magma-assisted rifting, Taupo Volcanic Zone, New Zealand. Journal of Volcanology and Geothermal Research, 190, 89-108.

Villamor, P, Berryman, K.R, 2001. A late Quaternary extension rate in the Taupo Volcanic Zone, New Zealand, derived from fault slip data. N.Z. J. Geol. Geophys. 44, 243-269.

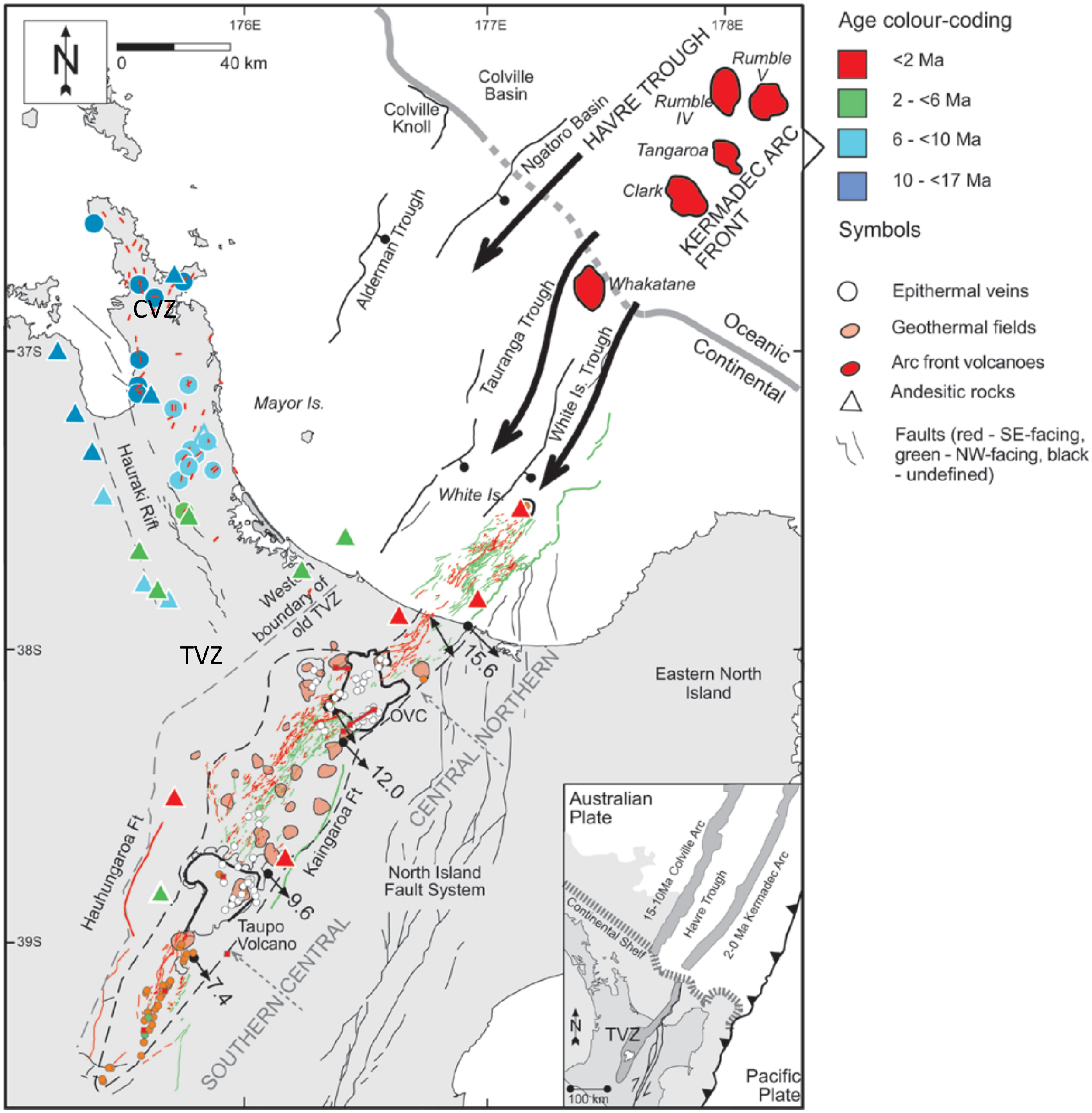


Figure 1. TVZ in its regional context (after Rowland et al., 2010; 2012). CVZ – Coromandel Volcanic Zone. Major basin-bounding offshore faults shown in black ± dip directions. Rift axes in offshore TVZ are arrowed. TVZ is partitioned along its axis into northern and southern TVZ (both andesite dominant) and central TVZ (rhyolite dominant), and also according to age: old TVZ (2.0-0.34 Ma) and young TVZ (< 0.34 Ma), grey and black dashed lines, respectively. All known volcanic vents active <0.61 ka (modern TVZ) are colour-coded according to type: red squares = basalt (linked by red line if associated with dike intrusion), orange small circles = andesite, green small circles = dacite, white small circles = rhyolite. Active calderas, Okataina Volcanic Centre (OVC) and Taupo Volcano, are shown by thick black lines. Other features (faults, epithermal systems, geothermal fields, and older volcanoes) are defined in key. Geodetic extension rates in mm/yr are shown along the length of onshore TVZ. Tension axes defined from earthquake first motion studies are indicated by double-headed arrows.

Geospatial variation in magmatic and volatile fluxes to the oceans and atmosphere from active subaerial/submarine volcanism in the New Zealand Primary Site

Ken Rubin[1], Bob Embley[2], Cornel de Ronde[3], Joe Resing[4], Bob Dziak[2], Bill Chadwick[2], Terry Plank[5]

[1] Dept. of Geology & Geophysics, Univ. of Hawaii, Honolulu, HI; [2] NOAA-VENTS/OSU Newport, OR; [3] GNS Science, Wellington, NZ [4] NOAA-VENTS-JISAO, UW, Seattle, WA; [5] LDEO, Palisades, NY

krubin@hawaii.edu

This proposed project is aimed at constraining magmatic and volatile fluxes from active New Zealand primary site volcanoes (subaerial and submarine) as functions of space and time through the site. Such an observational data set, covering the past century of volcanic activity, would provide a means to investigate several overarching questions as functions of structural and tectonic gradients throughout the greater NZ focus site magmatic system (e.g., crustal thickness, convergence rate, suducted sediment type/amount). These overarching questions include: (a) the underlying petrological and tectonic controls on the magnitude and extent of arc/backarc magmatism per unit time; (b) differences between fluxes from marine and subaerial volcanic systems; and (c) the relative influences of deep and shallow magmatic processes upon magmas and gases that erupt at the surface. By studying current and recently active systems along the Hikurangi, Taupo, and Kermadec arcs, the Havre Trough, and with possible extension to compositionally extreme juvenile volcanoes of the Tonga arc and Lau back-arc, this proposed project aims to explore multiple aspects of the GeoPRISMS Science and Implementation Plans (e.g., the broad themes “Fluids, Magmas and Their Interactions”, “Geochemical Cycles”, “Origin and Evolution of Continental Crust”) as well as NZ specific science questions outlined in the GeoPRISMS Implementation Plan (see last paragraph).

This proposed project would require an inventory and sampling of all active and recently active volcanoes in the NZ site and surrounding areas to the north, followed by geochemical analysis of lavas, pyroclasts, gasses, and fluids sampled at each site (petrology, geochronology, water chemistry, etc..). Importantly, the project would require the same amount of attention be devoted to submarine and subaerial volcanoes in order to fully characterize the range of processes, compositions, and fluxes that control subduction cycles. Although we know less, globally speaking, about the numbers of submarine volcanic eruptions in the recent past and their size, frequency or duration (see review by Rubin et al., 2012), we know that today and through most of geological history submarine volcanic eruptions have had substantial integrated compositional, thermal and ecological impacts on the world’s exosphere. Submarine eruptions are more difficult to detect and observe than subaerial eruptions, but strides in eruption detection, response speed, and observational detail over the past 25 years suggest that a comprehensive study of submarine volcanoes within a small focused area such as the NZ Focus Site (see Fig. 2) should be achievable. Active monitoring would be required, which for the submarine sites means hydrophone arrays, seismometers on land, repeat bathymetric surveys and water column monitoring (e.g., Resing et al., 2011; Chadwick et al., 2008; Watts et al., 2012), along with the aforementioned sampling at active volcanoes.

There is some data available already to jump start this process (see Fig. 1), plus observations at recently active submarine volcanoes in the area such as Rumble III (35.75S), Brothers (34.9S), Havre (31.1S), and Monowai (24.9S). Combined existing and new geochemical data from the subaerial and submarine volcanos will provide a detailed snapshot of the material fluxes exiting this system across the entire arc/backarc. Because of strong gradients along the arc these will allow a nearly unique investigation of the interplay of variable subduction parameters (e.g., sediment type and amount, Plank in press) and crustal structure on magmatic cycling in the arc. Furthermore, a comprehensive submarine/subaerial program would provide for the first quantitative assessment of the differences between compositions and magnitudes of magmatic products entering earth's exosphere across the water line from a single arc. An even greater understanding would arise from incorporation of existing data along the Tonga Arc and Lau Backarc (and perhaps new sampling as needed) because it extends the arc system at recently active volcanoes further in tectonic and compositional space (e.g., boninites at W. Mata).

This is clearly a project that could not be accomplished by just a few researchers. Rather, the data set envisioned by this project would require multiple research teams and collaboration with NZ partners to accomplish. Analysis and modeling of resulting data would likely significantly improve understanding of several SCD (Subduction Cycles and Deformation) themes as described in the science plan (e.g., 4.4. How are volatiles, fluids, and melts stored, transferred, and released through the subduction system? 4.5. What are the geochemical products of subduction zones…? and 4.6. What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?). Furthermore, the project addresses multiple NZ-specific science questions from GeoPRISMS Implementation Plan: D. What are the … respective contributions of subducted sediments and crustal assimilation along- and across-strike of the arc? and E. How does … the spatial and temporal variation of magmatism relate to the nature of slab-derived fluid-to-melt?, as well as comparative/thematic theme 3: Fore-arc to back-arc volatile fluxes. It is therefore clearly aligned with the goals of the GeoPRISMS initiative.

References:

Chadwick, WW, et al., 2008. Cyclic eruptions and sector collapses at Monowai submarine volcano, Kermadec arc: 1998-2007, Geochem. Geophys. Geosyst., 9, Q10014.

de Ronde, C.E J, et al. 2005. Evolution of a Submarine Magmatic-Hydrothermal System: Brothers Volcano, Southern Kermadec Arc, New Zealand, Economic Geology, 100, 1097-1133

Plank, T. in press, The Chemical Composition of Subducting Sediments, Treatise on Geochemistry (2nd ed.)

Resing, JA, et al., 2011. Active submarine eruption of boninite in the NE Lau Basin, Nat. Geosci., 4, 799-806.

Rubin, KH, et al., 2012. Volcanic Eruptions in the Deep Sea, Oceanography 25, 142–157.

Watts, A.B, et al., 2012, Rapid rates of growth and collapse of Monowai submarine volcano in the Kermadec Arc, Nature Geosci., 5, 510-515, doi:10.1038/ngeo1473.

Wright, IC et al. 2006., New multibeam mapping and geochemistry of the 30°–35° S sector, and overview, of southern Kermadec arc volcanism, JVGR, 149, 263-296.

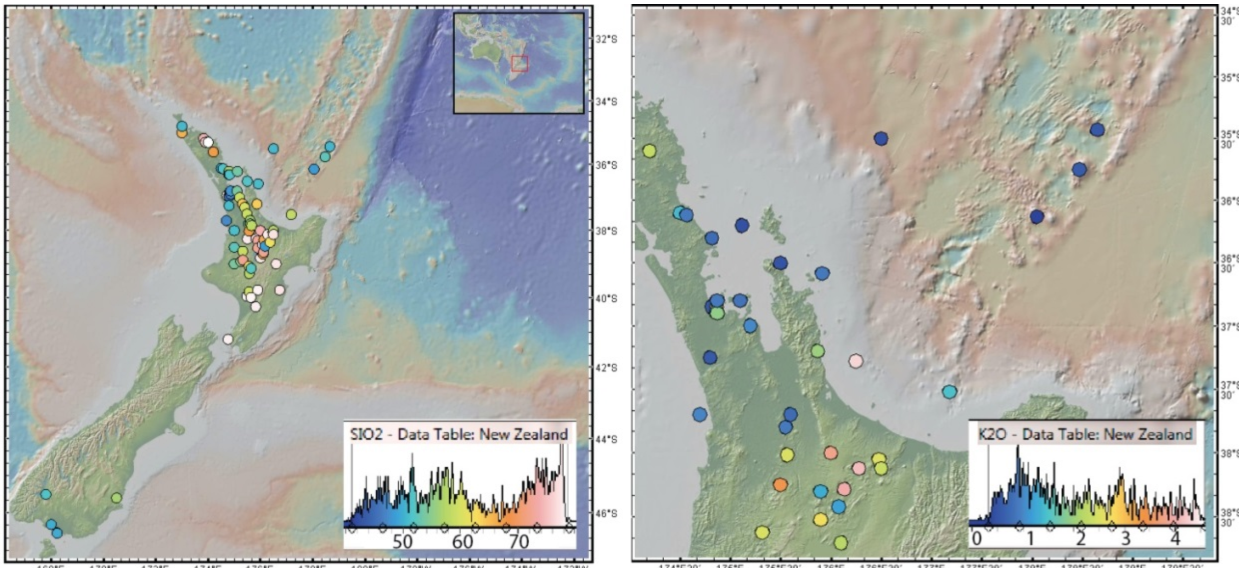


Figure 1. Map with samples available from PetDB/EarthChem in the NZ Focus Site. Panel A on the left shows SiO_2 data and panel B on the right is a zoomed-in view of K_2O data in the northern part of North Island and the southern Kermadec/Harve submarine system. Importantly, this is all available data, not filtered for eruption age. There would undoubtedly be substantially fewer samples if only historical or dated samples from the last 100 yrs were shown, although the data to make such a distinction are not presently available in the EarthChem databases.

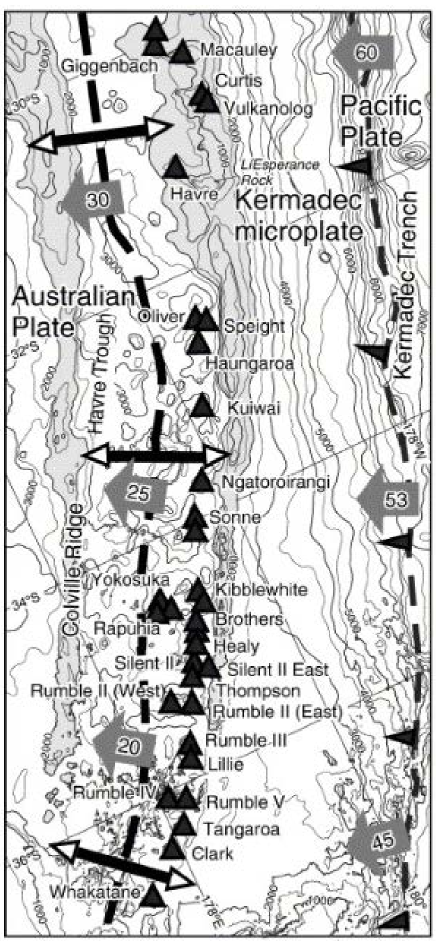


Figure 2. recently discovered volcanoes of the southern and central Kermadec arc (Wright et al., 2006).

Fluid Redistribution Coupled to Deformation
Around the NZ Plate Boundary

Richard Sibson[1], Ian Graham[2], Agnes Reyes[2]

[1] *Dept. of Geology, University of Otago, P.O. Box 56, Dunedin 9054, NZ,* [2] *GNS Science, P.O. Box 30-368, Lower Hutt 5040, NZ*

rick.sibson@otago.ac.nz

Crustal-scale fluid flow is a frontier area in Earth Science, critically relevant to exploration for, and future exploitation of, energy and mineral resources (oil, gas, geothermal power, hydrothermal mineralisation)[1,2]. The New Zealand plate boundary (NZPB) can be viewed as a geochemical processing system where the interplay of tectonic and magmatic processes promotes fluid redistribution between the atmosphere, continental and oceanic rock assemblages, the ocean water mass, and the deep Earth[3,4].

The diverse tectonics of the boundary, comprising opposite-facing subduction zones along the Hikurangi and Fiordland Margins linked by an imperfect transform fault system, gives rise to an array of sites where predominantly aqueous and other (hydrocarbon, CO_2, etc.) fluids are being actively redistributed within the crust. These include: (1) active hydrothermal circulation coupled to magmatism and extensional normal faulting in the Taupo Volcanic Zone (TVZ) (and its northeastward continuation along the Lau-Havre Trough); (ii) fluid loss from sediment compaction and compressional 'squeegee' deformation accompanying thrust/reverse faulting along the Hikurangi and Fiordland subduction interfaces; (iii) areas of ongoing compressional inversion involving steep reverse faulting associated with hydrocarbon migration in the Taranaki Basin and in the northwestern and southern South Island; (iv) fluid redistribution around major strike-slip faults, focused at structural irregularities and coupled to stress and permeability cycling, and (v) topography-driven flow in the uplifted Southern Alps and other mountain ranges flanking the linking transform fault system, and around major volcanic edifices.

Fluid redistribution is variously driven by topographic relief and precipitation, upwelling mantle and magmatic intrusion leading to convective circulation of hydrothermal fluids, compaction, deformation, and metamorphic dehydration of thick sedimentary sequences, changes in the regional stress state, and physicochemical processes (magmatic gas expansion, P-T changes, fluid mixing)[3,4]. While flow in near-surface systems typically occurs under near-hydrostatic fluid pressure (the 'normal state'), fluids at depth may be structurally compartmentalised and overpressured well above hydrostatic values. Flow systems are influenced by structural permeability and modulated by stress cycling which accompanies intermittent rupturing on faults, coupled to changes in fault-fracture permeability. For example, extensive hydrological perturbation accompanied the 2010 M_w7.1 Darfield, Canterbury, earthquake[5]. Though the physical conditions of seismogenesis (differential stress, confining pressure, pore-fluid pressure, temperature, strain-rate) likely vary significantly[6], fluid involvement in earthquake rupturing seems likely across the range of tectonic settings. The degree of fluid-overpressuring above hydrostatic also exerts a first-order control on crustal rheological and strength profiles.

The NZPB thus provides a world-class natural laboratory where dynamic flow systems are accessible to investigation by geological, geochemical and geophysical techniques, both onshore and offshore, and by numerical modelling. Questions to be addressed for each of the tectonic domains include the fluid sources, the rates of flow, the degree of water–rock interaction along flow paths, the influence of structural permeability and fluctuating stress regimes on fluid redistribution and phase separation, and the total fluid budget. Understanding this system will require a combination of geological, geophysical, and geochemical analyses coupled to numerical modelling. Such studies may also contribute significant insights into factors affecting crustal rheology and the physical conditions of seismogenesis in different tectonic settings.

References:

[1]Cathles, L. 1990. Scale and effects of fluid flow in the upper crust. Science, 248, 323-329.

[2]Geophysics Study Committee, US National Research Council, 1990. The Role of Fluids in Crustal Processes. National Academy Press, Washington, D.C.

[3]Giggenbach, W., Sano, Y., Wakita, H. 1993. Isotopic composition of Helium, and CO2 and CH4 contents in gases produced along the New Zealand part of a convergent plate boundary. Geochimica et Cosmochimica Acta 57, 3427-3455.

[4]Reyes, A., Christenson, B., Faure, K. 2010. Sources of solutes and heat in low-enthalpy mineral waters and their relation to tectonic setting, New Zealand. Journal of Volcanology and Geothermal Research, 192, 117-141.

[5]Cox, S., Rutter, H., Sims, A., Manga, M., Weir, J., Ezzt, T., White, P., Horton, T., Scott, D. 2012. Hydrological effects of the M_w7.1 Darfield (Canterbury) earthquake, 4 September 2010, New Zealand. New Zealand Journal of Geology and Geophysics 55, 231-247.

[6]Sibson, R., Rowland, J., 2003. Stress, fluid pressure, and structural permeability in seismogenic crust, North Island, New Zealand. Geophys. J. Int., 154, 584-594.

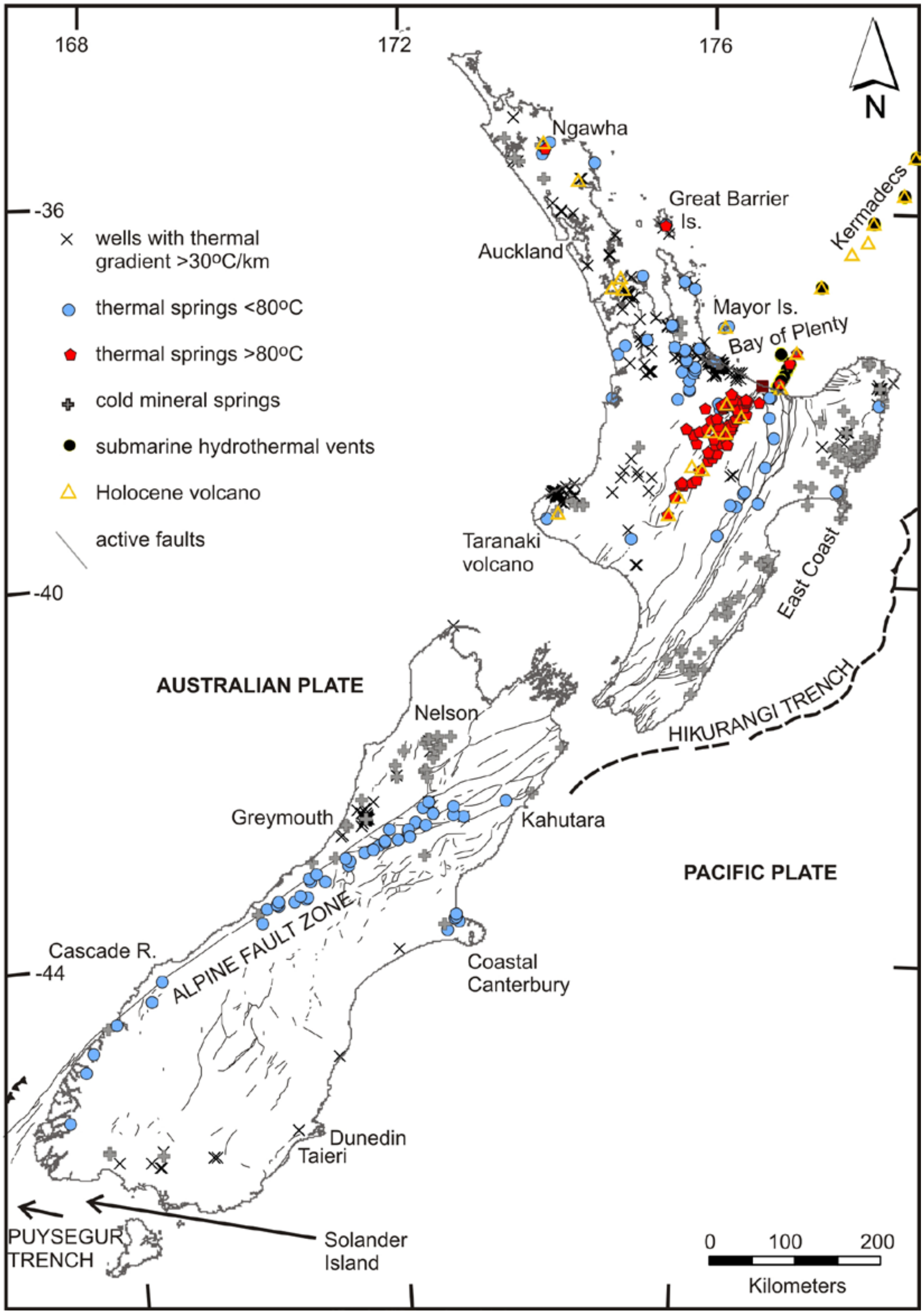


Figure 1. Location map of thermal (> 4 °C above annual ambient air temperatures) and cold mineral springs of New Zealand in relation to principal onshore faults[4].

Geochemical Fluxes through the New Zealand Arc System

Stuart Simmons[1], Adam Simon[2], Gordon Moore[2], Rebecca Lange[2]

[1] Energy and Geoscience Institute, University of Utah, Salt Lake City, Utah, USA; [2] Earth & Environmental Sciences, University of Michigan, Ann Arbor, MI, USA

stuart@hotsolutions.co.nz

The hydrothermal-magmatic activity occurring in high and low temperature hydrothermal systems in New Zealand provides a unique opportunity to trace mass transfer and coupled magmatic-hydrothermal processes in a convergent plate boundary, using the suite of elements that include: Ag, As, Au, Bi, Cd, Co, Cu, Fe, Ga, Ge, Hg, In, Mn, Mo, Ni, Pb, Pd, Pt, Se, Sn, Sb, Te, Tl, and Zn. Most of these elements behave incompatibly during crystallization, and all are commonly found in hydrothermal solutions (e.g., Williams-Jones and Heinrich, 2005; Simmons and Brown, 2006; Simon and Ripley, 2011). Recent analyses of deep, hot solutions from the Taupo Volcanic Zone show that there is an enormous hydrothermal flux of precious and base-metals, and related trace elements, but that there is considerable heterogeneity in the compositions of these deep fluids. This suggests that these constituents derive from mafic to intermediate composition magmas as well as the crust (Simmons and Brown, 2007). We propose to identify the sources of metals (listed above) and quantify their budgets and fluxes throughout the subduction zone factory (geochemical cycling), by broadening analytical studies and comparison of results to rocks/minerals occurring in the west Pacific ocean crust, sediment subducted in the Hikurangi trench, basement rocks of the North Island, young volcanic rocks of mafic, intermediate, and felsic composition, and to hydrothermal fluids from volcanoes and geothermal systems in low and high temperature systems. This information can also be used to place constraints on the petrogenesis of arc magmas and continental crust, and generalized to other well-studied arcs (e.g., Central American arc, and the Mexican Volcanic Belt).

Hydrothermal and Magmatic Activity in New Zealand

High temperature hydrothermal systems are concentrated in the Taupo Volcanic Zone where ~20 separate centers exist. These systems involve circulation of meteoric water to ~8 km depth, where it is heated and modified by mixing with magmatic volatiles, and subsequent water-rock interaction as the hybrid fluid(s) rises to the surface (e.g., Giggenbach, 1995; Rowland and Simmons, 2012). Chemical analyses of aqueous and gaseous species show that each center has a unique composition despite flowing through a similar stratigraphy of rocks. This likely reflects the variability of magmatic fluid compositions from compositionally distinct magmatic intrusions and the ratio of magmatic to meteoric fluid. One other high temperature hydrothermal system called Ngawha occurs in an intraplate setting, 300 km northwest of the magmatic arc (Simmons et al., 2005).

Additional hydrothermal activity is associated with low temperature systems that occur in sedimentary basins, along faults, and within the uplifted portion of the accretionary prism (Reyes et al., 2010). These occur scattered throughout the North Island, but in the South Island, they are clearly restricted to the Alpine Fault and related trans-tensional basins (Fig. 1).

Focus on Metals

While hydrothermal precious and base-metal transport is a salient feature of magmatic arcs, there are few studies that simultaneously examine the behavior of metals in magmas *and* hydrothermal fluids to understand the overall budget and flux of components in a convergent plate margin. The trace metal contents of magmas show considerable variability, suggesting heterogeneities in the source regions as well as modification during crystallization (e.g., Jenner et al., 2010; Jenner and O'Neil, 2012; de Ronde et al., 2012; Wysoczanski et al., 2012). Similarly, trace metal contents of hydrothermal fluids show variability that relates to magmatic inputs and hydrothermal water-rock interaction (Simmons and Brown, 2006 and 2007). Figure 2, for example, shows the contrast in trace metal patterns in hydrothermal fluids from two adjacent centers separated 10 kms apart despite sharing very similar host rocks. Without doubt, the enrichments in precious and base-metals seen in Rotokawa compared to Wairakei (Fig. 2) are due to varying supplies of metals from intruding magmas, which for Rotokawa is likely to be andesitic and for Wairakei basaltic (Giggenbach, 1995).

Sampling opportunities

New Zealand is an ideal natural laboratory because of the detailed understanding of the geological context for most of the hydrothermal and volcanic activity. Spring water samples are easily obtained from many high and low temperature hydrothermal centers, including those occurring in the forearc region, and on White Island volcano. In addition, some repeat sampling of production wells, using the titanium down-hole sampler, can be done on a limited basis assuming access to wells is possible during power plant shutdowns. A full suite of igneous rocks are easy to obtain from all the young volcanic centers, and DSDP/ODP drill sites in the western Pacific ocean, east of the Hikurangi trench, provide rock samples of oceanic sediment/crust that represent subducted material.

We discussed our proposed science plans with Dr. Shaun Barker at the University of Waikato, Dr. Julie Rowland at the University of Auckland, and Dr. Kevin Brown at the University of Canterbury, and envision collaboration with them and students to enrich the science and increase broader impact for all team members, including students.

References:

Bibby, H.M., Caldwell, T.G., Davey, F.J., and Webb, T.H., 1995, Geophysical evidence on the structure of the TaupoVolcanic Zone and its hydrothermal circulation: J. Volcan. and Geothermal Research, v. 68, p. 29-58.

Jenner, F. E., et al., 2010, The magnetite crisis in the evolution of arc-related magmas and the initial concentration of Au, Ag, and Cu: Journal of Petrology, v. 51, p. 2445-2464.

Jenner, F.E., and O'Neil, H. St. C., 2012, Analysis of 60 elements in 616 ocean floor basaltic glasses: Geochemistry, Geophysics, Geosystems, v. 13, Q02005, doi:10.1029/2011GC004009

de Ronde, C. E. J., et al., 2012, Sources of chalcophile and siderphile elements in Kermadec arc lavas: Economic Geology, v. 107, p. 1527-1538.

Giggenbach, W.F., 1995, Variations in chemical and isotopic composition of fluids discharged from the Taupo Volcanic Zone, New Zealand: Journal of Volcanology and Geothermal Research, v. 68, p. 89-116.

Hochstein, M.P., 1995, Crustal heat transfer in the Taupo Volcanic Zone (New Zealand): comparison with other volcanic arcs and explanatory heat source models: Journal of Volcanology and Geothermal Research, v. 68, p. 117-151.

Reyes, A. G., et al., 2010, Sources of solutes and heat in low-enthalpy mineral waters and their relation to tectonic

setting, New Zealand: Journal of Volcanology and Geothermal Research, v. 192, p. 117-141.
Rowland, J., and Simmons, S.F., 2012, Hydrologic, magmatic, and tectonic controls on hydrothermal flow, Taupo Volcanic Zone, New Zealand: Implications for the formation of epithermal vein deposits: Economic Geology, v.107, p. 427-457.
Simmons, S.F., and Brown, K.L., 2006, Gold in magmatic hydrothermal solutions and the rapid formation of a giant ore deposit: Science, v. 314, p. 288-291.
Simmons, S.F., and Brown, K.L., 2007, The flux of gold and related metals through a volcanic arc, Taupo Volcanic Zone, New Zealand: Geology, v. 35, p. 1099-1102.
Simon, A.C. and Ripley, E.M. (2011) The role of magmatic sulphur in the formation of ore deposits. Reviews in Mineralogy and Geochemistry, 73, 513-578.
Simmons, S.F., et al., 2005, Lake-filled depressions resulting from cold gas discharge in the Ngawha geothermal field, New Zealand: Journal of Volcanology and Geothermal Research, v. 147, p. 329-341.
Williams-Jones, A.E. and Heinrich, C.A. (2005) Vapor transport of metals and the formation of magmatic hydrothermal ore deposits. In: Economic Geology 100th Anniversary Volume. Hedenquist, JW, Thompson JFH, Goldfarb RJ, Richards JP (eds), 1287-1312.
Wysoczanski, R. J., et al., 2012, The tectonomagmatic source of ore metals and volatile elements in the southern Kermadec arc: Economic Geology, v. 107, p. 1539-1556.

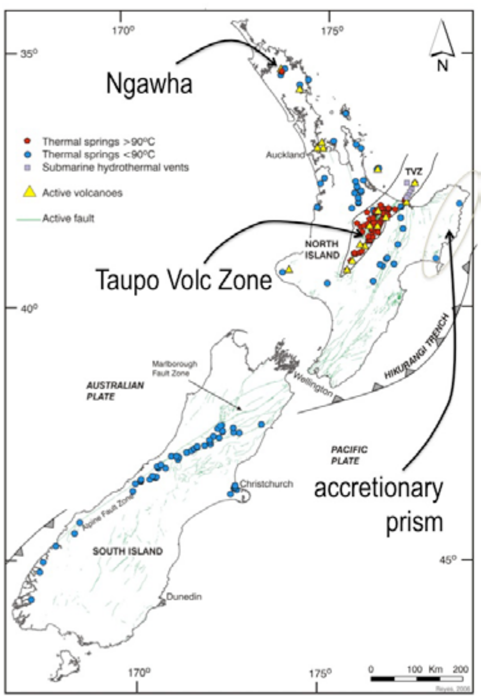
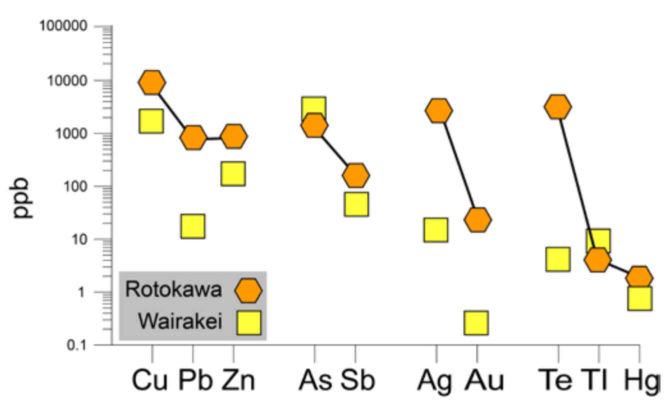


Figure 1 shows the distribution of hydrothermal activity in New Zealand. High temperature systems occur in the Taupo Volcanic Zone (TVZ), which is a young extensional volcanic arc with exceptional heat flow ~4200 MW (Bibby et al., 1995; Hochstein, 1995; Rowland and Simmons, 2012). Volcanism in the northern and southern segments is dominated by cone-building eruptions of andesite, whereas the central segment is dominated by explosive eruptions of rhyolite, with more than 15,000 km^3 of air-fall deposits, ignimbrites, and lavas. Within the TVZ, the thermal output of volcanic eruptions is ~25% of the total heat flow due to hydrothermal activity, which is the dominant mode of heat transfer on the time scales of ten thousands to hundred thousands of years (Hochstein, 1995). Other young isolated volcanic centers occur along the west coast of the North Island (Mt Egmont-andesite cone), and in the north part of the North Island (Auckland, Whangarei, and Kerikeri volcanic fields), the latter of which are made up of predominantly basaltic volcanoes.

Figure 2. The graph shows the trace metal patterns for deep hydrothermal fluids sampled with a titanium-sampler in production wells from Wairakei and Rotokawa fields. These two fields are separated ~10 km apart in the TVZ, and they share a common geological setting. Note the strong enrichments in Au, Ag, Cu, Pb, Zn and Te in Rotokawa, whereas As, Sb, Tl, and Hg are similar (Simmons and Brown, 2007, unpub).



Proposal to study subduction initiation in northern Zealandia

Tim Stern[1], Rupert Sutherland[2]

[1] *Victoria University of Wellington;* [2] *GNS Science, Lower Hutt*

tim.stern@vuw.ac.nz

Back-arc regions of subduction zones contain sedimentary records that hold clues to the subduction initiation process, and provide complementary insights to fore-arc studies (e.g. Izu-Bonin-Mariana and Tonga). The basins and sedimentary platforms northwest of New Zealand record onset of the Tonga –Kermadec (TK) system during the Eocene-Oligocene (see Gurnis et al. white paper). We propose (mainly) marine geophysical studies that will reveal clues as to how and why TK, and Hikurangi, subduction started.

Key features that require study are: Norfolk Ridge (NR); New Caledonia Trough (NCT); Taranaki-Wanganui basins; and Three Kings Ridge (TKR). The NR is where surface convergence was associated with initial subduction. What was the vergence and timing of thrusting, what vertical motions took place, and how do these observations compare and discriminate alternate geodynamic model predictions?

The New Caledonia Trough lies adjacent to Norfolk Ridge, was deformed in the subduction initiation event and subsided with large magnitude (Sutherland and al., 2010) that is precisely quantified (1.5 km) at its southern end near the north end of Taranaki Basin (Baur et al., 2013). What was the regional timing of NCT subsidence in relation to other aspects of subduction initiation, and what is its significance? Does the 1.5 km of Oligocene "platform subsidence" seen in oil company drill hole data from South Taranaki Basin at ~ 30 Ma (Stern and Holt, 1994) have a common cause as that in the NCT ? If so, the process occurs on a ~1000 km scale and is clearly geodynamically significant. These observations of plate scale vertical movements are possibly unique and have the potential to lead to a shift in thinking not only about subduction initiation, but also the origin of deep-water basins.

The Taranaki-Wanganui region lies at the southern end of the NCT and TK subduction initiation, and a large negative gravity anomaly near Wanganui attests to ongoing downward pull from below. Evidence from onshore Taranaki –Waikato, north of the Taranaki-Ruapehu line, suggests lower crust has been removed by a migrating instability of the mantle lid during the past 5 Ma (Stern et al., 2013). This may be a process common to evolved back arc regions (Levander et al., 2011; Saleeby et al., 2012). Does such a process occur on a large scale during, or after, subduction initiation? This southern region provides an opportunity to obtain insights into the process of lithospheric instability, and may yield a snapshot of the southern termination of subduction initiation that developed since the Eocene.

Satellite-derived, gravity data provide a first–order assessment of the isostatic state of offshore Zealandia (Wood and Davy, 2008). Resolving the true isostatic configuration requires, however, crustal thickness and upper-mantle seismic wave-speed data. Thus, primary data sets to help assess the isostatic state of Zealandia, and vertical movements, are: crustal-upper mantle images; images of sedimentary records of past events; and samples of sediment or volcanic rock associated with subduction initiation that can be dated and provide some constraint on the process. We need to measure lithospheric structure with marine airgun surveys shot into ocean-bottom seismometers, to constrain the final lithospheric configuration achieved by subduction initiation. We need multi-channel seismic-reflection images of strata that record deformation and vertical motions during the early stages of subduction initiation, and then to tie those strata to existing wells or sample them with new IODP boreholes. It may also be possible to directly dredge key samples from the seabed or use shallow-coring technology. The combined observations would provide powerful discrimination between different geodynamic models of subduction initiation, and this may be the only location on Earth that such an integrated study is possible.

References:

Baur, J., Sutherland, R., and Stern, T., 2013, Anomalous passive subsidence of deep-water sedimentary basins: a prearc basin example, southern New Caledonia Trough and Taranaki Basin, New Zealand: Basin Research - In press.

Levander, A., Schmandt, B., Miller, M. S., Liu, K., Karlstrom, K. E., Crow, R. S., Lee, C.-T. A., and Humphreys, E. D., 2011, Continuing Colorado plateau uplift by delamination style convective lithospheric downwelling: Nature, v. 472, p. 461-465.

Saleeby, J., Le Pourhiet, L., Saleeby, Z., and Gurnis, M., 2012, Epeirogenic transients related to mantle lithosphere removal in the southern Sierra Nevada region, California, part I: Implications of thermomechanical modeling: Geosphere, v. 8, no. 6, p. 1286-1309.

Stern, T., Houseman, G., Salmon, M., and Evans, L., 2013, Instability of a lithospheric step beneath western North Island, New Zealand: Geology, v. April issue.

Stern, T. A., and Holt, W. E., 1994, Platform subsidence behind an active subduction Zone.: Nature, v. 368, p. 233 - 236.

Sutherland, R., and al., e., 2010, Lithosphere delamination with foundering of lower crust and mantle caused permanent subsidence of New Caledonia Trough and transient uplift of Lord Howe Rise during Eocene and Oligocene initiation of Tonga-Kermadec subduction, western Pacific: Tectonics p. TC2004.

Wood, R. A., and Davy, B., 2008, New Zealand's UNCLOS Project-defining the continental margin: a summary and way forward: NZ Science Review, v. 64, no. 3-4, p. 59-64.

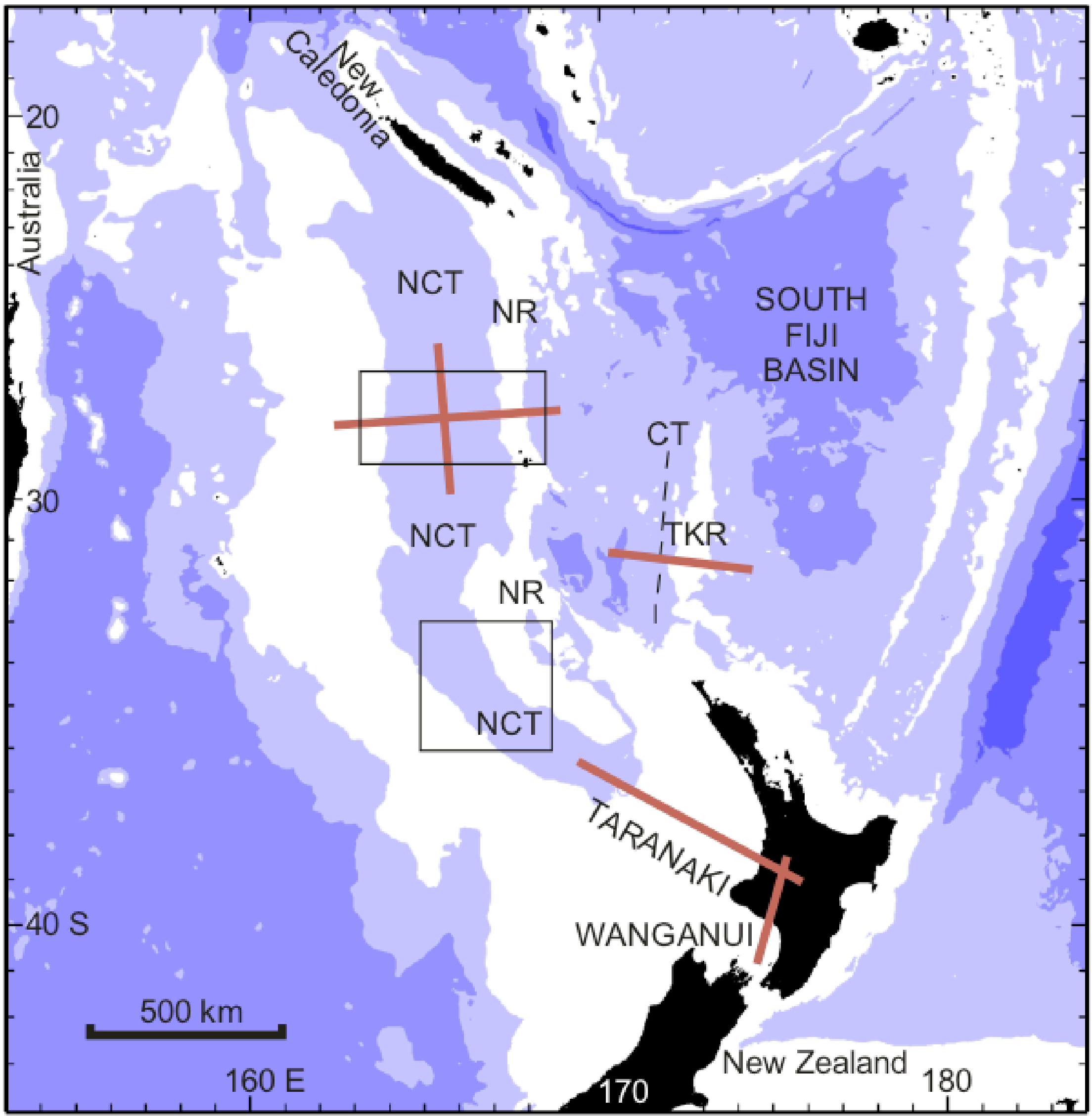


Figure 1. Red lines are proposed refraction transects, boxes show multi-channel seismic-reflection survey areas. New Caledonia Trough (NCT), Norfolk Ridge (NR), Cagou Trough (CT), Three Kings Ridge (TKR).

Mission Immiscible or supercritical fluid?

Yoshihiko, Tamura[1], Osamu, Ishizuka[2], Robert, J., Stern[3]

[1] *IFREE, JAMSTEC, Yokosuka, Japan;* [2] *GSJ, AIST, Tsukuba, Japan;* [3]*University of Texas at Dallas*

tamuray@jamstec.go.jp

This is a white paper relating the research theme 3 entitled 'Fore-arc to back-arc volatile fluxes' of '2.5. Comparative and Thematic Studies' in the GeoPRISMS Draft Implementation Plan. We don't have specific volcanoes to study the across-arc variation in New Zealand, but ongoing surveys in the Mariana arc might give a model, which should be tested in the New Zealand primary site.

Finding and studying unfractionated arc basalt is fundamental to understanding the nature of the mantle source and the processes that yield primary magmas above subduction zones. Unfortunately, arc lavas are characteristically evolved, multiply saturated, and rich in phenocrysts and primitive basalts – representing magmas still nearly in equilibrium with mantle peridotite - are rare. New strategies – especially targeting the deep flanks of intra-oceanic arc volcanoes using submersibles such as ROVs – are allowing us to break through the crustal filter. Previous work in the Izu-Bonin-Mariana (IBM) arc in the Western Pacific shows that small parasitic cones on the submarine flanks of larger volcanoes often erupt more primitive lavas than does the main edifice, which may be an island or submarine (e.g., Ishizuka *et al.,* 2008; Tamura *et al.,* 2011).

Pagan and Northwest Rota-1 (NWR1) volcanoes are located at the volcanic front and 40 km behind the volcanic front of the Mariana arc, respectively. Two geochemical basalt groups can be distinguished in Pagan at similar (10-11 wt %) MgO; these erupted recently, 500 m apart. Both contain clinopyroxene and olivine phenocrysts and are referred to as COB1 and COB2. In contrast, there are two petrographic groups in NWR1, which are cpx-olivine basalt (COB) and plagioclase-olivine basalt (POB). The chemical differences between Pagan and NWR1 could be attributed to whether the subduction components (hydrous fluid and sediment melt) are immiscible or miscible. The subducting Pacific plate beneath the Mariana arc is old (~160 Ma), thick, cold and dense lithosphere, and its Wadati-Benioff zone dips steeply (Stern *et al.,* 2003). Thus, the depths to the top of the Mariana Wadati-Benioff zone just below Pagan and NWR1 are ~100 km and ~200 km, respectively (Pozgay *et al.,* 2009).

Pagan COB2 and NWR1 POB have systematically higher contents of High Field Strength elements (HFSE) and HREE than Pagan COB1 and NWR1 COB, respectively. However, in terms of fluid- and melt-mobile incompatible elements such as Rb, Ba, Th, U, K, light and middle REEs, Pagan and NWR1 lavas differ. In short, Pagan patterns don't cross, but those in NWR1 intersect. COB2 has higher abundances of sediment melt than do COB1. On the other hand, NWR1 COB have higher or similar contents of subducted sediment components compared to NWR1 POB. In contrast to Pagan suites, NWR1 COB and POB show a linear and simpler trend on Pb isotope diagrams (Tamura *et al.,* 2011), suggesting mixing between ambient mantle and sediment melt.
In summary, observations from Pagan suggest that the subduction component responsible for more mantle melting of the COB1 source was mostly hydrous fluid. Both hydrous fluid and

sediment melt component may have unmixed in or above the subducting slab below the volcanic front, which might have added separately to the mantle wedge peridotite (mantle diapir) and resulted in two neighboring, but completely different primary magmas (COB1 and COB2) from the same diapir.

On the other hand, NWR1 COB has a greater subduction component, both hydrous fluid and sediment melt, than POB, perhaps reflecting that the subducting slab below NWR1 is > 100 km deeper than that beneath Pagan. At such higher pressures, hydrous fluid and sediment melt could have mixed into a uniform supercritical fluid (Mibe *et al.,* 2011; Kawamoto *et al.,* 2012), with different proportions yield distinct NWR1 COB and POB.

References:

Ishizuka, O., Geshi, N., Itoh, J., Kawanabe, Y. & TuZino, T., 2008. The magmatic plumbing of the submarine Hachijo NW volcanic chain, Hachijojima, Japan: Long-distance magma transport? Journal of Geophysical Research 113, doi:10.1029/2007JB005325.

Kawamoto, T., Kanzaki, M., Mibe, K., Matsukage, K. N. & Ono, S. (2012). Separation of supercritical slab-fluids to form aqueous fluid and melt components in subduction zone magmatism. PNAS doi: 10.1073/pnas.1207687109.

Mibe, K., Kawamoto, T., Matsukage, K. N., Fei, Y. & Ono, S. (2011). Slab melting versus slab dehydration in subduction-zone magmatism. PNAS 108, 8177-8182.

Pozgay, S. H., Wiens, D. A., Conder, J. A., Shiobara, H. & Sugioka, H. (2009). Seismic attenuation tomography of the Mariana subduction system: Implications for thermal structure, volatile distribution, and slow spreading dynamics. Geochemistry Geophysics Geosystems 10, doi:10.1029/2008/GC002313.

Stern, R. J., Fouch, M. J. & Klemperer, S. L. (2003). An overview of the Izu-Bonin-Mariana subduction factory. In: Eiler, J. (ed) *Inside the Subduction Factory.* Geophysical Monograph, American Geophysical Union 138, 175-222.

Tamura, Y., Ishizuka, O., et al., 2011. Two primary basalt magma types from Northwest Rota-1 volcano, Mariana arc and its mantle diapir or mantle wedge plume. Journal of Petrology, 52, 1143-1183.

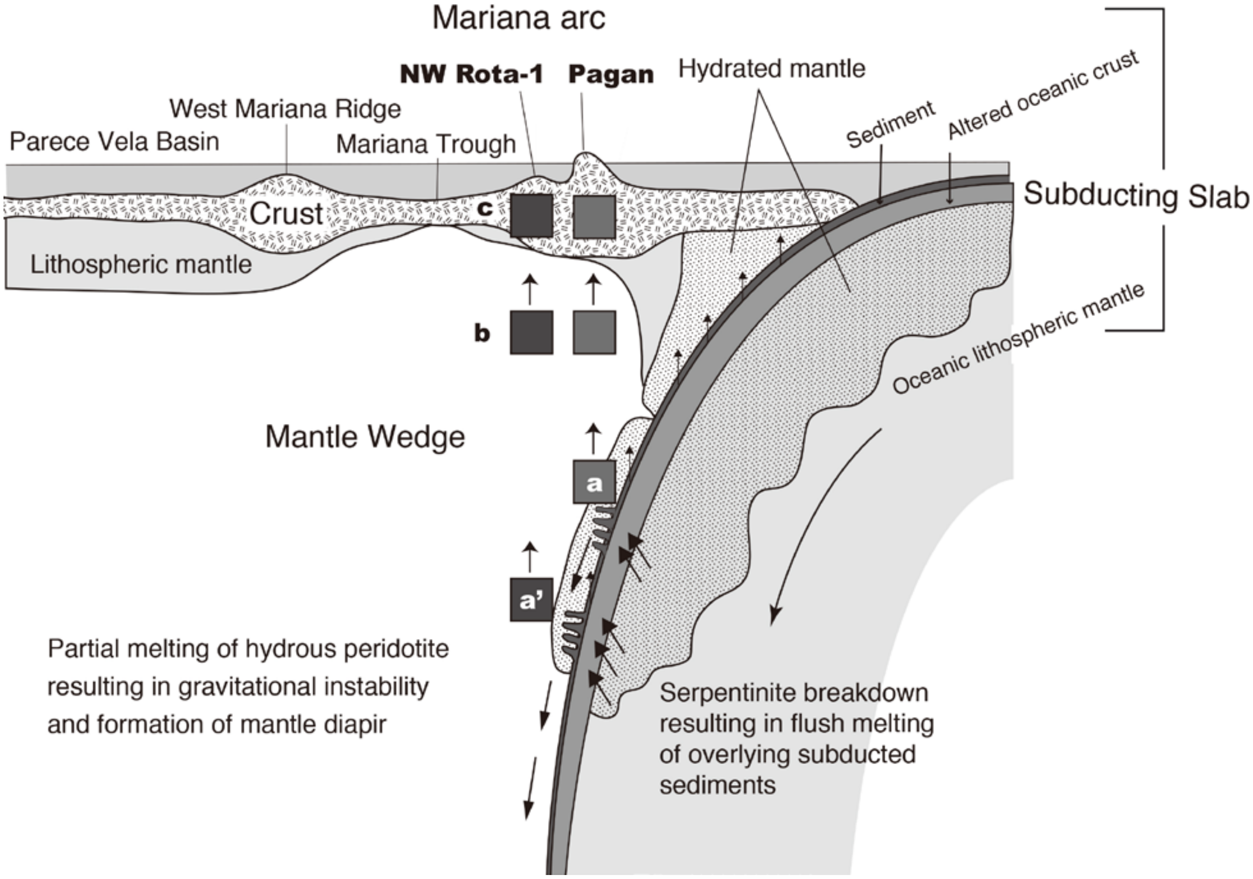


Figure 1. Section perpendicular to the Mariana arc-back-arc basin system, showing schematic upwelling of mantle diapirs. NW Rota-1 volcano is 40 km behind the volcanic front of the Mariana arc, which results in a significant difference Wadati-Benioff zone depth beneath NW Rota-1 and Pagan volcanoes. a) Mission Immiscible; a hydrous fluid coexists with a sediment melt, a') Mission miscible; a hydrous fluid mixes with a sediment melt to form a supercritical fluid.

Louisville seamount subduction: tracking mantle flow beneath the central Tonga-Kermadec arc

Christian Timm[1]*, Daniel Bassett[2], Ian J. Graham[1], Matthew I. Leybourne[1†], Cornel E.J. de Ronde[1], Jon Woodhead[3], Daniel Layton-Matthews[4] and Anthony B. Watts[2]

[1]Department of Marine Geoscience, GNS Science, PO Box 30-368, Lower Hutt, New Zealand, [2]Department of Earth Sciences, University of Oxford, Oxford OX1 3AN, UK, [3]School of Earth Sciences, University of Melbourne, Victoria 3010, Australia, [4]Department of Geological Sciences & Geological Engineering, Queen's University, Kingston, Ontario, Canada, † now at ALS Geochemistry, 2103 Dollarton Hwy, North Vancouver, BC, Canada

c.timm@gns.cri.nz

Subduction of alkaline intraplate seamounts beneath a geochemically depleted mantle wedge provides a rare opportunity to study element recycling and mantle flow in some detail. One example of a seamount chain – oceanic arc collision is the ~2,600 km long Tonga-Kermadec arc, where midway the Cretaceous Louisville seamount chain subducts beneath the central Tonga-Kermadec arc system. Here subduction of a thin sediment package (~200 m) beneath oceanic lithosphere together with an aqueous fluid-dominated system allows to track geochemical signatures from the subducted Louisville seamounts and to better understand mantle flow geometry.

Geochemical analyses of recent lavas (<10 ka) from volcanic centers west of the contemporaneous Louisville-Tonga trench intersection (Monowai, 'U' and 'V') show elevated $^{206}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and to a lesser extend $^{87}Sr/^{86}Sr$ values but N-MORB-type compared to centers to the north and south (e.g. Turner et al., 1997; Haase et al., 2002; Timm et al., 2012) but mostly similar N-MORB-type ratios of fluid-immobile trace elements (e.g. La/Sm < 0.9).

This suggests that the observed geochemical anomaly above the subducted Louisville seamount chain is predominantly fluid-derived and hence different from other anomalies observed along the Tonga-Kermadec arc (e.g. Todd et al., 2011), interpreted to be pre-existing mantle heterogeneities.

Absolute pacific plate reconstructions indicates an anticlockwise rotation of the subducted Louisville seamount chain occurring in the chain older than oldest unsubducted Louisville seamount (~77 Ma old Osbourn seamount; Koppers et al., 2004) –a corollary to the westward kink of the Hawaii-Emperor seamount chain near the ~76 Ma old Detroit seamount (Duncan and Keller, 2004). If combined the geochemical anomaly and the geodynamic evidence is consistent with localized mainly fluid-derived input of Louisville material into partial mantle melts.

Finally, the combination of the geodynamic observation and estimates of the timing of fluid release from the subducting slab via U-series data (e.g. Bourdon et al., 1999; Caulfield et al., 2012) allows to determine the mantle flow geometry, which is primarily trench-normal mantle flow, although a slow southwards mantle flow of ~ 6cm/yr. is permissible (Timm et al., in press).

References:

Turner, S.P. *et al.* Uranium-238/ thorium-230 disequilibria, magma petrogenesis, and flux rates beneath the depleted Tonga-Kermadec island arc, *Geochimica et Cosmochimica Acta* 61, 4855-4884 (1997).

Haase, K.M., Worthington, T.J., Stoffers, P., Garbe-Schoenberg, D. & Wright, I.Mantle dynamics, element recycling, and magma genesis beneath the Kermadec Arc-Havre Trough. *Geochemistry Geophysics Geosystems* 3 (11) 1071, doi:10.1029/2002GC000335 (2002).

Timm, C., Graham, I.J., de Ronde, C.E.J., Leybourne, M.I. & Woodhead J. Geochemical evolution of Monowai volcanic center: New insights into the northern Kermadec arc subduction system, SW Pacific. *Geochemistry, Geophysics, Geosystems* 12, Q0AF01, doi: 1029/2011GC003654 (2011).

Todd, E. *et al.*, Hf isotopic evidence for small-scale heterogeneity in the mode of mantle wedge enrichment: Southern Havre Trough and South Fiji Basin back arcs: *Geochemistry Geophysics Geosystems* 12 (9), Q09011, doi:10.1029/2011GC003683 (2011).

Koppers, A.A.P., Duncan, R.A. & Steinberger, B. Implications of a nonlinear $^{40}Ar/^{39}Ar$ age progression along the Louisville seamount trail for models of fixed and moving hot spots. *Geochemistry Geophysics Geosystems* 5 (6), Q06L02, doi 10.1029/2003GC000671 (2004).

Duncan, R.A. & Keller, R.A. Radiometric ages for basement rocks from the Emperor Seamounts ODP Leg 197. *Geochemistry Geophysics Geosystems* 5 (8), Q08L03, doi:10.1029/2004GC000704 (2004).

Timm, C., Bassett, D., Graham, I.J., Leybourne, M.I., de Ronde, C.E.J., Woodhead, J., Layton-Matthews, D., Watts, A.B., (accepted). Louisville seamount subduction and its implication on mantle flow beneath the central Tonga-Kermadec arc. Nature Communications

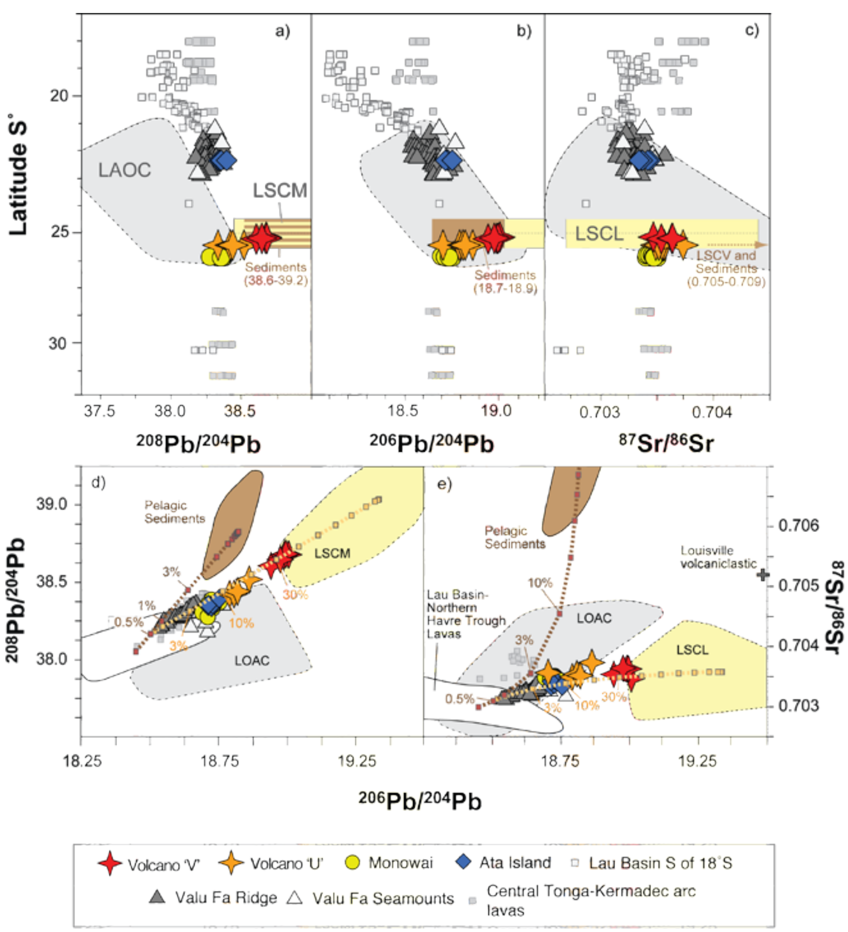


Figure 1. Pb and Sr isotope data, showing mixing calculations between the arc mantle and subducted Louisville material.

Havre Trough and the "Rifting Phase" of Back-arc Basin Evolution

Erin Todd[1], James B. Gill[2], John A. Gamble[3], Richard J. Wysoczanski[4], Fernando Martinez[5]

[1] United States Geological Survey, Anchorage, AK; [2] University of California Santa Cruz, Santa Cruz; [3] Department of Geology, University College Cork, Cork, Ireland; [4] National Institute of Water and Atmospheric Research, Wellington 6021, New Zealand; [5] School of Ocean and Earth Science and Technology, University of Hawaii at Manoa

etodd@usgs.gov

The Havre Trough is ready for multi-disciplinary study of globally important processes including deformation of wet mantle and crust, magma genesis at the critical spatial and temporal boundary between flux- and decompression-melting, and accompanying submarine metallogenesis. Coordinated international marine geological, geophysical, and igneous geochemical studies within GeoPRISMS can result in breakthrough understanding of the "rifting phase" of the evolution of back-arc basins and the links to proto-continental crust growth and their ore deposits.

The formation of back-arc basins by the extensional breakup of volcanic arcs is an integral part of the subduction cycle. Recent studies of the Havre Trough back-arc basin have developed hypotheses of tectonomagmatic processes occurring in early stage backarcs with global implications (Figure 1). For example, estimates of back-arc melt productivity exceed that of the volcanic front by at least an order of magnitude (e.g., Wysoczanski et al., 2010; Todd et al., 2011), so magmas associated with back-arc volcanism are arguably the most volumetrically significant geochemical products of subduction zones, which is a key question of the GeoPRISMS SCD Initiative. Up to half of the volume of southern Havre Trough back-arc crust is newly accreted material following rifting of the proto-Havre volcanic arc (Wysoczanski et al., 2010) (Figure 1a). Fresh basaltic volcanism occurs on the seafloor across most of the width of the backarc, based on sampling by dredge and submersible, and inference from towed camera and acoustic backscatter. Ar-Ar ages of large interspersed seamount volcanoes are <1 Ma. Most back-arc volcanism is diffuse, contrasting with more axially focused volcanism at spreading ridges in more mature backarcs like the central and eastern Lau Basin to the north.

Havre Trough back-arc seafloor morphology is also distinct from mature spreading centers. Seafloor bathymetry at Havre is complex, with short-segment pillow basalt-floored rift grabens between chains of large-volume constructional volcanic edifices extending as much as 80 km behind the volcanic front (i.e., "hot fingers") (Figure 1b). The occurrence of each seems to be independent of the distance to the trench: some of the deepest Havre Trough rift grabens (~4000 mbsl) abut the volcanic front, whereas one of the best-preserved symmetrical stratovolcanoes (Gill Volcano) is in the westernmost backarc (Wysoczanski et al., 2010). The contrasting morphology indicates that most of the basin width is from disorganized spreading (i.e., "rifting") that may result from extending wet asthenosphere, and the interplay of both flux and decompression melting in the evolving back-arc mantle (Figure 1a). For example, young volcanoes with arc-like chemistry ("arc regime") are found far into the backarc, both as freestanding stratovolcanoes and as arc-perpendicular constructional volcanic chains (Wysoczanski et al., 2010; Todd et al., 2010). In contrast, volcanism in intervening rift basins ("rift regime") is more MORB-like, similar to other BABB (Todd et al., 2011). Therefore, both decompression- and flux-melting can dominate at the same distance behind the volcanic front but in different tectonic settings at different distances along the arc (Figure 1b). Havre Trough is therefore an excellent site in which to study the three-dimensional aspects of back-arc deformation and magmatism.

For both arc and rift regimes, the widely distributed magmatic zone has two important consequences for interpretations of melting and material cycling at subduction zones. First, it samples a wide pressure range of slab-derived fluxes, and contains a larger mass-fraction of those fluxes than in the arc (e.g., Todd et al., 2011) (Figure 1b). Second, magmas across the back-arc are not aggregated, mingled and mixed in axial magma chambers, unlike during the spreading stage of more mature back-arc stages, so variations in both slab and mantle components are preserved. Therefore, the rifting stage of back-arc evolution is well-suited to monitoring the role of variable slab surface temperatures to depths of 6 GPa, and to evaluating its role in the evolution of the continental crust and upper mantle. In these respects, Havre is an analogue setting to the IODP Izu-Bonin-Mariana Rear Arc Expedition in March-May 2014.
Diffuse volcanism, diverse magma types, and complex morphology during the rifting phase of back-arc basin development may characterize many back-arc basins (e.g., western Lau Basin, northern Mariana Trough, both sides of the North Fiji Basin), as distinct from juvenile volcanic arcs and mature back-arc spreading ridges. Havre is the one place to study the processes within GeoPRISMS.

In summary, we propose that future multi-disciplinary and international investigations of the Havre Trough backarc are well suited to address two outstanding problems in the GeoPRISMS Draft Implementation Plan for the New Zealand Primary Site: *How do rifting and spreading, and the spatial and temporal variation of magmatism, relate to the nature of slab-derived fluid-to-melt and the rheology of the mantle wedge?* and *What are the magma transport pathways through the crust, and respective contributions of subducted sediments and crustal assimilation along- and across-strike of the arc?*

Finally, studies of submarine exposures within short-segment basins within Havre Trough may also address another Key Question of the GeoPRISMS SCD Initiative: *What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?* Trenchward scarps of the deep (~4000 mbsl) grabens closest to the volcanic frontal ridge (e.g., Figure 1a) may expose the oldest part of the arc and thus contain evidence about the age and nature of early arc volcanic rocks to compare with Fiji-Tonga and IBM (e.g., Reagan et al., 2010; Todd et al., 2012).

References:

Reagan, M. K., Ishizuka, O., Stern, R. J., Kelley, K. A., Ohara, Y., Blichert-Toft, J., Bloomer, S. H., Cash, J., Fryer, P., Hanan, B. B., Hickey-Vargas, R., Ishii, T., Kimura, J.-I., Peate, D. W., Rowe, M. C., Woods, M., 2010. Fore-arc basalts and subduction initiation in the Izu-Bonin-Mariana system. Geochemistry, Geophysics, Geosystems 11 (3), 17 pp.

Todd, E., Gill, J. B., Wysoczanski, R. J., Handler, M. R., Wright, I. C., Gamble, J. A., 2010. Sources of constructional cross-chain volcanism in the southern Havre Trough: New Insights from HFSE and REE concentration and isotope systematics. Geochemistry, Geophysics, Geosystems 11 (Q04009), 31 pp.

Todd, E., Gill, J. B., Wysoczanski, R. J., Hergt, J. M., Wright, I. C., Leybourne, M. I., Mortimer, N., 2011. Hf isotopic evidence for small-scale heterogeneity in the mode of mantle wedge enrichment: Southern Havre Trough and South Fiji Basin back-arcs. Geochemistry, Geophysics, Geosystems Q09011, DOI: 10.1029/2011GC003683.

Todd, E., Gill, J. B., Pearce, J. A., 2012. A variably enriched man-tle wedge during arc stages following subduction initiation in the southwest Pacific. Earth and Planetary Science Letters 335, 180–194.

Wysoczanski, R. J., Todd, E., Wright, I. C., Leybourne, M. I., Hergt, J. M., Adam, C., Mackay, K., 2010. Backarc rifting, constructional volcanism and nascent disorganised spreading in the southern Havre Trough backarc rifts (SW Pacific). Journal of Volcanology and Geothermal Research 190 (1-2), 39–57.

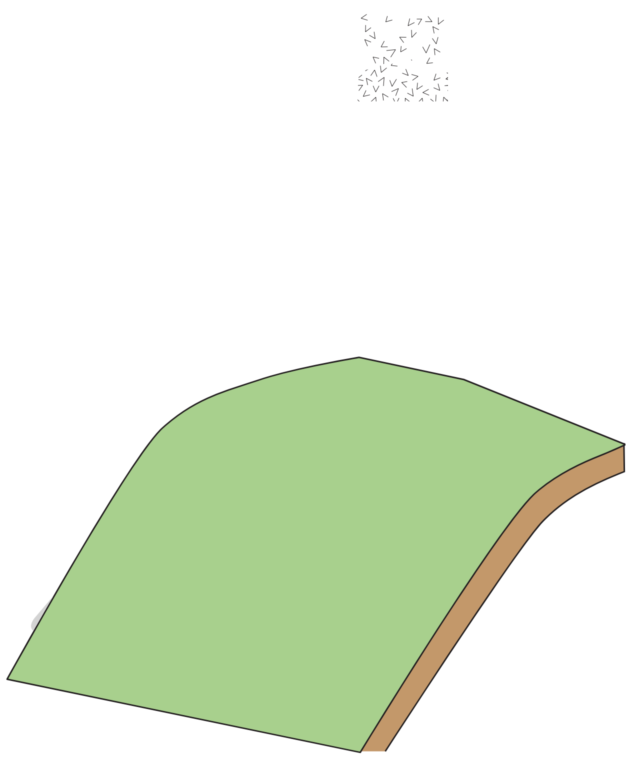


Figure 1a. Conceptual cross-sectional model of a backarc during the transitional rifting stage, showing intersection of flux- (blue lines indicate slab flux; yellow diapirs indicate flux melts) and decompression-melting (dashed triangle indicates decompression solidus) regimes and characterized by a broad zone of melt production. The relative contribution of slab flux with distance to the trench is indicated by the width of the blue lines. Patterned brown fill indicates remnant arc crust prior to back-arc extension, unpatterned brown fill represents rifted arc crust, and red fill indicates newly accreted oceanic crust, both within rift basins and as constructional volcanoes fed by intrusive dikes. Figure 1b. shows the model proposed by Todd et al. (2011) to explain along-arc changes in back-arc morphology and magma composition ("arc regime" vs. "rift regime"). Brown wavy lines represent slab isotherms (T1 and T2). Where the slab is hotter close the trench, slab flux is greater (shown here by more squiggly arrows), has a higher ratio of slab melt (orange) to aqueous fluid (blue), and yields greater melt productivity contributing to more constructional seafloor volcanism (i.e., "arc regime").

What should we look for at Hikurangi in light of our findings in the Japan Trench?

Virginia Toy [1], Patrick Fulton[2], Matt Ikari[3], Expedition 343 Scientists[4]

[1] Dept. of Geology, Univ. Otago, Dunedin, New Zealand; [2] Dept. of Earth and Planetary Sciences, Univ. California Santa Cruz, CA, USA; [3]MARUM, Center for Marine Environmental Sciences, Univ. Bremen, Germany; [4] Please refer to Chester et al., 2012 for these affiliations.

virginia.toy@otago.ac.nz

IODP Expedition 343 (the Japan Trench Fast Drilling Project, JFAST) successfully sampled the Tohoku subduction thrust shear zone, as well as folded and faulted Miocene sediments of the hanging wall sediment prism, and underthrust sub-horizontally bedded, comparatively undeformed, Cretaceous siliceous muds and cherts of the Pacific Plate (Chester et al., 2012). Comprehensive downhole and 'logging while drilling' (LWD) geophysical data were also collected across the plate boundary interface (e.g. Lin et al., 2013). Associated geophysical surveys provided high quality seismic images of the subsurface (Nakamura et al., 2013) and bathymetric data both before and after the 2011 M_w9.0 rupture, confirming a larger than expected horizontal displacement of the seafloor (>50m) that contributed to the devastating tsunami (Fujiwara et al., 2011). A subsurface temperature observatory was installed to measure possible thermal anomalies resulting from frictional heating on the fault (Fulton et al., 2013).

Physical properties and fluid chemistry were measured aboard the ship (Chester et al., 2012), and the recovered material has since been subjected to studies of frictional and hydrologic properties (Ikari et al., 2013, Hirose et al., 2013, Tanikawa et al., 2013; Ujiie et al., in prep.), composition, thermal history (Savage et al., 2012), macro- and microscale fabric (Chester et al., submitted; Dresen et al., 2012; Kirkpatrick et al., 2013; Rowe et al., in prep; Toy et al., 2012), clay mineralogy (Kameda et al., 2013), and magnetic properties (Mishima et al., 2013)
The plate boundary interface comprises smectite-rich (Kameda et al., 2013) 'scaly' clays, likely derived from incoming Pacific Plate pelagic sediments (Chester et al., submitted). These clays have low frictional strength, velocity-weakening tendencies at low shearing velocities (Ikari et al., 2013), and particularly low peak (pre-yield) strength at intermediate to high shearing velocities (Hirose et al., 2013). Velocity-strengthening behavior is typical at intermediate and high shearing velocities, as is a tendency to thermally pressurize (Ujiie et al., in prep.).

Borehole breakouts (Lin et al., 2013) and changes of focal mechanisms of aftershocks along with a number of normal faulting events in the hanging wall accretionary prism (Hasegawa et al., 2011) suggest near total stress drop at shallow depths during the 2011 earthquake (i.e. seismic efficiency approaching 100%, as opposed to expected efficiency of typical earthquakes on the order of <10%; McGarr et al., 1999). Thus, the subduction thrust probably behaved as per models of Noda & Lapusta (2013), where a particularly energetic rupture that initiated at seismogenic depths on the subduction thrust propagated into the shallow region where, despite a tendency toward velocity-strengthening behavior, low frictional strength and dynamic weakening mechanisms facilitated very large slip to the trench. ***Could the Hikurangi subduction zone generate similar larger-than-expected tsunami?*** We suggest that large shallow slip resulting in large tsunami may be possible if the shallow fault zone materials have mineralogy, structure, and hydrologic properties comparable to Tohoku (ie. are smectite-rich, low permeability and prone to dynamic weakening), as then low frictional strength at seismic slip velocities (~1 m/s) is likely. Measurement of frictional properties, and examination of structural records would lend more certainty to any predictions regarding the zone's behaviour. Abundant smectites are particularly likely at Hikurangi because of volcanic sediment input from the adjacent Taupo Volcanic Zone. Analysis of geologic signatures of heating within fault zone cores may also provide insight into the potential for large slip at shallow depths (Sakaguchi et al., 2011; Fulton and Harris, 2012). Furthermore, it is important to record the subsurface structure and bathymetry in order to clearly document any changes during future events. Equally important are pre-failure records of the in situ stress state, and monitoring of thermal and hydrologic conditions. In order to obtain these data, we need to drill into the Hikurangi subduction interface and the incoming plate sedimentary sequence at the earliest opportunity. We should also be prepared to mobilize in a rapid-response project similar to JFAST to examine changes in these parameters (particularly the stress state) after any future event, providing both greater understanding of the Hikurangi Margin, and enhancing our ability to predict seismic behaviour of other circum-Pacific subduction thrusts.

References:

Chester, F., Rowe, C., Ujiie, K., Moore, J.C., Kirkpatrick, J., Regalla, C., Remitti, F., Toy, V.,Wolfson-Schwher, M., Bose, S., Kameda, J., Mori, J., Brodsky, E., Eguchi, N., Toczko, S., and Exp. 343 and 343T Scientists. Submitted. Highly localized plate boundary thrust in the region of 50 m coseismic slip, M9.1 Tohoku-oki earthquake, 2011. Nature.

Chester, F., Mori, J., Toczko, S., Eguchi, N., and Exp. 343/343T Scientists. 2012. Japan Trench Fast Drilling Project (JFAST). IODP Preliminary Report, 343/343T. doi: 10.2044/iodp.pr.343343T.2012.

Dresen, G.H., Janssen, C., Wirth, R., Naumann, R., Morales, L.F.G., Toy, V.G., and Exp. 343 Scientists, 2012. Micro- and nanostructures of J-FAST 343 core samples – first results. 2012 Fall Meeting, AGU, San Francisco, CA.

Fujiwara, T. et al. 2011. The 2011 Tohoku-Oki Earthquake: Displacement Reaching the Trench Axis. Science 334, 1240 .

Fulton, P., Brodsky, E., Kano, Y., Mori, J., Chester, F., Kyo, M., Namba, Y., Eguchi, N., Toczko, S., Ito, Y. and Exp. 343 Scientists. 2013. The JFAST Fault Zone Observatory: Monitoring the frictional heat from the 2011 Tohoku Earthquake. Japan Geoscience Union (JpGU) Meeting, May 19-24, Chiba, Japan.

Fulton, P.M. and R.N. Harris (2012), Thermal considerations in inferring frictional heating from vitrinite reflectance and implications for estimates of shallow coseismic slip within the Nankai Subduction Zone, Earth Planet. Sci. Lett., 335–336, 206–215, 10.1016/j.epsl.2012.04.012.

Hasegawa, A., K. Yoshida, T. Okada. 2011. Nearly complete stress drop in the 2011 Mw9.0 off the Pacific coast of Tohoku earthquake, Earth, Planets and Space, 63-67, doi:10.5047/eps.2011,06.007.

Hirose, T., Tanikawa, W., Mukoyoshi, H., Tadai, O., Lin, W., Exp. 343 Science Party. 2013. Extreme Low Friction of the Tohoku Plate Boundary as a possible factor for seismic slip propagation toward the trench. JpGU Meeting, May 19-24, Chiba, Japan.

Ikari, M., Kameda, J., Kopf, A., Saffer, D., Marone, C., Exp. 343 Science Party. 2013. Frictional behavior of the plate boundary décollement zone in the Japan Trench, sampled during the Japan Trench Fast Drilling Project (JFAST). EGU Meeting, 7-12 April, Vienna, Austria.

Kameda, J., Ujiie, K., Hirose, T., Ikari, M. Remitti, F., Shimizu, M., Hamada, Y., Kimura, G., Chester, F., Mori, J. Eguchi, N. Toczko, S. 343 Exp. Scientists. 2013. Clay mineral characteristics of the plate-boundary fault at the Japan Trench. JpGU Meeting, May 19-24, Chiba, Japan.

Kirkpatrick, J., Rowe, C., Ujiie, K., Regalla, C., Remitti, F., Toy, V., Wolfson-Schwehr, F., Bose, S., Kameda,J., Moore,J.C., Chester, F., Exp. 343 and 343T Scientists. 2013. Structure and composition of the plate boundary décollement in the area of maximum slip during the 2011 Tohoku-Oki earthquake. JpGU Meeting, May 19-24, Chiba, Japan.

Lin, W., Conin, M., Moore, J.C., Chester, F.M., Nakamura, Y., Mori, J.J., Anderson, L., Brodsky, E., Eguchi, N., Exp. 343 Scientists (2013), Stress state in the largest displacement area of the 2011 Tohoku-Oki earthquake. Science 339 (6120), 687-690. doi: 10.1126/science.1229397.

McGarr, A., 1999. On relating apparent stress to the stress causing earthquake fault slip. J. Geophys. Res. 104 (B2), 3003–3012. doi:10.1029/1998JB900083.

Mishima, T., Yang, T., Mori, J., Chester, F., Eguchi, N., Toczko, S., Exp.343 Scientists. 2013. Rock-magnetic properties of the plate-boundary thrust material drilled during IODP Exp. 343 (JFAST). JpGU Meeting, May 19-24, Chiba, Japan.

Nakamura, Y., Kodaira, S., Miura, S., Regalla, C., Takahashi, Y., Obana, K.,Fujie, K., Cook, B., Conin, M., Chester, F., Mori, J., Eguchi, N., Toczko, S., Exp. 343 Scientists. 2013. Seismic imaging in the Japan Trench axis area off Miyagi, northeastern Japan. JpGU Meeting, May 19-24, Chiba, Japan.

Noda, H., Lapusta, N. 2013. Stable creeping fault segments can become destructive as a result of dynamic weakening. Nature. doi: 10.1038/nature11703.

Rowe, C., Moores, J.C., Remitti, F., Exp. 343 Scientists, in prep. The thickness of subduction plate boundary faults from the seafloor into the seismogenic zone.

Sakaguchi, A., F. Chester, D. Curewitz, O. Fabbri, D. Goldsby, G. Kimura, C.-F. Li, Y. Masaki, E. J. Screaton, A. Tsutsumi, K. Ujiie, and A. Yamaguchi, 2011, Seismic slip propagation to the updip end of plate boundary subduction interface faults: Vitrinite reflectance geothermometry on Integrated Ocean Drilling Program NanTroSEIZE cores, Geology, 39, 395–398, doi:10.1130/G31642.1.

Savage, H. Polissar, P., Sheppard, R., Rowe, C., Kirkpatrick, J., Exp. 343 Scientists. 2012. Evidence for frictional heating of the decollement in drillcores from Exp. 343: JFAST. 2012 Fall Meeting, AGU, San Francisco, CA

Tanikawa,W.,Hirose,T., Lin,W. and IODP Exp. 343 Scientists. 2013. Fluid transport properties of sediments near the plate boundary fault at Japan Trench. JpGU Meeting, May 19-24, Chiba, Japan.

Toy, V.G., Boulton, C.J., Barth, N.C., Carpenter, B., IODP Exp. 343 Scientists and IODP-MI, Goldsby, D., Kopf, A., Mitchell, T., Marone, C., Sutherland, R., Townend, J., Tullis, T. What can microstructural observations of natural faults tell us about the dissipative mechanisms that operated at the earthquake source? ECGS Workshop: Earthquake Source Physics on Various Scales, Luxembourg, October 3-5.

Ujiie, K., Tanaka, H., Saito, T., Tsutsumi, A., Mori, J., Kameda, J., Chester, F., Eguchi, N., Toczko, S., and Exp. 343 scientists. In preparation. Large slip on a shallow plate-boundary thrust promoted by low co-seismic shear strength.

Interaction of subduction and rifting on the exhumed Cretaceous convergent margin arc of Zealandia

Andy Tulloch[1], Nick Mortimer[1], Rose Turnbull[1], Keith Klepeis[2], Harold Stowell[3], Josh Schwartz[4], Jahandar Ramezani[5], Kaj Hoernle[6]

[1] GNS Science, Dunedin, NZ ; [2] University of Vermont, Burlington, VT USA; [3] University of Alabama, AL USA; [4] California State University, Northridge, CA USA, [5] Massachusetts Institute of Technology, Cambridge. MA USA, [6] IFM-GEOMAR, Kiel, Germany

a.tulloch@gns.cri.nz

Subduction and rifting are commonly spatially and temporally distinct processes, but the exhumed late Mesozoic convergent margin in New Zealand, and formerly adjacent continents of east Gondwana, is an ideal area to investigate their interaction. In particular, does intra-arc rifting affect the geochemical evolution of arcs, and can intra-arc and post subduction intra-plate rifting be distinguished?

The NZ segment of the convergent margin, extending 7000 km from Papua New Guinea via Queensland and NZ to West Antarctica, is the only location where arc (Median Batholith), forearc basin and accretionary prism are all preserved. The Median Batholith also contains one of the deepest (65 km in Fiordland[1]) arc roots available for study. Much of its exhumation is due to extensional denudation that preceded 85 Ma breakup[2] of east Gondwana, and which immediately followed (c. 102 Ma) cessation of magmatism (105 Ma). Thick sedimentary basins related to breakup also contain important repositories of information on the composition and tempo of arc and rift development. These relationships provide an unusually complete time and space section through continental crust from its base to basins that reside at the surface.

The Median Batholith[3] on a 90 Ma reconstruction is over 800 km long within Zealandia and separates a Paleozoic Western Province from the accreted Mesozoic terranes of the Eastern Province. It ranges in age from 230 to 105 Ma and is largely comprised of two margin parallel belts[4], separated by a prominent age gap at c. 135 Ma. The outboard (Pacificward) belt of 230-135 Ma plutons consists of typical low Sr/Y (LoSY[4]) plutonic and volcanic suites[5]. The inboard (wrt Gondwana) belt consists of 131-105 Ma, high Sr/Y (HiSY), TTG-like sodic plutons that dominate the deepest levels. Zircon U-Pb and garnet Sm-Nd geochronology indicate that thickening[6] and granulite facies metamorphism closely followed HiSY magmatism in Fiordland[7,8], and corroborate interpretations from metamorphic petrology of rapid vertical motion of the crust[9] during this final phase of subduction-related magmatism. Minor but widespread A-type and peralkaline granites may indicate discrete intra-arc extensional episodes.

The Whitsunday Volcanic Province of Queensland is a likely NW extension of the Median Batholith along the Lord Howe Rise[10], but has previously been interpreted as intra-plate rifting associated with formation of the Tasman Sea[11]. Because the shallow structural level exposed in Queensland contrasts with the deeper levels in tectonically extended and exhumed NZ, the potential for each area to inform on the other, as shallow and deep levels of the same subduction system, is significant. To the SE, the Median Batholith extends across the Campbell Plateau, where arc and rift magnetic anomalies overlap, and into West Antarctica. The exposed lateral and vertical extent, and strong HiSY signature, make the Median Batholith one of best Phanerozoic subduction zone TTG-like localities available for study. Strong similarities with the Peninsular Ranges Batholith[4] suggests Median Batholith features are not unique and have global application. First order questions on the New Zealand arc and its exhumation follow:

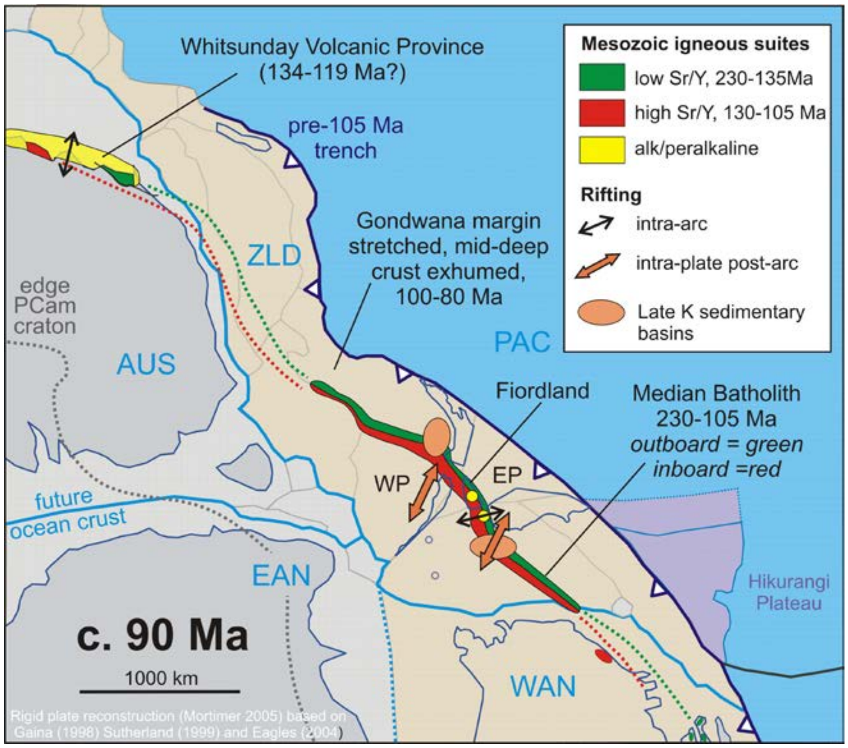
What geodynamic processes were associated with the sudden and complete switch to HiSY, TTG-like, plutonism at c. 135 Ma? Did the slab retreat, roll back or drop off, allowing hot asthenosphere to partially melt a thick basaltic crust underplated during 230-135 Ma subduction, or later underthrusting[4,12]? Were slab-derived fluids required for generation of HiSY magmas from basaltic underplate? Did asthenosphere wedge-generated magmatism cease at 135 Ma? Did episodic delamination of eclogitic residues contribute significantly to an overlying "Cordillera Zealandia"[13] by isostatic rebound (a current NZ Marsden Fund proposal)? Does peralkaline and A-type magmatism at c. 135 Ma suggest intra-arc extension was associated with the switch to HiSY magmatism? Is the geochemical rift signature observed in the Whitsunday Volcanic Province due to intra-arc rather than intra-plate, rifting? And, is it the equivalent of the 135 Ma intra-arc peralkaline magmatism in NZ?

When and where did subduction cease in NZ? Did an actively subducting slab cease to exist beneath the South Zealandia margin from 135, 105 or 85 Ma? How can this be recognised in the accretionary wedge? How can this be recognised in the Cretaceous igneous and metamorphic record? Is there still a stalled Hikurangi Plateau slab beneath South Zealandia[14,15]? Was cessation of subduction magmatism diachronous (120 Ma in Queensland, 105 Ma in Zealandia)? Did Gondwana breakup influence subduction cessation? When did intra-plate extension begin to affect Zealandia (>102 Ma?), how can it be distinguished from intra-arc rifting[16], and how might we distinguish intraplate alkaline magmas from possible A-type trends in the waning arc? Why did breakup in the central Zealandia segment occur well inboard of the arc[17]- was the lithosphere along the recently extinct arc relatively strong[18]?

References:

1. De Paoli, M.C., Clarke, G.L., Klepeis, K.A., Allibone, A.H., & Turnbull, I.M., 2009, The eclogite-granulite transition: mafic and intermediate assemblages at Breaksea Sound, New Zealand, Journal of Petrology, 50, 2307-43.
2. Kula JL, Tulloch AJ, Spell T, Wells ML, Zanetti K. 2009. Thermal evolution of the Sisters shear zone, southern New Zealand; formation of the Great South Basin and onset of Pacific-Antarctic spreading. Tectonics 20 TC5015
3. Mortimer, N, Davey, FJ, Melhuish, A, Yu, J, Godfrey, NJ, 2002. Geological interpretation of a deep seismic reflection profile across the Eastern Province and Median Batholith, New Zealand: crustal architecture of an extended Phanerozoic convergent margin, N. Z. J. Geol. Geophys., 45, 349–363.

4. Tulloch, AJ, Kimbrough, DL, 2003. Paired plutonic belts in convergent margins and the development of high Sr/Y magmatism: Peninsular Ranges batholith of Baja-California and Median batholith of New Zealand. Geol. Soc. Am., Special Paper 374 (Gastil Volume), 275–295.
5. Turnbull, RE., Weaver, SW, Tulloch, AJ, Cole, J., Handler, M., Ireland, TR. 2010. Field and geochemical constraints on mafic–felsic interactions, and processes in high-level arc magma chambers: an example from the Halfmoon Pluton, NZ . Jl Petrol. 51, 1477-1505.
6. Scott, J.M., Cooper, A.F., Tulloch, A.J., Spell, T.L.. 2011. Crustal thickening of the Early Cretaceous paleo-Pacific Gondwana margin. Gondwana Research 20, 380-394.
7. Stowell, H.H., Parker, K.A., Gatewood, M.P., 2010a. Sequential pluton emplacement, garnet granulite metamorphism, and partial melting during construction and modification of magmatic arc crust, Fiordland, New Zealand. Geochimica et Cosmochimica Acta, 74, A997.
8. Stowell, H.H., Tulloch, A.J., Zuluaga, C.A., Koenig, A., 2010b, Timing and duration of garnet granulite metamorphism in magmatic arc crust, Fiordland, New Zealand: Chemical Geology, v. 273, p. 91-110.
9. Allibone, A.H. Milan, L.A., Daczko, N.R, Turnbull, I.M. 2009. Granulite facies thermal aureoles and metastable amphibolite facies assemblages adjacent to the Western Fiordland Orthogneiss in southwest Fiordland, NZ. Jl of Meta. Petrology 27, 349-369.
10. Tulloch AJ, Ramezani J, Faure K, Allibone AH (2010) Early Cretaceous magmatism in New Zealand and Queensland: intra-plate or intra-arc origin? In: Buckman S, Blevin PL eds) New England Orogen 2010, vol. University of New Endland, University of New England, Armidale, pp 332-335.
11. Bryan, S. E., Constantine, A. E., Stephens, C. J., Ewart, A., Scho¨n, R. W., and Parianos, J., 1997. Early Cretaceous volcano-sedimentary successions along the eastern Australian continental margin: Implications for the break-up of eastern Gondwana: Earth and Planetary Science Letters, 153, 85-102.
12. Muir, R.J., Ireland, T.R., Weaver, S.D., Bradshaw, J.D., Evans, J.A., Eby, G.N. & Shelley, D., 1998. Geochronology and geochemistry of a Mesozoic magmatic arc system, Fiordland, NZ, *Jl of the Geol. Soc.*, 155, 1037–1053.
13. Tulloch, AJ. Beggs, M., Kula, J, Spell, T. 2006. Cordillera Zealandia, the Sisters Shear Zone and their influence on the early development of the Great South Basin. NZ Petroleum Conference Proceedings, http://www.nzpam.govt.nz/cms/pdf-library/petroleum-conferences-1/2006
14. Davy B, Hoernle, K., Werner R., 2008. Hikurangi Plateau: Crustal structure, rifted formation, and Gondwana subduction history, Geochem. Geophys. Geosyst., 9, Q07004, doi:10.1029/2007GC001855.
15. Reyners, M. 2012. The central role of the Hikurangi Plateau in the Cenozoic tectonics of New Zeland and the SW Pacific. Earth & Planetary Science Letters 361, 460-468.
16. Tulloch, AJ, Ramezani, J, Mortimer, N, Mortensen, J, van den Bogaard, P, Maas, R, 2009. Cretaceous felsic volcanism in New Zealand and Lord Howe Rise (Zealandia) as a precursor to final Gondwana break-up, *in* Ring, U., and Wernicke, B., eds, Extending a Continent: Architecture, Rheology and Heat Budget: Geological Society, London, Special Pub., 321, 89–118.
17. Dunbar, J.A. Sawyer, D.S. 1989. How preexisting weaknesses control the style of continental breakup. Jl Geophys. Res. 94, 7278-97.
18. Klepeis, KA, King D, De Paoli M, Clarke GL, Gehrels G, 2007. Interaction of strong lower and weak middle crust during lithospheric extension in western NZ. Tectonics 26.



Whitsunday Volcanic Province
(134-119 Ma?)
pre-105 Ma
trench
Mesozoic igneous suites
low Sr/Y, 230-135Ma
high Sr/Y, 130-105 Ma
alk/peralkaline
Rifting
intra-arc
intra-plate post-arc
Late K sedimentary basins
ZLD
Gondwana margin stretched, mid-deep crust exhumed, 100-80 Ma
edge
PCam
craton
AUS
PAC
Fiordland
Median Batholith
230-105 Ma
outboard = green
inboard =red
WP
EP
future
ocean crust
EAN
Hikurangi
Plateau
c. 90 Ma
1000 km
WAN
Rigid plate reconstruction (Mortimer 2005) based on Gaina (1998) Sutherland (1999) and Eagles (2004)

Subduction Inputs to the Hikurangi Margin, New Zealand

Michael Underwood[1], Philip Barnes[2], Joshu Mountjoy[2], Kathleen Marsaglia[3], Laura Wallace[4], Demian Saffer[5], Stuart Henrys[6], Susan Ellis[6], Yoshihiro Ito[7], Harold Tobin[8], Shuichi Kodaira[9], Nathan Bangs[4], Ake Fagereng[10], Heather Savage[11], Marta Torres[12]

[1]Univ. Missouri, [2]NIWA, New Zealand, [3]Cal State Univ. Northridge, [4]Univ. Texas Inst. For Geophysics, [5]Pennsylvania State Univ., [6]GNS Science, New Zealand, [7]Tohoku Univ., Japan, [8]Univ. Wisconsin, [9]JAMSTEC, [10]Univ. Cape Town, South Africa, [11]LDEO Columbia Univ., [12]Oregon State Univ.

UnderwoodM@missouri.edu

Introduction: The overarching goal for scientific ocean drilling across the northern Hikurangi margin transect is to characterize the compositional, thermal, hydrogeological, frictional, geochemical, and diagenetic conditions associated with the rupture area of recent slow slip events (SSE). We propose coring and logging of the incoming stratigraphy and upper oceanic basement to constrain the "initial conditions" prior to subduction of potential SSE host rocks. Correlation along strike (through core-log-seismic integration) will focus on contrasts between northern sections undergoing SSEs and southern sections characterized by strong interseismic coupling.

Subduction of Hikurangi Plateau Basement: At this stage, we know very little about the lithological details of Hikurangi subduction inputs. ODP drilling legs have targeted the regions east and south of New Zealand, including the Canterbury Basin offshore South Island (*Land et al*., 2010; *Expedition 317 Scientists*, 2011). To date, there has been no drilling anywhere in the Hikurangi Trough (Fig. 1). Data from ODP Site 1124 (*Carter et al*., 1999) are the most useful for correlation across the Hikurangi Plateau, which is a large igneous province on the subducting plate. Gravity modelling indicates that the plateau crust is ~12-15 km thick. The plateau formed ~120 Ma. Late-stage volcanism (~100-90 Ma) emplaced many seamounts from which samples of tholeitic and alkali-rich volcanic rocks have been recovered by dredging. The upper part of the basement sequence is relatively reflective in seismic sections, with moderate P-wave velocities (~2.5-3.5 km/s), interpreted as volcaniclastics, limestone and/or chert.

Sediment Inputs to the Subduction Zone: The volcanic/volcaniclastic basement of Hikurangi Plateau is covered by Cretaceous and Paleogene sedimentary strata, whose character is inferred largely by correlation of seismic-reflection data to Site 1124 (*Davy et al*., 2008). An older sequence (~100-70 Ma) contains clastic sediments probably eroded from the continental Chatham Rise to the south and deposited in low-energy marine environments. A younger sequence (70-32 Ma) is a condensed section; correlative strata at ODP Site 1124 consist of nannofossil chalk, mudstone, and subordinate chert, with several unconformities in the Oligocene, Eocene and Paleocene.

As the relative thin (<500 m) Cretaceous-Paleogene strata enter the subduction zone at northern Hikurangi, they are buried by about 1 km of intercalated trench-fill turbidites, hemipelagic sediment, and debris-flow/ mass-transport deposits. At southern Hikurangi, the Cretaceous-Paleogene stratigraphy is thicker (~3 km) and buried by up to 6 km of trench-wedge clastics (*Plaza-Faverola et al*., 2012). The trench floor includes an impressive (>1500 km long) meandering channel (Hikurangi Channel). Just before the channel reaches the vicinity of Gisborne Knolls (i.e., within the proposed drilling transect), it makes an unusual 120° hook to the southeast to carry sediments into the Central Plateau Basin and beyond (*Lewis*, 1994). Rerouting of the channel has been attributed to damming of the trench axis by subducting seamounts (*Lewis et al*., 1998).

Sources/Timing of Hikurangi Trench Sediment: The longer term history of trench sedimentation is important for this project because 3-D distributions of sand and mud influence 3-D distributions of permeability, pore pressure, and mechanical strength within the accretionary prism (*Underwood*, 2007). The Hikurangi Channel is fed primarily by a network of major submarine canyons from off the eastern South Island to Cook Strait Canyon offshore North Island (*Lewis*, 1994; *Lewis and Pantin*, 2002; *Mountjoy et al*., 2009). Poverty Canyon contributes from the north (e.g., *Parra et al*., 2012), whilst others such as Madden Canyon feed only slope basins. The close proximity of canyon heads to the shoreline, and an unusually narrow continental shelf, means that the delivery system remains active during highstands of sea level. Mega-scale collapse of the continental slope is thought to have occurred ~170 ka (*Collot et al., 2001*); however, mass failures into the trench remain poorly constrained in terms of timing and physical character. Accelerated trench sedimentation has probably led to phases of rapid accretionary-prism growth (*Barnes et al*., 2010). Along-strike variations in total sediment thickness seaward of the deformation front have probably modulated the transitions from subduction accretion (S. Hikurangi) to mixed frontal erosion and minimal accretion (N. Hikurangi). To clarify these links between sedimentation and frontal-prism tectonics, we advocate holistic documentation of 4-D facies evolution using riserless drilling and core-log-seismic integration.

Connection from Subduction Inputs to the Deep (Riser) Drilling Targets: Host lithologies for the SSE fault zone at north Hikurangi are unknown but might include Cretaceous volcaniclastic rocks, siliciclastic sandstone and mudstone, slivers of altered basalt, chert, and/or limestone (nannofossil chalk). To test that full range of possibilities, we advocate riserless drilling through the entire sediment package above Hikurangi Plateau, penetrating into the top of the basaltic lava and the volcaniclastic sequence (Fig. 1). We also propose drill ~400 m into the Gisborne Knolls seamount to capture a representative section of the upper, altered basalt.
Sampling the full suite of subduction inputs will allow us to test several overarching questions that relate to fault-slip behavior at depth: (1) What are the frictional properties, textures, interstitial fluid compositions, detrital mineralogy, diagenetic/metamorphic state, porosity, permeability, microfabric, and fracture density throughout the lithologic suite prior to subduction? (2) Can sediment/rock composition be linked in unique ways to mechanical and frictional properties? Are the properties of any incoming lithology (or lithologies) consistent with transitional frictional behavior at greater depths? (3) Did the onset of widespread glaciation and large-amplitude eustatic lowstands at ~2.5 Ma trigger faster sedimentation in the trench? If so, did the initiation of rapid trench sedimentation coincide with an acceleration of frontal accretion, or a change in partitioning of the stratigraphy above/below the frontal fault? (5) Does the trench-wedge stratigraphy retain any textural or compositional evidence of Milankovich cycles during the Pleistocene? Have global and/or local changes in climate caused shifts in clay mineral assemblages, such as those documented at ODP Site 1119 (Canterbury Drifts) by *Land et al*. (2010)? Alternatively, are eustatic cycles overprinted or obliterated by the

effects of local subduction tectonics? All of these questions are central to the North Hikurangi science plan because they ultimately feed back to the temporal and spatial heterogeneity of fluids and fault-slip behavior (i.e., down-dip and along-strike patchiness of SSEs).

References:

Barnes, P.M., and 9 others, 2010, Tectonic and geological framework for gas hydrates and cold seeps on the Hikurangi subduction margin, New Zealand: *Mar. Geol*., 272:26-48.

Carter, R.M., McCave, I.N., et al., 1999, *Proc. ODP, Initial Reports*, v. 181, Ocean Drilling Prog., College Station, TX.

Collot, J.-Y., Lewis, K., Lamarche, G., and Lallemand, S., 2001, The giant Ruatoria debris avalanche on the northern Hikurangi Margin, New Zealand: Result of oblique seamount subduction: *J. Geophys. Res*., 106: 19,271-219,297.

Davy, B., Hoernle, K., and Werner, R., 2008, Hikurangi Plateau: Crustal structure, rifted formation, and Gondwana subduction history: *Geochem. Geophys. Geosys*., 9(7).

Expedition 317 Scientists, 2011, Expedition 317 summary, *Proc. IODP*, 317, doi:10.2204/iodp.317.101.2011.

Land, M., Wust, R.A.J., Robert, C., and Carter, R.M., 2010, Plio-Pleistocene paleoclimate in the Southwest Pacific as reflected in clay mineralogy and particle size at ODP Site 1119, SE New Zealand: *Mar. Geol*., 274:165-176.

Lewis, K.B., 1994, The 1500-km-long Hikurangi Channel: trench-axis channel that escapes its trench, crosses a plateau, and feeds a fan drift: *Geo-Mar. Lett*., 14:19-28.

Lewis, K.B., Collot, J-Y., and Lallemand, S.E., 1998, The dammed Hikurangi Trough: a channel-fed trench blocked by subducting seamounts and their wake avalanches (NZ-France GeodyNZ Project): *Basin Res*., 10:441-468.

Mountjoy, J.J., Barnes, P.M., and Pettinga, J.R., 2009, Morphostructure and evolution of submarine canyons across an active margin: Cook Strait sector of the Hikurangi Margin, New Zealand: *Mar. Geol*., 260:45-68.

Parra, J.G., Marsaglia, K.M., Rivera, K.S., Dawson, S.T., and Walsh, J.P., 2012, Provenance of sand on the Poverty Bay shelf, the link between source and sink sectors of the Waipaoa River sedimentary system: *Sed. Geol*., 280:208-233.

Plaza-Faverola, A., Klaeschen, D., Barnes, P., Pecher, I., Henrys, S., and Mountjoy, J., 2012, Evolution of fluid explusion and concentrated hydrate zones across the southern Hikurangi subduction margin, New Zealand: an analysis from depth migrated seismic data: *Geochem. Geophys. Geosys.* 13, Q08019, doi:10.1029/2102GC004228.

Underwood, M.B., 2007, Sediment inputs to subduction zones: Why lithostratigraphy and clay mineralogy matter, in *The Seismogenic Zone of Subduction Thrusts*: Columbia Univ. Press, 42-85.

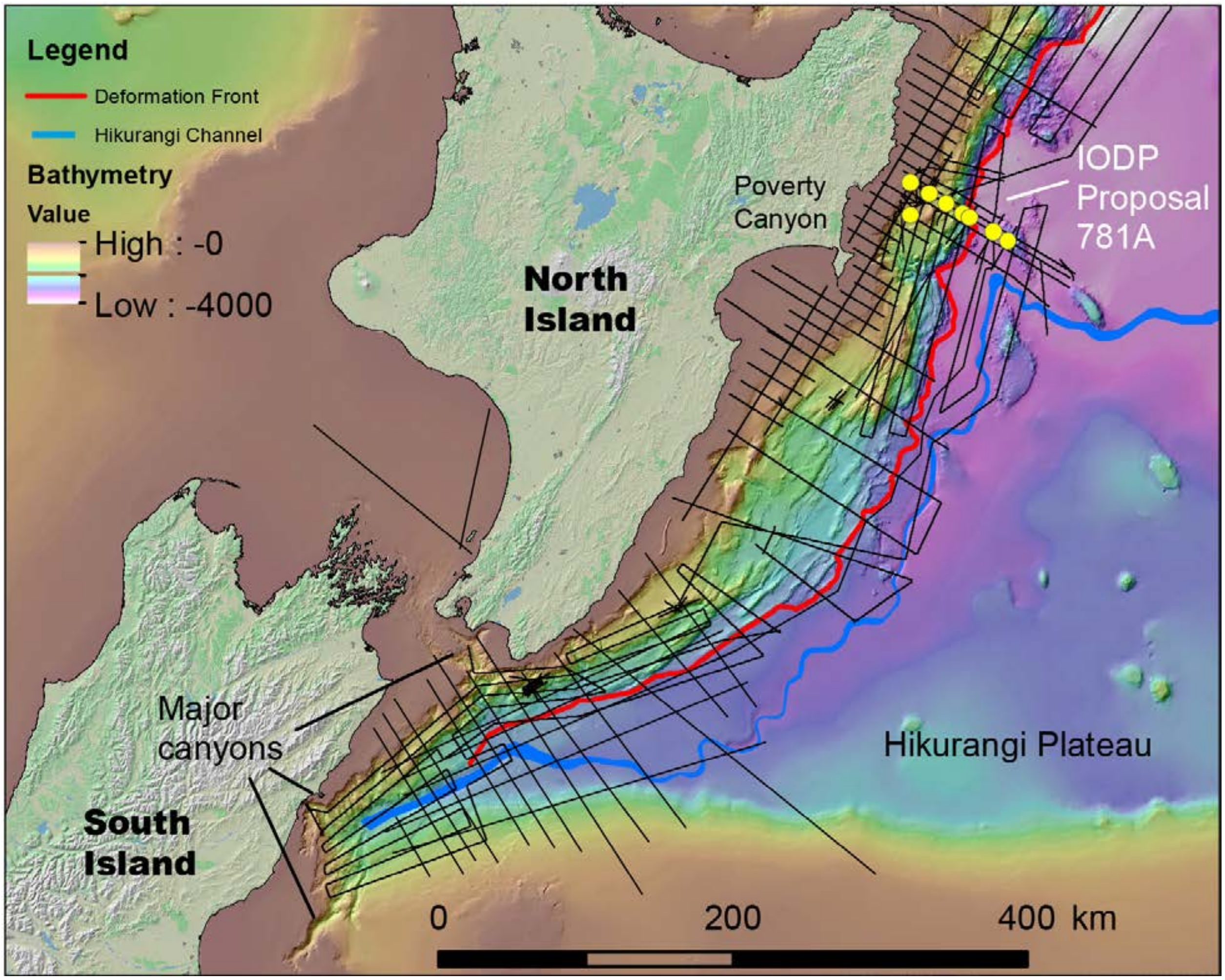


Figure 1. Map of Hikurangi margin with proposed IODP drill sites (yellow dots) and tracklines for seismic reflection profiles.

Variations in remote triggering susceptibility along the Hikurangi margin and implications for the time-dependent strength of subduction zones

Nicholas J van der Elst[1] and Heather M. Savage[1]

[1]*Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA*

Nicholas@ldeo.columbia.edu

Triggered micro-seismicity and tremor are tools for investigating the time-dependent strength of fault zones, revealing when faults are critically stressed and sensitive to small perturbations. Changes in triggerability may occur as a fault approaches a slow slip event or a large earthquake [*Savage and Marone*, 2008]. The Hikurangi subduction zone offers a unique window in which the recurrence time between slow slip events is short and fairly periodic, allowing for accurate sampling of the whole stick-slip cycle.

Preliminary work shows that Hikurangi has one of the highest rates of microseismic triggering of any subduction zones studied to date (Fig. 1). The high triggering susceptibility in Hikurangi may be related to the uniquely low coupling in this region, evidenced by episodic slow slip at relatively shallow depths (~15 km) [*Wallace et al.*, 2009]. In the Cascadia subduction zone, tremor is more sensitive to triggering by earth tides or passing surface waves during or near the occurrence of a slow-slip event than in the intervening stretches [*Rubinstein et al.*, 2009]. Micro-seismicity in several subduction zones has been shown to correlate more strongly with tidal stressing in the years before large megathrust earthquakes, including the 2011 M_W9.1 Tohoku earthquake [*Tanaka*, 2010; 2012]. Over the longer term, however, this subduction zone is relatively insensitive to triggered microseismicity from passing surface waves [*Harrington and Brodsky*, 2006; *van der Elst and Brodsky*, 2010]. Susceptibility to triggering therefore appears to evolve in response to changing strength or stability conditions on the fault.

Using a stacking method to pull out subtle triggered rate changes in large populations of micro-seismicity (previously applied to California and Japan [*van der Elst and Brodsky*, 2010]) we find that the northern Hikurangi margin responds strongly and systematically to surface waves from remote earthquakes (Fig 1). Spatial variations in the susceptibility to dynamic triggering along the subduction zone are evidence of the differences in strength between seismically coupled and uncoupled portions of the Hikurangi plate margin. The region of highest micro-seismic triggerability corresponds to the location of shallow slow slip events [*Wallace and Beavan*, 2010]. These two phenomena have not previously been observed to coincide. Cascadia and Japan, for example, both appear at least a factor of 3 less triggerable using the same method, with essentially no triggered micro-seismicity resolved in either location.

What do these triggered signals tell us about the distribution of strength and sliding stability along the Hikurangi plate margin? What do they tell us about the likelihood of large megathrust earthquakes here and in other subduction zones that lack remote triggering? The relationship between slow-slip, tremor, triggered micro-earthquakes and damaging megathrust events is only beginning to be worked out. The Hikurangi margin offers the unique possibility of studying the relationship between all of these sliding modes, throughout the slow-slip cycle.

References:

Harrington, R. M., and E. E. Brodsky (2006), The absence of remotely triggered seismicity in Japan, *Bulletin of the Seismological Society of America*, *96*(3), 871-878.

Rubinstein, J. L., J. Gomberg, J. E. Vidale, A. G. Wech, H. Kao, K. C. Creager, and G. Rogers (2009), Seismic wave triggering of nonvolcanic tremor, episodic tremor and slip, and earthquakes on Vancouver Island, *Journal of Geophysical Research-Solid Earth*, *114*

Savage, H. M., and C. Marone (2008), Potential for earthquake triggering from transient deformations, *Journal of Geophysical Research*, *113*(B5), B05302, doi 05310.01029/02007jb005277.

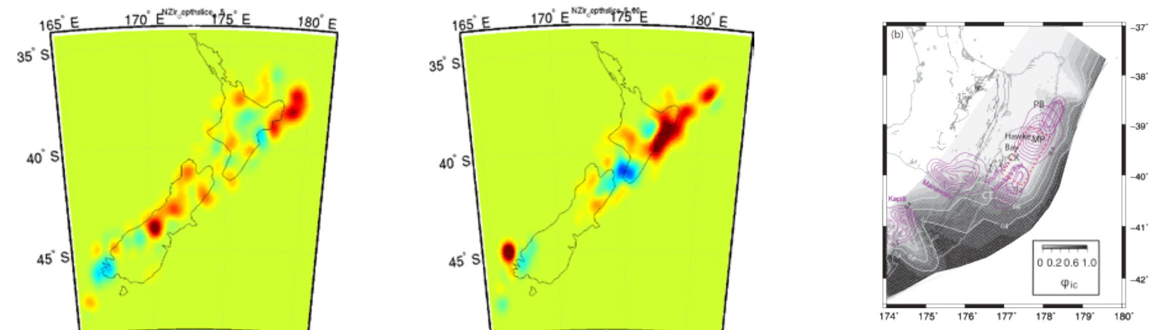
Tanaka, S. (2010), Tidal triggering of earthquakes precursory to the recent Sumatra megathrust earthquakes of 26 December 2004 (M-w 9.0), 28 March 2005 (M-w 8.6), and 12 September 2007 (M-w 8.5), *Geophysical Research Letters*, *37*

Tanaka, S. (2012), Tidal triggering of earthquakes prior to the 2011 Tohoku-Oki earthquake (M-w 9.1), *Geophysical Research Letters*, *39*

van der Elst, N. J., and E. E. Brodsky (2010), Connecting near-field and far-field earthquake triggering to dynamic strain, *J. Geophys. Res.*, *115*(B07311)

Wallace, L. M., M. Reyners, U. Cochran, S. Bannister, P. M. Barnes, K. Berryman, G. Downes, D. Eberhart-Phillips, A. Fagereng, S. Ellis, A. Nicol, R. McCaffrey, R. J. Beavan, S. Henrys, R. Sutherland, D. H. N. Barker, N. Litchfield, J. Townend, R. Robinson, R. Bell, K. Wilson, and W. Power (2009), Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand, *Geochemistry Geophysics Geosystems*, *10*

Wallace, L. M., and J. Beavan (2010), Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, *Journal of Geophysical Research-Solid Earth*, *115*



(a) 0-15 km **(b)** 15-100 km **(c)**

Figure 1. Susceptibility to dynamic triggering along the Hikurangi margin. ***(a)*** *Micro earthquake triggering susceptibility in the upper 15 km; warm colors reflect regions that respond more strongly to the surface waves of remote earthquakes. Cool colors (blue) reflect apparent negative rate changes and give an estimate of the uncertainty in the measurement.* ***(b)*** *Triggering susceptibility in the 15-100 km depth range. The peak triggering rates (red) are about 3 earthquakes/hr/per 100 km*^{2}*.* ***(c)*** *Zoom in on the north island, showing the zones of weak inter-seismic coupling and the location of slow slip events (violet contours) (from Wallace et al., 2009). The zones of weak coupling are also zones of strong remote triggering.*

Unlocking the Secrets of Slow Slip by Scientific Drilling at the Northern Hikurangi Subduction Margin, New Zealand

Laura Wallace[1], Demian Saffer[2], Stuart Henrys[3], Philip Barnes[4], Michael Underwood[5], Yoshihiro Ito[6], Harold Tobin[7], Shuichi Kodaira[8], Nathan Bangs[1], Joshu Mountjoy[4], Ake Fagereng[9], Heather Savage[10], Susan Ellis[3], Marta Torres[11], and the Hikurangi Margin Working Group

[1]Univ. Texas, Inst. For Geophysics, [2]The Pennsylvania State Univ.[3]GNS Science, New Zealand, [4]NIWA, New Zealand, [5]Univ. Missouri, [6]Tohoku Univ, [7]Univ. Wisconsin-Madison, [8]JAMSTEC, [9]University of Cape Town, South Africa, [10]LDEO, Columbia University, [11]Oregon State University

lwallace@ig.utexas.edu

Slow slip events (SSEs) involve transient aseismic slip across a fault (lasting weeks to months) at rates intermediate between plate-boundary displacement rates and the slip velocity required to generate seismic waves. The importance of these events as a mode of fault slip was unknown prior to the advent of dense, plate-boundary-scale geodetic networks during the last decade. Observations of SSEs and associated seismic phenomena at several subduction megathrusts have ignited a dynamic and exciting field of research in seismology and plate boundary fault mechanics. SSEs appear to bridge the gap between typical earthquake behavior and steady, aseismic slip on faults, but the governing physical mechanisms, rock properties, in situ conditions, and the relationship of these events to destructive, seismic slip on subduction thrusts are poorly known. This deficiency in our understanding is due partly to the fact that most well-studied subduction zone SSEs (Cascadia, southwest Japan) are too deep for high-resolution imaging or direct sampling of the source region. **A notable exception is the northern Hikurangi subduction margin, New Zealand, where well-characterized SSEs occur every 1-2 years, over a period of 2-3 weeks at depths of only <5-15 km below the seafloor** (Fig. 1). SSEs at northern Hikurangi are, therefore, shallow and frequent enough to sample, log, and monitor in the near field over several cycles of strain accumulation and release.

The Multi-phase Drilling Project proposal "**Unlocking the Secrets of Slow Slip by Drilling at the Northern Hikurangi Subduction Margin, New Zealand"** (781-MDP) outlines a plan for IODP drilling to discern the mechanisms of subduction zone SSEs by a transect of both riserless and riser drilling and borehole observatories above the SSE source and on the incoming plate (Fig. 2). The proposal for riserless operations (781A-Full) was submitted in October 2011. 781A-Full was forwarded by the IODP Proposal Evaluation Panel (PEP) with an "Excellent" rating and is now eligible for scheduling on *JOIDES Resolution*. A proposal for the riser operations will be submitted to IODP by 1 April 2013.

The riserless boreholes are designed to address three fundamental scientific objectives: (1) characterize the *state* and *composition* of the incoming plate and shallow plate boundary fault near the trench, which comprise the protolith and initial conditions for fault zone rock at greater depth; (2) characterize material properties, thermal regime, and stress conditions in the upper plate above the SSE source region; and (3) install borehole observatory instruments to monitor a transect of holes above the SSE source, to measure temporal variations in deformation, fluid flow, and seismicity.

For the riser drilling phase, we propose a single borehole to intersect the plate interface 5.5-5.8 km below the seafloor, to collect samples, geophysical logs, and downhole measurements across the subduction megathrust fault *where SSEs are occurring*. Our drilling strategy is also designed to take advantage of scientific opportunities on the way to the subduction interface, including a temporary observatory ~1.5 km above the SSE source, to be in place between drilling phases (Fig. 2). The deep borehole is required to address three fundamental scientific objectives: (1) reveal the composition, mechanical properties, and structural characteristics of the slow slip source zone; (2) characterize hydrological properties, thermal regime, and in situ stress conditions within the SSE source region, and (3) determine hydrological properties, thermal regime, and stress conditions within the upper plate above the SSE source.

Together, the data from our proposed program of riserless and riser drilling will test a suite of hypotheses and answer outstanding questions about the fundamental mechanics of faults and occurrence of slow slip events. **(1)** Are SSEs associated with elevated fluid pressures, and if so, what is the source of the fluids? **(2)** What are the roles of fault strength and frictional properties in facilitating slow slip? **(3)** What is the fault zone architecture associated with slow slip, and does slow slip occur over a broad shear zone or discrete slip zone? **(4)** Which lithologies host slow slip, and do they promote conditional frictional stability? If so, do both fast seismic slip and slow aseismic slip occur in the same location on the interface? **(5)** Do slow slip events propagate all the way to the trench? **(6)** How do fluid chemistry, pore pressure, temperature, and fluid flux (near the surface and at the SSE source) vary in response to SSEs, and vice versa? **(7)** Does temperature influence the down-dip limit of the seismogenic zone and the depth to slow slip events?

Most importantly, drilling into the aseismically creeping northern Hikurangi margin constitutes an ***ideal counterpart*** to deep riser drilling into the Nankai trough seismogenic zone, which is ongoing. If both subduction margins are eventually drilled, holistic comparisons of cores and logs between the two end-member locations will help to ***solve the mystery of why some subduction zones lock up and rupture in Great earthquakes (e.g., Nankai), while others are dominated by aseismic creep (e.g., North Hikurangi).***

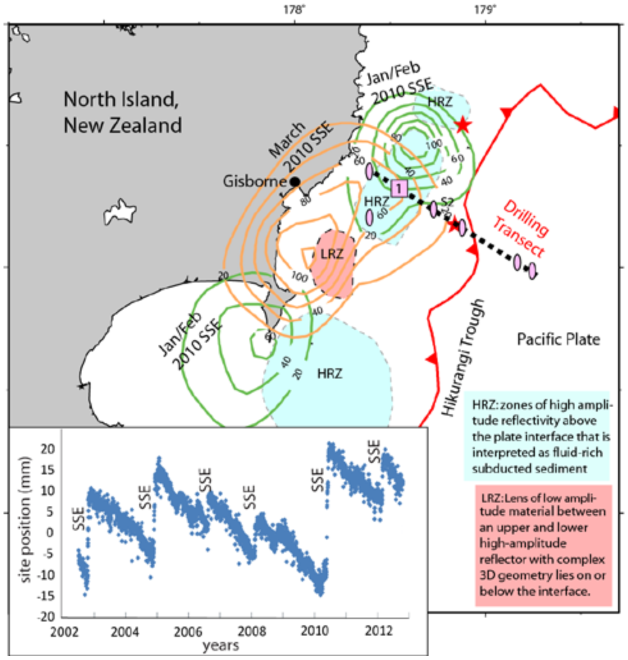


Figure 1. Tectonic setting and location of slip (colored contours) on the subduction interface in a sequence of SSEs in 2010. Black dashed line with pink ellipses shows the location of the proposed riserless drilling transect (proposal 781A-Full), while the pink square (labeled "1") shows the proposed riser drillsite to intersect the SSE source at 5.5-5.8 km bsf. 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.

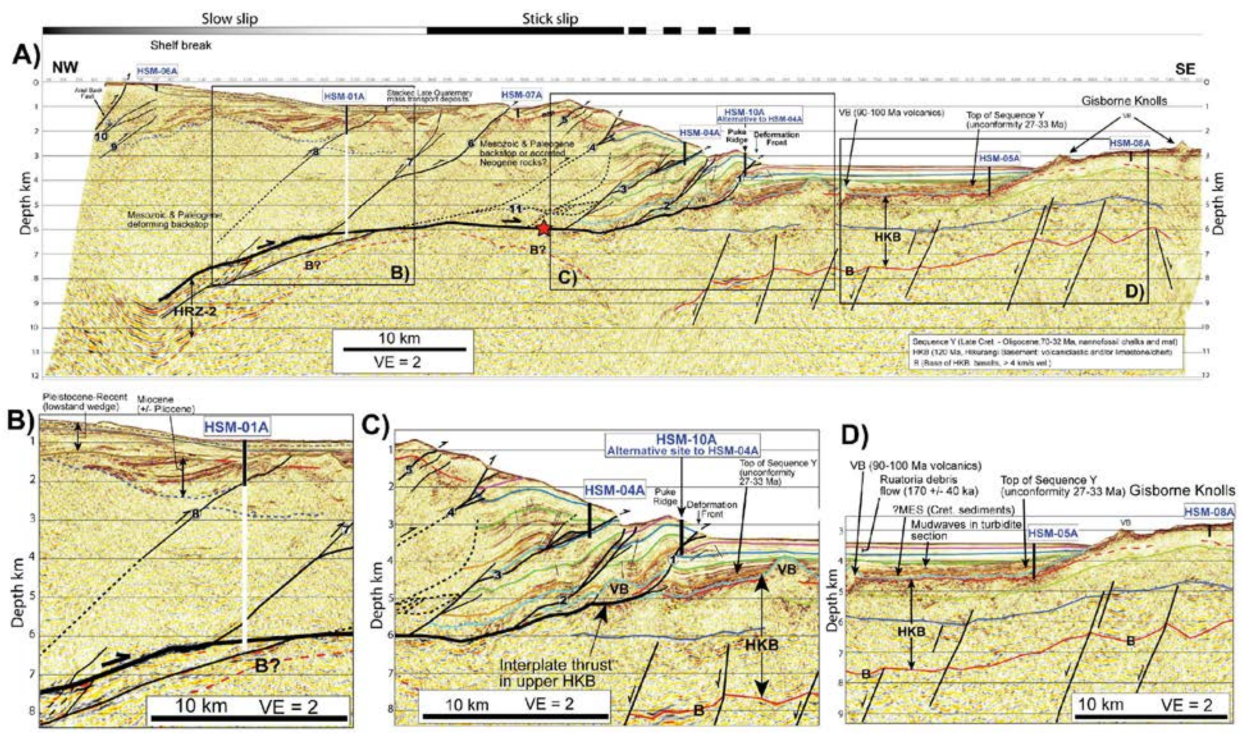


Figure 2. A) Interpretation of depth converted seismic profile 05CM-04 across the upper plate and subducting Pacific Plate east of Gisborne. The profile location is shown in Figure 2, and is co-located with the proposed drilling transect. B), C) and D) are enlargements of the upper margin, frontal accretionary wedge, and subducting plate, respectively. The bold black fault is the subduction interface. The stratigraphy of the subducting Hikurangi Plateau sequence is inferred from correlations to seismic reflection and ODP borehole (1123, 1124) data from east of the trench. Note that at the deformation front, the plate interface is developing in the upper part of the Hikurangi Plateau basement sequence (HKB). The high-amplitude reflectivity zone above the interface (HRZ) labeled on 1, and the red star shows the location of the March 1947 tsunami earthquake.

Seafloor and Subseafloor Monitoring of Slow Slip at the Northern Hikurangi Margin

Laura Wallace[1], Demian Saffer[2], Kimi Mochizuki[3], Yoshihiro Ito[4], Spahr Webb[5], Stephen Bannister[6], Bill Fry[6], Susan Schwartz[7], Anne Sheehan[8], Stuart Henrys[6], Evan Solomon[9], Patrick Fulton[7], Miriam Kastner[10], and David Schmidt[9]

[1]Univ. Texas, Inst. For Geophysics, [2]The Pennsylvania State Univ., [3]Univ. Tokyo, ERI, [4]Tohoku Univ, [5]LDEO, Columbia Univ. [6]GNS Science, NZ, [7]Univ. California-Santa Cruz, [8]Univ. Colorado, [9]Univ. of Washington, [10]UC-San Diego-Scripps Inst. Oceanography

lwallace@ig.utexas.edu

Slow slip events offshore the northern Hikurangi margin occur at shallow depths of <5-15 km approximately every eighteen months just offshore Gisborne, New Zealand. They typically last 1-2 weeks, producing horizontal displacements of up to 3 cm at onshore cGPS sites. The unusually close proximity of the Gisborne SSEs to the seafloor is in distinct contrast to Cascadia and southwest Japan where SSEs are at >30-40 km depth. Due to large slip and shallow depths, **vertical seafloor displacements in SSEs offshore Gisborne are expected to be 1-3 cm or more, much larger than for Cascadia SSEs.** The close proximity of north Hikurangi SSEs to the seafloor makes this region an ideal location for ***near-source*** monitoring of variations in deformation, seismicity, fluid pressure, fluid geochemistry, and temperature through multiple SSE cycles using a network of seafloor and subseafloor instruments. **To this end, we advocate the development of an integrated network of seafloor and subseafloor observatories** (Fig. 1)**.** The seafloor component should include ocean bottom seismometers (OBS) and absolute pressure gauges (APG; to measure vertical deformation). Borehole observatories would be focused on monitoring hydrogeological, thermal, geochemical, and deformation (via tilt, pore pressure, & flow rates) variations throughout multiple SSE cycles (see Hikurangi drilling white paper).

Seafloor OBS and Absolute Pressure gauges. The primary aim of a seafloor-based network of OBS and APG is to **improve our knowledge of the distribution of slow slip and related seismicity beneath the offshore region**. Specific goals are: **(1)** Determine the spatial distribution of SSE slip using vertical deformation data from the APGs. Based on recently recovered APG data from Cascadia, we expect to resolve vertical deformation signals of 0.5 cm and larger; **(2)** Identify and precisely locate seismicity and tremor related to SSEs at the offshore northern Hikurangi subduction margin, and assess the spatial and temporal relationship to SSE slip; **(3)** Passive source imaging with OBS to improve earthquake locations and inferring properties of the plate interface and surrounding crust in the SSE region. If we find that slow slip propagates all the way to the trench (Fig. 2), this will have major implications for our knowledge of the range of physical environments that promote SSE behavior, and could also open the possibility of shallow drilling into the SSE source area using less costly riserless drilling.

Sub-seafloor observatories. The primary goals of the borehole observatories are***:*** **(1)** Monitor temporal variations in pore fluid pressure, fluid geochemistry and flow rate within the shallow subduction thrust (near the trench) and upper plate throughout the SSE cycle. These data will quantify ambient pore pressure, provide information about potential links between hydraulic and geochemical transients and SSEs, and constrain the source region of fluids that may be mobilized through permeability enhancement associated with SSEs (e.g., Solomon et al., 2009; Davis et al., 2011). **(2)** Deployment of a string of thermistors in the boreholes will enable determination of ambient temperatures, evaluation of the thermal regime of shallow slow slip, as well as variations in temperatures throughout the SSE cycle. **(3)** Document formation pressure response to known tidal loading to constrain formation compressibility and hydraulic diffusivity (e.g., Wang and Davis, 1996). **(4)** Borehole tiltmeter, pore pressure, and flowmeter data (with the latter two used as a proxy for strain) can be integrated within the broader framework of OBS and APG deployments at north Hikurangi to provide key information on the spatial and temporal distribution of slip in SSEs on the shallow subduction thrust (Fig. 2).

In a pilot study, the University of Tokyo has recently recovered two OBS+APG offshore Gisborne (led by Kimi Mochizuki). A larger deployment of OBS and APG has been recently proposed to NSF and Japanese funding agencies (Fig. 1) for 2014. This proposed deployment is intended to capture deformation and seismicity related to a large SSE offshore Gisborne that is expected to occur sometime in 2014 (based on past behavior of SSEs there). We are in the process of developing proposals for observatory equipment to be installed in boreholes as part of IODP proposal 781A-Full (see white paper on Hikurangi margin drilling). To fully integrate the results from seafloor observations (OBS, APG) with those from the borehole observatories, we advocate deployment of a network of OBS and APG instruments at the same time that the borehole observatories are operating. Combined interpretation of data from these two complementary networks will greatly improve the spatial resolution of the distribution of slip and seismicity. The borehole observatories on their own will also reveal how physical properties such as fluid chemistry, pressure, temperature, and fluid flux (both above the SSE source and within the frontal thrust) vary through the SSE cycle.

References:

Davis, E., M. Heesemann, and K. Wang (2011), Evidence for episodic aseismic slip across the subduction seismogenic zone off Costa Rica: CORK borehole pressure observations at the subduction prism toe, Earth. Planet. Sci. Lett., 306, 299-305.

Solomon, E.A., Kastner, M., Wheat C.G., Jannasch H., Robertson G., Davis, E.E., Morris, J.D, 2009. Long-term hydrogeochemical records in the oceanic basement and forearc prism at the Costa Rica subduction zone. Earth Planet. Sci. Letters, 282, 240-251.

Wallace, L. M., and J. Beavan (2010), Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, J. Geophys Res., 115(B12402), doi:10.1029/2010JB007717.

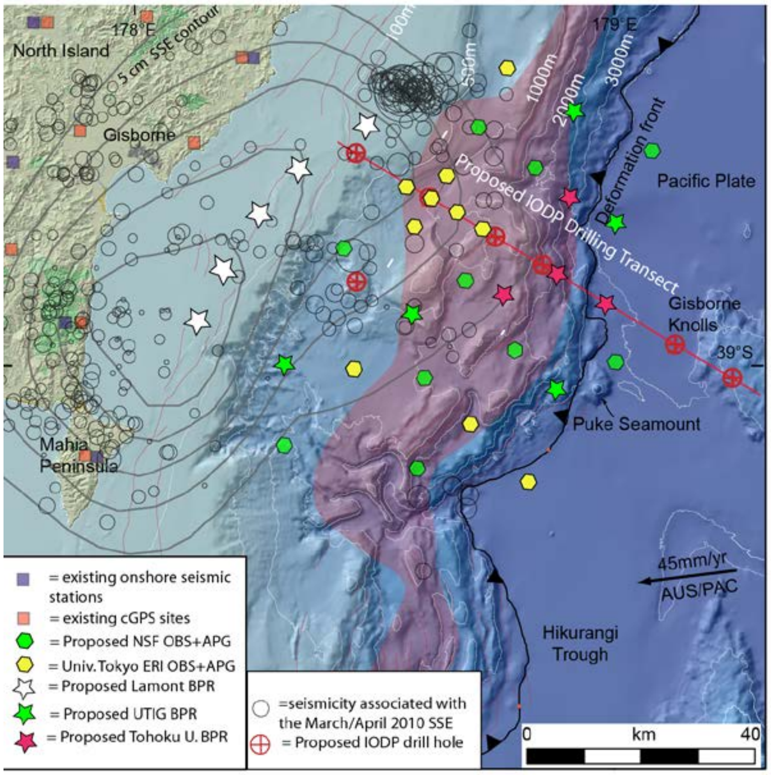


Figure 1. Bathymetry of the northern Hikurangi margin, IODP drilling transect (proposal 781A-full, red line), and a proposed 2014 deployment of OBS and APG (hexagons and stars). Purplish-red transparent area on mid slope is the envelope of viable riser drilling targets that would intersect the subduction interface. See key at lower left explaining the symbols on the figure. The gray contours indicate slip on the subduction interface in the March/April 2010 SSE offshore Gisborne, New Zealand (Wallace and Beavan, 2010); contour intervals are 30 mm, the starting (outermost) contour is 30 mm, innermost contour is 150 mm. Black circles are seismicity associated with the March/April 2010 SSE.

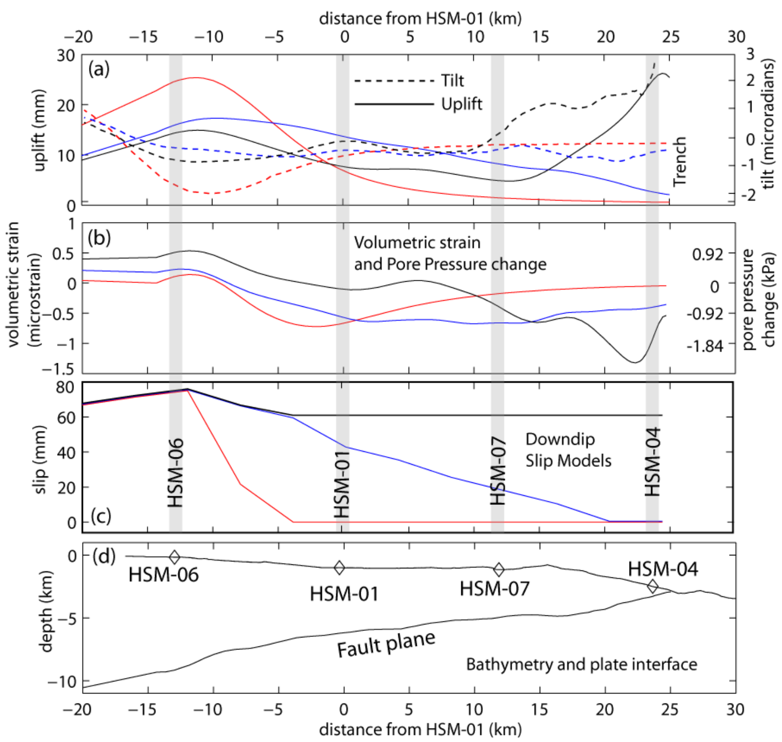


Figure 2. Forward elastic, half space dislocation models of 3 different SSE slip scenarios shown in (c). Tilt and uplift (a) are calculated at the seafloor and volumetric strain (b) is estimated for 300 mbsf. If conditions within the sediments are undrained there is a linear relationship between pore pressure (Pf) and volumetric strain, scaled by the bulk modulus (Ge and Stover, 2000). We assume a bulk modulus of 6.5 GPa, consistent with bulk moduli estimated for upper plate wedge sediments offshore Costa Rica (Gettemy and Tobin, 2003). Note that observed Pf change related to a similar-sized SSE offshore Costa Rica were much larger (~40 kPa) than we predict here. Thus, we suspect that we may be underestimating the influence of the volumetric strain on Pf change, and the actual signals could be even larger than shown here. Note the blue slip model is similar to our best-fitting slip from the March, 2010 SSE.

Determining slip behavior in the near-trough region of the Hikurangi subduction zone with GPS-Acoustic seafloor geodesy

Kelin Wang[1], C. David Chadwell[2], Motoyuki Kido[3]

[1]Pacific Geoscience Centre, Sidney, BC.; [2]Scripps Inst. Oceanography, La Jolla, CA.; [3]Tohoku Univ., Sendai

kwang@nrcan.gc.ca

The northern Hikurangi subduction zone is characterized by seamount subduction, a high degree of megathrust creep, and an abundance of shallow slow slip events (SSEs). Studying the relationship between these characteristics has important global implications, because it helps us understand how geological structures control megathrust slip behavior and size of subduction earthquakes. The main obstacle to this study is the paucity or lack of near-trench observations, and one of the most effective solutions is to make GPS-Acoustic (GPA-A) measurements across the trench.

At northern Hikurangi, GPS-A measurements will directly address two important questions: (1) the degree of megathrust locking near the trench and (2) the updip extent of SSEs. These two questions are closely related, because creep or "partial locking" can be an integrated effect of many SSEs of various sizes and timescales, including those too small or too slow to be detected by the present geodetic network. Currently, both questions are very poorly answered. Inversion of land-based GPS data can yield the scenario of a largely creeping megathrust with an updip narrow segment mostly locked (Wallace and Beavan, 2010) (Fig. 1, left), but the data could also allow a model of significant creep all the way to the trench because of their lack of near-trench resolution. Likewise, offshore SSEs could extend to the trench, but their updip extent cannot be reliably defined by the land-based GPS network. It has been argued that subducting seamounts and similar geometrical irregularities tend to cause creep and many small earthquakes (Wang and Bilek, 2011). At northern Hikurangi, the roughness of the subducting seafloor carrying a number of seamounts (Bell et al., 2010) makes creeping to the trench a possible scenario, with SSEs of different sizes and timescales being a likely creep mechanism.

The GPS-A approach (Fig. 1, right) has successfully captured interseismic, co-seismic and post-seismic motions along the submerged slopes of subduction zones (Gagnon et al., 2005; Kido et al., 2011). The resolution of the horizontal position approaches a centimeter or better after collecting data over a few days. To date, data have been collected primarily from ships that visit infrequently, limiting the temporal resolution. Recently, GPS-A has been adapted to moored buoys providing more continuous measurements. Potentially, GPS-A on wave-powered vehicles (e.g., Wave Glider) can replace ships for campaign measurements and even operate persistently above a seafloor site, mimicking a moored buoy. Additionally, a new type of benchmark is under development that would remain permanently on seafloor while instruments could be removed and replaced without causing an unknown offset in the time series of position. GPS-A geodetic measurements have excellent long-term stability and complement vertical deformation measurements with pressure gauges, which suffer from long-term drift.

For northern Hikurangi, we suggest deploying GPS-A sites along two trench-normal transects (Fig. 1, left) to address the two scientific questions discussed above. Top priority is given to question 1 regarding near-trench creep vs. locking. Scientifically, this question is the most critical and urgent for understanding the slip behavior and seismogenic potential of Hikurangi megathrust, and it cannot be addressed with other techniques such as seafloor pressure gauges and borehole monitoring. It also presents less operational and financial challenges than does the second question.

Primary (red squares in Fig. 1 left): Determining near-trench creep/locking with campaign-style visits using a ship or remotely-controlled, wave powered vehicle, such as a Wave Glider. The northern transect (line 05CM-04 of Bell et al., 2010) is located in an along-strike transition zone from creep to locking as defined using land-based GPS alone (Fig. 1 left). One of the three proposed sites is on the incoming plate (Fig. 2). Motion between the incoming-plate site and the overriding-plate sites over a time frame of a few years directly defines the state of near-trench locking or rate of creep. Relative motion between the two overriding-plate sites provides a rough estimate of the strain rate of the accretionary prism and facilitates comparison with other observations. The most landward site also serves to minimize the gap between land and seafloor measurements. The southern transect (line 05CM-01 of Bell et al., 2010) is located in an area where interpretation of land-based GPS indicates full locking to the trench (Fig. 1 left). We propose to have a minimum of two sites along this transect (Fig. 3). Having two transects allows the detection of along-strike changes in the monitored creep and locking behavior.

Secondary (red and yellow squares in Fig. 1 left): Near-field detection of SSE transients with continuous measurements using either a moored-buoy or Wave Glider. It involves (1) densification of the two transects by adding two more sites to each (yellow squares in Fig. 1 left) and (2) using moored-buoys for some of the sites. Most of the sites are directly above the plate interface that is updip of the SSE events defined with sub-aerial GPS and can readily detect seafloor displacements to determine whether the SSEs extend to the trench.

References:

Bell, R., Sutherland, R., Barker, D. H. N., Henrys, S., Bannister, S., Wallace, L., and Beavan, J., 2010, Seismic reflection character of the Hikurangi subduction interface, New Zealand, in the region of repeated Gisborne slow slip events: Geophysical Journal International, v. 180, no. 1, p. 34-48.

Gagnon, K., Chadwell, C., and Norabuena, E., 2005, Measuring the onset of locking in the Peru-Chile trench with GPS and acoustic measurements: Nature, v. 434, no. 7030, p. 205-208.

Kido, M., Osada, Y., Fujimoto, H., Hino, R., and Ito, Y., 2011, Trench-normal variation in observed seafloor displacements associated with the 2011 Tohoku-Oki earthquake: Geophysical Research Letters, v. 38, no. 24.

Wallace, L. M., and Beavan, J., 2010, Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand: Journal of Geophysical Research, v. 115, no. B12, p. 0-Citation B12402.

Wang, K., and Bilek, S. L. , 2011, Do subducting seamounts generate or stop large earthquakes? Geology, v. 39, 819–822.

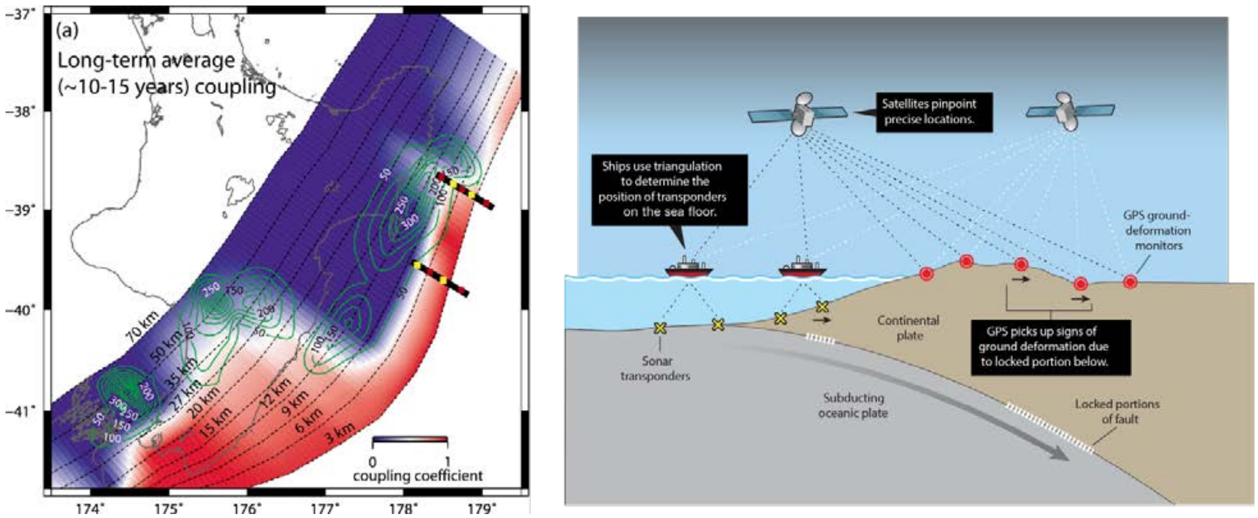


Figure 1. [Left] Near-trench locking of megathrust based on inversion of land-based data [Wallace and Beavan, 2010]. Seafloor geodetic transects (solid red squares) can directly constrain the state of locking or creep. [Right] The GPS-Acoustic technique [Newman, 2011]. While ships have been the main platform for GPS-A, moored buoys and small, remotely operated vehicles are beginning to replace ships. This will lower costs and increase access.

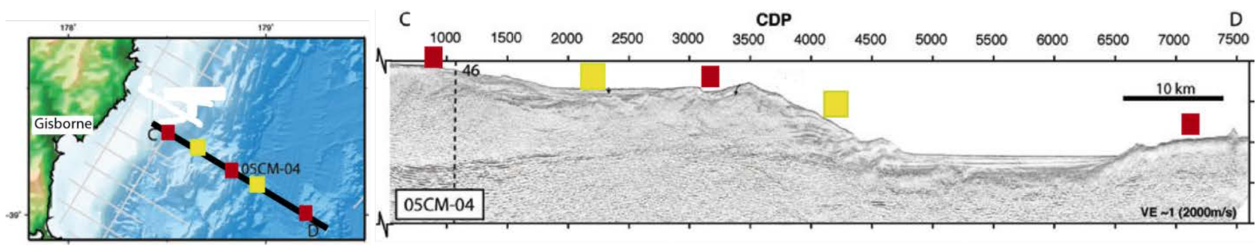


Figure 2. Proposed location of GPS-Acoustic seafloor sites of the northern transect along reflection profile offshore of Gisborne (Bell et al., 2010). Left shows map view, right shows profile. Red and yellow indicate primary and secondary sites, respectively, as explained in the text.

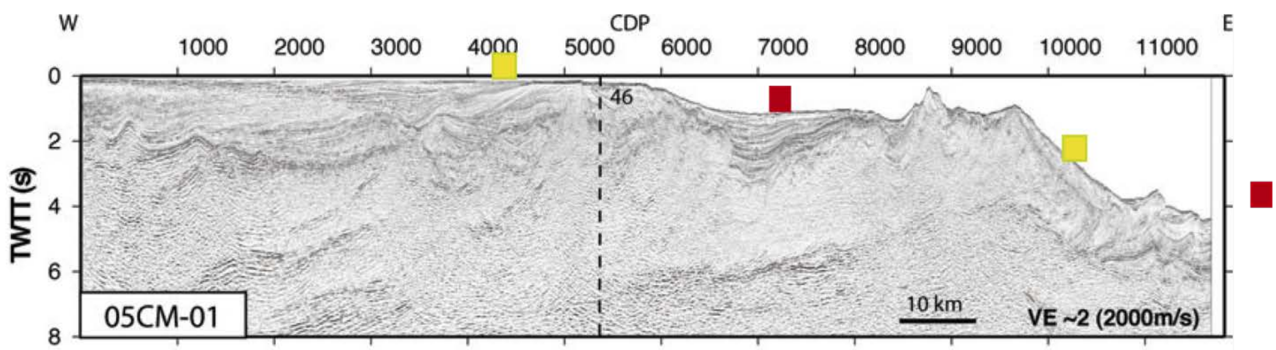


Figure 3. Proposed location of GPS-Acoustic sites of the southern transect along seismic reflection profile in the Hawke Bay area (Bell et al., 2010). See Fig. 1 left for transect location. Red and yellow indicate primary and secondary sites, respectively, as explained in the text.

Lateral Migration of Subduction Systems: Progression of the Hikurangi Margin Southwestward Through Increased Plate Coupling to Continuum Compression

Philip E. Wannamaker[1], T. Grant Caldwell[2] and Yasuo Ogawa[3]

[1]University of Utah/EGI; [2]New Zealand Geological and Nuclear Sciences; [3]Tokyo Institute of Technology

pewanna@egi.utah.edu

In newly-forming subduction zones on Earth, plates are torn apart and deep fluid generation and chemical element movement set forth, prior to the massive fluid release and arc magmatism of mature subduction. Such zones allow us to test how major fault zone geometries evolve from shallow levels to deep in the lithosphere as well as reveal the role of fluids in promoting rock failure by several mechanisms. Few subduction zones exhibit purely head-on meeting of the plates, but involve a strong proportion of strike-slip movement. Seriously damaging earthquakes in the deep subduction plane itself are well known (Alaska; Chile; Tohoku; Hawkes Bay; Pahiatua), but also occur on related continental strike-slip and thrust earthquakes (San Andreas; Anatolia; Chi-Chi; Murchison; Darfield).

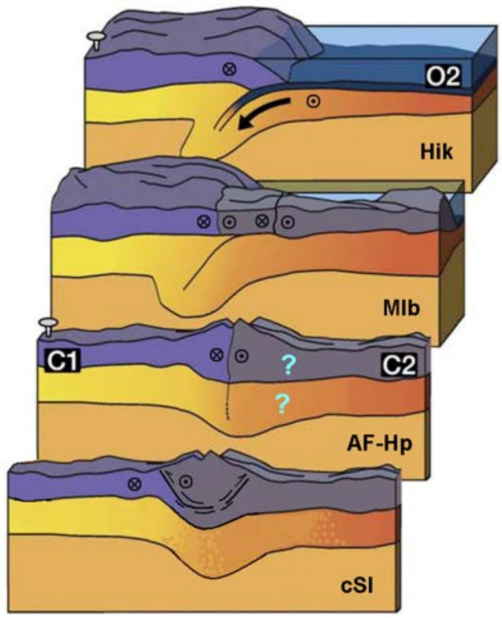
Evolving subduction processes are extant over the transpressional regime of New Zealand (Fig. 1)[1,2]. Dextral oblique subduction into the Hikurangi trench with relatively weak plate coupling gives way southwestward to the Marlborough (MLB) district of the northern South Island (SI). Here, subduction has migrated southwestward with tighter plate coupling, so that trench parallel deformation in the upper plate is taken up in a broad strike-slip fault system. The MLB region has received much study with geodetic[3], passive seismic[4], MT[5], structural[6] and geochemical[7] methods. Much less understood is the earliest subduction development further SW as the MLB faults converge to the more singular Alpine fault (AF) and the deep continuum compression of the central SI[8]. Obvious Benioff zone seismicity tapers to near zero (at depth) near Culverden, but uppermost mantle eq's further SW may indicate earlier subducted, possibly less hydrated, thick oceanic crust of the Hikurangi Plateau[9].

Convergence in the central SI is taken up primarily through ductile flow from the deep crust upward to the AF where embrittlement occurs, with some backthrusting[8]. Prograde metamorphism at depth in the root generates fluids which mobilize toward the AF and geophysically mark the main zone of ductile shearing[10,11]. The fluids break to the surface ~10 km inboard of the AF as they reach the brittle-ductile (B-D) transition along the inclined (~45^{o}) AF ramp, paralleled by a modern band of mesothermal As-Au occurences[10,12] (Fig. 2). However, this band converges to the intersection of the AF with the youngest MLB strike-slip fault (the Hope), with the intriguing implication that deep crustal, fluidized ductile flow has taken a vertical trajectory. This is but one example where imageable shearing at depth can trace boundaries representing the transition between distinct domains of major deformation. In MLB proper to the NE, MT imaging revealed the evolution of the main strike-slip faults to broad ductile shearing at depth, suggested a link between fluidized fracture meshes and new fault formation, and explained the source of fluids triggering enigmatic high-angle thrust faulting in the Murchison area[5] (Fig. 3). These are all slab-sourced fluids, but at a stage of subduction before the hot, circulating mantle wedge has been set up. Agreement with Q_P and V_P/V_S tomography is close[4].

Comprehending the leading edge of subduction would be advanced if we could trace the evolution of the major zones of deformation from the southern MLB regime into continuum central SI. Especially in the crust, block-bounding shear zones promote the long range interconnection of fluids which then become detectable geophysically[4,5,10,11]. Correspondence between seismicity and fluidization is key, as fluids can migrate from shears to nearby stressed zones and promote failure[5]. Any relation between growth of MLB faulting southward since Pliocene time and the earthquake potential of the North Canterbury region could be clarified if major crustal weaknesses can be mapped. The NZ SI is ideal for testing these parameters due to the compositional uniformity of the Torlesse Fm crustal column. A powerful experiment would combine MT and passive seismology (Fig. 2,3); the former is sensitive to small amounts of interconnected fluids and has bandwidth to follow structures to near surface, while the latter can map crustal root formation and mantle thickening while confirming the larger crustal fluidized zones. This is a key transition for uncovering the respective roles of fluids generated in subduction versus deep crustal metamorphism in lithospheric deformation.

References:

1. Furlong, K. P., Locating the deep extent of the plate boundary along the Alpine Fault zone, New Zealand: implications for patterns of exhumation in the Southern Alps: in *Exhumation associated with continental strike-slip fault systems*, ed. Till, A. B., et al., Geol. Soc. Amer. Spec Paper, **434**, 1-14, 2008.
2. Pysklywec, R. N., S. M. Ellis, and A. R. Gorman, Three-dimensional mantle lithosphere deformation at collisional plate boundaries: a subduction scissor across the South Island of New Zealand: *Earth Planet. Sci. Lett.*, **289**, 334-346, 2010.
3. Wallace, L. M., J. Beavan, R. McCaffrey, K. Berryman, and P. Denys, Balancing the plate motion budget in the South Island, New Zealand, using GPS, geological and seismological data: *Geo. J. Int*., **168**, 332-353, 2007.
4. Eberhart-Phillips, D., and S. Bannister, 3-D imaging of Marlborough, New Zealand, subducted plate and strike-slip fault systems: *Geophys. J. Int..*, **182**, 73-96, 2010.
5. Wannamaker, P. E., T. G. Caldwell, G. R. Jiracek, V. Maris, G. J. Hill, Y. Ogawa, H. M. Bibby, S. L. Bennie, and W. Heise, Fluid and deformation regime of an advancing subduction system at Marlborough, New Zealand: *Nature*, doi:10.1038/nature08204, 733-736, 2009.
6. Nicol, A., and R. Van Dissen, Up-dip partitioning of displacement components on the oblique-slip Clarence fault, New Zealand: *J. Struct. Geol*., **24**, 1521-1535, 2002.
7. Horton, T. W., J. D. Blum, D. Craw, P. O. Koons, and C. P. Chamberlain, Oxygen, carbon, and strontium isotopic constraints on timing and sources of crustal fluids in an active orogen: South Island, New Zealand, New Zealand J. Geol. Geophys., **46**, 457-471, 2003.
8. Davey, F. J., D. Eberhart-Phillips, M. D. Kohler, S. Bannister, G. Caldwell, S. Henrys, M. Scherwath, T. Stern, and H. van Avendonk, Geophysical structure of the Southern Alps orogen, South Island, New Zealand: in *A continental boundary: tectonics at South Island, New Zealand*, ed. Okaya, D., T. Stern, and F. Davey, Geophys. Monogr. Ser., **175**, Amer. Geophys. Union, 47-73, 2007.
9. Reyners, M., The central role of the Hikurangi Plateau in the Cenozoic tectonics of New Zealand and the south-west Pacific: *Earth Planet Sci. Lett.*, **361**, 460-468, 2013.
10. Wannamaker, P. E., G. R. Jiracek, J. A. Stodt, T. G. Caldwell, V. M. Gonzalez, J. D. McKnight, and A. D. Porter, Fluid generation and pathways beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric data: *J. Geophys. Res.*, **107**, ETG 6, 1-22, 2002.
11. Eberhart-Phillips, D., M. Chadwick, and S. Bannister, Three-dimensional attenuation structure of central and southern South Island, New Zealand, from local earthquakes: *J. Geophys. Res.*, **113**, B05308, doi:10.1029/2007JB005359, 2008.
12. Craw, D., and J. R. Campbell, Tectonic and structural setting for active mesothermal gold vein systems, Southern Alps, New Zealand: *J. Struct. Geol.*, **26**, 995-1005, 2004.
13. Eberhart-Phillips, D., and S. Bannister, Imaging P and S Attenuation in the Termination Region of the Hikurangi Subduction Zone, New Zealand, paper presented at Fall Meeting, American Geophysical Union, 2012.



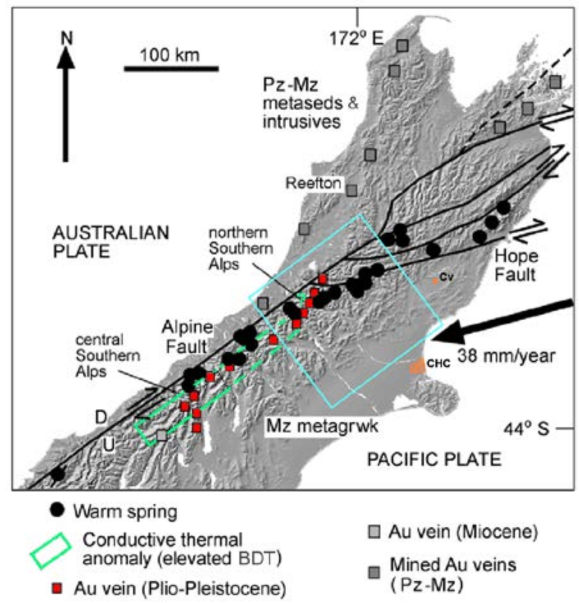


Figure 1. Schematic representation of tectonic transitions from Hikurangi (Hik) subduction, through Marlborough (Mlb) strike-slip, Alpine-Hope (AF-Hp) fault intersection, to central South Island (cSI) compression. Modified from ref. 2.

Figure 2. Central and northern South Island oblique compression and strike-slip setting with warm springs and mesothermal gold vein occurrences. Possible MT/passive seismic project area denoted by blue box. Modified from ref. 12.

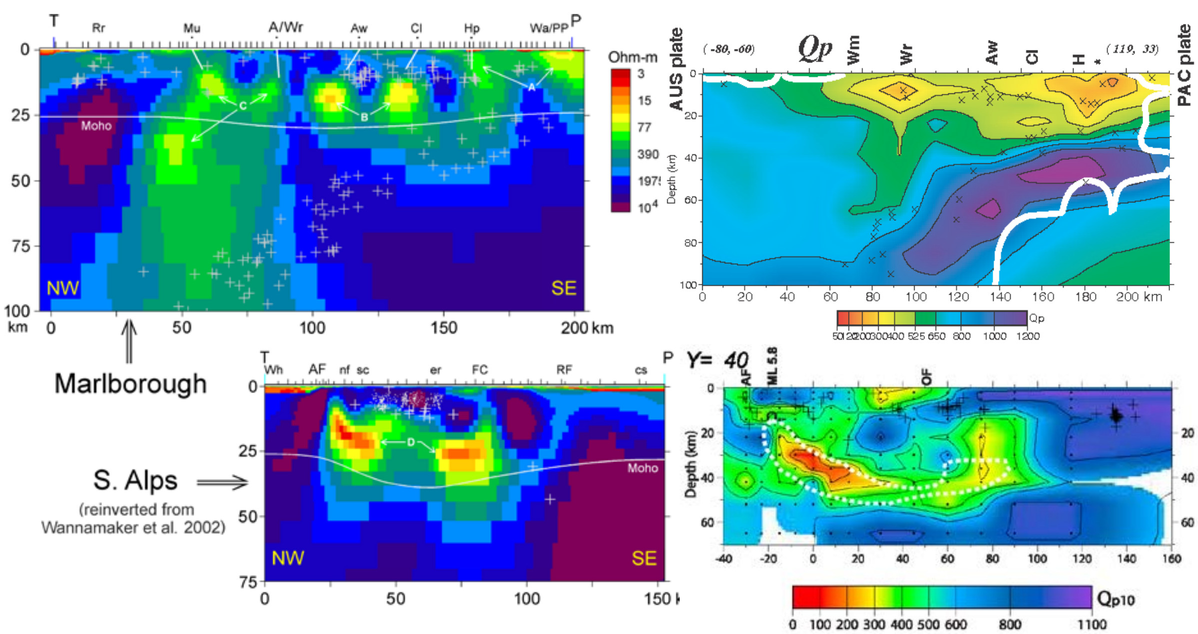


Figure. 3. Left: MT electrical resistivity inversion cross sections through the Marlborough and central Southern Alps regions of New Zealand South Island. White lines in MLB section denote downdip projections of major strike-slip or thrust faults. MLB Benioff zone and crustal seismicity of both sections shown as white pluses. Small white dots on cSI section are Arthurs Pass eq's. Labeled resistivity zones discussed in ref. 5. Right: P-wave attenuation cross-sections through MLB and cSI (ref. 11 and 13). Former is ~40 km NE and latter ~75 km SW of respective resistivity models.