

Geosciences  
2011

NELSON  
27 November -  
1 December



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# Geoscience Society of New Zealand 2011 Conference ABSTRACTS



St Arnaud, Lake Rotoiti,  
Alpine Fault



Mt Owen marble massif

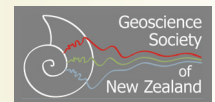


Marlborough Sounds



Awaroa Bay,  
Abel Tasman National Park

NELSON 27 November - 1 December 2011



Abel Tasman National Park





## **GEOSCIENCES 2011**

Annual Conference of the Geoscience Society of New Zealand

Nelson, 27<sup>th</sup> Nov – 1<sup>st</sup> Dec, 2011

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**New approach for the gravimetric quasigeoid modelling using Green's discretized integral equations and Molodensky's types of expressions**

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We develop and apply a new approach for the regional gravimetric quasigeoid modelling. This approach utilises the Green's discretized integral equations for solving the inner-zone contribution to the height anomalies using the local gravity data. The corresponding contribution of the distant zone is computed from the far-zone high-frequency global gravity field using the Molodensky's types of spectral expressions, which are modified for computing the far-zone contributions by means of truncated spherical harmonics. The reference long-wavelength gravity field parameters are generated from the coefficients of the global geopotential models (GGMs). The latest GGM models derived from the GRACE and GOCE satellite observables, gravity data sets from the GNS Science gravity database (onshore) and the altimetry-derived DNSCO8 marine gravity database (offshore), the global elevation data from SRTM30PLUS\_V5.0 and the new 15 × 15 m DTM of New Zealand are used for the numerical realisation. The results of the gravimetric modelling are finally combined with the GPS-levelling data using the final element approach. Numerical examples are given at the computation area of the South Island, covering part of the Southern Alps, with adjacent coastal regions and offshore areas.

**Detrital zircon provenances in accretionary complexes of the New England Orogen, eastern Australia and Eastern Province, New Zealand: a Devonian to Cretaceous memory bank at the Gondwana margin**

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Detrital zircon age patterns in accretionary complexes of the New England Orogen (NEO), Australia and Eastern Province, New Zealand,

record the development of contemporary, Carboniferous to Cretaceous magmatic arcs at the contemporary Gondwanaland margin. Deposition probably commenced in the NEO in Late Devonian time, with quartzose sediments carrying large proportions of recycled zircons. With the subsequent establishment of Carboniferous magmatic arcs, these were overwhelmed by volcanoclastic sediments, with significant pulses at c. 355 Ma, c. 340 Ma, and c. 320 Ma. With exhumation of subjacent plutons, zircons of these ages were recycled into later Carboniferous successions until c. 305 Ma. An Early Permian extensional phase terminated the accretionary wedge, with then only minor subsequent volcanism but extensive granite emplacement c. 290 Ma. In the Middle-Late Permian, the principal magmatic arcs moved outboard, with the development of the New England Orocline. This latter translated the old Carboniferous accretionary and magmatic sectors southwards.

With the old Gondwanaland hinterland now re-exposed (in present-day eastern Queensland), a new accretionary complex commenced with Late Permian quartzose sediments carrying large Paleozoic-Precambrian zircon proportions similar to their Carboniferous counterparts. With progressive emplacement of Late Permian-Triassic magmatic arcs, these were accompanied by major, mainly Triassic, volcanoclastic successions with principal magmatic pulses at c. 290 Ma, c. 250 Ma, and c. 230 Ma. Both quartzose and volcanoclastic sectors were subsequently translated, as suspect terranes, to their present New Zealand position (respectively Torlesse Composite, and Caples Terranes). The Jurassic stages of the New Zealand accretionary complex (Waipapa and Kaweka Terranes) are enigmatic as, despite their major successions, no parent magmatic arc is known in New Zealand or in eastern Australia. It is speculated that this might lie beneath the Lord Howe Rise. In Early Cretaceous time, sedimentary successions (Pahau terrane) were derived principally from the adjacent Median Batholith magmatic arc, with some recycling from older New Zealand terranes.

**A new species of fossil dolphin (Cetacea: Odontoceti) from Paturau coast, Nelson**

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Living or crown dolphins (Delphinoidea) embrace 3 speciose and ecologically diverse families: oceanic dolphins (Delphinidae), porpoises (Phocoenidae), and belugas and narwhals (Monodontidae). Collectively, these animals range through all oceans and even into rivers. Delphinoids have a good fossil record from the Late Miocene, and their molecular phylogenetic relationships are well-established. Paradoxically, many questions remain about their phylogeny, perhaps because of the speed of evolutionary radiation and major structural changes involved. To help address such issues, we are pursuing New Zealand studies on the extinct family Kentriodontidae, a group possibly at the root of the delphinoid radiation. A new species of Early Miocene archaic dolphin fits the concept of a kentriodontid grade: the unique specimen, OU22066 (Kaipuke Siltstone, Otaian-Altonian) is from a coastal outcrop near Sandhills Creek, south of Paturau River, Northwest Nelson. The dolphin had multiple simple conical teeth in a broad-based rostrum. Skull dimensions (320 mm long, 180 mm wide) suggest a body length of 2 m. In spite of general similarities with some previously-described kentriodontids, there are noteworthy differences in the narial region, braincase and skull base. If the Kentriodontidae is rediagnosed as a clade, then OU22066 is expected to belong elsewhere. Finally, kentriodontids in the strict sense from South Canterbury and North Otago will help to clarify family concepts, thus elucidating the early history of delphinoids.

**Style of magma-water interaction during the eruption of the Maungataketake volcano, Auckland Volcanic Field, New Zealand: insights from grain component characterisation**

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Maungataketake volcano (Elletts Mountain) is a basaltic volcano composed of a basal tephra ring from early phreatomagmatic eruptions, covered by scoria fall deposits and a lava crater infill that spilled out in a few places. The total volume of the volcanic products is c. 11 million m<sup>3</sup>. The age estimates for Maungataketake volcano ranges between 40 to 200 ka. This work focuses on the nature of the pyroclastic fragments within the base surge deposits, to interpret the dynamics of phreatomagmatic explosions and magma interaction with the host rocks of this area. Detailed mapping of base surge deposits was carried out to characterise the lateral and vertical facies changes. Samples were sieved, and component and grain specific analyses were performed using light microscopy and SEM. Juvenile pyroclasts are vesicular, palagonitised, and often ash-coated, suggesting highly efficient phreatomagmatic fragmentation and pulverisation of the magma and host sediments. Using Energy-dispersive X-ray Spectroscopy analyses, an average of juvenile to non-juvenile ratio of 1:5 was calculated. This indicates a very effective shallow excavation below this crater, approaching maar-like efficiencies. Total preserved volumes of pyroclastic deposits were estimated from Digital Elevation Models, and when combined with the measured juvenile to non-juvenile ratios, indicate c. 1.1 million m<sup>3</sup> of juvenile material was contained in the 5.6 million m<sup>3</sup> tephra ring. The lack of proximal pyroclastic breccias and the fine grained,

pyroclastic deposits rich in accidental lithics indicate that the magma-water interaction took place in fine-grained unconsolidated or weakly consolidated sediment, down to several hundred metres below the syn-eruptive surface. This onset of eruption could be regarded as typical for Auckland in many areas where magma rises through thick accumulations of recent and Tertiary sediments, with fragmentation occurring well below the level of the water table.

### **Permian-Triassic boundary sequences in New Zealand**

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The Permian-Triassic boundary holds a certain fascination and the actual event or process that caused it remains obscure. It must have been something profound, something catastrophic that impacted globally. It is commonly claimed that more than 90% of all life was extinguished 252 million years ago, marking the closure of the Paleozoic Era and the onset of the Mesozoic Era. The cause may have been terrestrial, related to a massive climate-related chemical perturbation affecting the atmosphere, hydrosphere, and hence most life. Stable isotope studies tend to support this idea.

In New Zealand we have several Permian-Triassic sedimentary successions that provide a potential record across the boundary interval. Two in particular have been described: (i) within Little Ben Sandstone (Maitai Group) rocks

exposed in the Nelson area (Dun Mountain – Maitai Terrane), and (ii) within Waipapa Group rocks exposed on Arrow rocks, Whangaroa Bay, Northland (Waipapa Terrane).

Theoretically, Permian-Triassic boundary records may exist within the Murihiku, Caples and Rakaia terranes (Eastern Province) and even the Takaka Terrane (Western Province). However, no suitable or convincing boundary sequences have been discovered thus far, and it is probable that the Caples Terrane is entirely Triassic in age.

Within the past few years, two new fossil-bearing sequences have been discovered within Waipapa Terrane rocks exposed on Waiheke and Motutapu islands in the Hauraki Gulf near Auckland. These sequences are deep-marine oceanic associations of coloured siliceous argillite, chert, tuff, and meta-basalt (pillow lava). Conodont and radiolarian fossils have established age control and biostratigraphic zonation. Coupled with stable isotope studies (C, O, S), the fossils provide important insight into oceanic conditions prevailing within the Panthalassa Ocean.

No other marine Permian-Triassic boundary records are known from the Southern Hemisphere. In this regard, New Zealand has much to offer and has become the focus of some international attention for Permian-Triassic boundary studies.

### **Compaction not crystallisation: Generating evolved magma compositions in shallow magma chambers**

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Conventionally, magma chambers are assumed to be reservoirs of molten rock occupying a crustal void, and fractional crystallisation dominates their geochemical evolution. Recent numerical modelling has concluded that very high (c. 0.01 km<sup>3</sup>/yr) magma fluxes are required to maintain a permanently molten magma chamber. However, the geochronologically-estimated long term average magma flux for plutons is 0.0001 km<sup>3</sup>/yr. This paper

proposes an alternative model reconciling this discrepancy. Compaction and melt migration operate within magma chambers, wherein the magma chamber spends most of its lifetime as an agglomerate of crystals with thermally-buoyant liquid present within the pore spaces. Furthermore, fractional crystallisation does occur, but the crystals that settle out still play an important role in the generation of evolved magmas via compaction, which forces out the buoyant pore-space fluids. Numerical modelling, featuring the build-up of plutons by under-accreting sills over different magma flux and melt viscosity values, indicates that compaction and melt migration (mush dynamics), not fractional crystallisation (slurry dynamics), dominates the geochemical evolution of shallow magma chambers. This model produces simulated plutons with significant proportions of eruptible melt at geochronologically-estimated long term average magma fluxes. Compaction and melt migration are affected by changing melt viscosity values; higher viscosities impede crystal settling, and thus impede the subsequent compaction of the matrix and the upward migration of thermally-buoyant melt. The lack of extrusive volcanism associated with felsic plutons is due to their high viscosities which hinder crystal settling, compaction, and melt migration. Compaction and melt migration are inoperable at very high magma fluxes, due to the high average temperature of the pluton not permitting significant amounts of initial crystallisation – and hence, crystal settling and compaction – to occur.

### **GeoNet's response to the Canterbury Earthquakes**

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and the GeoNet team**

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Subsequent to the multiple damaging earthquakes that have affected Canterbury since the 4<sup>th</sup> September 2010, GeoNet – through GNS Science – has deployed multiple temporary networks of broadband and short period seismographs, accelerometers, and GPS units to monitor ground motions and building responses. These supplementary

instruments were deployed to collect additional data to enhance the records from the permanent GeoNet network instruments. Many of these temporary instruments have been operating since shortly after the initial Darfield earthquake in September 2010. The permanent GeoNet network around Canterbury has the densest arrays of accelerometer in the country, meaning that the earthquakes and aftershock sequences are one of the best recorded in the world.

These are the first critically damaging earthquakes to occur in New Zealand in the internet age, as such GeoNet was able to disseminate a great deal of data to the public and officials using various means. Public interest in the GeoNet website ([www.geonet.org.nz](http://www.geonet.org.nz)) increased exponentially following the earthquakes. This increased interest in the website prompted GeoNet to offer wide-ranging features, as well as utilising several social media platforms. The GeoNet website has generated as much as 64 million hits in a single day. Since the initial September earthquake the amount and variety of information has grown to include aftershock forecasting and graphical features such as earthquake timelines.

### **Surface heat flow and its impact on the ground coupled heat pump environment**

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Ground coupled heat pumps (GCHPs) are efficient and effective 'green' forms of space heating. Although they are rare in New Zealand, they have the potential to become an attractive alternative to other, more conventional, heating systems. To enable more effective installation of these systems an investigation into the thermal environment that the systems operate in, particularly in Otago, is needed to provide information specific to New Zealand locations to GCHP installers and system designers. The quantity of heat supplied to vertically orientated GCHPs is governed primarily by: heat supplied to the base of the crust, heat generated within the crust, thermal conductivity of the bedrock and sediments, and near surface modulation of this heat by ground water convection.



At present there is little thermal conductivity data on the bedrock of Otago. Additionally, the degree of foliation within the rock and prevalence of sheet silicates will possibly result in high thermal anisotropy. Quantifying the thermal conductivity, both parallel and perpendicular to foliation, requires a highly repeatable method. The thermal conductivity probe dimensions (3 mm x 100 mm) poses a number of challenges to making repeatable measurements. These challenges include fracturing while attempting to slab the rock, rapid blunting of drill bits, setting up a drill press to allow drilling wet and ensuring the drill hole is straight to avoid damage to the probe.

Results are presented from representative samples of the Otago Schist textural zones collected from throughout Otago.

#### **Experimental results on the compaction of pumiceous lava domes**

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Lava domes present a serious threat to nearby communities as they are known to produce devastating pyroclastic flows as a product of instability during growth. It is therefore important to understand the key processes of dome formation to predict the dangers of such an event.

The stability of a dome is regulated by pore pressure within a vesicle network, which is itself controlled by permeability and amount of connectivity. This permeability will evolve throughout the eruption of the dome, as vesicles collapse, grow, or fractures form and heal. Here, we present experimental results of porosity and permeability evolution during compaction of rhyolitic, pumiceous dome material from Ngongotaha (c. 200 ka, <5% crystallinity, c.

60% vesicles) and Tarawera (1314 AD, 25–50% crystallinity, 60–35% vesicularity). This study tests the hypothesis that lava domes form from foam collapse by comparing properties of the experimentally compacted carapace pumice to denser material seen in the exposed cores of Tarawera and Ngongotaha.

Cylindrical samples, with flow banding perpendicular to the long axis, were deformed under an axial stress of 2.8 MPa at 800–900 °C, up a total axial strain of 50%. The porosity and permeability of the samples were characterized at strain increments of 10%. The samples exhibit strain hardening during compaction. A rapid reduction in permeability perpendicular to maximum stress orientation occurs during the initial stage of compression and continues to decrease with increasing strain and densification of the lava. The samples fail at lower temperatures (0–750 °C), suggesting that micro-fractures heal at higher temperatures (800+ °C) and enable bubble collapse. Development of permeability of each lava differs as the crystallinity affects the compaction process. The development of textures and microstructures is characterised using petrographic analysis and neutron computed tomography. The findings from the study are then put into the context of lava dome growth at Tarawera and Ngongotaha.

#### **Seismic stratigraphy of the Reinga and Northland basins, NW New Zealand: tectonic and petroleum implications**

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The Reinga Basin is an extension to the northwest of the Northland Basin and occupies a northwest-southeast trending bathymetric depression between the West Norfolk and Reinga Ridges. Analysis of a large multichannel 2-D seismic-reflection dataset is tied to previous work in the Northland, Deep-water Taranaki, and Taranaki basins to constrain seismic stratigraphic units using the seismic characters of unconformities formed during successive deformational events in the region.

Five phases are identified in the evolution of the Reinga Basin:

- The first phase (phase 1) involved extension that led to creation of major northwest-trending structures by normal faulting. The exact age of the sediments filling the grabens is unknown. The age of this event is discussed.
- The region subsided passively during phase 2, perhaps from the Late Cretaceous until Late Eocene time.
- Late Eocene compression (phase 3) led to strong folding and inversion of previous structures in the northwest part of the Reinga Basin. This phase has not been evidenced in the offshore part of the Northland Basin where seismic units are not significantly deformed.
- Oligocene to Early Miocene regional subsidence (phase 4) resulted in flooding of structures created during phase 3. This subsidence phase is contemporaneous with the emplacement of the Northland Allochthon between 23 and 20 Ma and with the activity of the Northland Volcanic Arc between 23 and 16 Ma in the Northland Peninsula.
- Uplift of the Wanganella Ridge, in the northwest part of the Reinga Basin, occurred at the end of Early Miocene (phase 5). Phases 4 and 5 occurred when the Three Kings Ridge was moving along the Reinga margin as the Norfolk and South Fiji basins opened and the Kermadec Trench was rolling back consuming the Northland trench.

The Reinga Basin has never been drilled, so that the age of the seismic units and corresponding depositional events are mainly deduced from Northland and Taranaki basin stratigraphy. Regional constraints are presented and potential petroleum systems are discussed.

### **Rock mass characterization and numerical modeling of coastal cliff failures in weak rocks in the Auckland-Region**

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Parts of the coastal area of Auckland, New Zealand, are constructed on weak flysch rocks from the Waitemata Group. Several failures have recently occurred along these cliffs and a review of the airborne LiDAR data of the study area suggests the presence of a few large old failures with unknown state of activity. This paper presents detailed mapping, material testing and numerical modeling results regarding the stability of the three recent slope failures. Traditional discontinuity surveys were conducted at each site and augmented by terrestrial photogrammetry data at two of the sites. Kinematic analyses were conducted at each site to assess the potential for simple structurally controlled failures. Small-scale toppling was feasible or marginally feasible at each site along exfoliation or unloading joints.

This study also reviewed previously published strength parameters of the Waitemata Group and combined them with new field observations of the rock mass quality using the Geological Strength Index (GSI) to derive equivalent rock mass strength parameters, which allows the construction of limit equilibrium slope stability models. These models have been used to investigate the sensitivity of the stability coastal cliffs around the Auckland region to various factors such as rock mass strength, presence/ orientation/strength along discontinuities and pore pressure. It was found that the rock mass strength properties of the Waitemata Group did not in itself lead to unstable cliff conditions in the Auckland region, but rather that a combination of elevated pore water pressure, anisotropy strength direction due to discontinuities, and cliff top loading was needed to lead to slope failure.

**Lithospheric responses to continental collision: Insight from numerical models  
- Withdrawn**

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The lithospheric response to continental collision may progress in different ways, the cause of which is still poorly understood. Here, we investigate the conditions leading to different responses to continental collision using numerical models. Our numerical results indicate that the lithospheric response to collision is mainly dominated by three types of processes: (i) subduction polarity reversal, (ii) delamination and back-stepping, and (iii) continued subduction. The switches between these processes are controlled by the competition between three (potential) weakness zones: (i) the mantle wedge, (ii) the lower continental crust, and (iii) the plate interface.

Subduction polarity reversal occurs if the mantle wedge is the weakest zone in the system. In arc-continent collision, this happens only if the viscosity of the mantle wedge is at least one order of magnitude lower than the average viscosity of the lithosphere. In continent-continent collision, one additional condition needs to be satisfied for subduction polarity reversal to occur: the ratio of the viscosity of the lower continental crust to the viscosity of the upper lithospheric mantle must be higher than 0.006. Subduction polarity reversal occurs as a result of failure of the overriding plate along the arc/back-arc boundary. Several factors affect the time of lithospheric failure including the convergence rate, the sinking velocity of the detached slab and strength of the mantle wedge, arc and back-arc. The response to collision is delamination and back-stepping if the lower continental crust is the weakest area in the system, and is continued as subduction if the plate interface is the weakest zone.

**Compressional wave anisotropy in the Haast Schist**

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The Haast Schist makes up a large proportion of the South Island crust. This study attempts to quantify how compressional wave velocities vary with respect to the foliation of these rocks, and what causes the variation. Seismic surveys are a powerful tool for examining deformation of the crust and the interpretation of survey data requires such an understanding of crustal geophysical properties.

The velocities and anisotropy of compressional waves propagating through the schist were measured or estimated at outcrop, hand specimen and thin section scale. Velocities were measured parallel to three orthogonal axes (X, Y, and Z) where possible. The X and Y axes were orthogonal to each other in the plane of foliation, with the X axis parallel to any lineation present in the sample. The Z axis was perpendicular to the foliation. If no lineation was present, then X and Y were arbitrarily placed in the foliation plane.

Measured seismic velocities were between 1000 and 4500 m/s. Core logger velocities were measured between 1000 and 6500 m/s. Velocities estimated from thin section were between 5500 and 7000 m/s. Most results from all length scales showed a relationship of  $X > Y > Z$  velocities. The differences between orthogonal velocities within each sample varied depending on the measurement method. Anisotropy ( $k$ ) in these velocities was: 40-100% for the seismic survey, 102-166% for the core logger, and 13-22% for thin section estimates.

The principle control on velocities is the degree of weathering of the rock. Sub-parallel joints and quartz veins may also affect velocities. Anisotropy is principally due to both lattice preferred orientation of intrinsically anisotropic minerals parallel to foliation, and the presence of foliation parallel cracks caused by weathering. Disruption of the foliation or presence of multiple fabrics reduces anisotropy.

**Fossil leaves provide evidence of a diverse  
swamp forest flora from a Late Oligocene  
/ Early Miocene site in the Gore Lignite  
Measures**

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Well preserved leaves from a Late Oligocene-Early Miocene leaf bed within Newvale Mine, Gore Lignite Measures, Southland, have provided evidence of a diverse oligotrophic swamp forest flora with abundant sclerophyllous elements. The leaves fell or were blown into pools of water on the surface of the swamp peat, in places forming dense leaf mats. These pools were fed by rainwater only, providing a highly acidic depositional environment that inhibited the growth of saprophytic fungi allowing the leaf cuticles to be exceptionally well preserved. So far, individual leaves/foilage of eight species of conifers have been recognised. They include numerous leaves of *Agathis* (Araucariaceae), and foliage of six genera of Podocarpaceae comprising two species of *Dacrydium* and one species each of *Dacrycarpus*, *Halocarpus*, *\*Microcachrys*, *Phyllocladus*, and *Podocarpus*. The angiosperms growing amongst the conifers comprised at least six species of Proteaceae including a species of *\*Banksia*, probable *\*Beauprea*, and two species placed in tribe Persoonieae. Other leaves include at least one species of Araliaceae, *\*Gymnostoma* (Casuarinaceae), two epacrids (Ericaceae), and a species of *Alectryon* (Sapindaceae). Nothofagaceae is represented by leaves of subgenus *\*Brassospora* now known only from New Caledonia and New Guinea. One of the most abundant angiosperm leaves probably represents *\*Callicoma* (Cunoniaceae), a small tree or shrub that now grows near waterways in eastern Australia. Strap-like leaves of at least two monocots, *Cordyline* and *Dianella/Phormium* are also present, those of *Cordyline* forming extensive mats. The Newvale leafbeds include the only macrofossil record of the endemic New Zealand genus, *Halocarpus*, and the oldest

macrofossil and only extra-Australian records of the Tasmanian endemic *Microcachrys*, and the iconic Australian flowering plant, *Banksia*. This would be the first record of *Callicoma* from New Zealand.

\*taxa no longer present in the New Zealand region.

**Anatomy of a subduction margin in a  
region of shallow slow slip, Hikurangi  
margin: Depth-converted multichannel  
seismic profile 05CM-04**

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We present an interpreted depth image of 05CM-04, a high fold (960 channel, 12 km long streamer), deep penetration, multichannel seismic (MCS) reflection profile. The profile runs from the shelf to outboard of the trench across the Hikurangi margin north of Gisborne, in a region of repeating, shallow slow-slip events (SSE's) on the subduction interface. Here, the interface is shallowest within the Gisborne SSE region, and interface reflection amplitudes suggest a possible role for fluids in facilitating SSE's. Consequently 05CM-04 is the centrepiece for drilling targets identified in an IODP proposal investigating SSE's, submitted in October 2011, and is the focus for new MCS and multibeam surveying (RV *Tangaroa*, October 2011) that will help refine and characterise drill site locations.

Two principal aspects of 05CM-04 benefit from observations in depth rather than time. First, the geometry of thrusts and possible out-of-sequence splays associated with seamount subduction are better resolved. This is important for understanding the roles, relative timing, and displacements of the various

faults, and how they may accommodate plate convergence near the trench. Second, the overall geometry of the subduction interface as it dips beneath the Hikurangi margin, and the geometrical relationships with faults splaying from it, are important for understanding wedge mechanics.

A wealth of active source, deep seismic data has now been acquired along the subduction plate boundary. 05CM (Ministry of Economic Development, MED) provides regional 2-D, deep penetration MCS data coverage of the central and northern Hikurangi margin, imaging the upper plate and subduction interface. It is complemented by more recent MED MCS reflection surveys and wide-angle onshore-offshore surveys to the north and south (e.g., RAU07, MANGO, EC005, PEG09, SAHKE). This comprehensive seismic dataset along the entire offshore Hikurangi margin allows characterisation of along-strike changes in the upper plate structure and subduction interface, which may be related to changing subduction parameters and behaviour.

**Fault characteristics and recent Holocene activity on the Wellington Fault, Kaiwharawhara, Wellington Harbour**

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The Wellington Fault is one of the major dextral strike-slip faults in central New Zealand, extending from Cook Strait through Wellington City and offshore along the eastern edge of Wellington Harbour, before continuing northwards into the Hutt Valley and beyond into the southern North Island. The offshore section of the fault off Kaiwharawhara Stream in Wellington Harbour has been re-surveyed recently using high-resolution geophysical techniques by NIWA (multi-beam echosounder) and Applied Acoustics (boomer sub-bottom profiling) to better define the faulting characteristics and recent earthquake history of this active fault. The multi-beam data indicates

very subtle surface expression of the Wellington Fault, while sub-bottom profiling sections indicate that there is about 11 m of seismically transparent marine mud, overlying a probably non-marine, highly reflective, layered, probably gravelly sequence in the Kaiwharawhara area. There is also a significant amount of near-surface gas masking imaged elsewhere in this area.

In addition, in January 2011, NIWA participated in a sonic drilling exercise, undertaken by FMG and Fugro GeoServices, to obtain a new 13 m long sediment core from the hanging wall of the fault that was augmented by subsequent gravity cores acquired by RV Tangaroa. The core data confirmed the seismic interpretations, with the upper 3 m of cored section comprising highly fluidised mud, with silty mud throughout most of the length of the core before a basal c. 1 m section of compacted gravels and clays was encountered. These data will be used to better constrain the recent (<10 000 year) fault activity on the Wellington Fault that will help elucidate the earthquake hazard presented to Wellington City and the lower North Island.

**Submarine faulting beneath Pegasus Bay, offshore Christchurch**

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We report results of a seismic reflection study of faulting in Pegasus Bay, conducted after the February 22<sup>nd</sup> M6.3 Port Hills aftershock. The objectives of this project were to contribute to understanding the wider crustal faulting and geological context of the Canterbury 2010-2011 earthquake sequence, and to determine whether or not active submarine faults capable of producing future large magnitude (M>6) earthquakes exist nearby, offshore. The results indicate that Cretaceous and Paleogene (>35 Ma) crustal faults are widely distributed throughout Pegasus Bay, are mainly south-dipping, up to 70 km in length, trend mainly east-west, and have vertical displacements of up to 1.5 km. Part of this ancient fault system

has been reactivated and partially overprinted by presently active deformation in North Canterbury. This deformation extends up to 30 km offshore beneath Pegasus Bay, and includes at least 11 major faults with evidence of renewed activity mainly in the last 1 Ma. The Quaternary faulting is concentrated beneath the northern part of the bay, but newly recognised, very weak deformation appears to extend southward to the northern coast of Banks Peninsula. Most of the active faults offshore are reactivated components of the older fault system. The major faults range in length from c. 10 to 38 km, and are inferred to be capable of producing earthquakes of magnitude M6.4 to M7.2. Estimated vertical rates of faulting are very low in the north of the bay (c. 0.05-0.28 mm/yr), and extremely low (<0.01-0.07 mm/yr) in the south of the bay. These rates indicate that earthquakes are likely to have very long recurrence intervals, of the order of 10,000 years in the north, to perhaps several tens of thousands of years in the south. We will discuss the spatial relationships between the faults and the evolving aftershock sequence.

### **Global temperature over human, ice age and geological time-scales**

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Earth's average annual temperature has been estimated with a precision of c. 0.1°C from direct measurements on land and at sea since 1860, and in the last two decades from satellite data. This has allowed us to characterise climate for the late Holocene as well as the shift in the last few decades in response to greenhouse gas emissions and land use change. General circulation models calibrated against this database are now being used to project future global temperature as radiative forcing increases through human activity. However projected global average temperatures over decades to centuries far exceed those of recent human history or even the last million years, judging from global records based on geochemical and paleontological proxies going back two millennia, and one site-specific but continuous ice core record with centennial-

millennial resolution that extends back over the 8 interglacial-glacial cycles of the last 850,000 years. Precision for average global surface temperature for the Holocene interglacial and for the Last Glacial Maximum 20,000 years ago and c. 6 °C cooler is considered to be 1-2 °C.

The most recent time in which Earth's climate was consistently warmer was the Pliocene 2 to 5 Ma ago, during which glacial periods were substantially warmer (by c. 4 °C), interglacial periods somewhat warmer (by c. 2 °C) for an overall value of c. 3 °C. This knowledge comes largely from the PRISM project with sea surface temperature estimates from several hundred sea floor cores, with context provided by paleoCO<sub>2</sub> estimates in the range 350 to 400 ppm. The precision for average global warm interglacial temperature based on peaks in the time range 3.0 to 3.3 Ma is estimated at 1-2 °C. The time resolution and spatial coverage of the data is orders of magnitude lower than that for modern global temperature, but the data are nevertheless seen as a significant test and constraint for Pliocene paleoclimate modelling, and provide realistic estimates of both global and regional temperature values and patterns for interglacial (and glacial) episodes in this time period.

Older time periods are more difficult to characterise because:

Geochemical and paleontological proxies are subject to more uncertainty

- An increasingly different paleogeography needs to be used as a boundary condition in Earth System modelling
- A spatially adequate database for each time period is constrained by what is available and accessible both on land and on the ocean floor.

Thus far most have focussed on key climate transitions (e.g., c. 34 and 14 Ma) and events (e.g., PETM, EECO and MMCO), but these are best appreciated in a context of trends through time. Some thoughts will be offered on strategies for developing realistic estimates of background trends through Cenozoic time for both global and regional climate states (including varying zonal gradients) to help understand the warmer world we are now entering.

**Neotectonics and kinematics of the  
Vernon and Awatere Faults,  
Northeast Marlborough**

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This project aims to resolve the kinematics of the dextral-oblique Vernon and Awatere faults, and to understand the Vernon fault earthquake history by integrating offshore and onshore late Quaternary neotectonic and paleoseismic data. Another driver of this project is to resolve the effect dip-slip displacement on the Vernon fault has on subsidence of the adjacent Big Lagoon, a location that potentially holds a subduction earthquake record for the southern Hikurangi Margin. A subduction earthquake signal could be found if the Vernon fault signal is removed from the Big Lagoon tectonic subsidence record in later studies. This study includes detailed neotectonic mapping of the Vernon and seaward Awatere fault traces and structural measurements of fault plane exposures. OSL dating and tephrochronology have been used to date key terrace deposits associated with displaced fluvial landforms, and paleoseismic events have been identified in a trench. Offshore, dip-slip rates and fault dips were measured, and earthquake events identified from high frequency boomer seismic data. Dip-slip rates and fault net-slip vectors suggest that the blocks between the Vernon and Awatere and the Vernon and Cloudy faults are rotating anticlockwise with respect to the surrounding blocks, causing a complex variation of dip-slip motion along-strike. The rotating block model agrees with the strike-slip faulting that is found close to Big Lagoon, therefore the effect of Vernon fault dip-slip on the subsidence of Big Lagoon has been negligible. The earthquake record suggests that the Vernon Fault ruptured at 30-11 ka, 11-9 ka, c. 9 ka and two events <9 ka.

**Development of a sequence stratigraphic  
model for a cool-water carbonate system:  
Oligocene limestones near Oamaru  
as case study**

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Sequence stratigraphic models have traditionally been developed for siliciclastic and tropical carbonate systems. However, the predominance of cool-water carbonate deposits in New Zealand necessitates a different model. Here we illustrate the use of biofacies depth indicators for correlation across local seamount highs for a cool-water carbonate in the Oligocene Oamaru region.

Detailed stratigraphic and thin section data were used to determine the depth below sea level of the deposits. Analysis of individual limestone units shows significant depth variation over short distances leading to rapid lateral facies transitions and poor correlation across the region. Sea-level curves were developed for each locality for better correlation and more sophisticated sea-level histories.

Results show that the lower limestone unit and syn-depositional volcanics form a transgressive systems tract (TST) which is capped by a regression-induced sequence bounding unconformity. Distribution of subaerial and submarine surfaces indicates the basin deepened to the west away from the then palaeo-highs of the volcanoes in the east. This was followed by another TST of greensand to limestone, capped by a second regressive karstic unconformity to correlative submarine erosion surface. Overlying this sequence boundary, deeper facies again predominated.

On sequence boundaries, we see a spectrum from the karst of subaerial exposure through to deeply bored submarine hardground surfaces dependent on their proximity to the palaeo-highs. Deposits at intermediate depths exhibit transgressive surfaces of erosion due to their less consolidated nature and susceptibility to reworking by waves. This illustrates how a sequence boundary within a cool-water carbonate system forms a laterally variable

surface dependent on local topography, degree of seafloor cementation, and the extent of relative sea-level change. A cool-water carbonate sequence stratigraphic model thus incorporates aspects of both the siliciclastic and the tropical carbonate models.

**Geomorphic and sedimentological controls on liquefaction near the Halswell River after the 4 September 2010 Darfield (Canterbury) Earthquake**

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On 4<sup>th</sup> September 2010, a magnitude  $M_w$  7.1 earthquake affected the Canterbury region, resulting in significant damage and disruption within Christchurch city and the surrounding areas. The main cause of damage to critical infrastructure and properties was the liquefaction of recent fluvial deposits which caused lateral spreading and subsidence. The pattern of liquefaction appeared to be concentrated around rivers incised within paleo-flood channels of the Waimakariri River, indicating a relationship exists between depositional setting and the liquefaction potential of sediments. The distribution of liquefaction damage was analysed in the non-urban Tai Tapu and Greenpark areas around the Halswell River, to the southeast of Christchurch. Here the controls on liquefaction could be observed without the built environment obscuring and altering the natural process and pattern. Surface ejecta was mapped from aerial photographs, and four transects were selected for detailed geomorphologic, stratigraphic, sedimentological, and geotechnical analysis. Observations by hand auger and Swedish Weight Sounding were made every 50 m with samples collected at selected auger sites for dry sieve analysis.

The results showed that the proportion of fine sediment (<63  $\mu$ m) and the subsurface compaction was influential on the liquefaction potential of sediments. It was found that loose, poorly compacted soils with a fines content of c. 25% were most likely to liquefy. Surface mapping demonstrated that the most liquefaction prone areas corresponded to paleo-channels of the Waimakariri River of Selwyn age sediments (<300 years). However, it was found that in these sediments did not liquefy at the surface if an overlying denser cap-layer, greater than the thickness of the liquefiable layer was present. Potentially liquefiable sediments also did not liquefy if the material was unsaturated and lying above the water table. It is anticipated that this research may be applied other similar environments within the Christchurch area which also experienced significant liquefaction during the earthquake.

**Geodetic images of coseismic rupture in the Darfield and Christchurch earthquakes**

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Using geodetic data from GPS and satellite radar interferometry we image the coseismic faulting in the three major Canterbury earthquakes of 2010-2011. The images may include a few days of aftershocks and possible afterslip. In the complex Darfield earthquake, the principal rupture - with magnitude  $M_w$  7.0 - occurred on the Greendale Fault, and at least four other structures ruptured with  $M_w$  6.2 and above. The Charing Cross reverse fault on which the Darfield earthquake initiated has almost pure reverse faulting with  $M_w$  6.5, as does the reverse fault southwest of Hororata with  $M_w$  6.2. As well as these previously identified fault segments, there is a clear  $M_w$  6.4 right-lateral strike-slip segment trending northeast from the large dilatational jog on the



Greendale Fault, as well as other segments emanating from near the eastern end of the surface rupture. There is also a  $M_w$  6.2 left-lateral segment trending north-northwest from the epicentre. While the model is not unique, all the additional segments lie reasonably close to trends of relocated aftershocks, including most of the  $M_w > 5$  aftershocks west of 172.5 °E. The aftershock magnitudes cannot account for the moment release, which we infer must have been coseismic or due to early afterslip. The fault model can be used to guide inversions of observed postseismic signals and for detailed Coulomb stress calculations. The February earthquake can be fairly well modelled with a mix of right-lateral and reverse slip on a single ENE-striking fault dipping south, but is better modelled as two faults with oblique slip on one fault plane and strike slip on a smaller, near-vertical fault to its south. The June earthquake is most simply modelled as left-lateral slip with a component of reverse slip on an NNW-striking fault dipping to the west beneath Brighton Spit and Sumner.

### **New Urban Geological Mapping: starting with 3-D Christchurch**

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A new Urban Geological Mapping project, part of GNS Science's Geological Map of New Zealand core science programme, has commenced this year. The aim of the project is to provide high resolution 3-D geological maps for New Zealand's urban areas to provide a foundation for urban planning, engineering, resource and hazard assessment.

Almost 72% of New Zealand's population is now concentrated in our 15 largest cities, and 86% of the population lives in towns of >40,000 residents. These areas comprise only 3% of the country's land area but carry the bulk of the investment in the built environment. They are well suited to such detailed 3-D geological maps. These statistics have driven the priorities of the new urban geological mapping work, although the recent Canterbury earthquakes have elevated cities with significant liquefaction potential.

The 3-D Urban Mapping project is focused on producing integrated, coherent lithostratigraphic and chronostratigraphic maps, with particular emphasis on the shallow subsurface. The maps will draw on data from many disciplines, will range in scale from 1:10,000 to 1:25,000 and will provide an essential source for derivative maps such as liquefaction susceptibility, and groundwater and aggregate resources.

The Canterbury earthquakes have focused attention on the state of knowledge of ground conditions beneath Christchurch. The massive re-build of the city requires high quality information upon which to base planning and engineering solutions. Many other urban areas in the country are as vulnerable as Christchurch.

This poster presents initial priorities for urban geological mapping and interim illustrations from the 3-D geological model we are developing for the Christchurch area, following five months of data collection and modelling. More than 12,000 boreholes and 1600 cone penetrometer and seismic cone penetrometer tests are providing constraints on near-surface stratigraphy.

### **Ambient seismic noise sources in New Zealand from three-component beamforming**

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Recent studies have shown the feasibility and benefit of using coherent signals contained in ambient seismic noise as an energy source in addition, or as an alternative, to traditional event-

based seismology. These weak but omnipresent signals have proven to extend our knowledge of crustal and upper mantle structures, and of time-variable geological processes. However, uncertainties in the source location and source mechanism of ambient seismic noise constitute a major obstacle in fully utilising the results of seismic noise investigations. Several authors have addressed this problem but focused on the source regions of vertical-component noise recordings only. In this study, we conduct plane-wave beamforming using vertical- and horizontal-component seismic noise recordings from a dense seismic network of 61 broadband instruments, deployed around Mount Taranaki in 2002, to investigate the source regions and source mechanisms of surface waves contained in the ambient seismic noise wavefield. We compare beamformer observations with locations of potential sources inferred from bathymetry and an ocean wave hindcast model of the New Zealand region employing theoretical frameworks for microseism excitation.

Our results indicate that the source regions of the secondary microseism are mostly located in deep water regions but get close to New Zealand's coastline off the coast of Fiordland and to the north and east of the North Island. Potential source regions of the primary microseism are mostly located on the continental shelf close to the coast. One of the strongest source regions appears to be Fiordland, where large ocean swells coincide with a narrow continental shelf.

Vertically and horizontally polarized surface waves around the secondary microseism are generated in similar areas but with differing intensities. However, around the primary microseism source regions seem to differ considerably. This is an important result for ongoing studies focused on inferring crustal and upper mantle structures from ambient noise cross-correlations in New Zealand.

## **Geoscience as a component of an all-of-government approach to recovery from the Canterbury earthquake sequence of 2010-2011**

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The Canterbury earthquake sequence is the most significant event in New Zealand since World War II. The impacts have consumed 8% of New Zealand's GDP, which, on a per capita basis, are perhaps eight times the impact of Hurricane Katrina on the US economy and four times the economic impact of the recent Tohoku earthquake and tsunami in Japan. In Canterbury, geoscience information has contributed significantly to civil defence crisis management and more recently to an all-of-government recovery effort coordinated through the Canterbury Earthquake Recovery Authority (CERA), and regional and local authorities in Canterbury. The earthquake sequence has comprised three main shocks (as of early October 2011), spaced at intervals of several months, each with particular spatial and temporal impacts. The extended duration of the sequence has resulted in major social, community, education, and economic disruption, creating much uncertainty in relation to the feasibility of land remediation in liquefaction damaged areas, and in judging the appropriate time to begin infrastructure, residential and commercial rebuild. The earthquakes have also resulted, in some parts of the region, ground shaking that has been much more severe than planned for in building codes. The appropriateness of codes, what residual capacity there should be in buildings and infrastructure to protect from rare but potentially catastrophic events, and whether a "city factor" is required to protect the socio-economic function of large cities, also needs input from the geoscience community. Crucial decisions for reconstruction and rehabilitation of communities is requiring substantial and ongoing coordinated input from seismologists, geologists, geotechnical engineers, landuse planners, structural engineers, landslide specialists, hazard and risk modellers, and social scientists. CERA is the coordinating agency, and geoscience input to their activities is a feature of this crisis, more so than in any previous natural hazard event in New Zealand.

## **Trace element zonation of Alpine Schist garnets: A hidden history of growth and breakdown**

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Garnet porphyroblasts are great mineralogical storage devices and commonly preserve a partial record of prograde and retrograde growth. However, when subject to moderate to high temperatures (>600 °C), diffusional post-peak metamorphic modification may occur to the four major end-members. It is being increasingly recognised, however, that rare earth elements are not readily susceptible to temperature-driven re-equilibration and can still preserve their concentration gradients characteristic of growth conditions.

Following this rationale, garnet grains from the Alpine Schist adjacent to the Alpine Fault in central Westland have been examined by EPMA and LA-ICP-MS at the University of Otago, and the growth profiles re-evaluated. Alpine Schist metamorphic garnets occur in the hanging wall of the central section of the Alpine Fault and appear to predominantly show pro-grade major element zonation growth profiles. Mapped isograds and the relatively constant whole rock geochemistries suggest that along-strike variations in garnet major element chemistry could be due to juxtaposition of different crustal sections by differential uplift parallel and normal to the Alpine Fault. However, considering trace elements, these garnet grains can be shown to reveal a complex history that has involved both gradual and abrupt changes in rare earth element budgets during growth. The changes are interpreted to be due to matrix depletion during growth, breakdown of major and accessory phases, diffusion during retrograde garnet breakdown, and dissolution-precipitation due to increasing strain into the mylonite zone.

There are important implications to these results. Firstly, major element growth zones are clearly dependent upon the abundance of other (often accessory) minerals. This means that abrupt changes in major element profiles may not correlate separate metamorphic

events. Secondly, knowing the concentrations of trace elements enables a first approximation of mineral phases that broke down during garnet growth, thus giving clues to which mineral reactions are most appropriate for geothermobarometry.

## **Pegasus Basin: a little-deformed window into an old friend, the East Coast Basin**

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The East Coast Basin has long tantalised oil explorers due to its abundance of oil and gas seeps, hydrocarbon shows, and plenitude of trapping structures. To date, only four exploration wells have been drilled in offshore licences, with promising gas shows encountered in three of them. However, we still lack a good understanding of the distribution and thickness of the key Cretaceous–Paleogene succession, which contains the basin's prime source rocks. This is due primarily to the pervasive post-23 Ma tectonic overprint that has deformed the East Coast Basin, as well as the large thickness of Neogene strata in the basin that prevents seismic from successfully imaging the important Cretaceous and Paleogene succession.

In 2010 the New Zealand Government acquired 3000 km of high quality 2-D seismic across Pegasus Basin, located off northeastern South Island, in an attempt to understand the likelihood of finding commercially-viable accumulations of oil and gas in this unexplored part of Zealandia. Prior to inception of the present-day plate boundary the Pegasus and East Coast basins were parts of the same geological entity, effectively remnants of the Gondwana subduction margin. Whereas Pegasus Basin has remained relatively unscathed by the post-23 Ma tectonic overprint, the East Coast Basin has been deformed and also accumulated great thicknesses of Neogene sediments.

Understanding the thickness, distribution and character of the Cretaceous and Paleogene succession is critical for modelling petroleum systems in the East Coast Basin. The succession identified and mapped in Pegasus

Basin therefore provides excellent controls on the likely package of rocks that underlie large parts of offshore East Coast Basin. This understanding will in turn help us to understand and model petroleum systems in the East Coast Basin, and will hopefully lead to the discovery of significant oil and gas reserves that will benefit New Zealand.

**The completion of the GeoNet Hikurangi Margin monitoring network: what comes next?**

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As the GeoNet Project enters its eleventh year of operation, the expansion of instrumentation along the Hikurangi Margin is almost complete. The Hikurangi Margin Network (HiMNet) is made up of short period seismometer and continuous Global Positioning System (cGPS) stations designed to measure seismicity and deformation associated with the subduction of the Pacific Plate under the Australian Plate, off the east coast of the North Island. The stations are positioned from East Cape to the Marlborough Sounds at approximately 20-30 km spacing, and extend inland from the east coast of the North Island for between 80 and 120 km. The network is scheduled for completion by late 2012, with a targeted total of 53 regional seismic stations and 80 cGPS stations.

In 2011-2012, the focus of GeoNet expansion will shift to the South Island, increasing instrumentation in Canterbury. Six new short period seismometer stations are planned for the region, from Greta Valley south to Burnside, and east to Okains Bay on Banks Peninsula. Strong motion accelerometer coverage in the region is also being extended and upgraded, with a view to creating a dense network with wide azimuthal coverage for recording the continued seismicity in Christchurch and Canterbury.

**Characteristics of sporadic and remotely triggered swarms in the central Southern Alps**

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The Southern Alps Microearthquake Borehole Array in the central Southern Alps recorded 12 earthquake swarms between November 2008 and April 2010. Three of these swarms appear to have been remotely triggered by the  $M_w$  7.8 Dusky Sound (15 July 2009) and the  $M_w$  7.1 Darfield (3 September 2010, UTC) earthquakes. Nine larger swarms of more than 15 events exhibit similar waveforms and magnitudes of  $0 < M_L < 2.9$ . All swarms occurred in the centre of the network and have well-constrained hypocentres. The focal mechanism solutions of the largest event in each swarm indicate either strike-slip (6 events), reverse faulting (3 events), or a combination of both. All mechanisms have one steeply dipping nodal plane ( $51$ - $86^\circ$ ) in common. Inter-event times versus durations of these swarm earthquakes above a cut-off magnitude of  $M_L$  1.0 show a characteristic pattern that is significantly different from that of a typical mainshock—aftershock sequence.

The triggered seismicity started after the passage of the surface waves and continued for several days. The seismicity rate increased steadily after the surface waves of the Dusky Sound earthquake and resulted in at least two swarms eight hours and three days later. After the Darfield earthquake, the first well-recorded swarm appeared four hours after the surface waves.

Shaking during both large earthquakes locally exceeded PGV and PGA values of 1 cm/s and 0.003 g, respectively. These values correspond to peak dynamic stresses of  $>0.09$  MPa, comparable to triggering thresholds ( $>0.01$  MPa) elsewhere. No remotely triggered seismicity has been observed following large distant earthquakes which caused less shaking (PGV c. 0.01 cm/s). The  $M_w$  6.3 Christchurch earthquake (21 February 2011), caused comparable PGA but slightly lower PGV values. We are currently investigating whether this

large South Island earthquake triggered any seismicity in the central Southern Alps.

conditions during the last 30 ka, in association with the New Zealand INTIMATE project.

### **Glacial/interglacial changes in the position of the subtropical front south of New Zealand**

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The Southern Ocean has a major influence on regional and global climate. The subtropical front (STF) is considered to be the northern extent of the Southern Ocean and is a major frontal zone that separates the warm, salty subtropical surface waters from the cold, fresh subantarctic surface waters. The STF is currently located at 45-47 °S south of Tasmania and flows across the Tasman Sea where it is diverted around the south island of New Zealand at 46-47 °S. Recent RV Tangaroa voyages in 2008 and 2011 have located the southern extent of the STF south of New Zealand at 49.5 °S in the Macquarie Ridge/Solander Trough. The STF then flows north along the east coast of the South Island until it reaches the Chatham Rise, flowing east at c. 44 °S.

Paleo-proxy evidence from cores in the Indian Ocean and south of Tasmania, suggest that the STF shifted north by 2-5 ° latitude during the Last Glacial Maximum (LGM) resulting from a northward shift in the westerly wind belt during the glacial. The STF, however, appears to be bathymetrically constrained to the east of New Zealand, trapped along the southern side of the Chatham Rise during both interglacials and glacials. We are analysing stable isotopes and foraminiferal assemblages from a suite of new cores collected in the Solander Trough and west coast of the South Island to determine changes in the position of the STF. The preliminary  $\delta^{18}\text{O}$  data and foraminiferal assemblage sea surface temperatures suggest that the STF shifted north along the west coast and south of New Zealand during the LGM by at least 2 - 2.5° latitude. This study aims to elucidate the location of the glacial STF around New Zealand and improve our understanding of the regional climatic

### **Offshore Nelson Cretaceous-Cenozoic: What the drilling of Tuatara-1 tells about the D'Urville sub-Basin**

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The drilling of Tuatara-1 by a joint venture operated by Australia Worldwide Exploration was the first offshore well in some twenty years to explore the Cretaceous-Cenozoic in the D'Urville sub-Basin which may be considered a southern extension to the larger Taranaki Basin. A thick sequence of mid Miocene terrestrial to shallow marine clastic sediments was encountered prior to terminating in granitic basement at 1911 m. The presence of gas and oil shows validated the existence of a mature source, albeit distant within the basin, but the level of hydrocarbon saturation was insufficient to commit to testing and the well was subsequently plugged and abandoned in August 2010.

Structural development of the Tuatara prospect occurred during the late Miocene through compression associated with right lateral movement on the Waimea-Flaxmore fault zone. Similar high amplitude eversion structures were recognised from seismic and drilled by Aquitaine NZ during the 1970s (e.g. Surville-1) without any success but the presence of structure conforming DHI's (amplitude brightening, flat spots and velocity pull-down) which bear resemblance to those on the Maari Field was good evidence for hydrocarbon accumulation. However in contrast to the basin-floor environment for the Maari Moki Formation the reservoir section at Tuatara-1 was deposited within the proximal delta top with a considerable thickness (c. 800 m) of fluvial channel sandstone and conglomerates with interbedded coals.

Information from Tuatara-1 is thus limited to a narrow stratigraphic window (Clifdenian to Waiauian) and the sequence within the main part of the D'Urville sub-Basin, reaching back into the Late Cretaceous remains speculative since

there are no direct seismic ties. Considerable variation in stratigraphic development is seen between sub-basins especially in proximity to the main eastern boundary fault to the Taranaki Basin. Suggestions are made as to possible correlatives which may provide the reservoir-seal pairs required to turn into prospects the structures which have been mapped closer to the now proven mature hydrocarbon kitchen.

#### **Pyrite + heavy mineral sand-coated granite cobbles at Lee Bay, Stewart Island**

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On the west side of Lee Bay on the Foveaux Strait coast of Stewart Island, pyrite-coated cobbles of granite occur loose in beach sand near the high tide mark. A coating of pyrite (c. 1 mm thick) completely covers the cobbles and is zoned, with an inner zone of fine grained, colloform pyrite and an outer framboidal zone. Framboidal pyrite is typically formed in anoxic sedimentary environments. Sub-rounded grains (0.1-0.4 mm) of hematite, ilmenite with hematite blebs, magnetite, feldspar, biotite (with rutile needles), quartz, feldspar, and zircon are present in the outer framboidal zone, with some ilmenite and hematite grains being partially replaced by pyrite. The assemblage of ilmenite-hematite-magnetite-biotite-zircon is similar, both in mineralogy and size range, to that found in heavy mineral beach sands. The source of the pyrite-coated cobbles is a weakly cemented conglomerate, which crops out at the back of the beach at Lee Bay, and contains cobbles of granite and amphibolite in a heavy mineral sand matrix. The in situ cobbles are coated by goethite, showing colloform textures, that appears to have replaced earlier formed pyrite. The goethite coating also contains grains of magnetite and biotite, similar to those seen in the pyrite coated cobbles. Sulfur isotope values (-13 to -2 ‰) of the pyrite coating are consistent with formation of the pyrite by microbial sulfate reduction (MSR), involving organic matter from the matrix of the gravel, reactive iron from dissolution of Fe-minerals in the heavy mineral sand and sulfate from seawater. Framboidal

pyrite-cemented chimneys and pebbles, forming by MSR about 40 cm below the surface of a tidal flat at Awarua Bay on the other side of Foveaux Strait, also demonstrate that MSR is a likely process for the formation of the pyrite coating at Lee Bay.

#### **Geology, petrology and geochemistry of the Alpine Dike Swarm**

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The Miocene-Oligocene Alpine Dike Swarm in the Southern Alps of northwestern Otago and south Westland developed as a consequence of transtensional propagation of the Alpine Fault plate boundary.

Intrusive members of the dike swarm range from ultramafic and feldspathic lamprophyres to more evolved tinguaite, trachytes and carbonatites. Recent work has shifted towards the carbonatitic component of the dike swarm, which has become of economic interest due to high concentrations of rare earth elements.

Lamprophyre dikes have entrained plutonic textured nodules derived from a crustal magma chamber beneath the Haast River area. Ultramafic and syenitic nodules represent cumulate equivalents of lamprophyre and tinguaite magmas respectively, and they provide constraints on the evolutionary history of these magmas.

Syenite nodules range from undersaturated varieties to layered clinopyroxene syenites and green clinopyroxenite with coarse grained apatite, titanite and zircon. The zircon is extremely coarse grained and constrains the age of intrusion in this part of the dike swarm.

Further north, at Modic Creek, there is evidence of lamprophyres containing xenoliths of inferred upper mantle origin. The mantle xenoliths are dominantly harzburgite, with possible garnet breakdown textures. The uplift of mantle xenoliths in this area implies that lamprophyre magmas intruded directly from mantle depths, without intersecting a plutonic complex.

## Vertical and lateral variations in the Ongatiti Ignimbrite, southeast of Te Kuiti

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Volcanic activity at Mangakino volcanic centre marks the onset of rhyolitic volcanism in the Taupo Volcanic Zone. This study focuses on the 1.23 Ma Ongatiti Ignimbrite, situated within the Ongatiti Valley, 15 km southeast of Te Kuiti. The study area is 28 km west of the Mangakino caldera rim, and to the west of the upstanding Mesozoic basement block of the Rangitoto Range.

Stratigraphic sections in well exposed 25 m high outcrops in the Ongatiti Valley show variations in pumice, crystal, and lithic abundance, both vertically and laterally. Two units can be distinguished within the Ongatiti Ignimbrite overlying a poorly exposed lowermost fall deposit: a lower densely to partially welded, crystal-rich, pumice-poor flow sequence, and an upper densely to partially welded pumice and crystal-rich flow sequence. The boundary between the two units is wavy and gradational, and varies in altitude over relatively short distances. This undulating boundary is considered to result from interaction of pyroclastic density currents flowing both over and around the high-standing Rangitoto Range, and then covering a highly irregular pre-ignimbrite topography in the King Country.

Stratigraphic variations in pumice, crystals, lithics and geochemical composition within these flow sequences in the Ongatiti Ignimbrite will be discussed in regard to the eruption, flow and emplacement mechanisms of the pyroclastic density currents.

## Lithological and fluvial influences on clast shape measurements in a temperate alpine environment: a case study from Fox Glacier

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Over the last 15 years, clast shape measurements have developed into a standard method for reconstructing the transport histories of sediments in glacial environments. Indeed, the combined use of form and roundness indices has been applied to clasts in temperate, polythermal, and cold-based glacier systems. The technique has also been extended to paleoenvironments, where assumptions are routinely made about: (i) passive versus active debris-transfer mechanisms; and (ii), the volume and origin of debris provision for moraine formation. The majority of these studies use the 'RA-C<sub>40</sub>' approach developed in Benn and Ballantyne (1994), but often researchers include clasts of varying lithologies within their samples of 50 clasts. The implication is that variable lithological properties may control clast form and roundness, rather than debris-transport mechanisms. Despite this, the role of lithology on clast shape in glacial environments has rarely been analysed. Furthermore, some studies found difficulties in using the RA-C<sub>40</sub> covariance plot in discriminating between clasts that have undergone subglacial transport, and clasts that have been modified by fluvial activity.

Here, an analysis of the effect of lithology on clast form and roundness is reported from a temperate alpine glacier. Clasts were sampled from slopes, ice marginal positions, and the foreland of Fox Glacier valley, where metamorphic grade increases down-valley. Argillite, greywacke and schist clasts were sampled to: (i) assess the utility of established clast shape indices in distinguishing different transport pathways, (ii) to evaluate the effect of lithology on clast shape, and (iii) to explore the discriminatory power of a different clast shape index. Results indicate that detailed

analysis of clast shape with respect to lithology, although time consuming, is a useful tool in the investigation of deposits in glaciated environments. With respect to the RA-C<sub>40</sub> technique, the suggested form-roundness relationships may not be valid and that more rigorous approaches may be required.

**1-D full waveform inversion of shallow amplitude anomalies in seismic reflection data from the Reinga Basin, offshore New Zealand.**

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The Reinga Basin is a relatively unexplored sedimentary basin located to the northwest of Northland, and is regarded as the northern continuation of the Northland Basin. The Reinga Basin is bounded to the west by the compressional West Norfolk and Wanganella Ridges, to the northeast the basin is bounded by Reinga Ridge and the Vening-Meinesz Fracture Zone. In 2008-2009, New Zealand Minerals and Petroleum with CGG Veritas acquired two 2-D multi-channel seismic surveys, Stratus-2D and Reinga-09 within the Reinga Basin, as a joint petroleum speculation survey. To date, no bottom-simulating reflections (BSRs) indicating the presence of gas hydrates have been identified in either survey. However, several areas of anomalously high amplitude and unresolved polarity have been identified within the probable gas hydrate stability zone (GHSZ). 1-D full wave form inversions have been undertaken of these anomalous amplitude areas to determine the nature of these strong reflections. Preliminary results from STRATUS-2D sequence 2 suggest that the anomalous amplitude zones are not directly related to the base of the hydrate stability zone. P-wave inversions of at least two regions indicate that there is possibly free gas structurally trapped by a faulted pop-up forming over a shallow igneous intrusion approximately 500 ms TWT below the seafloor. Reflection coefficients and inverted P-wave velocities also indicate that basalt may occur beneath the seafloor to the north of the pop-up.

**Portrayal of earthquake-related geoscience in New Zealand mass media**

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Stories in the public sphere relating to earthquakes collectively contribute to social constructions of earthquake-related disaster risk reduction (DRR) and the role of science in this. Review of literature relating to best-practice in DRR communication suggests that providing a range of perspectives that acknowledge uncertainties, and allow public understanding on which to base perceptions, judgments and related reduction decision-making and actions, is as important as accuracy. Results from analysis of New Zealand mass media stories preceding, and up until the first anniversary of the Darfield Earthquake, show that although a broader range of hazards and hazard effects have been presented since September 2010, mention of vulnerabilities and possibilities in reduction remains infrequent and narrow. Disaster, risk and reduction are referred to in decreasing order of frequency – the emphasis having been on recording damage and other earthquake effects rather than discussions of risk, risk assessment and its management (reduction). Stories focus on earthquake occurrence and the response and recovery phases of the DRR cycle, over readiness and reduction. Mention of applied geoscience, engineering and social science trail mention of seismic processes and other pure geoscience. Public desire for certainty has sparked interest in pseudo-scientific prediction without there having been the caution that prediction offers only limited risk reduction. Apologies as to limitations in fault location and prediction have been made without utilizing available opportunities to mention risk reduction. Attribution of responsibility for reducing exposure to seismic risk has focused on individual survival actions and household seismic adjustment, while suggesting government and experts be left to legislative and regulatory decision-making relating to reduction options in land use, response and recovery planning, insurance and construction. Greater emphasis on concepts of self- and community-efficacy and participatory process in DRR, and increased linking of how geoscience



contributes to avoidance and mitigation options seem warranted.

**Changing attitudes to carbon dioxide taxation: climate hazard adaptation is the key**

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Attempts to introduce a carbon dioxide emissions trading or taxation scheme in Australia have been deeply divisive – being partly responsible for the defeat over recent years of two prime ministers (with a third in the gun at the time of writing) and for three changes in leadership of the opposition. Since 2007, when about 70% of the Australian public favoured costly action to “prevent global warming”, a radical swing has occurred in public opinion so that about 70% now oppose the carbon dioxide tax that Julia Gillard introduced into parliament in September. These opinion changes reflect, first, the inaccuracy of temperature projections made by GCM computer models, and, second, a continuing lack of empirical evidence that any, let alone dangerous, global warming is actually occurring.

In such circumstances, it is not surprising that an alternative view has emerged regarding the most cost-effective way in which to deal with the undoubted hazards of climate change. This view entails setting a policy of preparation for, and adaptation to, change as it occurs, which is distinctly different from the previous emphasis given by western parliaments to the mitigation of global warming by curbing carbon dioxide emissions. The vigorous public debate over possibly dangerous human-caused global warming is bedevilled by two things. First, the inadequacy of the historical temperature measurements that are used to reconstruct the average global temperature statistic. And second, fuelled by lobbyists and media interests, an unfortunate tribal emotionalism that has arisen between groups of persons who are depicted as either climate “alarmists” or climate “deniers”.

In this context, all competent scientists accept: (i) that global climate has always changed, and always will; (ii) that human activities (not

just carbon dioxide emissions) definitely affect local climate, and have the potential, summed, to measurably affect global climate; and (iii) that carbon dioxide is a mild greenhouse gas. The continuing scientific debate, then, is about none of these issues, but rather about the sign and magnitude of any net global human effect, and its likely significance when considered in the context of natural climate change.

Climate change as a natural hazard is as much a geological as it is a meteorological issue. Thus it needs to be managed in the same way as other geohazards, i.e., by monitoring for the onset of dangerous events and by having a civil defence response plan to deal with events as and when they happen. In this regard, GeoNet is a world-best-practice hazard defence organisation that could easily assume responsibility for longer term climate risk alongside its present tasks. Policymakers in USA, Canada, and Japan have already abandoned the illusory goal of “preventing global warming” by reducing carbon dioxide emissions. Instead, dealing with climate reality as it unfolds represents the most prudent, practical and cost-effective solution to the global warming/climate change issue. Importantly, such a policy of adaptation is strongly precautionary against any possibly adverse human-caused climate trends that might, or might not, emerge in the future.

**When weather and earthquakes combine - a modern case study of submarine hazards in the deep ocean.**

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It is well established that earthquakes trigger submarine landslides and sediment gravity flows (SGFs – a generic term that includes hyperpycnal, debris and turbidity flows). New data from offshore Taiwan reveals that major storms also form SGFs, and that the combination of weather and earthquakes are a potent force behind the transport of sediment, nutrients and carbon far into the deep ocean as well as posing a hazard for subsea telecommunications cables that carry c. 95% of trans-oceanic voice, data and internet traffic.

Using data from faults generated in subsea cables across the Gaoping Canyon/Manila Trench system during the record-breaking Typhoon Morakot (2009), we show that a river flood can produce rapid, long run-out SGFs. One flow occurred near peak flood when sediment-charged river water sank into Gaoping Canyon and flowed at 16 m/s to c. 3700 m depth damaging 3 cables en route. Another SGF formed 3 days later when the river discharge was near-normal. Flood deposits in the canyon were apparently remobilised by waves/currents and formed a flow that travelled at 6-10m/s to break 6 cables over a >157 km run-out. Concomitant seismic activity was low (<M<sub>L</sub> 3.0).

Other cable disruptions in the same canyon/trench system affected by Morakot, collectively highlight the variable triggers of SGFs. In 2006 a M<sub>L</sub> 7.0 offshore earthquake with strong ground-shaking formed multiple SGFs that damaged 22 cables over >345 km-long path. In 2010, an onshore swarm of earthquakes with weak ground-shaking triggered a flow that broke 9 cables. In just 5 years a major cable corridor succumbed to SGFs produced by a flood, aseismic landslide, and minor and major earthquakes. We speculate that the 3 events are interconnected. The 2006 earthquake destabilised the terrestrial landscape to make sediment available for Typhoon Morakot. Those perturbations preconditioned the submarine catchment to fail under the low magnitude earthquake swarm of 2010.

## **Subaqueous eruption breccia of the Huka Falls Formation, Wairakei-Tauhara Geothermal System**

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Understanding the geology of geothermal systems is fundamental to successful exploration, exploitation and resource management. One key unit of the Wairakei-Tauhara geothermal system, near Taupo is the Huka Falls Formation (HFF) which is the main hydrological cap of the geothermal reservoir. The three-part lacustrine Formation includes a permeable Middle unit, stratigraphically located between Lower and Upper HFF fine-grained sedimentary and volcanoclastic deposits. The Middle unit consists of a rhyolitic pumiceous lapilli tuff with a lithic-rich coarse basal breccia. We have studied characteristics of the breccia from selected Tauhara drillcore, and use the size, angularity, lithology and petrology of pumice and lithic clasts to infer that the middle HFF was erupted through, and deposited in a lake from a vent located in the Tauhara field. We also infer that Middle HFF originated from explosive subaqueous eruptions of rhyolite magma which at shallow depth, fragmented and entrained rhyolite lava and pyroclastic tuffs (Waiora Formation) and lower HFF mudstone country rock.

Lithics also include medium-grained granodiorite fragments entrained from a shallow plutonic body, probably related to the deep geothermal heat source. Graphic intergrowth disequilibrium textures suggest that the plutonic body was partially crystallised at shallow depth and later fragmented and entrained by ascent of the Middle Huka Falls Formation rhyolite magma. Zoning of Ti in quartz crystals in the granodiorite lithics, revealed by CL-SEM, suggests cooling of the plutonic body occurred quickly.

Similarity in major and trace element XRF fingerprints of Middle Huka granodiorite lithics and Taupo rhyolite support a Taupo magma system as a likely source of the Middle Huka Falls unit.

**The Bishop Tuff, California: Deposit of a horizontally variable super-sized magma chamber?**

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The c. 0.76 Ma Bishop Tuff eruption in eastern California is one of the largest (c. 600 km<sup>3</sup>) eruptions on Earth in the last 2 Ma. As an archetypal example of the products of a compositionally stratified magma chamber, the Bishop Tuff provides an excellent opportunity to study processes which operate on this 'super-eruptive' scale. These processes are being compared with those inferred for New Zealand supereruption deposits such as the Oruanui, where growth of a non-stratified melt dominant body was extraordinarily rapid (c. 40 ka). Crystal specific studies of multiple pumice clasts from all units from the Bishop Tuff are being used to quantify not only the vertical stratification of the magma body, but also identify any lateral (geographic) variations which existed prior to eruption.

Re-examination of published XRF data (Hildreth and Wilson 2007, *Journal of Petrology* 49, 951) reveals variations in trace element concentrations within single ignimbrite packages, which are not dependent on crystal content, suggesting that there was some geographic change in availability of different magma types across the chamber. Laser ablation inductively coupled mass spectrometry (LA-ICPMS) analyses of sanidine has confirmed that some of the late-erupted crystals have a Ba-rich rim, which is accompanied by increases in Sr and LREE. This Ba-rich rim is not seen in the eastern units of the Bishop Tuff, and is not present in all crystals from the northern units. Microprobe analyses of plagioclase show no differences between core and rim major elements, but distinct differences within the northern units, again suggesting varying availability of small scale magma batches. Study of these sector-confined eruptive compositions will allow a more detailed model of the magma body to be constructed, and comparison to be made with models for caldera eruptions in New Zealand and around the world.

**Aeolian 'dust' flux in McMurdo Sound, SW Ross Sea, Antarctica**

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Significant volumes of aeolian (windblown) sand and dust are sourced from areas of exposed unconsolidated sediment surrounding McMurdo Sound, Antarctica. During winter, this sand and dust accumulates on floating ice fringing the southwest Ross Sea and is subsequently released into the ocean during springtime as the ice melts. In this region, unlike in warmer climates, ice and wind are the dominant agents of erosion and transport and the contribution of aeolian sand to seafloor sedimentation, both directly and indirectly (via links to biogenic diatomaceous silica), has long been considered important (e.g. Barrett *et al.*, 1984), but has never been quantified. Knowledge of the mass flux and particle size distribution of this material helps us understand the relative importance of geological processes supplying sediment to the ocean and when interpreting the geological record. The few existing sand and dust measurements from sea ice in McMurdo Sound suggest volumes up to four orders of magnitude higher than found in nearby continental ice cores, implying that this area represents a significant source of aeolian sediment for the region. This study aims to calculate the volume, composition and provenance of windblown material in McMurdo Sound, utilising a high spatial resolution (5 km grid spacing over 300 km<sup>2</sup>) suite of surface samples collected from the sea ice during the 2010/2011 field season. This new dataset covers an area that includes several important geological drill sites (e.g., Cape Roberts Project 1,2,3; CIROS 1,2; ANDRILL-2a) and previous localised aeolian 'dust' dispersal studies (e.g., Atkins and Dunbar, 2009). A physical model of regional aeolian sediment distribution will be produced. This will incorporate wind field data; ice and firn cores; plus physical particle transport processes, to constrain modal supply and the pattern of aeolian sedimentation in the southwest Ross Sea. This contemporary record

of aeolian flux will then be used to identify analogues described from previous drilling operations in the area.

**Magmatic gas transfer through Ruapehu Crater Lake: Insights into transfer processes and P-T-X conditions in the vent environment.**

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CO<sub>2</sub> emission through Ruapehu Crater Lake has been measured via airborne platform approximately monthly since 2003. At this sampling rate, CO<sub>2</sub> discharge appears to be cyclical, with rates variably ranging from <50 T/D to >2000 T/D. Emission cycles correlate with observed thermal cycling in the lake, pointing to an obvious relationship between magmatic heat and gas transport in the system. TOUGH2 modelling of this cycling points to temperatures varying between c. 300 – 500 °C in the vent.

Following a gas-driven, phreato-magmatic eruption in 2007, we commenced routine surface sampling of the two major upwellings over the northern and central vents for analysis of their dissolved gases in addition to non-volatile solutes. The lake water is collected by helicopter into an under-slung 25 litre bucket which is then delivered to persons on shore, who immediately take water into evacuated flasks fitted with Teflon-stopcocks. The headspace gases are then analysed by GC and GC-MS for CO<sub>2</sub>, H<sub>2</sub>, He, Ar, N<sub>2</sub>, O<sub>2</sub>, CH<sub>4</sub>, CO and C<sub>1</sub>-C<sub>6</sub> hydrocarbons, with appropriate corrections made for distribution of gas between the vapour and water phases in the samples. The results show the expected influence of atmospheric and magmatic end member contributions to the dissolved gas species, but also a systematic variation in composition with thermal cycling of the lake. CO<sub>2</sub> is the predominant gas in solution, followed by N<sub>2</sub>, H<sub>2</sub>, Ar, O<sub>2</sub>, CO and trace amounts of hydrocarbons (both alkanes and alkenes).

Relative variations in solute gas concentrations provide useful insights into potential equilibrium conditions beneath the lake. Both H<sub>2</sub>/Ar and CO/CO<sub>2</sub> ratios, for example, show coherence with measured lake temperatures, indicating changing equilibrium conditions in the hydrothermal environment during the heating cycles. H<sub>2</sub>/Ar ratios appear to adjust more rapidly to changing vent conditions than CO/CO<sub>2</sub> ratios. Although there is very little CH<sub>4</sub> in the solute gases, CH<sub>4</sub>/CO<sub>2</sub> ratios appear to subtly increase during quiescent periods, pointing to the likely existence of a discreet hydrothermal component resident in the vent system.

Despite the coherent behaviour of temperature-sensitive ratios and lake temperatures, a concern over the general applicability of this approach for monitoring purposes stemmed from our incomplete understanding of the processes controlling gas transfer through the lake, and whether these had any bearing on the observed gas ratios. In 2010, water-borne sonar surveys, gas sampling, and diffuse degassing measurements were conducted during a period of relatively low lake temperature and low gas emission (c. 23 °C and c. 180 T/D CO<sub>2</sub>). During these surveys, several upwelling bubble/suspension columns were recognised as strong sonar reflectors rising through the water column from the vent regions. However, only very rare and intermittent bubbles were ever observed breaching the surface, indicating that the bulk of the gas was indeed dissolving in the water column during ascent, and that observed solute gas concentrations were likely representative of those discharged from the vent. Diffuse degassing measurements of CO<sub>2</sub>, on the other hand, confirm that the dominant process of gas release from the lake is diffusion across the air-water interface.

Modelling of the dissolution process indicates that initial bubble size, path length and fluid viscosity are the dominant factors determining whether a discreet gas phase reaches the surface or the gas is completely dissolved into the lake water.

**Southwest Pacific in a warmer world:  
Ocean response to Marine Isotope Stage 11**

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Marine Isotope Stage (MIS) 11 occurred from 424 to 374 ka and is often cited as an analogue to the present interglacial period, as it is the most recent, long, stable warm period in Earth's history. During MIS 11, Earth's orbital configuration was characterized by a nearly circular orbit around the sun (low eccentricity), which resulted in a similar distribution of seasonal isolation as the Holocene. Ice core records from Antarctica also show that MIS 11 atmospheric greenhouse gas levels were comparable to pre-industrial levels and benthic oxygen isotope records suggest similar global ice volumes as today. The deglacial transition from MIS 12 to MIS 11 was the largest amplitude in the last 5 Ma and has been described as a major step in the global climate of the past 3 Ma.

We have investigated how this extended interglacial period was expressed in the mid-latitude southwest Pacific Ocean (ODP Site 1123) utilising geochemical and sedimentological proxies. Trace element analysis of planktic foraminifera (*G. ruber* and *G. bulloides*) by laser ablation ICP-MS has been used to derive paleo-ocean temperatures and ocean circulation changes at the site during Termination V. Mg/Ca paleothermometry reveals that the termination involved surface ocean warming of c. 10 °C in c. 10 ka. Peak Sea Surface Temperatures (SST) of 17.5 °C were recorded in MIS 11 at 426, and 404-414 ka, which are comparable to peak SST recorded during MIS 31 and MIS 1 obtained using similar techniques (Marr and Bolton, unpubl. data). Planktic oxygen isotope data lag ocean warming by c. 4 ka, reflecting polar response time. In addition to temperature change, Mn/Ca and Zn/Ca ratios of planktic foraminifera record substantial changes from MIS 12 to MIS 11 that potentially reflect changes in the relative

influence of micronutrient-rich subtropical water and subantarctic water during MIS12-11.

**Subsidence and tsunami over the past  
1000 years at Big Lagoon, Blenheim**

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Investigations of salt marsh stratigraphy at the eastern corner of Big Lagoon, near Blenheim, have revealed a complex and spatially variable sequence of muds, silts, organic-rich layers, paleosols, and sand horizons. This part of the north-eastern Marlborough coastline has clearly been highly dynamic over the past 1000 years.

Over 30 shallow cores (<2 m) were collected from the margins of Big Lagoon and within the small salt marsh ponds bordering Big Lagoon. At least 15 of these cores have an anomalous sand layer 1–10 cm thick, at 1–1.6 m depth. Several characteristics of the sand layer indicate it represents an extreme marine inundation event: it has a coarser grain size than the surrounding sediment, it fines upwards and thins landward, it has a sharp lower contact, and unusual microfaunal content with a high proportion of species exotic to the lagoon environment. These characteristics are consistent with deposition by a tsunami or an extreme storm. The sand sheet deposits of historic storms that overtopped the barrier have also been analysed for comparison. The paleo-inundation event deposit has a different microfossil assemblage, extends much further landward and is finer grained than the recent storm deposits. The spatial extent and microfauna of the deposit is more consistent with tsunami deposition. The inferred paleotsunami had an inundation distance of ≥360 m, and must have had a flow depth of >3.5 m to overtop the barrier.

Above the inferred paleotsunami deposit, and approximately 200 years younger, is a distinctive organic-rich muddy silt unit. This occurs at about 0.6–0.8 m depth in almost all cores. In

some cores the foraminifera assemblages show evidence of a sudden rise in relative sea level at the upper contact between the organic-rich unit and the overlying grey silt. The change in sea level is probably associated with coseismic subsidence of c. 0.4 m.

The northeastern Marlborough region, at the southern end of the Hikurangi subduction zone, is proximal to many active tectonic structures capable of generating tsunamis and crustal subsidence. We will discuss the progress toward identifying the cause of the tsunami and subsidence events in the past 1000 years at Big Lagoon.

### **Effects of volcanic ashfall on roofs**

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The impacts of recent volcanic ashfall on roofs is very significant and it is important to know how different types of roofing materials will react, and what effects different amounts of ash will have on them. Because of the difficulty of obtaining large quantities of fresh ash, which still contains the soluble gases from the volcanic eruption, a 'pseudo-ash' was prepared. The chosen material was crushed basalt from Banks Peninsula, Canterbury, 'dosed' with acidic water from either Crater Lake, Ruapehu or from the crater on White Island. Comparisons were made between this dosed ash and fresh ash to check their properties were similar. Once this was established, the pseudo-ash was used to evaluate the effects of ash on different types of roofing materials (galvanized iron, old corrugated iron, Coloursteel®, and zinc), using the fog chamber at the Building Research Association of New Zealand (BRANZ) facility

at Porirua. Samples were subjected to 6 hours of wetting and 18 hours of air drying every 24 hours to simulate types of conditions roofs might experience for periods of 1 day, 1 week and 1 month. The samples were then examined using SEM and XPS analysis at the University of Auckland to check on corrosion. None was found, indicating that for future tests, conditions in the fog chamber will need to be varied with for example, potentially longer periods of wetting per day or longer periods in the chamber. The kinetics of pH change and salinity may also vary between natural and 'pseudo' ash, and this will also need to be evaluated.

### **Journeys through shape and time – sclerochronology and heterochrony in New Zealand crassatellid bivalves**

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Sclerochronological studies of bivalves such as *Mercenaria mercenaria* and *Spisula solidissima* have shown the potential for mollusc shells to preserve high-resolution oxygen-isotope records of ambient sea water at the time of shell growth. These records have been used as palaeoclimate archives, but also provide insight into bivalve development and evolution.

Heterochrony, or change in developmental timing, is an important mechanism of evolution. An organism's life history can be significantly altered by slowing or accelerating the growth of an organ, the onset of sexual maturity, or attainment of a particular morphology. In the context of phylogeny, differences in development may constitute characters that are of use in discriminating between taxa.

In order to study heterochrony, individual age and growth-rate data are required. Knowledge of the time required for an organism to reach a given developmental stage is paramount.

However, in palaeontological studies, gathering these data can be difficult, and in some cases impossible.

Fossil bivalves and the techniques of sclerochronology, however, provide an exception to this. Marginal, accretionary growth of bivalves allows reconstruction of shape at different times during the organism's life, and also allows geochemical sampling of shell-material along the axis of maximum growth, so that the required chronological age data can be inferred from periodic (commonly seasonal) variations in stable isotope ratios.

This talk will discuss the application of sclerochronological methods to New Zealand bivalves from the family Crassatellidae, and resulting evolutionary and phylogenetic insights.

**Vegetation diversity in southern New Zealand at the Oligocene–Miocene boundary: floristic and paleoecological characterization of the Foulden Maar paleoforest**

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The flora surrounding the Early Miocene (c. 23 Ma) Foulden Maar paleolake included a highly diverse Lauraceae-dominated rainforest with macro- and/or microfossils of now extinct species of a wide range of gymnosperms

including *Araucaria/Agathis*, *Dacrycarpus*, *Dacrydium*, *Phyllocladus*, *Podocarpus*, *Prumnopitys* and *Wollemia*. In addition to ten species of Lauraceae, numerous other angiosperms including *Alseuosmia*, *Dysoxylum*, *Elaeocarpus*, *Fuchsia*, *Gevuina*, *Gymnostoma*, *Hedycarya*, *Laurelia*, *Mallotus/Macaranga*, *Myrsine*, *Nothofagus* and *Weinmannia* were present, together with species of Araliaceae, Loranthaceae, Menispermaceae, Myrtaceae, Rutaceae and Sapindaceae (amongst others). There were also diverse monocots typical of present-day New Zealand ecosystems, such as *Astelia*, *Cordyline*, *Luzuriaga*, orchids, *Phormium*, *Ripogonum* and *Typha*, and epiphytic ferns including *Davallia*.

The macrofossils include leaves, flowers, fruits and seeds and in several cases are sufficiently detailed to allow placement onto cladograms with putative modern relatives, improving the phylogenetic significance of the fossils and their utility for dating evolutionary trees (e.g., *Fuchsia*, *Laurelia*, *Luzuriaga*). Comparisons with the ecology of modern relatives to the fossils at the site suggest that the forest included canopy trees, understorey shrubs, epiphytes, mistletoes, ferns and vines, as well as forest margin pioneers and emergent aquatic macrophytes. The rainforest supported a mixture of wind-, bird- and insect-pollinated species, as well as both animal- and wind-dispersed fruit and seed types.

The paleoforest most closely resembled a warm temperate to subtropical notophyll vine forest, but was comprised of what are now Australian, New Zealand, South American, and New Caledonian elements. Apparent differences between the *in situ* macrofossils and the microfossils can be explained partly in terms of local versus regional scales, as well as variation in the soils and underlying geology surrounding the maar. The possible ecology, climate and habitats at the paleolake and their implications are discussed in terms of the diversity and uniformity of mid-latitude southern New Zealand at the Oligocene–Miocene boundary.

**Mechanisms of mid-ocean ridge basaltic eruptions: evidence from the Macquarie Ridge Complex, Australia-Pacific plate boundary south of New Zealand**

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Volcanic glass occurring as quenched rinds on pillow lava samples and shards in volcanoclastic breccia samples was collected from four seamounts along the Macquarie Ridge Complex, Australia-Pacific plate boundary south of New Zealand. Samples are alkaline to sub-alkaline enriched mid-ocean ridge basalts, containing 46.5 – 51.2 wt.% SiO<sub>2</sub>, 5.2 – 9.1 wt.% MgO, 2.3 – 5.1 wt.% total alkalis, and values of 1.2 – 2.5 for La/Sm<sub>N</sub>. Volatile element (H<sub>2</sub>O and CO<sub>2</sub>) concentrations of the samples were also measured. Numerous glass shards within individual volcanoclastic breccia samples define tight and distinct compositional domains, indicating that shards in each sample were derived from single and discrete magma sources.

Glass from pillow lava samples and the majority of breccia samples is non- to sparsely-vesicular, sub-alkaline to transitional basaltic in composition and has relatively primitive MgO contents. These samples were derived from magmas that rose efficiently through the crust and were erupted effusively onto the seafloor to form pillow lavas, or were subsequently fragmented by cooling-contraction granulation to form lava and glass shards deposited in volcanoclastic breccias.

One breccia sample comprises highly vesicular glass shards, has an alkaline and fractionated composition, and is highly enriched in incompatible trace elements. This sample was derived from a low degree partial melt that

underwent crystal fractionation and volatile exsolution during a stalled magma ascent. The slow ascent rate induced a build-up of gas pressure at the top of the conduit, which, in addition to the initial volatile concentration of the incompatible element enriched and alkaline magma, led to explosive eruption. This is likely to have occurred during the final stages of magmatism at the Australia-Pacific plate boundary south of New Zealand when seafloor spreading was ultraslow or had ceased, which induced low degrees of partial melting and retarded magma ascent rates.

**Cretaceous depositional ages for Alpine Schists of Torlesse affinity: implications for the tectonic evolution of the Eastern Province accretionary prism(s)**

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Within the ophiolitic Pounamu Ultramafic Belt (PUB) of the Toharoa, Hokitika, and Whitcombe River area, pelagic metasediments and quartzofeldspathic schists stratigraphically overlie metabasites and metaserpentinites. The geochemistry of these quartzofeldspathic schists suggests an affinity to the Torlesse Terrane. Detrital zircon populations are dominated by Permo-Triassic grains, but contain a substantial Cretaceous component, dated at 100-140 Ma. One sample from the Hokitika River has metamorphic zircon rims, dated at 70 Ma. A Cretaceous (100-140 Ma) detrital zircon population, overgrown by 65-85 Ma metamorphic rims, also occurs in quartzofeldspathic schist from the Mataketake Range in south Westland, 180 km to the southwest. Cretaceous detrital zircons are euhedral with fine scale oscillatory zoning indicative of crystallisation from a melt. Grains are relatively unabraded, suggestive of transportation and deposition as first cycle detritus.



Low-grade Torlesse greywackes immediately to the east of the PUB contain *Torlessia* and *Monotis* and are Triassic in age. Furthermore, the overall biostratigraphic zonation of the Torlesse Terrane is incompatible geographically and structurally with the Cretaceous depositional ages documented here, requiring some major intervening structural break. Various mechanisms are explored to explain the tectonic evolution of the Torlesse accretionary prism(s).

### **Climate-driven megafaunal turnover in the Late Pleistocene**

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The mechanisms of late Pleistocene megafaunal extinctions are still fiercely contested, with human impact or climate change commonly cited as the principal driver. A key limitation has been the reliance on fossil evidence, precluding the identification of major genetic transitions or population-level turnover. Analysis of genetic data from 25 detailed time series of regional extinctions and invasions across the Northern Hemisphere over the past 60,000 years reveals a major correlation with climate. The period of greatest cooling (30-15 ka) saw no significant extinctions, while rapid warming events appear to be associated with the replacement/extinction of major clades and species of megafauna. The presence of multiple cryptic transitions prior to the Pleistocene/Holocene boundary challenges a major paleontological argument against the role of climate change in the megafaunal extinctions, and suggests that human presence merely accelerated species turnover. In addition, studies of N15 isotope values in bones and soils from the latest Pleistocene reveal major changes in the period of megafaunal extinctions, raising questions about the relationship to environmental change.

### **The Waihemo Fault of north Otago: constraints on late Quaternary activity**

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The Waihemo Fault system runs northwest from Shag Point to Dansey's Pass in North Otago. Offshore it lines up with the edge of the Bounty Trough. To the northwest, it continues as the Hawkdun Fault system as far as the McKenzie basin. The fault system underwent major normal displacement during the mid-Cretaceous, resulting in lower-grade schist in the northeast hanging wall. Faults of the system were reactivated in the late Cenozoic with reverse movement uplifting the present Kakanui Mountains, with maximum displacement in the centre of about 1000 m.

An outcrop of the main reverse fault at Pigroot Creek shows schist in the hanging wall, thrust over steeply dipping Tertiary greensand overlain by a strath surface, river sands, and gravels. One set of sands are preserved beneath the overthrust schist whereas the younger set truncates the fault and is draped over the scarp. The total preserved offset is 1 m. Optically Stimulated Luminescence (OSL) dates on the older gravels give an age of  $58.7 \pm 12.4$  ka whereas the younger gravels yield an OSL age of  $14.1 \pm 1.3$  ka. The total displacement between the two sets of gravels must be much greater than 1 m, as the hanging wall has been considerably degraded post-58 ka.

A detailed profile was measured upstream. No remnants of the older gravels were found, with the most likely occurrence dated by OSL within error of the younger date. By projecting a surface parallel to the strath beneath the older gravels from these dated upstream gravels to the fault, an approximate minimum displacement of 10 m was calculated to have occurred between the two sets of gravels. For typical displacements on faults of this size, a maximum return period of 10,000-20,000 yr can be estimated, indicating that the lack of events after 14.1 ka is no indication that activity on this structure has ceased.

## **Sub-glacial volcanism in western Ross Sea?**

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New multibeam bathymetry data in the western Ross Sea, Antarctica, extend the field of unusual flat topped seafloor mounds located west of Franklin Island (OGS Explora Mounds) by about 6 km further east. An additional six mounds have been delineated, with some appearing to be coalesced features. The total field covers an area about 20 km square and lies at a depth of about 500 m. The north-western margin trends north-northeast, drops sharply away into water depths of about 850 m and is probably fault controlled. The mounds have a northerly trend and tend to be circular in the east and linear in the west. The largest mound is about 4 km across and 100 m high. The mounds have a steepest slope to the southeast, and shallowest slope to the northwest, consistent with erosion by a northwest icesheet movement. Three similar features were delineated about 25 km to the south of Franklin Island at a depth of 650 m, and one 5 km east of Franklin Island at a depth of about 400 m. Seismic, gravity and magnetic data indicate that the mounds are largely low density, non-magnetic bodies overlying a largely non-disrupted sedimentary section. Some mounds, however, have an associated small (c. 50 nT), short wavelength, normal or reversed magnetic anomaly, suggesting a magnetic core to the mounds. Their morphology and proximity to inferred subsurface gas hydrates and associated mud volcanoes and pock marks suggest they may be carbonate banks, but they also occur close to a major volcanic bank and similar mounds are found along the volcanic Franklin Island ridge. Our preferred interpretation is that they are of volcanic origin, erupted under a grounded ice sheet as hyaloclastite edifices.

## **Glaciotectonic processes of the central Alpine Fault: a gravimetric study of the central West Coast, South Island, New Zealand**

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The rugged topographic relief of the central West Coast reflects ongoing interplay between active tectonic and climatic processes. Major geomorphological features have formed in response to ongoing convergence between the Pacific and Australian continental plates. The principal locus of this collision is the transpressive Alpine Fault. Quaternary slip rates along the Alpine Fault have been determined using the offset of glacial surface features on timescales of tens to hundreds of thousands of years. Using geophysical techniques, we develop an alternative method for quantifying local fault offset using the displacement of subsurface features, enabling us to infer slip rates for the central Alpine Fault.

In this study 361 new gravity observations were collected in the Wanganui, Whataroa, Waiho, and Fox floodplains on the western (footwall) side of the Alpine Fault. When combined with existing data this gives a total of 932 measurements over the four catchments. These gravity data are used to model the subsurface structure of the flood plains, revealing information on the extent of climatic erosion, the fault-bound South Westland Basin and the dextral offset along the central Alpine Fault.

We examine dextral offset on the Alpine Fault since the Last Glacial Maximum by determining the structure and geomorphology of deeply incised glacial erosional channels. By examining how the lower reaches of four major rivers – the Wanganui, Whataroa, Waiho, and Fox – have been translated with respect to their channels on the eastern (hanging wall) side of the Alpine Fault, we have quantified horizontal fault

displacement in each catchment. Preliminary results show fault offsets of  $383 \pm 388$  m,  $372 \pm 88$  m, and  $450 \pm 99$  m for the Wanganui, Whataroa, and Fox River valleys respectively. These give slip rates between  $13.7 - 20.2 \pm 21.5$  mm/yr,  $13.3 - 19.6 \pm 5.7$  mm/yr, and  $16.1 - 23.7 \pm 6.5$  mm/yr, respectively.

### **Preliminary on-fault evidence for the most recent Alpine Fault surface rupture, Gaunt Creek, New Zealand**

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The dextral-reverse Alpine Fault forms the boundary structure between the Australian and Pacific plates, and is one of the largest sources of seismic hazard in New Zealand. The central section (c. 200 km) of the fault has no previously documented on-fault evidence of the most recent surface rupture (MRSR) and is a challenging setting to obtain paleoseismic data due to thick rainforest and high relief along the rangefront of the Southern Alps.

Using a combination of Light Detection and Ranging (LIDAR), field geologic and geomorphic mapping, we located an unmapped recent scarp of the central Alpine fault next to Gaunt Creek in Westland. There we excavated an exposure along the edge of a fluvial terrace riser where it intersects this scarp and exposed a 4 m high thrust scarp partially buried by post-earthquake overlapping alluvium. We logged this trench exposure and obtained radiocarbon samples from faulted sediments to assist in dating paleoearthquakes along the Alpine Fault. Here we report this fault-zone as a clay gouge zone that thrusts hanging wall Pacific Plate mylonites and cataclasites over unconsolidated late Holocene footwall alluvium. Radiocarbon dates from the scarp coupled with the tectonic geomorphology suggests that this scarp was generated during the most recent earthquake along the Alpine Fault, which most likely occurred around 1717 AD.

This exposure at Gaunt Creek represents the first exposure of the MRSR in bedrock along the Alpine Fault and represents an important site to characterize recent dynamics of the fault. Further analysis at the site may yield slip rate data and further sampling may provide insight into earthquakes along the Alpine Fault. Because the Alpine Fault has not ruptured in historic times, it is approaching the end of its seismic cycle and is a significant seismic hazard to New Zealand.

### **The Mangapapa landslide dam: A geological and geotechnical assessment**

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The Mangapapa landslide dam is situated in the hill-country near the Rangitikei valley, at the headwaters of the Mangapapa River, Manawatu-Wanganui, New Zealand. It is a large rotational slide in Mangaweka Mudstone with an approximate volume of 200,000 m<sup>3</sup>, which formed during the February 2004 precipitation storms which affected the lower North Island. The study was undertaken to analyse the factors which lead to the initiation, and likely failure mode of the landslide.

The field investigation involved traditional engineering geological mapping combined with terrestrial photogrammetry. The rock mass properties of the outcrop were described using the Geological Strength Index (GSI) and the New Zealand Geotechnical Society Guidelines, with samples taken for laboratory strength testing. Discontinuity measurements were recorded in the field, and from 3-D models created by terrestrial photogrammetry. The discontinuity pattern of the site is complex, however kinematic analysis does reveal that flexural toppling is possible mechanism of failure for the hillslope. Investigation of the deposit in 2011, shows that the dam has been breached, with a deep erosive channel cut through the deposit. The lake still remains approximately the same size as when first formed in 2004, with a small prograding delta at the stream inflow site to the lake.

Computer modelling involving limit equilibrium method of slices technique was carried out to determine the initiation factors for the slope failure. A model was created with the rock mass properties defined using Mohr-Coloumb parameters. The initial factor of safety for the site was 1.628 (obtained using Morgenstern and Price method), with increasing pore pressure (defined as  $R_u$ ) being unable to cause instability of the slope. Only with weakened rock mass properties combined with high pore water pressure is the factor of safety of the slope calculated to be unstable.

### **The role of frictional plasticity in normal fault evolution**

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A computational model is used to investigate the evolution of stress and frictional plastic strain in the vicinity of a normal fault over several seismic cycles. A 2-D crust, 60 km across, 25 km deep, and opening at a rate of 12 mm/yr, hosts a single fault dipping at 50° that is subject to repeated lock-slip cycles. Extension of the lower crust is accommodated by viscous creep and in the upper crust by a combination of fault slip and distributed frictional plastic strain (brittle failure). The latter component, which is taken as a proxy for proto-fault development, localises within the hanging wall and is conspicuously absent from the footwall. This asymmetry is described in terms of a frictional plastic failure shadow, defined as the difference between in-situ stress and the Mohr-Coulomb failure stress. The failure shadow flanks the fault to a distance of 1 to 2 km due to episodic coseismic stress drops, and extends disproportionately into the near surface (<2 km) of the footwall block. This second feature is attributed to coseismic recoil and horizontal compression of this fault block, thus lowering the differential stress.

A gradual shallowing of fault dip is also observed over repeated seismic cycles. The total rotation rate is divided into two components of approximately equal magnitude; a slow interseismic rotation associated with horizontal extension and vertical contraction of the crust; and a rapid coseismic rotation driven by pressure changes in the mid-crust. These processes are juxtaposed to present an evolutionary scenario for a zone of normal faulting, and their relevance to observations of basinward -migration of faulting is discussed.

### **Boulder beaches of Tasman Bay: Unique geomorphic features**

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Coarse-gravel beaches and platforms are common features along the eastern margin of Tasman Bay, at the north end of the South Island, New Zealand. Boulder beaches at Nelson, Cable Bay, Croisilles Harbour, and Greville Harbour have traditionally been interpreted as spits, however, incident wave energy is too small to transport boulders and cobbles persistently along the beaches and platforms by longshore drift. Storms may have been more intense during the Pleistocene, but wave energy was still constrained by the geometry of Tasman Bay, which would have been largely exposed during glacial, low sea levels. A model concerning the origin of the beaches and platforms must account for the: (i) local source, (ii) rounded shape, and (iii) poor sorting of the gravels. The boulder beaches appear to be *in situ* features derived from a resistant bedrock, which lies seaward and buried by the platform gravels. The overall shape and position of the beaches is a product of geologic structure and not coastal processes.

All of the boulder beaches have a gravel ridge of pebbles and cobbles lying on a boulder platform. The gravel ridge lies above mean tide level, has fore slope dips of 10° to 15°, and consists of well sorted pebbles and small cobbles. The boulder platform, which begins just below mean tide, dips 1° to 2°, and extends seaward several hundred metres until it is buried by mud and sand of Tasman Bay. The

boulders and cobbles on the surface of the platforms occur as a thin lag and overlie thick accumulations of clast-supported polymictic gravels. Importantly, these features of the Tasman Bay boulder beaches are distinctly different from mixed sand-gravel spits, which are also present in Tasman Bay and clearly a product of present-day coastal processes.

### **Marine Isotope Stage 7 – Ocean response to a warmer world**

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A key question facing environmental science is “How will the ocean respond to the present phase of changing climate?”. Satellite observations show ocean change in a warming world is accompanied by more algal blooms including coccolithophores that contribute to the base of the marine food chain. Such observations, however, span a few decades and a longer, more representative record of plankton change may be derived from the sedimentary archives of past warm climates.

Marine Isotope Stage (MIS) 7 at 191-243 Ka is the penultimate interglacial and may provide an analogue for future ocean change. Marine cores P71 from north of New Zealand (33°51.3'S, 174°41.6'E) and ODP 1120 from Campbell Plateau (50°3.803'S, 173°22.300'S) show abrupt switches from foraminiferal-rich to coccolith-rich sediments in MIS 7, indicating a major change in plankton productivity. The locations of P71 and ODP 1120 allow comparison between Subtropical and Subantarctic oceanic regimes respectively. This study aims to identify the causes of this plankton switch by reconstructing oceanic conditions during MIS 7.

Stable oxygen isotopes are used to establish an age model for core P71. Grain size, CaCO<sub>3</sub>, trace elements, and stable isotopes are deployed as proxies to identify blooms, structure of the water column and sea surface temperatures. Initial results show prominent

nannofossil blooms in MIS 7a, confirming the switch from zoo- to phytoplankton. This is consistent with high Southern Hemisphere insolation during MIS 7a favouring nannofossils tolerant of high light levels. Ocean conditions for the blooms include warmer sea surface temperatures than present, a well mixed upper water column and increased Subtropical inflow. Preliminary results from subantarctic site ODP 1120 suggest less nannofossil productivity during MIS 7a. By investigating the paleoenvironmental conditions that caused the nannofossil blooms in MIS 7a an estimate of future impacts may be achieved.

### **The response of Tasman Glacier, Southern Alps, New Zealand, to the February 2011 Christchurch earthquake**

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Glacier retreat resulting from iceberg calving represents one of the major controls on ice loss from water-terminating glaciers (ice sheets, tidewater and freshwater glaciers) globally. Calving is a particularly important natural process, as calving glaciers can become partially de-coupled from climatic forcing, with such glaciers responding to factors other than equilibrium-line fluctuations. However, the impact that calving has on the transfer of mass between the cryosphere and hydrosphere is still heavily debated, and the physical mechanisms behind calving remain poorly understood. Hitherto, the initiation of calving events has largely been attributed to underlying glaciological mechanisms (including fracturing of ice due to high longitudinal stress gradients) and changes in the proglacial water-body characteristics.

Here we present the first evidence for the occurrence of large-magnitude calving events following high (>M<sub>w</sub> 6) magnitude earthquakes as a potentially important triggering mechanism of calving in tectonically active areas. We describe the response of Tasman Glacier, New Zealand, a freshwater-terminating glacier undergoing accelerated calving retreat, to the M<sub>w</sub> 6.3, M<sub>w</sub> 5.7, and M<sub>w</sub> 4.5 22<sup>nd</sup> February 2011

Christchurch earthquakes and the subsequent calving event. Time-series analysis of timed video and photo records of the glacier front immediately before, during, and after the 22<sup>nd</sup> February earthquakes demonstrate that the large calving event on the 22<sup>nd</sup> February 2011 occurred in direct response to a resonance effect caused by shear (S-) waves oscillating the terminus at the ice-water interface. We also provide evidence that, in this instance, the magnitude of calving was amplified because Tasman Glacier had reached a critical threshold for buoyancy-induced calving in relation to perturbations in lake level. Prior to this event, small- to moderate magnitude calving, leading to the retreat of Tasman Glacier, had been dominated by waterline melt at the terminus destabilising the subaerial ice cliff, with recent (post 2006) large calving events primarily driven by torque-induced-buoyancy driven calving.

Our study illustrates that in tectonically active areas coseismic-initiated calving can have a periodic effect on retreat, potentially destabilising a glacier system leading to accelerated retreat.

### **Earthquakes, rockfall and tsunami - realities of a fiord on an active plate boundary**

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The plate-boundary Alpine Fault runs immediately offshore of the popular tourist destination of Milford Sound, which is visited by more than half a million tourists each year. Glaciers retreated from the area starting approximately 17 ka, leaving behind a legacy of extreme topography, including some of the worlds' highest sea cliffs. Visitors come to view the spectacularly steep and rugged landscape, with many cruising the fiord by boat.

Seismic reflection data suggests that laminated sediments are largely absent in Milford Sound, and that post-glacial sediment infill is dominated by massive deposits of rock avalanche debris. High-resolution multi-beam sonar data, when

combined with available seismic data, reveals the presence of over 20 large post-glacial rock avalanche deposits which blanket much of the fiord bottom. We have also mapped several large terrestrial landslide deposits in the lower catchment; radiocarbon dating shows that these terrestrial deposits are less than 8100 years old.

Coseismic landslides are common in New Zealand; seismic shaking serves as the primary trigger for failures that are preconditioned by progressive degradation of rock mass strength since deglaciation. At Milford Sound, given the close proximity of the Alpine Fault and the high seismicity of the Fiordland region, large landslides are most likely earthquake-initiated. Therefore, establishing an accurate spatial and temporal record of past landslide activity near Milford Sound is an important aspect of understanding and preparing for the possible impacts of a future Alpine Fault or Fiordland subduction-zone earthquake. These impacts may include landslide-generated tsunami, such as those that have killed 174 people in the fiords of western Norway.

We will review the latest landslide distribution data for the Milford Sound area, and discuss possible implications for natural hazards and future risk management.

### **Observations of guided waves within the Alpine Fault, Westland**

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In early 2011 two shallow boreholes (<150 m) were drilled through the Alpine Fault principle slip zone at Gaunt Creek, central Westland and a borehole observatory installed. Historical activity on the fault has been minimal and recent

temporary seismic arrays deployed to observe microseismic activity remain ambiguous on the location of the Alpine Fault principle slip zone at depth (Boese et al., 2011). The observation of Fault Zone Guided Waves will identify events occurring on connected portions of the main Alpine fault system, helping to characterise its interseismic behaviour and physical properties.

Borehole seismometers were installed within the mylonitic cataclasites of the hanging wall and the granitic cataclasite sequence of the footwall close to what are thought to be the principle slip surfaces. Active source and earthquake seismology associated with this installation will eventually help link high resolution observation from recovered core and *in situ* geophysical well logs to more regional geophysical observations. Seismic data quality to date is high. Relative signal strength within the array reveals relative rock competency within the fault sequence and the strong structural control on incident seismic energy. Regional aftershock activity following the 2010  $M_w$  7.1 Darfield Earthquake dominates much of the event catalogue although high rates of local microseismic activity are also observed. Approximately fifty proximal events per month with P-S times < 1 s have been observed. Fault Zone Guided Waves from events with P-S times of up to 4.3 s are observed indicating that episodic, although low magnitude, earthquake activity does occur on the main Alpine Fault trace or strongly linked faults. A preliminary wavelet analysis has been performed on seismic phases trapped within the fault.

#### **A new 1:1 million scale geological map of North Island, New Zealand**

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With the completion of the QMAP 1:250,000 Geological Map of New Zealand dataset, it is now possible to produce a new 1:1 million (M) scale geological map of New Zealand derived from it. The 1:1 M scale map is particularly suitable for presenting a national-level view of New Zealand geology and it is intended to be made available as a printed map, a digital

dataset and through a webmap application. An accompanying illustrated text, summarising the geology of New Zealand, will be produced after the maps are published. The new map will replace the first edition 1:1 M map, published in 1972, which is now out of print.

The process of compiling the map has involved the simplification of each of the 21 QMAP's by selective amalgamation of geological units and redrawing to smooth complicated boundaries and remove small or very thin polygons, as appropriate for reproduction at the smaller scale. Faults are mapped, including most of the known active faults, but of necessity there is significant "thinning" where there are dense clusters of faults in the QMAP dataset. Positional accuracy of the selected 1:1 M faults is retained from the QMAP data. North Island compilation and digital capture is well advanced and an early draft version is presented here; compilation of South, Stewart, and the Chatham islands is underway.

The new 1:1M map will be served to the international OneGeology web portal, replacing the digitised version of the first edition map that is currently available. The 1:1M dataset, including associated attribute data, will be hosted on a server in Wellington and be accessible, using web browser software, from anywhere in the world with internet connectivity.

#### **Models of mixed brittle-viscous behaviour and strain localisation near the base of the seismogenic zone tested against an exhumed natural shear array in the Southern Alps**

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The transition from brittle to ductile deformation with increasing pressure and temperature in the crust is accompanied by a change in strain

localisation, from narrow faulting to km-wide viscous shear. Such transitions can also occur locally near the brittle-ductile transition as a result of differing deformation mechanisms between minerals at microstructural scale, or from rheological layering at larger scales. In a fossil brittle-ductile shear array exhumed in the hanging wall of the Alpine Fault, quartz veins embedded in quartzofeldspathic Alpine Schist have been sheared across a spaced array of small, near-vertical faults. The displacement in schist is generally brittle, whereas that in the quartz veins is variably brittle-ductile. The faults are spaced approximately 0.4 m apart, with a mean displacement of 70 mm per fault, and the depth of deformation has been estimated at 20-25 km.

We demonstrate, based on energy minimisation principals and numerical models, that a shear array such as that observed in the Southern Alps can arise as from mixed brittle-viscous layering in schist and quartz layers near the “tipping point” where brittle and viscous strengths between layers are almost equal. A spaced fault array forms as a result of the competition between viscous and brittle deformation, since the lowest-energy configuration for deforming viscous layers is by distributed shearing, whereas for brittle layers it is by localised faulting. Our models predict that the spacing and degree of localisation will change with ambient strain-rates, temperature, effective stress, and layer thickness and distribution. Since the shear array deformed at depth in the hanging wall of the Alpine Fault, the orientation and magnitude of effective stress and strain-rate may also have cycled transiently over that fault’s seismic cycle, consistent with geological evidence for mixed mode I-II crack formation and fluid pressure cycling.

## Improved data acquisition efficiency using towed EM

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Conventional marine controlled source EM (CSEM) surveys are acquired with autonomous receiver stations located at the seafloor in a sparse layout. A continuous source signal is then emitted from a dipole towed close to the seafloor. At the end of the survey the receiver stations are collected and the recorded data is downloaded for processing and analysis.

With the towed EM system both source and receivers are towed behind the same vessel in an arrangement very similar to 2-D streamer seismic. The dipole source is 400 or 800 m long and towed at 10 m below the sea surface. The receiver cable is towed at 100 m depth and has receiver offsets between 500 and 8,000 m. A transient source signal is used, allowing deterministic deconvolution of the source signature, which can be of any shape. We have now tried a pseudo random binary sequence (PRBS), a square-wave and an optimized repeated sequence (ORS), which in terms of spectral content can be described as a square-wave with the even harmonics included.

There are multiple benefits of the towed EM system:

- Operationally similar to marine streamer seismic
- Improved survey efficiency with source and receivers towed by the same vessel
- Real-time monitoring of source and receivers, and QC of incoming data
- On-board pre-processing
- Dense sub-surface sampling



- Receivers towed above the seafloor. The influence of strong local anomalies at the seabed is therefore minimized
- Facilitates simultaneous acquisition of EM and 2-D seismic

Successful field tests were conducted mid-year 2010 over the Peon gas field and the Troll oil and gas field in the Norwegian sector of the North Sea. A total of 615 line km were acquired over a period of 138 hrs, and the data has been successfully processed and inverted to delineate all targets.

### **Rock-slope failures and glacial valley erosion rates at Vestfirðir peninsula, northwest Iceland - Withdrawn**

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Broad 'U'-shaped valleys and fjords are classic fingerprints of glacial erosion, often associated with pronounced relief, and increased denudation rates. A seemingly intractable problem is that glacial erosion acts across a range of spatio-temporal scales, with few reliable estimates of long-term ( $10^3$  -  $10^1$  ka) erosion rates during oscillatory Quaternary climate. Methods of constraining glacial erosion rates include sediment yields at short (<ka) timescales, cosmogenic radionuclides at intermediate (ka) timescales, and low-temperature thermochronometry at Ma timescales.

An alternative method of estimating glacial erosion rates can be made by considering the size, type (modified or unmodified) and distribution of rock-slope failures in the Vestfirðir peninsula of northwest Iceland. The area consists of an upland plateau 500-970 m a.s.l., indented by >30 fjords eroded during Quaternary glaciations. The geology of the region is strikingly uniform, consisting of upper Tertiary flood basalts with thin interbedded sedimentary layers. Within glacial-

valleys, field reconnaissance and analysis using GoogleEarth reveal that both modified and unmodified rock slope failures (RSFs) occur, with the unmodified RSFs consisting of a scar, and an adjacent debris lobe immediately downslope. Most of these unmodified features are <1 km wide, while in contrast, modified RSFs tend to be larger (>1 km), lack an adjacent debris lobe, with the scar truncated by glacial erosion to varying degrees. The size-frequency differences between modified and unmodified RSFs can be attributed to glacial erosion, with the smallest RSFs from the last interglacial completely removed from the valley sides, whereas larger (modified) RSFs have survived. Thus, delineating the smallest surviving RSF provides a depth of glacial erosion along valley sides during the last MIS2-5d glacial cycle, which can be converted into a glacial erosion rate using paleoclimate records. The largest RSFs appear to grow by elongation, corroborating a model of cirque formation identified in the New Zealand Southern Alps.

### **Vertical land motion from GPS, DORIS, and combined satellite altimetry and tide gauge sea level records in Tahiti and New Zealand**

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The determination and monitoring of vertical land motion is of crucial importance in the observation of long-term sea level change and its reconstruction, but is among the most challenging, tasks for space geodesy. We compare the vertical velocity estimates of Tahiti Island obtained from five independent geophysical measurements, namely a decade of GPS and DORIS data, 17 years of sea level differences (altimeter minus tide gauge (TG)), ICE-5G (VM2 L90) Glacial Isostatic Adjustment (GIA) model predictions, and coral reef stratigraphy. Except for the GIA model, all the techniques are in a good agreement and reveal a very slow subsidence of the Tahiti Island that averages -0.5 mm/yr, which is barely significant. We also present altimeter minus tide gauge sea level difference time series for the long record tide gauges in New Zealand.

**Evolution of an unstable Turbidite Channel Complex: Whangaparaoa Head, Waitemata Basin, New Zealand**

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Whangaparaoa Peninsula Head, New Zealand, exposes part of the Miocene Waitemata Basin infill, located in a convergent tectonic setting. The Waitemata Group comprises deepwater gravity flow deposits including slumps, slides, debris flows and turbidites. Outcrops at Whangaparaoa Head demonstrate the evolution of an unstable channel complex involving large erosional events associated with the emplacement of Mass Transport Deposits (MTDs), deposition of channelized conglomerates, levees and highly deformed material interpreted to result from lateral collapse.

Levee deposits are represented by thinly bedded turbidites containing climbing ripples, convolute laminations and ripped-up mud clasts (CCC turbidites). An incisional MTD contains a basal, clast-supported block/boulder class conglomerate which grades to a chaotic, matrix-supported boulder conglomerate. The upper section contains slide blocks of folded sandstones and deformed heterolithics. A slump deposit contains stacked, large-scale folds and is bounded by flat lying strata. Channelised deposits are represented by thick bedded, amalgamated medium-grained pebbly sandstones to very large pebble-sized conglomerates, with an incisional base. Amalgamation surfaces are inferred from sharp grain-size breaks with associated horizons of rip-up clasts. The evolution of this channel occurs as follows system can be explain in stages: (i) early incision of the channel, and deposition of levees, (ii) channel incision

and sediment by-pass from multiple, highly erosive and depositional debris flows (MTD), (iii) over-deepening of channels from debris flow incision, slumping occurs as levees fail, (iv) aggradational channel turbidites deposits flanked by levees as the system heals.

Whangaparaoa Head provides an example of an evolving turbidite channel complex, providing evidence of multiple incisional, collapse and heal events. A variety of flow types are involved in these deposits displaying the heterogeneity of the system. We can infer large-scale architectural implications from these observations.

**Experimental calibration of phreatic and hydrothermal explosions: A case study on Lake Okaro, New Zealand**

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Phreatic and hydrothermal eruptions often occur with little or no warning, representing a significant hazard. They occur at a range of temperatures and pressures within varying rock types. These eruptions can lead to increased local permeability and the development of shallow hydrothermal resources. A range of mechanisms including heating or decompression allows hydrothermal/ supercritical fluid to rapidly flash to steam, triggering an eruption.

Previous studies have focused exclusively on either physical characteristics of eruptions or experimental modelling of trigger processes. Here, a new experimental procedure has been developed to model phreatic fragmentation based on shock tube experiments for magmatic fragmentation by Alidibirov & Dingwell (1996). Water saturated samples are fragmented from a combination of argon gas overpressure and steam flashing within vesicles. By integrating physical characteristics of porosity,

permeability and mineralogy with analysis of these experimental results a model of phreatic fragmentation is proposed, to aid future hazard modelling.

The phreatic explosion forming Lake Okaro, Taupo Volcanic Zone, was used as a case study. Eruption was triggered within the Rangitaiki Ignimbrite, therefore serving as the experimental sample material. To evaluate alteration effects, both original material and hydrothermally altered samples were analysed. Experiments were performed at room temperature and 300°C and pressures from 4 to 15 MPa, to reflect the conditions at the study location while also assessing the effect of water saturation on fragmentation. First analyses of grain sizes reveal a clear shift to smaller grain sizes with saturated samples (independent of pressure/sample type) possibly reflecting improved efficiency in the conversion of energy, most likely in combination with strength reduction due to saturation. We provide herewith a first parameterisation of conditions for phreatic and hydrothermal eruptions and offer an explanation for the reduction in grain size associated with phreatic eruptions.

**Causes and consequences of climate change during the Mi-1 Event: palaeoclimate data from the Foulden Maar core**

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Foulden Maar is an annually-resolved maar lake deposit dating from the Oligocene/Miocene

boundary. The deposit represents the first high-resolution terrestrial record of the O/M boundary and the rapid deglaciation of Antarctica that occurred during the second half of the Mi-1 event. A c. 180 m long core from the centre of the lake bed comprises c. 60 m of basal graded breccias, sands and muds overlain by c. 120 m of diatomite punctuated by volcanogenic horizons. The diatomite succession consists of mm-scale light-dark couplets and diatomaceous turbidites.

Radiometric dates from basaltic clasts found at c. 110 m depth (close to the base of the diatomite succession) give ages of  $23.45 \pm 0.25$  Ma and  $23.68 \pm 0.36$  Ma. Palaeomagnetic analysis places the base of the diatomite succession at the Oligocene-Miocene boundary and the peak of the Mi-1 event. Orbital tuning shows that the diatomite section of the core covers 100,000 years.

Wavelet analysis of high-resolution RGB data shows that 2-8 year ENSO-scale cycles are present throughout the diatomite succession. These cycles are modulated by a 2000-year signal, similar to that found in present-day ENSO records. Millennial-scale cycles are also present and may be related to glacial advance and retreat.

Stomatal index values from *Litsea* and *Podocarpus* leaves show an atmospheric carbon dioxide level of c. 400 ppmv at c. 23.01 Ma (77 m depth below the top of the core), with concentration increasing to c. 800-1200 ppmv at c. 22.98 Ma (55 m) and dropping back to c. 400-600 ppmv at c. 22.9 Ma (0 m, the present-day surface outcrop). This short-lived, rapid increase in atmospheric carbon dioxide concentration coincides with the initiation of the deglaciation phase of the Mi-1 event and implies that CO<sub>2</sub> was the driver of this deglaciation.

## Source-scanning the $M_w$ 6.2 Christchurch Earthquake

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The  $M_w$  6.2 Christchurch earthquake yielded one of the densest datasets of near-field ground motions ever recorded. We exploit the density of this dataset by using it to search a 3-D volume around the source region for likelihood of potential sources at discretized time steps during the rupture process. We accomplish this by dividing the source region into a regularized grid of voxels. At each 0.1 s following the origin time, we define the likelihood of rupture in each model element by calculating the travel time from the respective element to each recorded seismogram and summing the normalized envelop magnitude of the seismogram at the hypothetical arrival time. We use an infinite-frequency ray approximation which implies a 1-D wave sensitivity and a relatively smooth medium through which the waves propagate. This allows us to describe the general nature of the rupture evolution in 4-D by substituting migrating point-sources for a more realistic discretized finite fault. To test the use of the point-source approximation and the limits of resolution resulting from our signal pre-processing, we are currently generating synthetics based on the summing of temporally offset dislocation patches. With no a-priori information other than a background velocity model, we are able to determine the appropriate conjugate fault plane as well as make bulk estimations of rupture velocity. We also describe general characteristics of the evolution of energy radiation. We believe that this method can be a powerful tool in determining fault geometry in the critical first few hours following a major event. Furthermore, we believe that these observations provide important constraints on the geometry and strength of asperities for forward calculations of the seismic wavefield.

## Remarkable preservation of carbonaceous plant fossils in blueschist facies metamorphic rocks from Nelson, New Zealand

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Evidence of ancient life is widespread in sedimentary rocks that have been buried at shallow depths in the Earth's crust. However, metamorphism is detrimental to the preservation of biological information, thereby limiting the geological record in which traces of life might be found. We report here on fossil leaves from Marybank Formation, Nelson, New Zealand, which display remarkable morphological and chemical preservation, yet have been subjected to blueschist (c. 350 °C and 8 kbars) facies metamorphism.

Leaves and stems are easily identified at the macroscale. A combination of microscopy (TEM) and spectromicroscopy (STXM-XANES, EFTEM, Raman) methods were used to examine both carbonaceous material and inorganic nanocrystals within the fossils down to nanoscale. Initial biological polymers have been completely transformed to graphitic carbonaceous matter down to the nm-scale.

Fossil carbonaceous material shows a high degree of graphitic ordering. sp<sup>2</sup> hybridized carbon atoms are locally associated with carboxylic radicals and other oxygenated functional groups. EFTEM, EDX analyses, and FT-HRTEM diffraction patterns reveal the presence of numerous acicular anatase and rutile nanocrystals (c. 100 nm) within the fossils. This is the first report of nano-TiO<sub>2</sub> partial mineralization of biological tissues. Textural evidence provided by TEM points to a diagenetic authigenic growth of oxides, probably associated with an early hydrothermal event. Polygonal structures with walls mineralised by micas within the leaf midribs and blades, may derive from the original cellular ultrastructure of the leaves or, alternatively, from the shrinkage during burial of the gelified remnants of the leaves in an abiotic process.

The Nelson fossils show that life-forms can survive major geodynamic processes, such as high-pressure metamorphism which cause deep changes and homogenisation of their carbon chemistry and structure, yet still retain their morphology with remarkable integrity. It suggests the geological record in which traces of life can be found may be much greater than previously thought.

**Compressional reactivation of E-W basement faults in the region of the 2010-2011 Canterbury earthquake sequence: Questions of inheritance**

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The 2010-2011 Canterbury earthquake sequence involved the rupturing of blind, inherited discontinuities as well as new-formed immature faults, all previously unrecognised.

Re-interpretation of public domain exploration wells, seismic reflection lines and gravity surveys in the region between the Ashburton and Ashley Rivers allows reconstruction of the top-to-basement surface, with the imprint of an ENE-WSW to E-W fabric of former normal faults inherited from Late Cretaceous-Eocene rifting. The band of rupturing illuminated by seismicity lies along the southern boundary of the Late Cretaceous Pegasus-Rangiora basin, terminating against the Banks Peninsula structural high.

Structures revealed by a set of medium-to-good quality seismic lines in the Ashley River region (Surveys by Indo-Pacific Ltd, IP-256-99 and IP-256-00 tied to the Arcadia-1 well) form a good analogue to the Greendale Fault, some 20 km to the south, where comparable information is not available. Interpretation of depth-converted seismic lines reveals compressional inversion of inherited, high-angle east-west blind faults with asymmetric folding and detachment of the Neogene cover sequence, and propagation of new faults through the Pliocene and Quaternary cover sequences. A component of strike-slip is suggested by “flower” geometry along some of the faults.

The largest rift-related normal faults within the inherited extensional fabric penetrate to at least mid-crustal levels within the Rakaia Terrane. Such steep, pre-existing, east-west structures are favourably oriented for reactivation in the contemporary stress field, where maximum compression ( $\sigma_1$ ) is oriented  $115^\circ \pm 5^\circ$ .

However, the complexity of rupturing revealed by the distribution of seismicity and focal mechanisms cannot solely be ascribed to reactivation of inherited faults, and requires development of new fault segments linking older structures and branching from pre-existing discontinuities, as well as creation of northwest-southeast conjugate strike-slip faults that are not readily apparent in the inherited basement fabric.

**Imaging active and relict seafloor methane seep sites: a comparison of seafloor 3D seismic reflectivity and multibeam sonar backscatter intensity at Omakere Ridge, Hikurangi Margin, New Zealand**

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Omakere Ridge is an anticlinal thrust ridge in water depths of 1100-1700 m on the Hikurangi Margin, east of the North Island of New Zealand, and an area of active seafloor methane seepage associated with an extensive gas hydrate province. Methane seep sites on the Hikurangi Margin are characterised by localised build-ups of hard authigenic carbonate and chemosynthetic seep fauna that exist on a seafloor otherwise characterised by soft, muddy sediments. Previous studies have shown that these seep sites appear as areas of high backscatter in sonar images, but backscatter data alone do not provide detailed information on the present level of activity of a seep site, or the thickness of the carbonate build-up.

Here we present a comparison of seafloor seismic reflectivity and multibeam sonar backscatter intensity data collected from active and relict methane seep sites on Omakere Ridge. High-resolution P-Cable 3-D seismic reflection data and 12 kHz EM120 multibeam sonar data were collected in March 2011 during the RV Sonne cruise SO214. Seafloor seismic amplitude maps have been derived from the shipboard post-stack migrated data cube. A pronounced acquisition artifact is manifest in the seafloor horizon slice as high and low amplitude stripes that alternate periodically in the crossline direction. We have removed this

artifact from the seafloor horizon slice using Kx-Ky filtering, followed by direct sampling and deterministic removal of the very-low-frequency components in the spatial domain. The seismic amplitude map has then been transformed into a calibrated seafloor reflection coefficient map. Sonar backscatter mosaics have been created after correcting for instrument response, angular variation in backscatter and bathymetry. Several backscatter mosaics were incorporated into a stacked mosaic over the study area to attenuate random noise. The high sonar backscatter response at the seep sites is generally accompanied by high seismic reflectivity. However, the presently active seep sites exhibit lower seismic reflectivity than the extinct Moa site.

The joint interpretation of seismic reflectivity and sonar backscatter data holds promise as a powerful tool for improving our understanding of seep activity and carbonate build-up at methane seep sites on Omakere Ridge and the wider Hikurangi Margin.

**Characterisation of active structures and Quaternary channels on the shallow shelf of Otago by high-resolution seismic and side scan sonar imaging**

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The shallow and narrow continental shelf off the coast of Otago has unique geological characteristics due to the juxtaposition of active coast-parallel contractional faults related to the nearby Pacific-Australian plate boundary and late-Miocene shield volcanism that affects the structural and sedimentological regimes of the region. For example, the offshore extent of the active Akatore Fault, a northeast-southwest trending reverse fault that runs along the coast southwest of Dunedin, is poorly constrained to the northeast where it intersects the Dunedin Volcanic Complex. Historical earthquakes, including those of 1974 and 1989, are attributed to this fault or others closely associated

with it. The Dunedin Volcanic Complex also has impacted Quaternary erosional and sedimentation patterns on the shelf as a result of topographical features that affect drainage and sediment transport.

Single-channel electro-acoustic boomer seismic reflection data and side scan sonar profiles have been collected along a c. 35 km long section of the shallow shelf southwest of Dunedin over the last three years in water depths between 10 and 75 m and to a maximum of 28 km offshore. Survey lines (mostly perpendicular to coast) are c. 250 m apart near shore and up to 5 km apart offshore. Primary reflections were recorded to sub-seafloor depths of <100 m.

Several significant structures have been imaged within the survey area, principally the Akatore and Green Island Faults. The Akatore Fault is imaged very near shore in the southern portion of the survey, and a minimum post-Miocene displacement of 55 m was calculated. Offset on the Green Island Fault, a high-angle reverse fault, was relatively well constrained to c. 200 m (east side up). Pleistocene paleovalleys are also imaged along this section of the coast, providing evidence for the drainage system present in the area during periods of sea level low stands.

### **Plio-Pleistocene cyclostratigraphy from marine sediment cores, Wilkes Land, East Antarctica**

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Wilkes Land as a marine-based margin of the East Antarctic ice sheet (EAIS), could respond dynamically in “warmer-than-present” Pleistocene interglacials and Pliocene warm periods, as has been recorded for the West Antarctic ice sheet (ANDRILL). Sites U1361 and U1359, are situated on the eastern levee of Jussieu submarine channel, and were collected during the Integrated Ocean Drilling Program (IODP) Leg 318 expedition to Wilkes Land, East Antarctica. These sites are examined to identify the timescales and potential driving mechanisms that have led to sedimentary

cyclicality recorded in the continental margin sediments.

Sedimentary cyclicality over orbital cycles is influenced by the complex interplay between variations in ocean circulation, variability of the sea-ice field with implications for the activity of local coastal polynya, and oscillations in the proximity of the EAIS grounding line. An integrated approach combining physical properties and sedimentary core lithofacies within a well-constrained chronostratigraphic framework will be used to evaluate the nature and timing of cyclic sedimentary processes occurring at this margin.

The age-model, constructed using magnetic polarity and biostratigraphy constraints, is of sufficient resolution to allow Milankovitch periodicity to be identified. Spectral analysis techniques are used to determine orbital components in the data, and their phase relationships with other climate forcing time series will be evaluated. Continuous segments of the cores characterising the Plio-Pleistocene will be targeted for the initial phase of this analysis.

Initial studies on the cores indicate periodic oscillations in physical properties logs including magnetic susceptibility, density, natural gamma, and colour reflectance data. Compilation of these time series and comparison to other data sets (e.g., facies analysis, geochemical datasets) from IODP Leg 318 will help identify sedimentary processes and temporal variability of past oceanic and ice sheet changes, and allows for assessment of the sensitivity of the marine based margin of the EAIS to orbital forcing through the Late Neogene.

### **Holocene origins of Lake Oneke, Wairarapa**

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Lake Oneke, in the southern Wairarapa, is today an unusual 6 km<sup>2</sup> alternating tidal lagoon-brackish lake. Foraminiferal faunas indicate

the early Holocene (6500-4000 cal yr BP) presence of an elongate (30 km long), mostly intertidal embayment extending up the lower Wairarapa Valley beneath present-day Lakes Onoke and Wairarapa. Foraminifera-based elevation estimates suggest that during the early Holocene, this embayment subsided at a rate of c. 12 mm/yr, sufficient to accommodate the accumulating mud and retain an extensive area (>20 km<sup>2</sup>) of tidal flats. A slowing rate of subsidence accompanied by eustatic sea level fall probably account for late Holocene aggradation.

A much larger, ancestral Lake Onoke (c. 20 km<sup>2</sup>) was created 4000-3000 cal yr BP, presumably by the growth of a gravel barrier across the previously open mouth to the sea. During the late Holocene, river sand prograded southwards into ancestral Lake Onoke creating swampy alluvial flats that separate modern Lake Onoke from its freshwater counterpart, Lake Wairarapa.

### **Getting the most out of New Zealand exploration wells**

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There are some 300 petroleum exploration wells in and around New Zealand that can provide a wealth of geological data and insights from their petrophysical logs. As part of the Petroleum Exploration and Geosciences Initiative (PEGI) project, funded by New Zealand Petroleum & Minerals, the aim of one of the modules was to create a digital well database and petrophysical atlas for New Zealand exploration wells. The scope of this module involved evaluating digital wireline logs, from openfile petroleum reports, over several basins in New Zealand.

Once the initial evaluation was done, the task was to develop a consistent framework for assessing rock properties and petrophysical parameters of reservoir and seal rock intervals, thereby creating a petrophysical atlas of

New Zealand. Work focussed on basic data collection and deriving standardised practices for the New Zealand setting. This project was a pilot study that provided reviewed and analysed data from a selection of wells, in digital format, using the following workflow:

1. Load raw well data into an industry standard database system (in this case, Petris Recall™).
2. Undertake rigorous quality control of the raw data, to produce a suite of consistent and reliable curves.
3. Develop and document a standardised methodology for quality control and analysis applicable to the New Zealand petroleum setting.
4. Perform basic petrophysical analyses following the standardised methodology to develop a consistent analytical framework.
5. Provide a digital output of the results, including a table detailing basic well information, available data, coefficients and constants used in the analyses, and additional notes relevant to the well analysis, and a summary plot of all the output data.

The results of this study will be released to the geological community next year by New Zealand Petroleum & Minerals, as part of the wider PEGI release. This poster displays the methodology used in the petrophysical analyses of a selection of Taranaki Basin exploration wells.

### **Performance of guttering under ash loading: Volcanic Ash Testing (VAT) Facility**

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This project makes a preliminary analysis of the impact of volcanic ashfall on roofing materials and the performance of gutters under ash loading. Testing was undertaken in the Volcanic Ash Testing (VAT) Facility, housed in the basement of the von Haast



building at the University of Canterbury, part of a multidisciplinary, multi-organization 'VAT Lab' collaboration. At this facility, an adjustable frame, capable of holding roofing iron at different angles and different types of guttering, has been constructed to assess the effects of different loadings of volcanic ash. The frame is able to be tilted from horizontal to 50°, and ash is dispensed from an overlying sieve, which dispenses the ash evenly over the surface in a rocking motion. Due to the successive earthquakes only preliminary tests with dry pseudo-ash using this facility were able to be achieved, it is anticipated further tests will be carried out later in the year.

Initial testing of galvanized roofing iron and plastic (Marley) gutters showed that at low roof angles (15°) most ash stayed on the roof and the effect on the gutter was minimal; at medium angles (25°) ash began to move downslope on the roof and collect in the gutters, particularly below the troughs of the corrugated iron roof. Ash thicknesses were higher on the outside (front) of the gutter, with some ash sticking to the inside of the gutter and entering the roof cavity; at high angles (45°) ash moved rapidly down the roof troughs and straight into the gutter, rapidly blocking it. Once spouting infilled talus-like aprons of ash accumulated within roof troughs, with the position of ash remaining static between 200 – 250 mm from front edge of roof, with excess ash material shed over front lip of guttering.

### **Evolution of the Colville and Kermadec Arc mantle**

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The Colville-Lau volcanic arc, an intraoceanic arc active c. 17-5 Ma (Mortimer et al., 2010, JVGR, 190, 1-10), represents the earliest known manifestation of subduction zone volcanism in the region of the present day Kermadec Arc – Havre Trough. Opening of the Havre Trough

(c. 5.5 Ma) split the Colville arc producing two sub-parallel ridges: Colville Ridge to the west and Kermadec Ridge to the east. In the Southern Kermadec arc, the Kermadec Ridge lies trenchward of the currently active volcanic front, with no evidence of recent magmatic activity. Relatively fresh lava samples from the Colville and Kermadec Ridges were collected in three dredges on the RV Tangaroa KARMA cruise (Kermadec ARc Minerals) in May 2010. This provides a unique opportunity to compare and contrast volcanism from two arcs in the same region over c. 17 Ma, particularly the magmatic processes involved in formation of an arc system and depletion and fluxing of the mantle wedge by slab fluids over time.

The Ridge samples are highly porphyritic basalts (45–52 wt% SiO<sub>2</sub>) with distinctive whole rock major element compositions that reflect accumulation of predominantly plagioclase (+olivine). Glass compositions follow tholeiitic melt evolution trends that overlap modern volcanic front basalts and basaltic-andesites: the Miocene magmas predominantly differ from the modern system in the crystal loads they have incorporated. Plagioclase phenocrysts have comparable An contents ( $\leq \text{An}_{98}$ ) but significantly higher K-contents ( $> \text{Or}_{0.4}$ ). Preliminary trace element data suggest the mantle wedge source has become progressively more depleted since Miocene times, and that the Miocene mantle wedge carried a well-developed subduction signature, albeit with not as high fluid enrichments as the present day arc (e.g., Ba/Nb = 84 – 300 compared with Ba/Nb c. 80- 500).

### **High-flying diatoms: Widely dispersed microfossils from a New Zealand supereruption.**

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We present the first documented occurrence of diatom remains in the deposits of a widely dispersed volcanic eruption. Thirty-six freshwater diatom species have been found in the phreatomagmatic deposits of the 27 ka

Oruanui supereruption from Taupo volcano. The abundance of diatoms and their presence throughout the phreatomagmatic phases of eruption suggest that they originated from paleo-Lake Taupo, an extensive lake overlying the vent site during the Pleistocene. Although diatoms are also found in deposits 10-40 km from the Oruanui vent, the greatest abundances are at a site c. 80 km to the northeast (near Murupara-Galatea), indicating that size fractionation and preferential settling downwind played a role in deposition. The most common diatom in the Oruanui deposits, *Aulacoseira ambigua*, occurs in relatively few New Zealand lakes but is dominant in one of two previously documented Huka or Whirinaki diatomites from paleo-lake Taupo. The floras are predominantly (>75%) planktonic, which is also consistent with a deep lake origin.

Using these data we propose a novel mechanism for the long-distance dispersal of windswept diatoms in large-scale volcanic plumes, which are known to deposit material hundreds of kms from source. Wider implications for this newly recognised mechanism include: (i) a means of characterising the source of surface water in phreatomagmatic eruptions (i.e. seawater or freshwater), (ii) providing information about material excavated and dispersed during explosive eruptions, and (iii) the possibility that diachronous diatoms (i.e., 'older' diatoms deposited on top of young strata) may be explained by contamination from far-field volcanic processes. By extension, volcanogenic diatoms are a possible source for some diatom remains found in Antarctica ice cores.

#### **Foraminiferal evidence for Holocene synclinal folding at Porangahau, southern Hawkes Bay, New Zealand**

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Porangahau, southern Hawkes Bay, lies above the Hikurangi Subduction Zone in the transition zone between strong and weak plate interface

coupling. This coastal area is unusual in the absence of uplifted Holocene coastal terraces or active fault traces. Holocene estuarine foraminiferal faunas in five short cores in the southern part of the Porangahau coastal plain were used to estimate paleo-tidal elevations of sediment accumulation. These show that the western side of the plain, deposited c. 6 ka, has been uplifted by 100-250 cm, after allowing for mid Holocene higher sea level. Faunas in the estuarine sediment infill forming the southeastern part of the plain indicate compaction-corrected subsidence of c. 80-400 cm since 3 ka. We infer that the Fingerpost Syncline extends northwards beneath the Porangahau coastal plain and is actively deforming with a Holocene tilt rate of 0.017-0.05 °/ka on the western flank.

#### **Electromagnetic image of the Hikurangi subduction interface, Raukumara Peninsula, New Zealand**

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Data from a pilot magnetotelluric survey of 34 sites along two lines roughly parallel and perpendicular to the strike of the subduction on the Raukumara peninsula have been inverted. This 3-D inversion shows a dipping electrically-conductive zone aligned with the subduction interface which at deeper levels is interpreted to mark a zone of under-plated sediments in good agreement with seismic data. The strike-perpendicular profile lies at the northern margin of a patch of the subduction interface that undergoes slow slip events. Large along-strike resistivity changes are also observed which suggests that the process of sediment and fluid transport varies significantly along strike with important implications for inter-plate coupling.

**The SAHKE Experiment: acquisition and preliminary results across the interseismically locked southern Hikurangi margin, New Zealand**

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The passive and controlled source Seismic Array HiKurangi Experiment (SAHKE) project is designed to investigate the structure of the forearc and the physical parameters controlling locking at the Australian-Pacific subduction plate boundary beneath the southern North Island. The first tranche of SAHKE data were acquired between November 2009 and April 2010, in conjunction with a government-funded marine seismic survey, and included a dense temporary array of 50 seismometers with c. 7 km spacing that recorded local and teleseismic earthquakes over a four month period. In addition, over 69,000 offshore airgun sources were recorded by the distributed array during the marine multichannel seismic survey. An additional coast-to-coast onshore-offshore transect was augmented by deployment of 20 ocean bottom seismographs. In the second tranche of SAHKE, 12 in-line 500 kg explosions were recorded on an 832 station coast-to-coast deployment during May 2011. Station spacing was 100 m and, between Kaitoke and Featherston, the spacing was reduced to 50 m. Preliminary 2-D tomography and ray-tracing of the transect data provides improved geometry of the subducting Pacific plate beneath the lower North Island.

**Explosive volcanism in the Kermadec Arc, SW Pacific: Insights from sediment cores**

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Studies along the Kermadec Arc over the past two decades have shown the presence of numerous volcanoes with histories of caldera collapse, and abundant evidence of explosive eruptions involving evolved magmas (dacite to rhyodacite). However as there are only two substantially emergent volcanoes in the arc, Raoul volcano and Macauley volcano, the history of this explosive volcanism is difficult to constrain. On Raoul Island at 3.7 ka there was a change from basaltic-basaltic-andesite activity to dacite, and it is unknown if this reflects a new style of activity or if older silicic volcanism has occurred. Sediment cores collected offshore from Raoul and Macauley islands on the *R/V Tangaroa* TAN0706 voyage in May 2007 yield numerous tephra layers that reflect eruptions dating back to well before 50 ka.

A preliminary study (Shane and Wright 2011, *J. Quat. Sci.* 26, 422) identified 27 homogeneous tephra layers erupted over the past 50 ka. Re-examination of these cores and further analysis using visual examination, X-ray imaging, spectrophotometry and magnetic susceptibility has yielded a further 27 homogeneous tephra layers, along with other tephra layers with bimodal glass compositions. Initial data from microprobe analysis on glass shards provides evidence of dacitic volcanism predating 50 ka, implying that silicic volcanism is not simply a recent development. Dating using O-isotopic analysis of foraminifera will be used to extend the existing radiocarbon chronology to provide a time-resolved record of explosive volcanism at these centres. Trace elements in single glass shards and age constraints provided by the O-isotopic analyses will be used to correlate tephra layers between cores and hence arrive at an accurate assessment of the number of individual eruptions represented in the cores.

## How did pre-European Maori perceive geology?

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Maori oral tradition and science are largely independent bodies of knowledge, but their comparative study may lead to a better understanding of pre-European Maori knowledge of earth systems. This study should extend to pre-European place names and their relationship with local geographic and geologic features.

We recognise Maori oral tradition as a vehicle carrying accepted cultural practises and traditions (tikanga and matauranga) through the generations. In the absence of the written word, these oral traditions, the foundation of Maori culture and society, were treasured by those who were responsible for them, and passed on to specially selected guardians of younger generations. Stories commonly included characters akin to 'superheroes' who undertook impossible tasks in difficult circumstances. These extraordinary characters and their achievements are seen as incredible when viewed with a hard scientific eye. However, the stories commonly include 'background' observations of a world recognisable by the people of the time as reflecting the 'real' world.

Completion of the national QMAP series of 1:250,000 geological maps provides an opportunity to test Maori oral tradition against modern geological understanding. Preliminary comparison reveals some observational elements in common between these bodies of knowledge and suggests that Maori knew more about geology than they have previously been given credit for.

Comparison of these knowledge bodies and identification of common observations potentially

benefits each. Maori will better appreciate pre-European knowledge and science may retrieve pre-European observations, providing information that can be independently tested.

## Evidence of drilling predation and sublethal damage in Late Cretaceous brachiopods from the *Ostrea* Bed, North Canterbury, New Zealand

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Several hundred brachiopods were separated from a bulk sample taken from a single locality of the Late Cretaceous *Ostrea* Bed at the top of the Broken River Formation in the Weka Pass area of North Canterbury. The specimens were divided among three different species but only two of these were used further in this analysis because the third was represented by only a few individuals. Complete shells of each of the two more common species were examined for signs of drilling predation and sublethal marginal damage.

The small rhynchonellide, *Wekarhynchia cataracta* Hiller 2011, showed evidence of drilling predation in 21% of its sample. Holes were recorded in both dorsal and ventral valves but usually only one valve of each individual is bored. In most cases, a single hole appears in a shell but there may be as many as three. Drill holes tended to be concentrated in the posterior half of each shell and in most cases away from the margin. The other species examined, *Ostreathyris allani* Hiller 2011, showed no evidence of drilling predation. The relatively thick shell and strong radial ornament of this aberrant terebratulide is believed to have offered protection against this form of attack. The identity of the predator(s) involved cannot be unequivocally ascertained but carnivorous gastropods are thought to have been the most likely perpetrators. However, no gastropod specimens were recovered from the bulk sample.

A small number of specimens exhibited damage to the shell margin, which had subsequently been repaired by continued shell deposition. Such injuries are paired, i.e., they occur on both dorsal and ventral valves, and were probably caused by crushing durophagous predators, such as fish or crustaceans. As with drilling predation, marginal damage was only identified in the rhynchonellide brachiopod but is interpreted as representing inadvertent attack whereas the drilling predation appears to represent targeted attack.

### **The formation and hydrothermal alteration of the Samail Ophiolite, Oman**

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The Samail Ophiolite in the Hajar Mountains of Oman is the largest, best exposed, least deformed outcrop of ophiolite worldwide. This provides the unique opportunity to study a representative section of oceanic lithosphere extending over 500 km along strike. The geology surrounding Ghuzayn in the Wadi Hawasina region of the Hajar Mountains was mapped at the scale of 1:10,000 and rock samples were collected for laboratory analysis. The dominant rock types in this region are those of the Samail Ophiolite group with minor outcrops of associated sedimentary units. The exact setting in which the Samail Ophiolite formed is still debated, as the geochemical signature of the volcanic units is not distinctive. Isotopic evidence from the Ghuzayn volcanics is inconclusive due to depletion of trace elements as a result of hydrothermal alteration. The ophiolite suite has been extensively altered as a result of seawater derived hydrothermal fluids circulating through the crust prior to obduction. In the Ghuzayn region, mineralisation associated with hydrothermal alteration has resulted in the accumulation of volcanic massive sulphide deposits which formed in a setting analogous to modern day black smokers. Determining the precise history of hydrothermal alteration events is problematic due to limited data and the overprinting of successive events which has resulted in complex alteration textures and mineralogy.

### **The early Eocene Succession at Tora, New Zealand; stratigraphy and paleoclimate**

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A succession of sedimentary rocks previously unstudied in a paleoclimate context is exposed at Tora, southeast Wairarapa. This study aims to produce a detailed paleoclimate and paleoenvironmental record of the warm climates of the late Paleocene to the middle Eocene from the sedimentary rocks using microfossil assemblage studies and reconstructed sea surface temperatures based on foraminiferal Mg/Ca ratios.

A moderately coherent package of calcareous and siliceous mudstones of early Eocene strata that is exposed in Awheaiti and Pukemuri Streams contains relatively well-preserved foraminiferal assemblages suitable for geochemical and biostratigraphic analysis. Stratigraphic relationships are complicated by faults, folding and syn-depositional slumping, but careful mapping in conjunction with foraminiferal and calcareous nannofossil biostratigraphy has produced a near-complete succession of Teurian to Heretaungan strata (c. 55-46 Ma).

Stable isotope ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) analysis of bulk carbonate has produced patchy results, with strongly negative values suggesting diagenetic alteration of the original carbonate and possible some contamination with carbon from organic matter. Preservation improves in younger material and stable isotope results suggestive of diagenetic alteration will be used to screen out samples used for Mg/Ca analysis. A subset of foraminiferal specimens from the best preserved samples will be selected and subsequently analysed via the Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) method to determine Mg/Ca ratios, which will be used to reconstruct Early Eocene sea temperatures.

This study aims to provide a critical North Island reference for sea temperatures during a period of extreme global warming, referred to as the Early Eocene Climatic Optimum. Particular focus will be given to correlating the results with mid-Waipara River, and Hampden Beach sections as well as DSDP Site 277 (Campbell Plateau). Research will be integrated into the GNS Science Global Change through Time Programme, and findings used to test climate models for Eocene greenhouse conditions.

### Revised date for the Taupo Eruption

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Taupo volcano in the central North Island is the most frequently active and productive rhyolite volcano on Earth. Its latest explosive activity about 1800 years ago generated the spectacular Taupo eruption, the most violent eruption known in the world in the last 5,000 years. We present here a new accurate and precise eruption date of AD 232 ± 5 (1718 ± 5 cal. yr BP) for the Taupo event. This date was derived by wiggle-matching 25 high-precision <sup>14</sup>C dates from decadal samples of *Phyllocladus trichomanoides* from the Pureora buried forest near Lake Taupo against the high-precision, first-millennium AD subfossil *Agathis australis* (kauri) calibration dataset constructed by the Waikato Radiocarbon Laboratory. It shows that postulated dates for the eruption estimated previously from Greenland ice-core records (AD 181 ± 2) and putative historical records of unusual atmospheric phenomena in ancient Rome and China (c. AD 186) are both untenable. However, although their conclusion of a zero north-south <sup>14</sup>C offset is erroneous,

and their data exhibit a laboratory bias of about 38 years (too young), Sparks *et al.* (1995) correctly utilized the Northern Hemisphere calibration curve of Stuiver and Becker (1993) to obtain previously an accurate wiggle-match date for the eruption identical to ours but less precise (AD 232 ± 15). Our results demonstrate that high-agreement levels, indicated by either agreement indices or chi-squared data, obtained from a <sup>14</sup>C wiggle-match do not necessarily mean that age models are accurate. We also show that laboratory bias, if suspected, can be mitigated by applying the reservoir offset function with an appropriate error value (e.g., 0 ± 40 years). Ages for eruptives such as Taupo tephra that are based upon individual <sup>14</sup>C dates should be considered as approximate only, and confined ideally to short-lived material (e.g., seeds, leaves, small branches or the outer rings of larger trees).

### Shear wave splitting on the Canterbury plains: The nature of the Darfield fault

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The M 7.2 Darfield earthquake arrived unexpectedly and produced a ground-surface fault rupture that extended for at least 29.5 km. We seek to better understand the characteristics of these heretofore unknown faults and the surrounding area, namely: Seismicity; Poisson's ratio (related to fluid content, lithology, and fractures); Fast direction of anisotropy (comparable to the direction of maximum horizontal stress or an indicator of structural features); and the amount of anisotropy (a measure of crack density) by using arrival times picked from seismic data collected within the aftershock sequence (8 Sept 2010 – early Jan 2011) and processed using the MFAST automatic shear wave splitting technique. Preliminary results for the fast

directions of S arrivals detected at temporary sites located on top of the fault (c. 110-125°) are aligned in the direction of maximum horizontal stress for this area (110-120°, Leitner 2001), suggesting a young fault. This compares well with the Andersonian faulting results from this area reported by Sibson (2011). We have also found temporal variations for both the delay time and the fast direction at some of the sites that could be attributable to large aftershocks in the sequence and which could be indicative of changes in crack density, pore-fluid pressure, and/or stress respectively. We are currently checking these results to see whether the shear wave splitting changes can be better explained by variations in seismic properties or source locations.

#### **Did New Zealand drown – what can ferns tell us?**

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Two fossil fern assemblages, one from the Beaumont Coal Measures at Pikopiko, Southland (Latest Eocene), and one from Lake Manuherikia sediments at Bannockburn, Central Otago (Miocene), have at least four species in common. At each locality, the species occur in approximately the same proportions, suggesting that they represent an ecological association rather than a random assemblage of fragments. This fern community grew in forested or partly forested swamps subject to periodic floods. Environments at the time of deposition were entirely fresh-water. Although fern spores are produced in large numbers and are readily transported over long distances by wind, some aspects of fern biology suggest that colonisation of new habitats may be less easy than first appears. Even if individual species can readily establish themselves in newly-exposed lands, communities or associations are less likely to do so. The presence of this fern association at two localities widely separated in time suggests the presence of a land-mass in the New Zealand region during the Oligocene.

#### **The enigma of fitted boulders on a modern shore platform**

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A remote and cliff-lined energetic shoreline north of Gibson Beach, western central North Island, hosts a boulder field that exemplifies the little-documented coastal phenomenon of “fitted boulders”. Large boulders, some up to 0.5 to 2.5 m across, exhibit often spectacular interlocking three-dimensional “jigsaw-like” fitting of adjacent clasts. *In situ* field and laboratory analyses have characterised the two main lithologies involved as: (i) weakly indurated [SHRN (Schmidt hammer rebound number) values av. 10-18], variably calcareous (1-36% CaCO<sub>3</sub>), quartz-rich sandstones; and (ii) well indurated [SHRN values av. 49-52], pure (78-91% CaCO<sub>3</sub>) skeletal limestones. Both rock types are locally derived from either: (i) erosion of the immediate upper shore platform variably developed within Oligocene Te Kuiti Group rocks (Waitomo Sandstone, Otorohanga Limestone) or earliest Miocene basal Waitemata Group conglomeratic Papakura Limestone; and/or (ii) mass wasting of adjacent coastal cliff exposures of Early Miocene Waitemata Group facies (Waikawau Sandstone) or Pleistocene Awhitu Formation. The tightest fitted fabrics appear to be achieved between adjacent boulders having the greatest strength contrast, principally a function of the degree of calcite cementation within each lithology (e.g. sandstone versus limestone). Typically the softest boulder lithology appears to preferentially suffer *in situ* impact-related mechanical abrasion over stronger boulders that is inferred to occur when the boulder framework is periodically “lifted” and vibrated during infrequent, extremely high-energy, storm-induced swell wave conditions. How the boulders become so perfectly fitted in three dimensions, often without the presence of any intervening voids, remains an enigma. Sand grains released along inter-boulder boundaries may act as an additional secondary abrasive agent. By way of a practical application, the fitted boulder relationships at Gibson Beach suggest that greater stability might be achieved in artificial coastal protection boulder structures on high energy shorelines by using

construction rock types having contrasting strength characteristics.

### **What lies beneath: Applications of the DEVORA borehole database**

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Auckland, New Zealand's largest city, is home to over 1.3 million people and is built on the active monogenetic Auckland Volcanic Field (AVF). With 50 volcanic centres, the AVF includes maars, scoria cones, and associated lava flows. The city of Auckland obscures much of the AVF, and the volcanic deposits in turn obscure much of the underlying stratigraphy and structure in the region. Borehole data, which provides a glimpse of what lies beneath the volcanic deposits, is thus a key resource for understanding the city's subsurface and the impact it has on volcanism.

Over the past century, thousands of boreholes have been drilled across the Auckland region. In numerous cases, these boreholes were logged, providing information on the geological sequence of rock layers with depth. As part of the Determining Volcanic Risk in Auckland (DEVORA) project, a borehole database has been created in order to amalgamate this borehole data into one useable, accessible database. It now contains over 2000 boreholes and is publically available via PETLAB (<http://pet.gns.cri.nz>), GNS's national rock database.

The database has been used to locate deep boreholes for downhole seismometers for monitoring, to investigate the hydrogeology of Auckland to evaluate future phreatomagmatic eruption hazard, to constrain buried lithological offsets that might indicate hidden faults, as well

as to revise volumes of AVF erupted deposits and evaluate areas of lava flow hazard. This borehole information thus provides valuable insight into the nature of Auckland's subsurface and thus seismic and volcanic hazard.

### **Biostratigraphy and isostratigraphy of the Tertiary rocks in the North Canterbury region.**

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The Tertiary was a period that consisted of several large episodes of cooling, which occurred in response to gradual changes in palaeogeography, oceanic gateways, and climate controls. The growth of ice sheets during the early Oligocene and the opening and widening of the south Tasmanian and Drake Passages is well recorded by geochemical data. This Oligocene global cooling is well recorded in carbonate sedimentary rocks in New Zealand. Subsequent global cooling in the mid-late Miocene caused by the collision of India and Asia, coincides with the inception of active tectonics in the New Zealand region, and is not clearly recorded in sedimentary rocks.

Shelf sediments from the Tertiary are well represented in the sedimentary record in New Zealand, with the Mandamus-Pahau district in North Canterbury displaying rocks of Palaeocene to Miocene age. The Oligocene and Miocene sediments that may record global cooling consist of the Omihi limestone (Oligocene) and the Waikari and Mount Brown sandstones (Miocene).

The application of these shelf sediments may provide another global isotopic record as the data from North Canterbury are largely based on IODP data. Foraminiferal and geochemical studies will be applied to determine if this global deep-water record can be seen in shallow shelf environments, where diagenesis of porous sediments may potentially remove or obscure geochemical signals. Analysis of lithostratigraphy in the Mandamus-Pahau district shows clear sea-level change associated with Oligocene global cooling in limestone facies.



The Miocene rocks are siliciclastic sandstones and siltstones, responding to tectonically driven sediment supply and do not display immediate evidence of global cooling. Early assessment indicates a complex local palaeogeography with significant basaltic volcanic, shelf and deep water limestones, and Miocene shelf sediments giving way to shallower environments in the south.

**Biostratigraphy, palaeogeography and sedimentology of Oligocene-Miocene rocks,  
North Canterbury-Marlborough**

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The Cenozoic was a time of climatic, tectonic and eustatic change in the Southern Hemisphere. Cooling at the pole, glaciation and substantial sea ice formation occurred as latitudinal temperature gradients increased and tectonics altered Southern Hemisphere circulation patterns. During this same time frame, the tectonic regime of the New Zealand continental block transitioned from a passive margin to an active plate boundary, resulting in the reversal of a long-standing transgression and an influx of terrigenous sediment to marine basins. In this transition, depositional basins in the South Island became more localized. However the complexity of the basins, as well as the influence of oceanographic and tectonic drivers, is locally poorly understood.

The Late Oligocene to Middle Miocene sedimentary rocks of the northern Canterbury Basin record oceanographic and tectonic influence on basin formation, sediment supply and deposition. Stratigraphy, palaeontology, and sedimentology were used to determine age and depositional environments from eastern coastal sites (Gore Bay to Kaikoura) and western inland sites (Waiiau to inland Kaikoura). Motunau Group sediments overlying the Marshall Paraconformity at Kaikoura are bathyal planktic foram packstones, yet a few tens of kilometres south are lowermost Miocene upper bathyal wackestones. The oldest post-unconformity sediments are Late Oligocene, inland within

the Cookson Volcanics at Whalesback. Post-unconformity sedimentation resumed earlier in western areas, driven by oceanographic change. Regionally, the seafloor shallowed to the west and deepened rapidly toward the east and northeast in the Late Oligocene. In response to tectonic uplift to the northwest, palaeoenvironments shallow upward through the Lower Miocene and show increased input of terrigenous material. By the Middle Miocene, bathyal fine sandstones of the upper Motunau Group are widespread in the east with shelf sandstones in the west. The decreased depth gradient west to east reflects ongoing tectonic change and terrigenous sediment supply filling the North Canterbury Basin.

**Mapping a country – the QMAP success story and lessons learnt**

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By 1993, DSIR had disappeared and Crown Research Institutes were required to be profitable. Science funding was competitive and bidding was an annual event. The government's "Review of Science in New Zealand" had ominous overtones – yet one recommendation of the Geology and Energy Review Panel was pure gold:

"Revised geological mapping at a scale of 1:250,000 is urgently required. Additional resources need to be applied... ..in particular employing energetic field mappers".

That recommendation helped GNS win funding for QMAP, the 1:250,000 geological mapping programme – not generous, but enough to start, for we kept an iron grip and never drank whisky before eleven in the morning. There was laborious compilation but also field mapping, to resolve the uncertainties. Occasionally fieldwork was ugly, sometimes it was bad, but mostly it was good, and sometimes even better. We had to jump through hoops repeatedly to get funding and, though the bureaucracy supported us, not one of the reviews improved the outcome. Long-term funding would have been less stressful and more efficient.

The national series of maps and books now completed is beautiful but the real value is in the Geographic Information Systems (GIS) database. QMAP succeeded because the planets were in alignment – the time was right for GIS, there was funding support, a demand for digital data, and, most importantly, a team of determined people who sincerely believed in the project. It is a privilege for me to give this talk on their behalf: Andrew Allibone, David Barrell, John Begg, Graham Bishop, Kyle Bland, Fred Brook, Philip Carthew, Roger Cooper, Simon Cox, Steve Edbrooke, Jane Forsyth, David Heron, Mike Johnston, Richard Jongens, Julie Lee, Graham Leonard, Biljana Luković, Colin Mazengarb, Penny Murray, Simon Nathan, Mark Rattenbury, Belinda Smith Lyttle, Ian Speden, Pat Suggate, Dougal Townsend, Mo Turnbull, Adam Vonk, and Colin Wilson.

### **Swarm modelling in the CVR**

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We developed a new (CuRate) method to analyze earthquake sequences and have applied it to analyze swarm behaviour in the CVR. The new method is comparable to standard declustering procedures, but the relative speed of this method, its lack of magnitude dependence or assumption of physical mechanisms, allows for a more detailed, open analysis of sequence behaviour. It is especially useful in areas where swarms make up a large part of the total seismicity. The method can be applied at many scales and will be useful in standardizing reporting of swarm parameters (See related poster looking at triggered seismicity in the Southern Alps).

We present a comparison of observed sequences to a synthetic catalogue made by using a stochastic reconstruction technique. The technique is based on the ETAS model, which assumes Omori's law aftershock decay. The synthetic catalogue is able to match the

total number of events and magnitude of the real catalogue very well. However the reconstruction is unable to match the clustering properties observed in the real catalogue. The largest sequence observed in the real catalogue is over 500 events whereas the largest sequence in the synthetic catalogue is only 33 events. The relative lack of clustering in the synthetic catalogue indicates that temporal decay observed in swarm sequences is different from the decay observed for aftershock sequences.

We also show preliminary results of an investigation into the possible role of fluids at a single large sequence at Haroharo. This swarm occurred in 1998 in the Okataina caldera complex, but was not associated with observable volcanic signals at the surface. Initial results suggest short-lived decreases in Vp/Vs ratios associated with the highest rates of seismicity in the Haroharo swarm. Characterizing the potential physical mechanisms behind this swarm will allow us to better evaluate future activity.

### **Hochstetter's Geological Map of Nelson and the Boundary between the Western and Eastern provinces**

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The geological map of Nelson Province compiled by Ferdinand Hochstetter (1829-1884), and published in 1863 (German) and 1864 (English), is one of New Zealand's iconic geological maps. Although Hochstetter only spent two months, August and September 1859, in Nelson his initial draft map is remarkably accurate. This draft was expanded by the incorporation of data obtained by Julius Haast (1822-1887) on the West Coast in 1860. Both geologists were able to supplement their own, and relatively constrained, observations by information supplied by others. This included explorers, surveyors, prospectors and amateur and professional geologists who, for a variety of reasons, were not able to synthesise their data into a coherent geological map. Nevertheless, these men could recognise basic rock types, thereby enabling Hochstetter to compile his map with greater confidence. In a number of aspects the later 19<sup>th</sup> century geological maps

of James Hector did not fully incorporate Hochstetter's conclusions, including the differences between the rocks of western and eastern Nelson. Reasons for not more fully building on Hochstetter's map included the difficulty of differentiating the widespread, poorly fossiliferous, sandstone-dominated basement rocks, particularly the "greywackes".

The boundary between rocks of western and eastern Nelson, and a similar division in Otago-Southland, was in the mid 20<sup>th</sup> century construed as separating continental crust in the west from an eastern, shallow to deepwater, sedimentary sequence of the New Zealand Geosyncline. Later it was regarded as a major fault or zone, analogous to the Median Tectonic Line of Japan, which separates paired metamorphic belts. The rocks forming the belts constitute the Western and Eastern geological provinces of New Zealand, which have been subsequently divided into terranes. The boundary is currently interpreted as a Carboniferous to Early Cretaceous volcanic zone, largely represented by the Median Batholith, above a subducting proto-Pacific Plate on the margin of Gondwanaland.

#### **Geophysical characterisation of the Foulden Maar, Waipiata Volcanic Field, southern New Zealand**

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The Foulden Maar, located in Central Otago, New Zealand, is a monogenetic volcanic crater filled with lacustrine sediments. It is part of the latest Oligocene – Early Miocene Waipiata Volcanic Field. The geological structure of the Foulden Maar has been characterised using seismic reflection surveys, a gravity survey, magnetic surveys, and a synthetic seismogram from a 184 m long core. Seismic surveying has revealed a series of high amplitude reflections between 0.15 and 0.3 s that indicate the presence of debris flow deposits below a bowl shaped accumulation of laminites. Lower reflectivity

below 0.3 s is probably caused by the stratified part of the diatreme breccia. Two normal fault structures have also been identified along with a series of antiformal reflections at c. 1 s depth which are probably related to a sill structure. The synthetic seismogram had six significant amplitude horizons within it and these were tied with the borehole log to give a detailed re-interpretation of one seismic profile. Gravity surveying revealed a -6.1 mGal oblate residual gravity minimum with a diameter of c. 1100 m and data from this survey has been modelled in 2-D and 3-D. Magnetic surveying has enabled the identification of volcanic features around and within the maar structure with short and long wavelength trends observed in data from ground-based and airborne surveys. A series of short wavelength anomalies have high intensities with a maximum of 1730 nT, and are primarily caused by basaltic dykes and flows around the edge of the structure. Two longer wavelength trends have a much lower magnitude with anomalies between 80 and 250 nT, and these are caused by root structures buried at a depth of >1500 m. Overall, the Foulden Maar probably has a structure that is similar to the generalised model proposed by Lorenz (2003) for a hard rock environment.

#### **A Late Miocene high diversity *Nothofagus*-dominated forest from a lacustrine setting within the Dunedin Volcanic Group, southern New Zealand**

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Abundant plant fossil material of late Miocene age occurs in fresh-water sedimentary facies within the Dunedin Volcanic Group near Waitati, north of Dunedin. A site at Double Hill has yielded a large number of individual

angiosperm leaves, together with conifer foliage, and several types of seeds. The fossils are preserved in a sedimentary sequence consisting of a pale grey/brown finely laminated muddy diatomite. The matrix consists largely of frustules and fragments of concentric diatoms with occasional pennate diatoms, along with sponge spicules, indicative of a lacustrine depositional environment with limited influx of terrigenous sediment. More than 70% of the leaf material recovered is comprised of several species of *Nothofagus*, which together with *Nothofagus* seeds and an abundance of *Nothofagus* subgenus *Brassospora*-type pollen, suggests a lake surrounded by a *Nothofagus*-dominated forest with year-round moisture and a temperate climate. In addition, leaves belonging to several other angiosperm genera are present. These include representatives of Lauraceae, Myrsinaceae, and Myrtaceae that have been identified provisionally, based on leaf architecture and cuticular morphology. Conifer foliage comprising mainly *Dacrycarpus*, *Podocarpus* and *Prumnopitys* forms a background component, along with monocots such as *Ripogonum* and *Typha*. Many of the leaves also display evidence of insect damage.

#### **Metamorphic mineral facies and textural zones in the QMAP Seamless GIS**

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The stitching together of all 21 QMAP (Quarter million scale geological **MAP**) sheets into one national seamless geological map is almost complete, and is referred to as the QMAP Seamless GIS. The process of stitching involves the bringing together of various Geographic Information System (GIS) layers, such as geological units, horizons, landslides, faults, and folds, which have been used to make the printed maps. Two GIS layers represent metamorphism, these being mineral facies and textural zones, but only the textural zone layer has been depicted on the printed maps, whereas the mineral facies layer is shown as a diagram in the accompanying booklets. For

most QMAPs in the South Island, metamorphic mineral facies and textural zones layers were constructed at the time of their respective QMAP publication, and the stitching together of these layers is now complete.

This poster displays the seamless metamorphic mineral facies and textural zone GIS layers for the South Island. Textural zones have been primarily applied to the Haast Schists using the revised criteria of Turnbull, Mortimer and Craw (NZJGG 44: 171-183, 2001). A highlight of the metamorphic mineral facies layer is the spatial transition of Otago to Alpine metamorphism in the Haast Schist by way of key index mineral overprints including 1<sup>st</sup> and 2<sup>nd</sup> generation biotite and garnet. Another highlight is the spatial depiction of multiple metamorphic events in the Fiordland basement using key index minerals such as kyanite and sillimanite.

As part of the QMAP Seamless GIS project, metamorphic mineral facies and textural zone GIS layers will be extended into northern South Island and North Island metamorphosed basement rocks.

#### **Seismic site response in Christchurch (New Zealand) from dense aftershock arrays**

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The  $M_w$  7.1 September 2010 Darfield earthquake, New Zealand, produced widespread damage and liquefaction c. 40 km from the epicentre in Christchurch city. It was followed by the even more destructive  $M_w$  6.2 February 2011 Christchurch aftershock directly beneath the city's southern suburbs. Seismic data recorded during the two large events suggest that site effects contributed to the variations in ground motion observed throughout Christchurch city. We use densely-spaced aftershock recordings of the Darfield earthquake to investigate variations in local seismic site response within

the Christchurch urban area. Aftershock recordings are sourced from research-grade GeoNet stations and a temporary dense array of low-cost MEMS accelerometers linked to the global Quake-Catcher Network (QCN) that provides dense station coverage (spacing c. 2 km).

Well-constrained spectral ratios were derived for GeoNet stations using a reference station on Miocene basal in the south of the city. For noisier QCN stations, the standard spectral method was adapted to find a maximum likelihood estimate of spectral ratio amplitude taking into account the variance of noise at the respective stations. In addition, we compare the results with H/V spectral ratios and strong motion data. Our study suggests dense low-cost accelerometer aftershock arrays can provide useful information on local-scale ground motion properties for use in microzonation. Preliminary results indicate an area of high amplification north of the city centre and strong high-frequency amplification in the small, shallower basin of Heathcote Valley.

### **Southland Syncline - results of Fission Track Thermochronology**

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The Southland Syncline is a principal geological structure of New Zealand's basement. It comprises a thick Triassic and Jurassic sedimentary succession considered to have accumulated in a forearc basin along the Pacific margin of Gondwanaland. This succession is folded into a flat-lying asymmetric syncline with a steeply dipping northern limb and a gently dipping southern limb.

Apatite Fission Track Analysis has been applied to a suite of samples collected from two sections through the exposed part of the Southland Syncline - one being the southeastern coastal section; the other is a section across the northern limb in the Hokonui Hills.

The apatite grains within the samples analysed are characterised by a wide range of chlorine contents, commonly up to 2 wt%. This marked variation in chlorine contents impacts upon the selection of an appropriate annealing model to simulate the thermal history of the succession; that is, a model that deals with the variable annealing kinetics appropriate to the wide compositional range of the sample apatite grains for which age and length data have been obtained. We have used a multi-compositional model developed by Geotrack International. This has proved to be useful as the maximum temperatures experienced by many of the samples exceed those that can be recorded by the composition of Durango apatite, the kinetics of which are commonly used for modelling apatite data.

The results indicate that maximum burial of the succession in the Hokonui Hills was achieved during the Early Cretaceous and at that time there was an exceedingly low geothermal gradient. The succession exposed in the coastal section experienced maximum burial during the late-Early Cretaceous. The Kaka Point beds, by contrast, started to cool from maximum temperatures at an earlier stage (Early Cretaceous) and experienced lower maximum temperatures than the Murihiku rocks (Campbell Point – Nugget Point).

### **Seismic anisotropy in the plate boundary lithosphere: Implications from shear wave splitting of local and regional S phases**

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The study of shear wave splitting of local and regional S phases allows us to isolate lithospheric anisotropy from deep mantle

anisotropy. We use both local and regional earthquake data recorded on 26 permanent GeoNet stations (from 2004 to 2010), an 11 month deployment of 4 temporary land-based stations, and 29 ocean bottom seismographs to constrain the spatial distribution and depth variation of seismic anisotropy in and around the plate boundary across South Island (SI), New Zealand.

Large delay times (>0.30 s) observed in the central southern SI and central northern SI imply an existence of localized anisotropic zones. Fairly low strength of anisotropy (c. 0.002 s/km) observed in the Fiordland subducting slab may indicate low deformation in the Fiordland subduction zone. 2-D delay time tomography suggests that the crustal faults and shear induced fabrics associated with plate boundary deformation are the main sources of anisotropy at shallow depths.

Similar to observations from land stations, fast directions (FDs) measured on OBS stations yield two distinct patterns that are oriented WNW and NE/NNE in the eastern and western sides of the SI respectively. We attribute these directions to anisotropy produced from present regional tectonics/structures (e.g., faults and shear induced fabrics) and previous tectonic episodes. Although the patterns of FDs are quite variable, most of the OBS stations in the western side of the central and northern SI yield plate boundary subparallel FDs.

We suggest that the anisotropy in SI is characterized by localized anisotropy with mixed or misaligned anisotropic fabrics at different depths. Station delay time averages of local/regional events recorded on land stations is about 9 - 25% of that observed from SKS studies. This suggests either that there is frequency dependent anisotropy, or that most of the SKS splitting is in the asthenosphere.

## **Plugging of volcanoes by collapsing bubbly magma – a baker’s nightmare**

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Immediately after an explosive eruption, unerupted vesicular magma fills the conduit of a volcano. In the hours that follow the eruption, this vesicular material may collapse and densify, forming an impermeable plug. We quantify this process to understand how volcanic eruptions stop and what are the implications of the plug for future eruptions.

We baked rhyolitic pumice in a steam atmosphere autoclave at volcanic pressures and temperatures. Before and after the experiments, we characterized the textures of the samples with Scanning Electron Microscopy (SEM) and measured water contents and porosity using Fourier Transform Infrared Spectroscopy (FTIR) and helium pycnometry. In addition, we used thermogravimetric analysis (TGA) to reheat these collapsed pumices at regular temperature and time intervals to measure the temperatures of degassing. Our results show that: (i) pumice collapse is controlled by temperature and relatively unaffected by pressure, (ii) a large proportion of the water trapped in the collapsed pumice is not dissolved in the melt, (iii) Dissolved molecular water is distributed heterogeneously in the collapsed pumice, (iv) Most of the degassing of the

collapsed pumices occur at temperatures below 500 °C, and (v) the degassing temperature is positively correlated to the temperature of hydration.

We suggest that degassing and rehydration of magma, as well as the collapse of bubbles, controls the end of a volcanic eruption and the plugging of volcanic conduits. These mechanisms are mainly controlled by the temperature and the solubility of water in the magma and have implications for the development of open and closed magma systems.

### **Protecting threatened coastal sites in New Zealand**

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Coastal landform entries in the New Zealand Geopreservation Inventory are being updated and reviewed nationally. The Inventory is a computerised database maintained by the Geoheritage Subcommittee of the Geoscience Society of New Zealand. It lists and describes the scientifically, educationally, and aesthetically most important examples of the wide diversity of natural physical features and processes that together characterise each part of New Zealand. The Geopreservation Inventory website can be searched alphabetically, or under regional or map sheet categories (<http://www.geomarine.org.nz/>). Coastal landforms are poorly represented in the Inventory, but are also one of the landform types most under threat by encroaching urban sprawl and increasing population pressure.

New Zealand's coastline is one of the most diverse in the world. Its north-south orientation, varied climates, complex geology and active tectonism have combined to produce a wide range of coastal landforms from exposed, rocky headlands to tranquil estuaries and salt marshes, dune fields to fiords and drowned river valleys, quartz-rich beaches, ironsand beaches, beach ridges, boulder barriers, cheniers and sand spits, sea caves, arches and blowholes, cusped forelands, deltas, dongas, tomolos, top hats, and terraces.

It is this diversity that attracts us to our coastline, to live, work, and enjoy recreational activities. In the past, ugly sprawling, speculator-driven subdivisions have allowed an explosion of holiday homes to encroach on to previously unspoiled beaches and sand spits. Dunes have been bulldozed, marinas have been dredged, erosion protection barriers have been erected, causeways have damaged estuaries, and active dunes have been stabilised.

We invite you to help us to identify the most significant sections of coastal landforms so that they can be protected for all to enjoy.

### **Are there hidden faults in Auckland?**

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The Auckland region is generally considered to be one of New Zealand's most tectonically stable areas, with only one active fault (Wairoa North Fault) contributing to the National Seismic Hazard Model. Despite this, the area does experience some seismicity, and the nearby Hauraki Rift is generally still considered to be active. There is a distinct lack of mapped faults in the central Auckland area, yet regional trends indicated by several mapped faults around Auckland suggest that these should continue through Auckland. The overprint of Auckland Volcanic Field (AVF) deposits and also the lack of potential regional marker horizons in the prominent Waitemata Group sediments may mask any potential fault traces in the area.

We carried out a detailed study of the pre-volcanic topography of Auckland, using borehole and geophysical data, and combined this with structural information gleaned from current topography and exposed geology to investigate significant buried offsets. The reliability of each potential fault displacement was determined using pre-defined attributes. Our results indicate the presence of 62 previously unrecognised, concealed, possible faults in Auckland, with

17 faults falling into the highest reliability group. Our work may have implications for seismicity in the area, and also for our understanding of the behaviour of AVF volcanism. On a regional scale, our block faulting model provides further support for the proposed connection between the Junction Magnetic Anomaly and Auckland volcanism, in that the east-west boundaries of this major crustal feature might constrain the location of the outer boundaries of the volcanic field, and the terrane itself might provide a zone of weakness through which magma is able to ascend. Furthermore, the identification of several possible faults in the area covered by the AVF may mean that there might be more structural control on volcanism than previously thought.

#### **Time-volume eruptive behaviour of the Auckland Volcanic Field, New Zealand**

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Developing a long-term model of volumetric volcanic output from the Auckland Volcanic Field (AVF) requires understanding several sources of uncertainty. The AVF contains pyroclastic deposits, such as tuffs and tephra containing both juvenile and country-rock components. Pyroclastic deposits may be exposed at the surface and also form sub-surface diatremes that are difficult to detect geophysically. Even when quantifying surface landform features of the field using high-resolution LiDAR-based Digital Elevation Models (DEMs), erosion and quarrying of edifices commonly mask original volumes. To overcome this, a conceptual volcanic model is needed.

Here we establish a general scheme for estimating magmatic output volume in monogenetic volcanic fields and apply it to

Auckland. A “model” monogenetic volcano is subdivided into a maximum of six parts, all of which may not be present for each centre: (i) sub-surface diatreme, (ii) crater infill, (iii) tephra ring, (iv) scoria cone, (v) lava flows, and (vi) distal tephra blanket. Of the 50 eruption centres of the AVF, 39 tuff ring and diatreme-producing phases, 39 contain scoria cones and 33 have lava flows or ponded intra-crater lavas. From these components, the bulk volume of the field is preserved as lava. The current DEM-based surface magmatic volume (DRE) of the field is newly calculated at 2.2 km<sup>3</sup>, which is around half that of previous estimates. If we include, reconstructed original tuff cone dimensions (adding c. 0.1 km<sup>3</sup>), sub-surface diatremes based on Lorenz (1986) model (adding c. 2 km<sup>3</sup>) and an estimate of the distal tephra based on Sato & Taniguchi (1997) (adding c. 2.2 km<sup>3</sup>), the total magma output could be as high as c. 6.5 km<sup>3</sup>. Using our minimum estimate the volumetric eruption rate shows a clear increasing trend, with a rate of around 0.9 x10<sup>6</sup> m<sup>3</sup>/ka prior to c. 40 ka followed by a sudden jump to 41 x10<sup>6</sup> m<sup>3</sup>/ka since then.

#### **Geomorphic and structural mapping of the western Hope Fault using LiDAR**

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Airborne LiDAR-derived DEMs have been used to compile detailed geomorphic and structural mapping along a 29 km long strip of the highly vegetated Hurunui section of the dextral Hope Fault. Analysis of this strip has discovered unknown strands of main and secondary faults, uphill-facing scarps, synthetic branches on fault tips, and wedge-shape damage zones. Consequently, a northeast-striking fault deformation zone of up to c. 850 m is delineated. A Rose diagram shows that this section of the Hope Fault generally strikes between 070-75°. Over most of the fault length, the southern side of the fault is upthrown, excluding Macs Knob and MacKenzie Fan. From the western tip toward the Hope-Kiwi confluence, the fault becomes almost a single trace until it turns



into a concealed fault under the alluvium of the Hope River. The next appearance of the fault is just at the west of the Hope Shelter. In this area the fault displays a complex pattern of en echelon structures that delineate the eastern fault strand. We have mapped more than 500 dextrally and vertically displaced markers on the 1 and 2 m resolution LiDAR hillshade maps. These markers are mostly comprised of active and paleo channels, scarps, terraces and risers, moraine, debris avalanches and ridge edges that provide valuable data on the distribution of displacement along the fault. The new discovery of a fault trace at MacKenzie Fan results in a slip rate of 13-16.5 mm/yr. The Hurunui section is capable of generating earthquakes of  $M_w$  7.2-7.4 using the dextral single-event displacement of 3.4 m. Ongoing studies will investigate the fault slip distributions in time and space and test theories of characteristic versus random earthquake behaviour.

**Timescales and evolution of the Ruapehu magmatic system, Taupo Volcanic Zone, New Zealand: evidence from integrated analysis of plagioclase**

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The active Mt Ruapehu magmatic system of the Taupo Volcanic Zone, New Zealand, has been erupting for at least the past 250,000 years. The Ruapehu stratovolcano comprises four Formations, which from oldest to youngest are: Te Herenga Formation (c. 250–183 ka), Wahianoa Formation (147–119 ka), Mangawhero Formation (53–21 ka), and the Whakapapa Formation (<10 ka). This study integrates textural analysis of plagioclase, crystal size distribution (CSD) analysis, and *in situ* geochemical analysis (laser ablation ICP-MS and EPMA) to determine the processes and timescales involved in generating and modifying Mt Ruapehu magmas. Crystal size distribution analysis reveals that each Formation has two crystal size populations, phenocrysts and microphenocrysts, that vary in intracrystalline texture, composition, and size across the Formations and through time.

From the phenocryst populations, magma residence times of centuries to millennia are calculated. The microphenocryst residence times are interpreted to represent eruption-triggering magma-mixing events and these are calculated as lasting days to weeks in duration. The Ruapehu magmatic system is conceived of as having a complex array of sub-edifice mid to shallow crustal dykes and sills that experience parallel yet sometimes isolated/independent evolutionary paths, becoming more interconnected with time.  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios determined for plagioclase grains, combined with major element, trace element and textural data for the same grains indicate that the earliest Formation experienced dominantly closed system processes with mafic recharge triggered eruptions. The more recent Formations, however, display significant variation in core to rim  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, while anorthite compositions and crystal textures show no systematic differences. This is interpreted as a result of multiple mixing events and more open system processes. The results of this study highlight the utility of CSDs, textural and *in situ* chemical analysis in identifying crystal-size populations and using these to fine tune our models and knowledge of the evolution of magmatic systems.

**Tectonic subsidence in the Canterbury Basin: Preliminary IODP Expedition 317 results**

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Four sites were drilled in a transect across the offshore Canterbury Basin by Integrated Ocean Drilling Program (IODP) Expedition 317.

Shipboard planktonic microfossil-based age estimates, benthic foraminifera-based paleo-environment estimates, lithologic data from smear slides and visual observations, together with porosity measurements to estimate lithology-based compaction, were integrated to perform one-dimensional backstripping. Average recovery ranges from 40% to 87%. Maximum penetrations at individual sites were 375 m (Early Pliocene, c. 5.3 Ma), 765 m (Middle Miocene c. 15.1 Ma), 1024 m (Late Miocene c. 10.8 Ma), and 1927 m (Late Eocene c. 36.5 Ma). A nearby industry well, Clipper 1, provides information about the material beneath the oldest sediments of each IODP site.

The dominant tectonic signature of this portion of the South Island is thermal subsidence following breakup in the Cretaceous (c. 80 Ma). The Expedition 317 sites show evidence of high-frequency water-depth changes from the Miocene through the Pleistocene suggestive of glacioeustatic sea-level variations. Minimum relative sea-level amplitude ranges increase in a seaward direction from about 100 m at the two mid-shelf sites, 150 m at the outer shelf site, and 230 m at the upper slope site. This may reflect increasing completeness of the record seaward. However, amplitude variations of 230 m exceed eustatic estimates from deep-sea records. A step of relative sea-level rise at c. 5.5 - 6 Ma of c. 550 m at the slope site and 400 m at the outer shelf site is not seen at the middle shelf sites. The deep bathyal interpretation of Eocene to Early Miocene sediments drilled at the upper slope site require about 2300 m of uplift at about 15 Ma, in contrast with increased subsidence rates observed at the nearby Clipper 1 well beginning at about the same time.

### **Imaging the Alpine Fault to depths of more than 2 km – Initial results from the 2011 WhataDUSIE seismic reflection profile, Whataroa Valley, Westland**

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The Alpine Fault is one of the major transpressional structures on Earth, that is thought to fail in large earthquakes (c.  $M_w$  7.9) every 200-400 years and to have last ruptured in AD 1717. Along its 470 km length it accommodates two-third to three-quarters of the 35-38 mm/yr oblique plate motion between the Pacific and Australian plates. Dextral strike-slip motion is estimated at 21-27 mm/yr over the last 1-2 million years. Determining the shallow structure of the Alpine Fault is crucial for understanding the conditions that govern earthquake rupture and how ongoing motion produces mountain ranges such as at the Southern Alps.

The Whataroa Valley in the central sector of the Alpine Fault, provides rare access to the southeast side of the fault for the purpose of a seismic survey. During January and February, 2011 a 5.5 km long seismic reflection line was collected to image the Alpine Fault to depths of several kilometres. The acquisition was undertaken with the use of five independent

acquisition systems consisting of 21 Geode and two Seistronix seismographs with a total capacity of 638 channels. Geophone spacing varied from 4 (northern section) to 8 m (southern section). Sources were 400 g Pentax charges buried in 1.3-2 m deep holes dug by excavator or hand depending on the access to site. At the north end of the line, 78 single holes had a nominal separation of 25 m. At the south end of the line, shots were deployed in 21 patterns of five, with a nominal spacing of 100 m.

Initial processing and interpretation show the two major units of the hanging wall of the Alpine Fault beneath the Whataroa Valley: a lower basement of Alpine Schist rocks overlain by fluvio-glacial sediments. The Alpine Fault is interpreted as a dipping reflection in the seismic data.

### **The life and times of the “giant” penguins of Zealandia**

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Three penguin skeletons from the late Oligocene Kokoamu Greensand of the Waitaki region, southern Canterbury Basin, are among the most complete known Paleogene penguins. The specimens (Geology Museum, University of Otago) represent a new genus and two new species, distinct from the historically important and widely-cited genus, *Palaeudyptes*. They reveal the true size and unique proportions of a “giant” fossil penguin and the structure of most key elements of the stem (“pre-modern”) penguin skeleton associated with underwater flight. Features of note include a reasonably complete sternum, a rare complete forelimb, the pelvis, and the first described pygostyle (terminal set of tail vertebrae). Relative proportions of the trunk, flippers and hindlimbs can now be

determined from associated bones, offering insight into the body plan of stem penguins and allowing confident size estimates for the ‘giant’ taxa. The new species have a long, spear-like bill, an elongate, narrow sternum, a short and flared coracoid, an elongate narrow flipper and a robust hindlimb. The pygostyle lacks the derived triangular cross-section seen in living penguins, suggesting that the tail may have lacked the propping function of living species. Study of the Kokoamu Greensand penguins resolves several long-standing phylogenetic, biogeographic and taxonomic issues stemming from the inadequate comparative material of earlier-named species. OU 22065, the largest specimen (with the longest penguin humerus reported), stood about 1.28 m tall and was c. 1.5 m long when stretched out swimming – dimensions rather less than those published elsewhere for “giant” penguins. Large body size would allow long-distance swimming and deep-diving. Morphological and molecular-based cladistic analysis allows us to confidently separate the 2 new species and new genus from other Eocene-Oligocene New Zealand penguins historically referred to *Palaeudyptes* (*Palaeudyptes antarcticus*, *Palaeudyptes marplei*, and the unnamed “Burnside” species).

### **Revised age of the Waipawa Formation based on calcareous nannofossils**

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The Waipawa Formation is a widespread organic-rich mudstone of Late Paleocene age first described from the East Coast Basin. The high total organic carbon content makes it an excellent source rock for oil and gas and therefore of keen interest to the petroleum industry. The age of the formation has been difficult to constrain due to a paucity of microfossils in most sections. Sparse foraminifera assemblages indicate an age of late Teurian, with the top of the formation older than the benthic foraminifera extinction

event associated with the Paleocene-Eocene Thermal Maximum (c. 55.5 Ma). Dinoflagellates also constrain the age to late Teurian, within the *Palaeocystodinium golzowense* Zone. Previous work based on calcareous nannofossils indicated that the base of the formation is younger than the first occurrence (FO) of *Fasciculithus tympaniformis* (60.48 Ma), which occurs in the underlying Whangai Formation. Recent analysis of outcrop samples from Angora Road and Tawanui in southern Hawkes Bay, and Pahaoa in the Wairarapa, found that nannofossils are rare to abundant within the Waipawa Formation. At Angora Road and Pahaoa, the base of the formation is located above the FO of *Heliolithus cantabriae* (59.76 Ma), within upper Zone NP5. The top of the formation occurs just above the FO of *Discoaster mohleri* (58.32 Ma; Zone NP7) at Angora Road, although this datum occurs 0.4 m above the top of the Waipawa-equivalent unit at Pahaoa. Nannofossils are rare in a single sample from Tawanui, but samples above and below the Waipawa-equivalent unit (uppermost Te Uri Member) constrain the age to between Zones NP5 and NP8. Prior work from Mead Stream yielded a similar age of Zone NP6-8. On balance, calcareous nannofossils constrain the age range of the Waipawa Formation to approximately 59.5 to 58 Ma, suggesting deposition of the unit occurred over 1.5 million years.

## Geomorphic structure and paleoseismicity of the central Alpine Fault revealed through LiDAR imagery

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In the central South Island, the northeast-striking, dextral-reverse Alpine Fault forms the principal component of the Australia-Pacific plate boundary. The fault accommodates high slip rates of c. 25-29 mm/yr (dextral) and up to 6-11 mm/yr (reverse), mostly uplifting Pacific Plate rocks that form the Southern Alps. However, the associated rapid uplift and erosion and dense temperate rainforest along the western side of the island have typically hampered geological efforts to better understand the surficial structure of the Alpine Fault.

A 34 km long x 1.5 km wide swath of airborne LiDAR (Light Detection and Ranging) survey along the central section of the Alpine Fault between Franz Josef and Whataroa has been flown and processed. A 2 m DEM developed from the LiDAR has provided unhindered bare-earth images of the tectonic geomorphology along the fault.

Two of the research highlights for this work have been: (i) the mapping of more than 250 NE- to ENE-striking dextral to dextral-normal slip fault traces and N- to NNE-striking dextral-reverse to thrust fault traces, and (ii) paleoseismic trenching of a mapped linear scarp on the true right side of Gaunt Creek adjacent to the DFDP-1 drill site. The former confirms the models of partitioning and shallow fault segmentation shown by Norris and Cooper (1995) but delineates more complex, finer scale structure. The latter documents repeated late Holocene, low-angle faulting across a NNW-striking fault scarp. We have documented faulting on this trace which corresponds with the most recent rupture event on the fault in c. AD 1717.

The Alpine Fault is thought to rupture in large to great (M7.8-8) earthquakes every 200-400 years, giving the LiDAR data applicability in refining the surface rupture hazard posed to the town of Franz Josef through which the fault crosses.

**Are there palaeoclimatic signals in tephric loess deposits aged c. 30 to 15 cal ka near Rotorua, northern New Zealand?**

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We present a multi-proxy palaeoclimatic record, spanning c. 33–15 calibrated (cal) ka and including the extended Last Glacial Maximum (eLGM), derived from analysis of tephric loess in the Rotorua area. The loess deposits were dated, synchronized, and correlated using up to six rhyolitic marker tephras with known (but approximate and provisional) ages. As well as stratigraphy, proxies assayed to derive paleoclimatic information included loess thickness, opal phytoliths, magnetic susceptibility, grain size, total carbon and nitrogen contents,  $\delta^{13}\text{C}$  analysis, and potassium and phosphorus contents. Our results suggest that the eLGM in the Rotorua region began c. 27.1 cal ka and lasted until c. 19 cal ka. Four climatic phases were identified. Phase 1 (c. 33–27.1 cal ka) was characterised by generally warm conditions, the lowest rates of loess accumulation, and a peak in forest cover before cooling into the eLGM began. Phase 2 (c. 27.1–24.7 cal ka) was dominated by cold conditions, highest rates of loess accumulation, and change to a grassland-dominated environment. Phase 3 (c. 24.7–19 cal ka), characterised by cool conditions, was a complex phase with a possible interstadial around c. 24.1–23.9 cal ka. Significant warming occurred during phase 4 (c. 19–15.4 cal ka) along with a decrease in loess modal grain size, increase in total carbon content, and a continued decrease in grassland cover since phase 3. Developing a

more-detailed understanding of paleoclimatic fluctuations within the eLGM and the transition into the postglacial period (LGIT) is an essential part of the Australasian INTIMATE project. Our results are broadly consistent with palynological, aeolian-quartz-flux, palaeolimnological, and beetle-based evidence from elsewhere in New Zealand but the timing of changes remains imprecisely constrained. The 'mid-eLGM' interstadial at c. 24.1–23.9 cal ka may link to an Antarctic isotope maxima (AIM2) identified in EPICA ice-core records.

**Nature and economic potential of glauconite on central Chatham Rise, New Zealand**

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Chatham Rise is a broad, elongated submarine platform to the east of central New Zealand. The surficial sediments on the central portion of the Rise at depths of 200-500 m include significant concentrations of glauconite (10-80 wt%) associated with skeletal carbonate, fine terrigenous material and locally abundant phosphatic nodules. Sub-bottom 3.5 kHz profiles have established the distribution, geometry, and thickness (10-200 cm) of these surficial deposits. Over 140 grab, dredge, or piston core samples have been analysed for their texture, mineralogy, and geochemistry. Glauconite most commonly occurs as dark green to black, very fine to fine sand-sized (0.2 mm), polished ovoidal and lobate pellets, and less commonly as infills within foraminiferal tests or as variably replaced rock fragments and phosphatic clasts. Notable features of some glauconite pellets include altered outer rims, expansion cracks, opaque inclusions and variable degrees of limonitisation. XRF/XRD analyses reveal mainly mature varieties with elevated  $\text{K}_2\text{O}$  (7-9 wt%),  $\text{Fe}_2\text{O}_3$  (19-23 wt%) and a dominant 10Å glauconitic mica content. K-Ar dates on pellets are currently being acquired, while previous work suggests a possible Late Miocene age. Consequently the glauconite

pellets have a predominantly allogenic or perigenic origin (i.e. derived/reworked) and in the modern setting are neither strictly *in situ* nor authigenic. A possible major source of the pellets is from submarine erosion of underlying Tertiary sediments with glauconite dispersal occurring during intensified bottom current circulation at times of lowered sea level within the complex Subtropical Front over Chatham Rise. Glauconite is widespread in many Late Cretaceous-Cenozoic sedimentary deposits in the New Zealand rock record and the Chatham Rise occurrences could provide a useful uniformitarian analogue for some of these. Also the Chatham Rise glauconites have potential economic significance as a future source of potash agricultural fertilizer, as a soil conditioner and as an industrial effluent filter.

#### **An overview of the fauna of Foulden Maar - terrestrial life in New Zealand at the Oligocene-Miocene boundary**

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The diatomaceous sediments preserved in Foulden Maar provide a unique window into the terrestrial plant and animal life of southern New Zealand at the Oligocene–Miocene boundary, c. 23 Ma. The small deep maar lake was effectively a closed system with anoxic bottom waters, capturing and preserving in exquisite detail both lake organisms and those of the surrounding rainforest. Examination of c. 120 m of laminated sediments recovered in a 183 m long core shows that the lake biota was dominated by a single species of pennate diatom for more than 100,000 years, suggesting a remarkably stable, silica-dominated lake ecosystem. At least one species of siliceous freshwater sponge, *Spongilla* was also abundant through this time. *Spongilla* probably lived on bacteria, algae and diatoms, further recycling silica.

At least two species of fish were the dominant predators within the lake. The most common, *Galaxias effusus* Lee, McDowall & Lindqvist provides the earliest record globally of the Southern Hemisphere family Galaxiidae. Specimens range from large-eyed juvenile

inanga to 140 mm long adults all preserved as intact skeletons on bedding planes. A recently discovered eel provides the first record of fossil *Anguilla* from the Southern Hemisphere.

In terms of diversity and quality of preservation, Foulden Maar is one of the most important Southern Hemisphere localities for fossil arthropods with 114 specimens collected to date. One is a water beetle, while the rest are forest dwellers and flying insects blown into the lake. They include termites (Isoptera), scale insects and flat bugs (Hemiptera), 6 families of beetles (Coleoptera), 2 families of flies/midges (Diptera), 4 families of ants/wasps (Hymenoptera), and 3 spiders (the only spider fossils known from New Zealand). Insect-plant interactions preserved on leaves (galls, mines, different types of feeding damage, domatia structures) also provide further indirect evidence for a diverse insect fauna.

#### **The composite QMAP 1:250 000 Geological Map of New Zealand**

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The completion of the last of the 21 geological maps coming from the QMAP 1:250,000 Geological Map of New Zealand project has enabled assembly of a composite geological map at that scale using GIS software and large format plotters. The composite map demonstrates the foresight of the early decision to colour largely by stratigraphic age such that major coeval stratigraphic units can be recognised. This includes the colouring of Cretaceous intrusions in green hues, contrary to previous established practise. The main exception to the colour by age rule has been the depiction of recent volcanic units; pink hues for the Quaternary rhyolite eruptive and intrusive rocks, and red hues for Miocene and younger mafic units that largely retain their original volcano shape.

In detail, the composite map shows mismatches across individual sheet boundaries. These have emerged through improvements based on new information becoming available for later maps during the 16 year span of the QMAP project.

The mismatches are being reconciled in the QMAP Seamless GIS, made easier (compared to other countries) by the early adoption of data standards and consistent mapping philosophy as well as the relatively short duration of the project.

### **Constraints on Late Miocene heat flow in southern Taranaki Basin**

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In determining the thermal history of sedimentary successions there are several variables that can be difficult to constrain, including the surface heat flow during the period of burial and the thickness of section removed at unconformities. In most studies, the present surface heat flow value is used as a constraint in such modelling, which utilises thermal history indicators (such as apatite fission track length distributions) even though this parameter likely varies during the burial and erosion phases within a basin.

In southern Taranaki Basin the surface heat flow during the peak burial (Late Miocene) can, unusually, be constrained for several drill hole sections because it is possible to establish the amount of section eroded at the Late Miocene – Pliocene unconformity from seismic reflection mapping. Knowing the complete burial history, the apatite fission track data for Fresne-1, North Tasman- 1 and Surville-1 can be used to solve for the heat flow (c. 80 mW/m<sup>2</sup>) at the time of peak burial immediately preceding the start of inversion and erosion. Having determined this value, we apply it to Blackwater-1 and Bounty-1 holes in Murchison Basin and use available apatite fission track data to resolve the amount of section eroded above the well heads.

The Late Miocene heat flow value of 80 mW/m<sup>2</sup> is greater than the current transient values for southern Taranaki Basin (c. 70 mW/m<sup>2</sup>) with the decrease possibly being attributed to a change in tectonic regime and the emplacement beneath this region of subducted Pacific Ocean

slab. Given that oil generation is time and temperature controlled, higher heat flows in the Late Miocene will also translate into earlier and more substantial oil and gas generation in the vicinity of the inversion structures than previously thought.

### **Shrimp cities in the Whakapohai Formation, Late Cretaceous, South Westland Basin, New Zealand: *Ophiomorpha irregulaire* and associated trace fossils**

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Steeply dipping indurated marine sediments of the Late Cretaceous Whakapohai Formation (WHF) exposed near Moeraki River outlet, 25 km north of Haast, are part of the uplifted eastern margin of South Westland Basin. WHF overlies quartzose sandstone, siltstone, coaly shale, and minor volcanic conglomerate of Tauperikaka Coal Measures.

The lowermost 50 m of WHF is a tidal heterolithic association of cross-stratified glauconitic sandstone and thinly bedded sand and mudstone. It includes ichnogenera *Asteriacites*, *Diplocraterion*, *Gyrochorte*, *Gyrolithes*, *Ophioichnus*, *Macaronichnus*, *Palaeophycus*, *Protovirgularia*, *Planolites*, *Rosselia*, *Rhizocorallium*, *Skolithos*, and *Teichichnus*. Starfish traces comprise *Ophioichnus* (probable substrate-rowing marks of ophiuroids), and *Asteriacites lumbricalis* and *A. quinquefolius* (resting impressions of ophiuroids and asteroids). Although no shelly molluscs are preserved, *Lockeia* (bivalve resting traces) and *Protovirgularia* (bivalve trails) are common. Lenticular and wavy bedding, single- and double-mud drapes, sigmoidal bedforms, and ichnofauna indicate an estuarine setting.

The upper 40 m of WHF consists mainly of well-bioturbated slightly muddy fine-grained sandstone. Laminated sand and mudstone beds are intercalated through its lower 10 m. Trace fossils in this shoreface association are dominated by *Ophiomorpha irregulaire* burrows

(probably made by decapod crustaceans). *Gyrochorte*, *Macaronichnus*, *Ophiomorpha nodosa*, *Palaeophycus*, *Planolites*, *Scolicia*, *Shaubcylindrichnus*, and *Terebellina* occur sporadically. At Monro Beach one bedding plane exposes an *Ophiomorpha irregulaire* maze consisting of 50-70 mm wide meandering galleries that extend over an area of 2.5 x 1.8 m. Sand-filled, steeply inclined *Ophiomorpha irregulaire* shafts are commonly modified by microfaulting and smearing of wall-lining mud pellets within and beyond the burrow fills, deformation that may be related to differential compaction during deep burial. First described from the Late Cretaceous Blackhawk Formation, Utah, and considered rare outside the Western Interior Seaway of North America, *Ophiomorpha irregulaire* is also reported from the Cretaceous of India and Jurassic of Argentina. This report further expands its post-Gondwana distribution.

#### **LiDAR data illuminates Holocene activity of the Wellington Fault in the Tararua Ranges**

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North of Kaitoke Basin, the c. 53 km long Tararua section of the Wellington Fault traverses the densely forested Tararua Ranges and is the least understood section of that active dextral fault. A 6 x 1.5 km strip of LiDAR data was flown and processed along the Waiohine River near Totara Flats, where the fault has captured and dextrally displaced the river course by c. 6 km. Analysis of a 2 m DEM allows us to map active traces and variably displaced fluvial features. Based on trace geometry, we infer that the fault dips northwest at only  $42 \pm 3^\circ$  where it crosses the gorge, suggesting heave may contribute significantly to horizontal slip on this dextral-reverse fault. Using LiDAR, we mapped seven Quaternary fluvial terraces, six fan levels, and landslides. Profiling the data allowed us to correlate terraces and fans and measure scarp heights. We field-checked features in the DEM. Radiocarbon data indicate that a terrace c. 30

m above the river was abandoned at c. 10 ka, and that a forest c. 3 m above the river (Q1a), was buried in gravel at  $1420 \pm 20$  AD. Q1a is dextrally displaced by c. 3 m in the Waiohine gorge, indicating it pre-dates the most recent event (MRE). Nearby fault-ponded sediments have radiocarbon ages of <1654 AD. These data indicate that the MRE may have coincided with that on the Wellington-Hutt Valley section. Six gullies and fan-related risers incised into the 10 ka terrace are displaced dextrally by  $25 \pm 3.5$  m, indicating a minimum dextral-slip rate of c. 2.5 mm/yr. The 10 ka terrace has a c. 16 m high scarp. A lower terrace with an age less than or equal to that of the dextrally-offset landforms has a  $6.3 \pm 1.3$  m high scarp. If dip-slip rate has been constant, these data imply a maximum dextral slip rate of 6 - 6.5 mm/yr.

#### **Palaeomagnetism of Palaeogene sediments from south-eastern Zealandia: Implications for early Antarctic glaciation**

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We sampled three Palaeogene onshore sections from the southeastern New Zealand region: at the mid-Waipara River in Canterbury, at Fairfield Quarry near Dunedin, and on subantarctic Campbell Island. These sections may hold the record of a transient Antarctic glaciation prior to major ice sheet growth in the Oligocene, but accurate magnetostratigraphy is required to correlate the sedimentary records.

Palaeomagnetic work was complicated by extremely weak magnetisations and by the lack of existing data on comparable sediments. We conducted a thorough rock magnetic and mineralogical investigation to enable reliable interpretation of the palaeomagnetic results, with a particular focus on the relationship between glaucony and magnetic remanence. The rock magnetic work showed that the magnetic mineralogy differs markedly from that of previously studied younger sediments from the same regions, but also indicated that reliable palaeomagnetic directions could be determined for the majority of sites.



We used stepwise thermal demagnetization to analyse the magnetizations from each sampled section, interpreting the data with a custom-written interactive software package. This allowed the construction of magnetostratigraphies for each of the sections, significantly improving on the previous biostratigraphic constraints. In addition, palaeocurrent directions were determined by measuring the anisotropy of magnetic susceptibility.

Gaps in the composite record of the three sections are consistent with the hypothesis of an early Cenozoic bottom-water pulse caused by a glacial episode. This work also produced detailed rock-magnetic data on previously unexamined sediments from the Palaeocene and Eocene of the eastern New Zealand margin, which will be valuable for future palaeomagnetic studies on similar sediments. The palaeomagnetic analysis software developed for this project is freely available and suitable for use in a wide variety of other palaeomagnetic studies.

#### **LGM-Holocene glacial and depositional history of the Ross Ice Shelf, Coulman High, Antarctica**

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As part of the ANDRILL (Antarctic Geological Drilling) site survey at Coulman High, four access holes were made through the Ross Ice Shelf using a hot water drill. In total 28 sediment cores were collected with the longest core measuring 1.29 m.

Prior to splitting, all cores were x-radiographed at NIWA, Wellington. These images show a coherent stratigraphy between cores from each site and with short cores collected in the wider Western Ross Sea and McMurdo Sound. Magnetic susceptibility, wet bulk density, P-wave velocity and colour reflectance data were collected using a multi sensor core-logging tool. All cores show similar vertical

succession of lithologies, which from the oldest to the youngest consist of a clast-rich sandy diamictite, overlain by a terrigenous silty clay that is mostly massive but has intervals of subtle laminae, finally passing upwards into a silt-bearing diatom ooze with a bioturbated lower contact.

The cores will underpin a project that will tie in with previous work done in the Ross Sea region on short sediment cores that suggest modern calving line conditions were established in the region sometime between 9 and 6.5 ka. With this proposed project we aim to test this hypothesis by examining these new cores to the east of Ross Island. We will present data on grain size and petrographic analyses used to reconstruct the evolution of the region from ice sheet to ice shelf and open marine conditions. A radiocarbon chronology helps constrain the age of ice sheet lift off and ice shelf calving events during the Holocene. Together with previous studies, these Coulman High cores provide insights to the glacial and depositional history of the Ross Ice Shelf since the Last Glacial Maximum, and will enable a glacial-interglacial depositional model to be established.

#### **New Zealand Marine Sediment Database**

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NIWA (and its pre-decessor NZOI) have been collecting and analysing sediment from the seafloor around New Zealand and the South Pacific since the late 1950's. The station details (such as station id, position, and date) were traditionally logged in ledger books and the sediment analysis (grain size analysis: % sand, % mud, % carbonate) was filed in paper folders. We have just completed a data rescue project involving the digitisation of sediment analysis of 30,000 samples, reconciling the data with the existing station database, and transferring the data into a GIS.

This digitised dataset has highlighted major gaps and quality control issues. These will be targeted, corrected and filled with samples in the NIWA archives. Eventually this dataset will

allow an improved seafloor sediment map of the New Zealand EEZ and help to map and understand marine benthic habitats. It will also provide information about sediment pathways, areas of sediment accumulation and erosion and possible marine sediment resources.

The next stage of this project will be to create a public searchable web interface for this data and provide data storage for all New Zealand marine sediment data. Please contact us if you have any published grain size, carbonate, general sedimentary data, to contribute to the database.

### **Deep rock damage in the San Andreas Fault revealed by P- and S-type fault-zone-guided waves**

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Damage to fault-zone rocks during fault slip results in the formation of a channel of low seismic-wave velocities. Within such channels guided seismic waves, denoted by Fg, can propagate. Here we show with core samples, well logs and Fg-waves that such a channel is crossed by the SAFOD (San Andreas Fault Observatory at Depth) borehole at a depth of 2.7 km near Parkfield, California, USA. This laterally extensive channel extends downwards to at least half way through the seismogenic crust, more than about 7 km. The channel supports not only the previously recognized Love-type- (FL) and Rayleigh-type- (FR) guided waves, but also a new fault-guided wave, which we name FF. As recorded 2.7 km underground, FF is normally dispersed, ends in an Airy phase, and arrives between the P- and S-waves. Modelling shows that FF travels as a leaky mode within the core of the fault zone. Combined with the drill core samples, well logs and the two other types of guided waves, FF at SAFOD reveals a zone of profound, deep, rock damage. Originating from damage accumulated over the recent history of fault movement, we

suggest it is maintained either by fracturing near the slip surface of earthquakes, such as the 1857 Fort Tejon M 7.9, or is an unexplained part of the fault-creep process known to be active at this site.

### **Ihungia igneous conglomerate: ophioliticlastic island-derived detritus preserved along the head scarp of a large Miocene submarine gravitational slide?**

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The earliest Miocene cover sequences of the East Coast Allochthon (ECA) contain some small isolated outcrops of distinctive mafic igneous-derived conglomerates and serpentinite-bearing sandstones (Ihungia igneous conglomerate, lower Tolaga Group). We propose that just prior to deposition of these units, there was eastward, downslope displacement of a large portion of the ECA, forming a large reentrant, perhaps in a multi-staged event. Notably, our proposed Ihungia reentrant, which follows the trace of the ECA-Ihungia contact, is essentially the same shape and scale as the other Modern reentrants along the shelf edge of the Raukumara Peninsula. The latter are thought to have formed by submarine mass wasting and are associated with downslope debris fields and mass transport deposits (MTDs). In the Miocene Ihungia example, there would have been subsequent deposition of sediment across and along the margin of the reentrant (submarine escarpment) with sediment accumulating in what we refer to as the Ihungia basin. The ultramafic to mafic gravel and sand components in the Ihungia units were likely delivered via slope canyons from emergent, parts of the ECA (islands with exposed peridotite, gabbro and basalt). In this scenario, MTDs should underly and rim such a basin, and we believe that mapped mélange

and debris flow units are the onshore exposed equivalents of these deposits. Our model has implications for what we would expect to see in offshore seismic profiles, essentially patterns more similar to the modern Matakaoa reentrant seismic profiles, rather than an intact, buried frontal thrust sheet of the Allochthon like that seen off Northland; indeed this appears to be the case. On a broader scale our results suggest that mass transport processes have been active along, perhaps even dominating, this margin since just after emplacement of the ECA in the Early Miocene.

### **Textural characteristics of pyroclasts from the maar-forming Rotomahana segment of the 1886 Tarawera eruption, New Zealand**

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On 10 June 1886 Tarawera and Rotomahana (Okataina Centre, Taupo Volcanic Zone) produced New Zealand's largest, most destructive historic eruption, opening a 17 km fissure across Tarawera Mountain and adjoining Rotomahana basin. The last 9 km transected marshlands and an intensely active geothermal system, excavating coalesced maar craters now holding modern Lake Rotomahana. Dilute pyroclastic density currents reached 6 km from their crater sources, forming lithic-rich deposits with predominantly basalt pyroclasts in varying percentages and a range of textures, colours, densities and grain sizes.

Juvenile clasts from Rotomahana have densities (vesicularities) from 700-2500 kg/m<sup>3</sup> (9-77%). Rotomahana deposits are fine-grained even in proximal outcrops, so these densities are for smaller clasts (typically 10-50 mm), which are the coarsest juvenile clasts available. Most pyroclasts have multiple textural domains, with vesicles predominantly non-spherical and irregularly shaped.

Vesicle number densities (VNDs) for Rotomahana clasts are unusually high

(c. 10<sup>8</sup> cm<sup>3</sup>), comparable to those of pyroclasts from the Plinian phase of Tarawera. Histograms of volume-fraction size distributions show a narrow range of values, which is bimodal, with peaks around 0.19 mm and 2.2 mm. Vesicle-size distributions plot as curved segments, suggesting non-steady nucleation and growth, and are also similar to those determined for Tarawera Plinian clasts.

This similarity is surprising. Magma flux at Rotomahana was much lower than at Tarawera, seemingly precluding rapid ascent from source, yet textures suggest Rotomahana magma shared the history of that erupted from the Tarawera, with a sudden, large decompression producing high VNDs and microlite contents (>90%).

### **Carbon dioxide degassing at Lake Rotomahana**

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Lake Rotomahana was formed during the 1886 Mount Tarawera eruption along a 17 km long fracture between Mount Tarawera and Waimangu. Pre-1886, there were two small lakes in the area occupied by present day Lake Rotomahana. Violent phreatic and phreatomagmatic eruptions deepened and enlarged the two small lakes to form the Rotomahana Crater, now filled to a depth of c. 125 m forming a lake five times larger. Today thermal activity occurs mainly along the western shore of the lake with intense bubbling areas occurring in the lake close to these geothermal manifestations.

A total of 484 CO<sub>2</sub> flux measurements were taken at the surface of the lake in the period January-March 2011 using a floating accumulation

chamber method. A high mean CO<sub>2</sub> flux of 1297 g/m<sup>2</sup>/d measured at the lake surface is due to the subaqueous fumaroles (vents) discharging into the lake and are confirmed by the presence of bubbling observed in the field and on the lakefloor. In January 2011, more than 100 lakefloor vents were detected by a FURUNO FCV echo sounder confirming that intense hydrothermal activity occurs on the lakefloor. Therefore two mechanisms of CO<sub>2</sub> transfer at the lake-atmosphere interface have been ascertained: (i) CO<sub>2</sub> degassing by diffusion from the water to the atmosphere is the main mechanism of transfer and covers 94 % of the lake, with a mean CO<sub>2</sub> flux of 25 g m<sup>-2</sup> d<sup>-1</sup>, and (ii) CO<sub>2</sub> degassing via bubbles at the surface and represent only 5% of the total degassing. Applying a geostatistical method a total CO<sub>2</sub> emission rate from the entire lake is estimated to be 549 ± 72 t/d showing that Rotomahana is an active volcano.

**Unroofing active and ancient mountains:  
applications of the Ti-in-quartz  
geothermometer to sedimentary rocks and  
river sediments**

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Application of the titanium-in-quartz geothermometer (Wark and Watson 2006; Thomas, Watson et al. 2010) is investigated as a provenance tool for ancient and modern siliciclastic sediments in the lower South Island. This geothermometer allows determination of crystallization temperature of quartz on the basis of titanium (Ti) substitution at known pressure and a (TiO<sub>2</sub>). Temperatures calculated using the Ti-in-quartz geothermometer can be precise (often better than ±15 °C) for quartz in igneous and metamorphic rocks. Additional uncertainties in temperature estimates are introduced for detrital grains. Analysis of quartz grains is relatively simple and rapid, with data obtained using LA-ICP-MS.

Examination into titanium concentrations and resultant calculated temperatures in modern riverine quartz vary by location. Variations are interpreted to reflect changes in the metamorphic

grade of bedrock sources upstream. Additional variations between grain sizes within samples show partitioning of higher temperature quartz into smaller grain sizes. Sedimentary rocks of the Cenozoic East Otago sequence exhibit stratigraphic changes in Ti-in-quartz that are consistent with shifts from proximal to distal to reworked sources of sediment during regional marine transgression and regression.

Additional analyses using petrography and neodymium isotopes are employed to augment inferences formed using Ti-in-quartz geothermometry. These further assess quartz Ti concentration as a tool for provenance determination in addition to providing supplementary information.

**The possible inundation of Zealandia –  
does palynology offer any clues?**

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Whether or not the continent of Zealandia was inundated in Oligocene time is important for the interpretation of the history of New Zealand's biota. Fossil pollen grains preserve a record of ancient vegetation; 20 localities where rocks were deposited close to the suggested time of inundation were selected for palynology studies. Well preserved diverse pollen and spores were recovered in most samples and for those where only poor floras were recovered there are credible reasons (sedimentological, diagenetic, or hydrothermal).

The palynofloras represent a regional subtropical lowland coastal forest. Diversity is at least three times that of the modern day, even excluding from consideration the large numbers of undescribed taxa. The palynofloras show no signs of stress – for example there are at least eight different gymnosperm pollen types, some of which probably represent several individual species.

The palynology has cast some doubt on the validity and applicability of the previously recognised pollen-based biostratigraphic zones. If the zones are valid then it seems unlikely they can be used to adequately test the inundation hypothesis, because of the comparatively long time period represented by any single zone. A lot can happen in a million years.

The common intercalation of Oligocene–Early Miocene pollen-rich terrestrial sediments and shelly shallow marine facies offers a new approach, for strontium isotope dates on carbonate shells can be used to help establish an absolute age scale for the pollen zones, and to determine the timing of maximum submergence.

The study has reinforced the view that the Late Oligocene–Early Miocene vegetation remains poorly understood. Can palynology disprove Oligocene inundation? Probably not – but it does provide support for the view that a stable, well vegetated land mass prevailed.

#### **Southward propagation of the Marlborough Fault System: fault linkage and blind faults in North Canterbury**

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Geomorphological and paleoseismic studies provide insight into the fault geometry and kinematics of a series of dextral northeast-striking faults, including the Porters Pass, Hawdon, Bullock Hills, and Esk faults, in the South Island of New Zealand. These faults show post-glacial offsets that are significantly larger than predicted from offset - surface rupture length regressions derived from empirical relationships. Geomorphological mapping reveals slip rates as high as 9 mm/yr for the Hawdon Fault and Bullock Hills Fault over an expected fault length of c. 140 km. Surface expressions of some parts of the studied faults are obscured by glacial gravels, indicating that blind faults are present in parts of the Southern Alps and may be the source for a component of a reported slip

deficit in North Canterbury. We hypothesize that the Porters Pass, Hawdon, Bullock Hills and Esk faults are segments of an incipient fault system that stretches from the western tip of the Porters Pass fault to the Hope fault, east of Hanmer Springs. Considering the location, similar strike and dextral deformation mode, we suggest that this 140 km long dextral strike-slip fault system marks the southernmost extension of the Marlborough Fault System resulting from the ongoing southward propagation of the Pacific-Australian plate boundary in New Zealand's South Island.

#### **Magma history from $^{87}\text{Sr}/^{86}\text{Sr}$ isotopes at Ngauruhoe, New Zealand**

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New tephrochronological studies of Ngauruhoe demonstrate the volcano's explosive eruption history dates back over c. 7000 years, which makes it around 4500 years older than previously thought. Ngauruhoe has undergone several different phases of activity over its lifespan, with short, bursts of high-frequency and high-intensity eruptions (VEI 3-4) being separated by an overall apparently low rate of VEI 2+ eruptions. The main high-intensity burst, between c. 2900 and 2700 cal. yr. B.P. produced 64% of its known explosive eruptions of >VEI 2. This phase representing 3% of the volcano's lifespan produced over 57% of its total pyroclastic volumetric output. Following this burst, eruption frequency has declined, and smaller scaled eruptions (VEI 1-2) occurred separated by intervals up to c. 400 years. By examining  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopes of volcanic glasses from tephros and lava bulk samples from the

cone, the first correlation between pyroclastic and cone/lava records has been achieved. This has also provided information about magma-crustal interaction and the magma storage system of Ngauruhoe. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios range from 0.704727 to 0.70558 systematically over three cycles during the overall eruption history. The start of each cycle shows low values, indicating recharge of new magma into crustal reservoirs, whereas ratios increase as magma stagnates mid-crust and begins to assimilate crustal materials. By linking the conditions in the magma system through isotopic analysis, with the observed eruption rate, a geochemistry driven probabilistic hazard model is now being constructed for this volcano.

#### **Indonesian palaeoceanographic history using detrital Pliocene corals**

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Narrowing of the Indonesian Seaway is suggested to have been the driver for significant climate change beginning c. 3 - 4 Ma. Seaway narrowing is hypothesized to have changed the source of the Indonesian Throughflow (ITF) entering the Indian Ocean from the warmer, saltier South Pacific Ocean to the cooler, fresher North Pacific. Such changes in sea surface temperature (SST) and sea surface salinity (SSS) were instrumental in the aridification of Eastern Africa and the development of modern climate drivers, such as El Niño Southern Oscillation (ENSO). Much of the evidence for changes in ITF behaviour is derived from marine cores in the Indian Ocean, rather than studies within the Indonesian Seaway.

In this study, we use detrital Pliocene corals, entrained within turbidite debris flows of the Viqueque Megasequence in East Timor, to develop 'in situ' proxy records for paleo-oceanographic change. The geochemistry of coral skeletons is controlled by the prevailing ambient ocean conditions at the time of skeletal deposition, meaning they are a crucial proxy for palaeoclimate reconstructions. Preliminary U/Pb dating reveals an isochron age of 2.58

Ma. Detailed assessment of multiple corals, using XRD, SEM, petrographic analysis, and X-radiography, has revealed exceptional preservation of the primary aragonite skeleton with minimal diagenetic textures. Therefore, geochemical analysis of these fossil corals using stable isotopes and trace elements ( $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ , Sr/Ca) to interpret palaeo-SST and SSS provides insights into oceanographic history of the Indonesian region during this important period of global climate change.

#### **Oligocene islands of Zealandia: evidence from sandstones and limestones**

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Zealandia experienced maximum marine inundation (MMI) in the interval 23-26 Ma (late Duntroonian to early Waitakian stages; latest Oligocene to earliest Miocene). There is debate as to whether Zealandia was totally submerged at this time (Landis et al. 2008) or if there were emergent islands (King et al. 1999). To test these alternate hypotheses two reconnaissance investigations were made: (i) a new detrital framework provenance study of Late Eocene, Oligocene and Miocene marine sandstones from the Waiiau, Te Anau and Murchison Basins, and (ii) an interpretation of the non-carbonate content of New Zealand's limestones (Morgan 1919; Kitt 1962).

The quartz-feldspar-lithic content and geochemical compositions of sandstones have specific matches with local basement sources and change little across the MMI interval. The sandstones are interpreted as immature first-cycle clastic deposits. These are different from reworked deposits of mixed provenance as might be expected if there had been total or substantial drowning of Zealandia.

Most New Zealand Oligocene limestones have a substantial non-carbonate component. Where petrographic data are available (e.g., Smith et al. 1989) this component is shown to comprise mainly angular grains of quartz and feldspar. These New Zealand Oligocene data contrast with those from modern submerged carbonate banks (e.g. Bahamas and Maldives) which are

distinctly more carbonate rich. A terrigenous Oligocene source is indicated.

While some parts of Zealandia may indeed have been totally submerged in the Duntroonian-Waitakian, sedimentary petrology studies of sandstones and limestones both suggest the presence of persistent local sediment sources (island landmasses) adjacent to at least the Waiiau, Te Anau and Murchison Basins.

**Postseismic ground deformation  
after the 2010 Darfield, New Zealand,  
earthquake from Synthetic Aperture Radar  
Interferometry (InSAR) data - Withdrawn**

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The September 2010  $M_w$  7.1 Darfield Earthquake was a complex event that caused rupturing of multiple fault planes. Inversion of geodetic data indicates that most of the earthquake's moment release resulted from right-lateral strike-slip motion on a previously unrecognized east-west striking Greendale Fault. A number of other blind faults also contributed to the event including a northeast-striking reverse fault near Charing Cross, coincident with the earthquake hypocentre, and another reverse fault west of the Greendale fault near Hororata.

We analyzed Synthetic Aperture Radar Interferometry (InSAR) data following the Darfield earthquake to investigate postseismic ground deformation after this event. X-band and L-band InSAR measurements from German TerraSAR-X, Italian Cosmo-SkyMed and Japanese ALOS satellites indicate several centimetres of postseismic deformation at the location of the Charing Cross reverse fault, and a small amount of afterslip on the Greendale Fault. We also report on localized time-dependent postseismic deformation at a restraining bend along the Greendale Fault. The interpretation of such postseismic observations will help to assess the impact that the 2010 Darfield event had for earthquake hazard in the Canterbury region.

**Submarine landslides in Cook Strait  
Canyon. Distribution, earthquake triggering  
and tsunami hazard**

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The Cook Strait Canyon is a deeply incised bedrock submarine canyon system between the North and South Islands of New Zealand. More than 100 landslides have been mapped and characterised using 25 m resolution digital elevation models derived from Simrad EM300 multibeam data. Morphometric spatial analysis shows that the primary pre-conditioning factors for instability are canyon incision leading to oversteepening of lower canyon wall slopes. A series of sediment cores collected from selected landslides in February 2011 have been used to determine geotechnical properties and sampled for datable material to constrain the age of failure. Earthquakes are the primary trigger inferred for large scale submarine slope failures. Cook Strait has numerous active fault lines, and is adjacent to the Hikurangi Subduction Zone, and thus experiences high levels of ground shaking over geomorphic timescales. We infer that earthquakes are the dominant trigger for submarine landslides in Cook Strait, and use dated core samples to correlate landslide occurrence to specific events (e.g., 1855 Wairarapa M 8.2). The head of Nicholson canyon is within 15 km of Wellington and has experienced large-scale (0.5 km<sup>3</sup>) slope failure in the past. Numerical modelling of tsunami generation and propagation indicates that these landslides pose a hazard to Wellington coastal communities and infrastructure. This work is the first step towards developing a comprehensive tsunami risk model for the Wellington region, and a methodology that can be applied elsewhere.

**The high tide of the mid-Pliocene:  
Reconciling ice volume and global  
sea-level**

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Ice volume calibrations of the deep ocean foraminiferal  $\delta^{18}\text{O}$  record imply orbitally-influenced sea level fluctuations of up to +25 m amplitude during the mid-Pliocene, 4-3 million years ago when Earth's average surface temperature was c. 3° C warmer and atmospheric  $\text{pCO}_2$  levels were up to 400 ppm. These sea level oscillations drove recurrent transgressions and regressions across the world's continental shelves which are recorded in far-field, shallow marine sedimentary successions in Virginia and New Zealand. Backstripping of these continental margin records implies Pliocene sea-level highstands of c. +20 m, compared with eustatic estimates of c. +40 m derived from the tectonically-uplifted Orangeburg (eastern USA) and Alaskan marine terraces.

This century Earth reached atmospheric  $\text{pCO}_2$  levels comparable to those experienced 4-3 million years ago during the warm Pliocene Epoch, and this geological analogue is becoming increasingly important for assessing the likely magnitude and rate of future polar ice sheet melt and global sea-level rise.

New geological drill core data from the Antarctic continental margin (ANDRILL AND-1B) and ice sheet modelling imply rapid ice volume loss, during orbitally (obliquity)-paced Pliocene interglacials, equivalent to +7 m sea level rise, involving complete loss of the marine-based West Antarctic Ice Sheet (WAIS) and melting around the marine periphery of the East Antarctic Ice Sheet (EAIS). The model results are consistent with both: (i) well-dated evidence from AND-1B sediment cores implying a dynamic WAIS, and (ii) paleoglaciological evidence from the Transantarctic Mountains

that appears to preclude substantial ice loss from the EAIS.

It appears that progress is being made towards closing the Pliocene sea-level budget. New generation ice sheet models supported by proximal Antarctic geological records allow for a maximum global eustatic highstand of c. +17 m during early Pliocene interglacials (assuming complete deglaciation of Greenland and +3 m from thermosteric effect), which reconciles quite well with the far-field sea-level reconstruction.

**James Hector and the first geological maps  
of New Zealand**

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James Hector was involved in the organisation of a national exhibition that was held in Dunedin in early 1865. About the same time he was appointed to be the founding Director of the New Zealand Geological Survey. He took the opportunity to compile a geological map of the whole country, based on surveys of different provinces. It was to be the first of several maps of New Zealand that Hector produced over the next 20 years.

The 1865 map was hand-drawn on Whatmans card, and was a painstaking reduction of the provincial maps. Hector acknowledged that it was compiled from the work of Crawford, Haast, Hochstetter, and himself

Although Hector had intended to publish the 1865 map, financial cutbacks meant that this was not possible for several years. By 1869 he had gathered information in areas previously little known especially Northland. The 1869 map is more generalised than the 1865 version, possibly because of the limitations of lithography.

Geological knowledge moved ahead rapidly in the 1870's because Hector had parties in the field every summer, with emphasis on developing local stratigraphy and defining the age of major units. The 1873 map contains the most detailed legend of any of Hector's



maps, naming and grouping together the main lithological units.

Hector's reconnaissance surveys were essentially completed by the end of the 1870's. He produced several similar geological maps in the 1880s for exhibitions and national handbooks, of which the 1883 map is typical. This was the first of his maps to adopt international nomenclature and colours.

After Hector retired in 1903 the Geological Survey adopted a programme of detailed mapping of areas, based on their economic potential. No new national geological map was published until 1948.

### **Complex interactions between New Zealand's oceanographic water masses and West Coast Canyon geomorphology**

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Submarine canyons form prominent geomorphic features that incise the continental margin. They provide conduits for off-shelf escape of terrestrially-derived material to the deep-ocean and distinctive habitats for benthic communities. The West Coast, South Island supports two large canyon-channel complexes fed by steep, short-reach rivers that carry c. 30% of New Zealand's total riverine contribution to the sea, and form important point-sources of land-derived nutrients and bio-active material. Dependant on location, sediments within this channel-levee system range from well-sorted, mica-rich silts and sands to coarser turbidite deposits and last glacial gravels.

New Zealand lies at the critical junction between northern-tropical climate influences and those

of the Southern Ocean and its sedimentary archives hold the keys of understanding complex climate interactions back many thousand of years beyond historical records. The West Coast, New Zealand region is an ideal location to understand of the history of the westerly wind system through time as the interaction between orographic effects and the westerlies produce significant precipitation on the West Coast of the South Island. As part of this study generation of a detailed high-resolution paleoceanographic history is undertaken; in particular records of sea surface temperature and bottom water properties/intermediate and deep-water circulation (isotope proxies) as well as atmospheric temperature change (glacier advance/retreat; pollen) throughout the Quaternary in the southern Tasman Sea. Here we present the chronostratigraphy derived from stable isotopes, biostratigraphy, paleomagnetism and dating of four Marion duFresne IMAGES cores extending at least 1.5 Ma, with sedimentation rates up to 10 cm/ky. Observations for millennial scale cooling in New Zealand can be controversial, due to poor age control, poor spatial coverage, low stratigraphic resolution of existing records, and lack of sensitive temperature proxies. In this context, long sediment cores collected in this sector of the New Zealand region will provide an opportunity to access high-resolution records of recent oceanographic changes and terrestrial response on the New Zealand landmass.

### **Strike-slip analysis of the Stanley Fault, Papuan Basin, Papua New Guinea.**

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The fault flanking the Stanley gas/condensate discovery in the western foreland portion of the Papuan Basin, Papua New Guinea, has long been recognised as having a Tertiary episode of sinistral strike-slip. The fault, extending laterally for several tens of kilometres and having extensive reflection seismic data coverage, is conventionally thought to have had an extensional origin around Late Triassic or Early Jurassic, but the case is put here that this and other local faults show dip geometry characteristic of having always been strike-slip.

Geometry characteristic of extensional faulting is evident only very locally, in what is interpreted as a releasing bend section of the fault. However this fault bend also shows evidence (a short-cut thrust fault) of a restraining phase, which is taken to indicate an episode of dextral strike-slip movement on the fault. This and related local faults show many of the classic characteristics of a strike-slip system. New appraisal/development drilling on the Stanley Field this year has provided examples of small-scale strike-slip structure in cores, and log data correlation has yielded new information on fault movement timing. The Stanley Field structure is recognised as resulting from two phases of inversion on a restraining bend or fault termination geometry, and the timing of these phases (and probable additional intermittent stress variations) can be clearly demonstrated from well-log and seismic-reflection data. Locally there have been four successful hydrocarbon tests (Stanley, Elevala, Ketu, and Ubuntu) and only one failure (Kiunga). Kiunga, adjacent to a releasing bend in a sinistral strike-slip scenario, is the only structure among the five tests to show extensional geometry character, and this may be a significant factor in the failure of this structure to retain hydrocarbons.

#### **Lessons from limestone dykes on Chatham Islands, New Zealand**

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Chatham Islands sit atop the eastern end of Chatham Rise, a submarine high of submerged continental crust protruding into the southwest Pacific Ocean from the South Island. The islands stand topographically proud due to intra-plate basaltic volcanism initiated in the Late Cretaceous and continued intermittently through the Cenozoic. The scattered occurrences of Tertiary sedimentary rocks on the islands are mainly temperate skeletal limestones, rich in bryozoan remains and benthic foraminifera, whose distribution and geometry have been strongly influenced by cone building associated with coeval eruptions of basaltic lavas and volcanoclastic tuffs.

Locally on Chatham and Pitt Islands subvertical limestone dykes penetrate the volcanic and volcanoclastic deposits of Late Cretaceous (Southern Volcanics, Kahuitara Tuff) and especially Eocene (Red Bluff Tuff) age. The dykes have exposed heights of a few to 60 m and range up to 3 m wide, although most are dykelets (0.5-50 cm wide) or stringers (<0.5 cm wide). They have sharp but undulatory outside walls and typically bifurcate or anastomose within the host volcanic deposits. While many seemingly resulted from passive rapid infilling of fissures by mass flows of skeletal carbonate (i.e., neptunian dykes), others show sidewall striations, internal wall-parallel laminated and fabric-aligned sediment, and lithoclasts of earlier fill lithologies suggestive of hydrodynamic, suction-controlled forceful injection of sediment (i.e., clastic dykes) and intra-fissure grain sorting. Fissuring, fill and injection may relate to seismic activity and tensional stresses accompanying development of the associated volcanoclastic tuff mounds.

Dyke fills can be monolithologic or, more commonly, multilithologic, involving discrete units of highly diverse types of skeletal limestones, micrite, crystalline spar, and/or volcanoclastic material, and an equally wide spectrum of carbonate diagenetic fabrics. Certainly the carbonate fills exhibit far greater facies and diagenetic varieties than in any associated limestone, and in places an appropriate source limestone is entirely missing from the local stratigraphy.

#### **Orbital forcing of mid-latitude Southern Hemisphere glaciation inferred from magnetic grain-size proxy on the Challenger Plateau**

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Magnetic grain-size from RV Marion Dufresne cores MD06-2988 & -2989 collected in  $\leq 1790$  m water depth from the south Challenger Plateau

record orbitally-forced terrestrial climate signals over the last two million years.

Magnetic grain size in the cores was determined from anhysteretic remanent magnetisation ( $\kappa$ ARM) and volume magnetic susceptibility ( $\kappa$ ) measured on u-channel samples using a pass-through cryogenic magnetometer with an in-line susceptibility bridge and solenoid in the shielded room at the University of Otago Paleomagnetic Research Facility. Age control was achieved through correlation of the paleomagnetic inclination and relative paleointensity (NRM/ARM) records to radiometrically dated geomagnetic excursions and polarity reversals.

Fine magnetic grain-size intervals ( $\kappa$ ARM/ $\kappa$  ratio increasing by a factor of twenty, due to substantial increases in  $\kappa$ ARM) in MD06-2988 and MD06-2989 are inferred to be a clay content proxy, recording influx of glacial 'rock flour' into Hokitika Canyon during glaciations in the Southern Alps (MIS 58, 52, 38, 36, 20, 10 and 6). Several stadials occur during insolation minima (both hemispheres) and bracket unusually warm interstadials.

**Miocene - Pliocene effusive and explosive shallow subaqueous volcanism in the northern Chatham Island, SW-Pacific: evidence for the dominantly submerged nature of the Zealandia microcontinent**

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The Chatham Islands are crucial to understanding the paleoenvironmental history of Zealandia and evidence of Eocene submergence is clearly shown by the eroded Surtseyan and associated edifices of Red Bluff Tuff. Volcanic rocks in the northern Chatham Island itself are grouped into the Northern Volcanics, which are poorly exposed, slightly younger volcanics that were also erupted subaqueously. The youngest volcanism in Chatham Islands, forming the Miocene to Pliocene Rangitahi Volcanics, is the

key to establishing the paleoenvironment of the region at this time.

Here we provide a field-based summary to demonstrate that the region was still submerged in Miocene – Pliocene time and the preserved volcanic successions show strikingly similar volcanic facies and features to the older Red Bluff Tuff and Northern Volcanics that were clearly erupted in a subaqueous environment. New K-Ar radiometric age dating on coherent volcanic rocks from volcanic plugs, volcanic debris-filled conduits, and various volcanic breccias from undated locations revealed a broader age distribution of volcanic events than previously thought. This suggests more dispersed and potentially overlapping intraplate volcanic episodes through the Cenozoic.

A major problem at the Chathams is distinguishing volcanics formed under similar subaqueous conditions in different eruptive episodes which build up a complex pile of volcanic rocks that are preserved in a single erosion remnant. The present day elevation of facies changes from subaqueous to subaerial accumulation of pyroclasts suggests that the geomorphic horizon c. 100 m above present sea level represents the sea level at about 5 Ma. A significant morphological step in the same elevation in the erosion remnants of Surtla/Surtseyan origin buttes is evident. We suggest that Chathams must have been still a shallow marine region pitted by Surtseyan tuff cones in Miocene – Pliocene time, and at least 100 m of uplift/sea-level drop is inferred in the last 5 Ma.

**Active faults in New Zealand: what are we missing?**

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The recent  $M_w$  7.1 Darfield Earthquake produced rupture of the ground surface along

a fault that was not known to exist prior to the earthquake. How many more active faults remain undiscovered, how best to identify these faults, and what hazard they might pose are all important questions arising from the Canterbury earthquakes.

In this talk we use aerial photograph, fault trenching, seismic reflection, LiDAR, and historical seismicity information post 1845 to cast light on the first two of these questions for New Zealand. On the Taranaki Peninsula, where active normal faults generally have slow displacement rates  $<0.5$  mm/yr, seismic reflection lines reveal that  $<50\%$  of active faults produce mappable traces and that even where active traces have been mapped these constitute  $\leq 50\%$  of the sub-surface fault length. Similar statistics also apply on the Rangitaiki Plains in the Bay of Plenty, where a recently published LiDAR digital elevation model (Begg and Mouslopoulou, 2010) reveals many more active normal faults with longer traces than was previously identified from c. 1:16,000 aerial photographs and field mapping. In common with the Taranaki example the rates of sedimentation over much of the plains are comparable to the fault displacement rates (0.2-2 mm/yr) and fault scarp burial may be common.

To further test the incompleteness of the geological record, historical large magnitude earthquakes since 1845 are considered for all of New Zealand. Of the onshore events with magnitudes  $>7$  only about half show evidence of surface rupture along the primary fault surface and have the potential to be recorded in the future geological record. For the historical data, however, the main reason active faulting was not observed is that either ground surface rupture did not occur or was below the detection threshold. Together, lack of surface rupture and scarp concealment (or destruction) by surface processes are likely to mean that many active faults, particularly with slower displacement rates ( $<0.5$  mm/yr), have not yet been discovered. The Taranaki and Bay of Plenty studies suggest, however, that acquisition of data, including LiDAR and seismic reflection lines, can significantly reduce this knowledge gap.

Begg, J.G., Mouslopoulou, V., 2010. Analysis of late Holocene faulting within an active rift using lidar, Taupo Rift, New Zealand. *J. Vol. Geotherm. Res.* 190, 152-167.

### **Plio-Pleistocene evolution of the Southern Victoria Land climate system as seen in New Harbor drill cores**

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The Taylor Valley (DVDP-10, -11) and Ferrar Fiord (CIROS-2) drill cores offer a window into the history of Southern Victoria Land glaciers and the Antarctic climate system during the late Neogene. Here we present new paleomagnetic studies from these drill cores which date five phases of sedimentation in the Taylor/Ferrar fiords and reveal a climate modulation of magnetic mineralogy in southern Victoria Land during the late Neogene.

Magnetostratigraphies were constructed from stepwise AF and/or thermal demagnetisation of discrete specimens from drill cores. Correlation of magnetostratigraphies with the magnetic polarity timescale was guided by biostratigraphic and radiometric constraints. Environmental magnetic studies were conducted to determine changes in concentration, grain size and magnetic mineralogy through time. A parallel rock magnetic study was also conducted of regional basement rocks to quantify the source of magnetic minerals.

The new ages models and environmental magnetic records indicate that during the latest Miocene to early Pliocene, wet based glaciers filled the Taylor and Ferrar fiords and that glaciers retreated during the Pliocene warm period leaving open marine conditions and deep fiords ( $>300$  m). Magnetic minerals in these sediments are variably oxidised indicating terrestrial soil formation and probably warmer and wetter conditions at a time when the Ross Sea was free of ice and sea surface temperatures were  $5^\circ$  C warmer than today.

We recognise the first significant cooling in DVDP-11 after 2.6 Ma by a shift to current winnowed sediments sourced from the Ross Sea. After 1.7 Ma sediments are almost exclusively lacustrine and were deposited in ice dammed lakes which formed when West Antarctic ice expanded across the Ross Embayment and abutted the Transantarctic Mountains. Magnetic mineralogy after c. 2.6 Ma is dominated by a ubiquitous, paramagnetic component which coincides with the shift from warmer/wetter, sub-polar conditions to dry, polar dominated conditions.

**Floods, ocean storms and stratigraphic variability over a year-long experiment on the muddy and energetic Poverty Bay shelf**

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Sediment yields in the muddy Waipaoa River catchment today are among the highest on earth; the product of tectonics, easily erodible lithologies, a vigorous maritime climate, and deforestation. Accordingly, terrigenous inputs dominate the marine sediment record on the adjacent Poverty Bay continental shelf sequence, with thick expanded sections that contain a high-resolution archive of environmental change. Significant advances in the understanding and behaviour of the Waipaoa Sedimentary System have been afforded through the MARGINS Waipaoa Source-to-Sink initiative, but the balance of processes that drive sediment dispersal, deposition, and erosion over sub-annual timescales on the energetic continental shelf remains largely unknown.

The multi-institutional "Waipaoa Investigation of Seabed Energetics" (WISE) project has the goal of determining how the shelf sedimentary

record is produced by diverse processes. After a year-long experiment that included four research cruises and the longest time-series of *in situ* oceanographic, hydrodynamic, and stratigraphic data for a New Zealand shelf setting. Around 230 precision multicores were slabbed for X-ray analysis using a portable digital imaging system and subsampled for radiochemical tracers (Pb-210, Be-7). X-radiography is an excellent diagnostic tool for identifying strata and the architecture of sedimentary structures preserved in cores. Provisional comparison of X-radiographs at reoccupied core sites over one year suggests that changes occur over monthly timescales and single events can lead to profound changes to the sea floor stratigraphy on the inner and mid-shelf. Concurrent near-bed oceanographic data are compared directly with strata formation and destruction, and placed into a broader framework that examines the history of marine events together with floods. This experiment raises significant philosophical questions about the fidelity and completeness of the geological record, and emphasises the transient nature of many deposits affected by strong oceanographic drivers.

**Kinetics of methane genesis in serpentinization systems**

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Molecular hydrogen (H<sub>2</sub>) in serpentinization systems may result in the production of both abiogenic and biogenic methane (CH<sub>4</sub>). However, the proportion of CH<sub>4</sub> resulting from each process has not been determined. Here, we examine abiotic CH<sub>4</sub> production by Fischer-Tropsch type (FTT) catalysis during serpentinization at 200 °C and 0.03 GPa. By constraining the factors that control abiotic CH<sub>4</sub> formation, we investigate how biological

processes may modify the production of CH<sub>4</sub> observed in mid-ocean ridge and forearc serpentinization environments.

Experiments show that the rate of CH<sub>4</sub> production is dependent on magnetite formed during serpentinization. At steady-state conditions, abiotic CH<sub>4</sub> production is autocatalytic. This work also demonstrates that the ratio of H<sub>2</sub> to CH<sub>4</sub> may be used as a proxy to assess the presence and productivity of life in subsurface serpentinization systems. The H<sub>2</sub>/CH<sub>4</sub> ratio of 42 divides abiotic (>42) from biotic (<42) systems in olivine-rich hydrothermal environments.

### **GeoNet: monitoring New Zealand's natural hazards**

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New Zealand is a country in motion. We face earthquakes, volcanoes, tsunami, landslides, and geothermal activity. In many places where you live and work these hazards have the potential to cause devastating social and economic loss.

Operated by GNS Science and funded by the New Zealand Earthquake Commission (EQC), the GeoNet Project was set up in 2001 to provide real-time monitoring of these hazards. The project uses nationwide networks of seismograph, GPS, and strong-motion accelerographs to collect data on New Zealand's strain and deformation patterns, earthquakes, volcanoes, and a growing network of tsunami gauges collect measurements of sea-level fluctuations

The completion of these networks in the last ten years has improved the timing and accuracy of incoming data, and the project's focus has now shifted to the extension of regional seismic and GPS networks, the growth of the regional tsunami gauge network and the development of data products to promote better uptake of this valuable resource.

The data collected by the New Zealand GeoNet Project are fundamental to a better

understanding of the natural hazards faced by this country and in turn, this knowledge will improve their detection and management. It is hoped that the dissemination of accurate and timely information by GeoNet will aid planning and community preparation before a disaster strikes, and facilitate effective emergency responses afterwards, speeding the subsequent recovery of affected communities.

### **The GeoNet Project: data for research into New Zealand's natural hazards**

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GNS Science, through the GeoNet Project, has greatly improved monitoring of geological hazards in New Zealand and the collection of enhanced research data on the processes that cause earthquakes, volcanic eruptions and related effects.

GeoNet uses a wide variety of sensing equipment located throughout New Zealand. The New Zealand National Seismograph Networks accurately measure the location, magnitude, depth, and other characteristics of earthquakes with enhanced volcano monitoring provided by the Regional Networks. In addition to seismometers capable of characterising tsunami-causing earthquakes, a growing network of tsunami gauges collect measurements of actual sea-level fluctuations. Over 250 strong-motion accelerographs measure the extremely high ground accelerations associated with large damaging earthquakes, yielding information on the performance of structures during earthquakes. The Global Positioning System (GPS) network highlights areas within the crust where strain is building up or being released.

The GeoNet Data Centre is responsible for the capture of all geophysical data streams from field instruments or third party sources, the basic processing of raw data and the maintenance of archives. GeoNet provides free access to hazards data and information through its website ( [www.geonet.org.nz](http://www.geonet.org.nz)). This ranges from basic earthquake reports and Volcanic Alert Bulletins, to the retrieval of fundamental data sets such as GPS Rinex files, earthquake

hypocentre derivations, and instrument waveform data. The GeoNet Team regularly liaise with users of the data and information to ensure they are aware of its scope and the mechanisms for its distribution or retrieval.

GeoNet hazards data and information helps strengthen scientific research capabilities, enabling scientists to pursue new avenues of research that will not only lead to a better knowledge of geological hazards, but also reinforce existing research.

**Palynostratigraphy from Benneydale:  
refining the paleogeography and  
implications for the Oligocene drowning  
event, King Country, New Zealand**

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The debate about whether the New Zealand subcontinent (Zealandia) was completely inundated by the late Oligocene – early Miocene marine transgression continues. Palynofloras present in the Waikato Coal Measures, near Huntly, date those beds as late Eocene to early Oligocene. Nearshore and coastal environments in which Araucariaceae were prominent existed in the area at that time (Pocknall 1991). The southernmost exposure of the top of the Waikato Coal Measures occurs near the adit of the old Benneydale Coal Mine. This outcrop of the coal measures and the overlying beds were sampled in January 2010. The section at Benneydale is dated as Late Whaingaroan with the sediments falling into the *Rubipollis oblatius* Zone. The presence of *Nothofagidites cranwelliae* dominating over the older *N. matauraensis* and the absence of *Proteacidites isopogiformis* suggests the section is no younger than Duntroonian. The presence of nannofossils in the overlying unit from cores collected from Mangapehi Coal Field, immediately to the north, confirms the presence of a strong marine influence in the area in the early Oligocene. The palynostratigraphy

suggests that at the time of deposition the area lay in a deltaic environment with swamps commonly occupied by ferns. It appears that southern beech forest with casuarinas occurred in the drier areas and around the swamp. The climate was most likely humid, warm-temperate. The new dates indicate the upper boundary of the Waikato Coal Measures is gradually younging to the south. These data have been integrated to update paleogeographic maps of the area and refine the position of the Oligocene paleoshoreline. It would appear that during the Whaingaroan to Duntroonian the King Country remained largely terrestrial with much of it low lying near the coast.

Reference:

Pocknall, D.T., 1991. Palynostratigraphy of the Te Kuiti Group (late Eocene-Oligocene), Waikato Basin, New Zealand. *New Zealand Journal of Geology and Geophysics* Vol. 34: 407-17.

**A geodetic study of the Central Otago Fault System**

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The Otago Fault System is an area dominated by a series of actively growing northeast-trending asymmetric anticlines above buried reverse faults in the southern South Island of New Zealand. Geological studies indicate that the average total shortening rate across the system is 2-3 mm/yr. This region was the subject of several early geodetic studies based on classical data which reported fairly high (0.5 microrad/yr) strain rates which are difficult to reconcile with geological estimates of fault slip rates.

We have analysed approximately 10 years of recent satellite based geodetic data for about 20 stations evenly distributed over a broad corridor extending from the north-western end of Lake Wanaka to Dunedin. We divided the data into three sub-networks to study the

variation of geodetic strain over the region. In the northern two sub-networks, the strain rate tensors indicate shear strain consistent with dextral movement on north-east trending structures. The strain rates decrease from  $70 \times 10^{-9}$  in the northernmost network to  $23 \times 10^{-9}$  for the central network and are probably dominated by elastic strain accumulation on the Alpine Fault.

The southernmost network, which extends from the east coast to just west of the Rock and Pillar range, has a strain tensor consistent with uniaxial contraction. The principal axis of contraction is about  $16 \times 10^{-9}$ , which is consistent with geological estimates of rates of total shortening across the Otago Fault System. The orientation of the principal axes of contraction ( $110^\circ$ ) however, is not quite perpendicular to the northeast-trending structures which dominate the Otago Fault System and generally trend between  $030^\circ$  and  $050^\circ$  in the area covered by this network. This discrepancy may suggest that other structures such as the northwest trending Waihemo Fault also may make a contribution to the shortening in the region.

#### **Temporal impacts of volcanic ash in freshwater systems**

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Volcanic ash can result in the acidification and metal contamination of freshwater systems. Short-term chemical and pH fluxes in water have been attributed to ash surface leachates while dissolution of the glassy matrix has been linked to metal input over longer time periods. Using pristine basaltic-andesite volcanic ashes from Mount Ruapehu (New Zealand), Mount Sakurajima (Japan), and Soufrière Hills (Montserrat), we investigate the influence of ash on initial pH fluxes and metal dissolution rates in freshwater systems. All ashes provide an immediate pH decrease directly related to sulphur released from ash surface leachates. Initial pH decreases for all ashes are transient with the degree of acidification lessening following ash leachate removal via water rinse(s). Metal release rates from the glassy

matrix of ashes are dependent on surface area and ash to water ratios. As an example, ash from the 17 June 1996 eruption of Mount Ruapehu with an Al release rate of  $3.2 \mu\text{g/hr}$  (ash to water ratio of 0.01:20) will exceed World Health Organization drinking-water standards ( $0.1 \mu\text{g/L}$ ) in 2 minutes. Overall, our results demonstrate the bi-temporal hazard of volcanic ash in freshwater systems that may include drinking water supplies.

#### **Long-lived isotopes: tracking changes in paleocean circulation and ice sheet dynamics of the Antarctic-Southern Ocean system**

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The daughter products of long-lived isotope systems  $^{176}\text{Lu} \rightarrow ^{176}\text{Hf}$ ,  $^{147}\text{Sm} \rightarrow ^{143}\text{Nd}$  and  $^{238,235}\text{U}, ^{232}\text{Th} \rightarrow ^{206,207,208}\text{Pb}$  have seawater residence times that are shorter than ocean mixing time-scales. Hence, these tracers in seawater record changing source inputs (continental and hydrothermal) into the ocean through changes in the intensity and style of continental weathering, as well as changes in ocean circulation. Isotopic signatures for these systems in the paleocean can be recovered by analysis of authigenic ferromanganese (Fe-Mn) sediments.

We have measured Hf-Nd-Pb isotope ratios in two Fe-Mn nodules from the Bollons nodule field southeast of New Zealand ( $52^\circ\text{S}$ ,  $174^\circ\text{E}$ ) spanning an age range from 14 to 0 Ma ( $^{10}\text{Be}$  dates). The nodules come from the point where the Antarctica Circumpolar Current (ACC) enters the Pacific Ocean in concert with the Deep Western Boundary Current, but with the more energetic ACC dominating the deep circulation. Nd isotope ratios show little



variability ( $\epsilon\text{Nd} = -8.4$  to  $-7.6$ ) suggesting that the amount of continental input from Antarctica into the ACC has changed little over the past 14 Ma. However, Hf isotope ratios show substantial differences ( $\epsilon\text{Hf} = +7.1$  to  $+3.2$ ) with high and variable values from 14 to 10 Ma, followed by a sharp decrease to the lowest values at 10 Ma, which have remained relatively low to the present-day except for a small increase during the Pliocene. The large decoupled variations in Hf-Nd isotopes are interpreted to track the development of permanent Miocene ice sheets on Antarctica, which through mechanical weathering more efficiently destroy zircon crystals to release unradiogenic Hf (with low  $\epsilon\text{Hf}$ ) into the ACC during periods of more intense and extensive glaciation. In addition to Hf-Nd-Pb isotopes, trace element analysis of the Fe-Mn nodules has been undertaken to examine if any secular changes in ocean trace chemistry are recorded over the past 14 Ma that are coupled to isotopic changes.

**Structure and paleoearthquake records of active submarine faults, Cook Strait, New Zealand: Implications for fault interactions, stress loading, and seismic hazard**

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A new interpretation of active faulting in central Cook Strait, New Zealand, reveals tectonic structures associated with the spatial transition from subduction to continental transform faulting. Marine seismic reflection profiles and multibeam bathymetric data indicate there are no through-going crustal faults connecting the North Island Dextral Fault Belt and the Marlborough Fault System in South Island. The major faults terminate offshore, associated with 5-20 km-wide step overs, and a change in regional fault strike. This structure implies that propagation of strike-slip earthquake ruptures across the strait is not probable. Faulted sedimentary sequences in the Wairau Basin (Marlborough shelf), correlated to glacio-eustatic sea-level cycles, provide a stratigraphic framework for fault analysis. A high-resolution study of the

post-glacial (<20 ka) vertical displacement history of the Cloudy and Vernon faults reveals up to six and five paleoearthquakes, respectively, since 18 ka. These long-timescale records indicate variable recurrence intervals and stress drop, thus conforming to the variable slip model of earthquake behaviour. Integration of these data with other submarine and terrestrial paleoearthquake records indicate the presence of clustered earthquake sequences involving multiple faults. Different sequences do not always involve the same faults. It appears that earthquake clustering is driven by fault interactions that lead to specific loading conditions favouring the triggering of earthquakes on major faults in relatively short time intervals. Present day regional Coulomb stress distribution has been calculated, in two scenarios considered to represent minimum and maximum loading conditions. The models, incorporating secular tectonic loading and stress changes associated with major crustal earthquakes, indicate high stress loading in a large part of central Cook Strait. These conditions may favour the triggering of future damaging earthquakes in this region.

**A Tahorakuri Formation caldera boundary at Ngatamariki**

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Geologic results of drilling in the Ngatamariki field by Mighty River Power, characterised by GNS Science staff scientists, has identified a large subsidence feature at the southern margin of the field, consistent with caldera collapse during the eruption of Tahorakuri Formation ignimbrite. Well NM5 penetrated more than 1000 m of ignimbrite, which appears absent in Crown well RK8, only 3 km to the south. A paleogeographic reconstruction of the period following the eruption shows a lake within the crater and the eruption of andesite/dacite lavas along the southern caldera margin.

Recent drilling in the Rotokawa field, adjacent to the south of Ngatamariki, shows evidence of a dramatic northeast-southwest oriented open rift fault at the northern margin of the field, which

appears coeval with the eruption of Tahorakuri and caldera collapse at Ngatamariki. The rift is approximately 400 m wide by 700 m deep, filled with andesite and Tahorakuri ignimbrite, and down-drops the original andesite surface by approximately 250 m on its northern side. The rift subsequently became a focus of deposition for Waikora formation greywacke gravels, sourced from the margin of the Taupo Volcanic Zone to the northeast. A reversal in direction of sediment transport following Waikora deposition indicates regional re-inflation after deflation from the Tahorakuri eruption.

### **Applications of Probabilistic Tsunami Hazard Assessment in New Zealand**

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Tsunami are a significant coastal hazard for New Zealand. Evacuation plans and land use planning are important measures for mitigating this hazard, but for these to succeed it is critical to be able to evaluate the scale of the threat posed. For this purpose methods are being developed for performing Probabilistic Tsunami Hazard Assessment (PTHA) that should allow quantitative assessment of the tsunami hazard over specified timeframes and levels of confidence. The development of PTHA draws extensively on the ideas of Probabilistic Seismic Hazard Assessment (PSHA), but deviates from it in important respects, most notably the necessity to model the wave field from source to site.

We will present examples of PTHA regarding the tsunami hazard posed to New Zealand from distant tsunami sources in South America, and from nearby sources on the Pacific-Australian plate boundary. We will also present our view that the two major challenges for PTHA are to incorporate epistemic uncertainty into tsunami hazard models, and to bring tsunami hazard models onshore to include spatial estimates of the inundation hazard. We will demonstrate the progress we have made towards these goals with examples of the tsunami hazard in northern

New Zealand posed by the Kermadec and southern New Hebrides subduction zones.

### **Marine Isotope Stage 11 environments using dinoflagellate cysts**

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Marine Isotope Stage (MIS) 11 (434 – 341 ka) had an orbital configuration very similar to the Holocene and is hence an important analogue of climate/ocean change for the remainder of the present interglacial. MIS11 ice core records show a sustained (c. 30 ka) period of Holocene-like climatic stability, with sea level and atmospheric CO<sub>2</sub> near pre-industrial levels.

We use MIS 11 dinoflagellate cyst assemblages to reconstruct upper ocean conditions from three locations around New Zealand. The sites examined are MD06-2989 off the West Coast of the South Island, IODP1352 from the Canterbury Shelf, and DSDP 594 to the east of the South Island.

In this presentation, we discuss two areas of results from the dinoflagellate cyst assemblage record. Quantitative identification of assemblages characteristic of modern water masses enable us to trace paleo-water mass locations, while a suite of 311 modern sea floor samples are used as a training set for a transfer function to derive paleo sea surface temperature (SST).

Of the three locations, the West Coast site has the most robust age control and is the most suitable depositional environment for application of the dinoflagellate cyst transfer function. That record shows a c. 6 ka period of peak warmth, when SSTs were comparable to temperatures inferred from early Holocene marine records in the region. This was followed by a prolonged (>30 ka) period of SSTs similar

to modern values. The period of maximum warmth appears to coincide with peak warmth in Antarctic ice cores, and dinoflagellate assemblages suggest interglacial warmth persisted until c. 375 ka.

### **GIS analysis of LiDAR data to determine geomorphic controls on the erosion and deposition patterns of lahars**

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LiDAR provides for the ability to rapidly acquire high resolution elevation data at defined intervals creating a series of snap shots of the terrain over time. This can be analysed to provide Digital Elevation Models and accurate quantification of geomorphic change. Pre- and post-LiDAR surveys of the 2007 Mount Ruapehu Crater Lake breakout lahar display the net impact a lahar has on the landscape over its flow path, as well as provide a proxy for the net sediment entrained and transported. Between 22 and 40 km from source, the lahar was carrying its maximum sediment load of  $3 \times 10^6 \text{ m}^3$ , a quantity that remained stable for this stretch of river. Despite this stable total quantity of sediment carried, a complex interplay of erosion and deposition continued, effectively exchanging and recycling the sediment between the flow and its substrate. Controls on this exchange appear to relate to channel sinuosity, depth, width, roughness and local slope. Mapping the geomorphic characteristics of the path highlights a pattern of migrating central flow, with central and lateral bar formation and migration. Examining these deposits directly shows that deposition occurred primarily during and following peak stage, with the flow cannibalising these deposits during later stages and at times moving the bedforms. The pattern of erosion and deposition provides a useful indicator of the net sedimentological response of the lahar. Furthermore, when combined with stage height data and flow velocities the geomorphic analysis also provides an ideal platform for comparing theoretical calculations of dynamic flow parameters, such as bed shear

stress, to real world examples to explain the resulting patterns of erosion and deposition. Being able to then define specific zones where sediment entrainment (erosion) is expected can now be incorporated into complex mass flow simulations to provide better forecasts of the hazards expected for these types of events.

### **Analysis of liquefaction, ground deformation, and subsurface geology in Avonside throughout the Canterbury earthquake sequence**

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A small (c. 579 m<sup>2</sup>) residential property in Avonside has been continuously monitored for liquefaction and associated ground deformation since the September 4<sup>th</sup>, 2010  $M_w$  7.1 Darfield Earthquake. Detailed site investigations include Dynamic Cone Penetration Tests (DCPT), Swedish Weight Sounding (SWS), laser surveying, hand augering, and trenching. Liquefaction ejecta patterns and volumes are estimated following the M 7.1 September 4<sup>th</sup>, M 6.3 February 22<sup>nd</sup>, M 5.3 April 16<sup>th</sup>, M 5.6 and 6.0 June 13<sup>th</sup> events, and M 5.5 June 20<sup>th</sup> events. No other aftershocks generated surface ejecta or observable ground deformation at this site, including the M 4.9 Dec 26 aftershock, suggesting a site specific liquefaction threshold of c.  $0.15 \pm 0.04 \text{ g PGA}$  for shaking durations of c. 5 s, consistent with empirically derived threshold estimates using DCPT data. SWS tests and augering reveal silt and fine sand deposits to depths of >5-7 m, indicating a large reservoir of potentially liquefiable material at this site. Trenching reveals thin (<4 cm diameter) silt-sand ejecta pipes sourcing a liquefiable layer at depths of c. 2.1 – 2.4 m. Ground deformation has generally involved differential subsidence that in some cases exceeds 0.3 m. Subsidence was generally greatest in areas with the greatest liquefaction however differential surface loading due to the location of urban dwellings appears to have played only a secondary role in influencing the magnitude and location of liquefaction and subsidence at this particular site.

**Shelf-to-canyon sedimentation in the Hokitika-Cook submarine canyon complex, Westland, New Zealand**

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The Hokitika/Cook canyon complex is a major bathymetric feature incised into the continental shelf off South Westland. The existence of the canyons strongly affects shelf sedimentation. The interaction between canyon heads and shelf sediments can have important implications for biogeochemical cycling (i.e., organic carbon) and may influence whether economic mineral deposits (i.e., relict placer deposits) remain exposed or buried. Little work has been done in this region to define the transport pathways across the continental shelf and into the canyon complex. We present here modern sediment textural patterns from grab samples and cores across the shelf and into the canyons.

Surface sediments are dominated by allochthonous fine sand to mud typical of storm dominated shelves where modern terrigenous sediment input is high. Coarser material is usually biogenic in origin with rarer detrital gravels restricted to canyon heads. The inner shelf (<50 m depth) has moderately well sorted fine – very fine sand, reflecting an environment where constant agitation and resuspension via waves and currents occurs. At middle shelf depths (150 – 50 m), poorly sorted mud blankets topography forming a ‘mud belt’ largely due to a decrease in sediment resuspension and settling from hypopycnal plumes. On the outer shelf, mean grain size is coarser north of the Hokitika Canyon compared to the south. The canyon head sediments are generally coarser with relatively high sand and gravel percentages, polymodal distributions, and higher glauconite proportions.

Textural results from this study indicate the canyons are influencing surface sediment textures. Modern muds mantle the steep slopes of the southern rims of the canyons.

On the northern rims, sediments appear out of equilibrium with the prevailing modern environment on the shelves, suggesting at least some of this material is relict from low sea level stands. The distributions suggest that large volumes of mud are exported into the canyon from net shelf transport to the north-northeast.

**Future geological maps and what we think you need**

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The conclusion of the 1:250,000 QMAP Geological Map of New Zealand project has been immensely satisfying and we now have modern and regionally consistent national geological map coverage at this high level scale. The demand for QMAP’s high quality geological maps and digital data shows no sign of abating, and the premise is that new maps at different scales will also be welcomed. The challenge is now to develop GNS’s successor geological mapping programme “Geological Map of New Zealand” and the projects therein.

One of these projects is QMAP! The 21 individual geological maps are nearly all stitched into the QMAP Seamless GIS but there is still considerable work ahead harmonising the feature attribute data. New geological mapping acquired within and externally to the project will also be incorporated to keep the digital dataset up to date.

Another project involves detailed geological mapping of New Zealand cities and is extending the traditional map concept by incorporating subsurface information from drill holes and geophysical methods. The Christchurch earthquakes have highlighted the need to identify and map out poor quality ground there and in similarly vulnerable cities.

A mix of regional geological mapping is also underway including completion of the 1:250,000 geological map of southern Victoria Land, a new 1:1M Geological Map of New Zealand and a geological map of Tongariro National Park. In addition, medium-scale maps centred around areas with potential resources such as

minerals, coal, groundwater, and geothermal are commencing and will utilise interpretation of newly acquired airborne geophysical imagery.

Printed maps are still strongly sought-after despite the versatility of their digital data equivalents and the accessibility of these data through web service applications. A range of geological map products is envisaged with increased use of 3D geological modelling for conveying subsurface information and utilisation of other emerging technologies.

### **The role of crustal structure in the development of the 2010-2011 Canterbury earthquake sequence**

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The continuing aftershock sequence from the  $M_w$  7.1 Darfield earthquake of 4<sup>th</sup> September 2010 has raised important questions, including: Why has there been such a prolonged and productive aftershock sequence? And why has there been a concentration of larger aftershocks near Christchurch? Here we investigate these questions by carrying out a fine-scale 3-D tomographic inversion for crustal structure using arrival time data from aftershocks, regional seismicity and active source data. We carry out a series of gradational inversions, using the recently determined New Zealand nationwide 3-D seismic velocity model as our initial model. Our 3-D model shows that structural features shallow around the northern edge of Banks Peninsula, a basaltic shield volcano that was active during the period 12 – 6 Ma. Our results suggest that crustal structure has played a first order role in the development of the earthquake sequence. At approximately 10 km depth, we have a c. 100 Ma-old plate boundary, marking the subduction thrust where the Hikurangi Plateau subducted under the edge of Gondwana. This plateau is extremely strong and has a very deep brittle-ductile transition –

small earthquakes extend down to 35 km depth in the mafic plateau. The larger earthquakes in the sequence occurred within the greywacke and schist capping this strong plateau. The high stress drops and strong shaking from these events suggest high fault friction. The productive aftershock sequence is a likely consequence of strain perturbations at the ends of the mainshock rupture being accommodated by brittle creep (i.e., earthquakes), because there is no shallow ductile layer to bleed off this strain. The concentration of larger aftershocks near Christchurch appears to be a consequence of the change in crustal structure around the northern edge of Banks Peninsula concentrating changes in Coulomb failure stress from the mainshock in this region.

### **Can the fault database contribute more to seismic hazard analyses?**

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The present New Zealand National Seismic Hazard Model (NSHM), which uses the standard methods of probabilistic seismic hazard analysis, has two main earthquake occurrence inputs: (i) characteristic earthquakes on mapped faults, and (ii) distributed seismicity based on the past earthquake catalogue.

Characteristic earthquakes on mapped faults are rare events; the concept of characteristic earthquakes is increasingly being questioned. We consider here whether the data can be combined in some other way to produce a more informative model of long-term earthquake occurrence.

We propose a new model that makes use of both types of known earthquake sources – mapped faults and catalogued earthquakes – but does not invoke the concepts of fault segments or characteristic earthquakes. The model has two components: one based on proximity to past earthquakes, taking into account the magnitude of each; and the other based on proximity to mapped faults, taking into account the slip-rate of each. An inverse power law is used to model the diminution of earthquake occurrence rate with distance from known sources. The parameters

of each component are optimised using a target catalogue, and the combined model is estimated as an optimal linear combination of the two components. The model is applied to the New Zealand region using the active fault database and the earthquake catalogue since 1964. In a retrospective analysis, the combined model has an informative gain (log likelihood increase) per earthquake of about 0.15 over each of its components.

We conclude that the NSHM could be improved by using the fault information, along with the earthquake catalogue, to estimate the distributed-seismicity component of the model.

**Climate change and fluvial activity  
in Northland: a model for valley floor  
evolution during the Holocene**

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This paper presents the first results from a project aimed at evaluating the effect of short-term climate change on Holocene fluvial activity in Northland, New Zealand. Located in the northernmost part of North Island, river dynamics in the area are believed to have been primarily controlled by climate change throughout the Holocene. In this study, the first of its kind in New Zealand, interpretative valley floor mapping, sedimentology, and <sup>14</sup>C-dating has been used to reconstruct the alluvial history of eight sites in the Northland region. <sup>14</sup>C-dated palaeoflood deposits and sedimentary discontinuities preserved in floodplain and palaeochannel environments provide evidence for changing hydrology during the Holocene. Floodplain sedimentation rates indicate an acceleration of valley floor infilling after 1000 cal. yr BP, which predates the widely accepted date of 'first settlement' by people in

New Zealand at c. 850 cal. yr BP. Pronounced river terrace development at a number of sites raises questions as to the evolution and preservation of fluvial units under conditions of a tectonically stable Holocene. This suggests variations in sediment flux driven by climate may be responsible for terrace development and a model accounting for valley floor evolution in Northland river systems during the Holocene is presented.

**Location of active faults using geomorphic  
indices in eroded landscapes, South  
Taranaki, New Zealand**

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The South Taranaki region has a number of active faults that show surface expression in Pleistocene-Holocene materials of the central volcanoes of the North Island and Quaternary materials near the coast. When mapped fault traces cross inland into the older, heavily eroded, Tertiary mudstone and sandstone they finish abruptly. Our aim is to decipher if active faults extend into the Tertiary terrain.

Current methods to locate active faults using geomorphic interpretation of stereographic aerial photography cannot provide complete information on fault activity in this region due to erosion occurring at a greater rate than surface rupture of faults, and dense tree cover. International studies of tectonic activity in eroded landscapes have identified geomorphic indices as useful reconnaissance tools to locate active faults in such circumstances. Building on previous studies this research uses geomorphic indices applied to a Digital Elevation Model (DEM) within a Geographic Information System. Four indices were tested: (i) stream length-gradient index, (ii) stream channel sinuosity, (iii) hypsometry, and (iv) drainage basin asymmetry. Results were obtained by applying the indices to four national DEMs of differing resolutions. The comparison between the DEMs allowed for testing of the quality of the

geomorphic indices as well the scale at which geomorphic indices could be applied.

Results show that the geomorphic indices used can identify changes of landscape equilibrium state at a catchment and stream channel scale. However, the myriad of physical processes occurring at a range of temporal scales within this area make identification of a tectonic signature a challenging task. Conclusive examples of tectonic processes are evident and analysis suggests these examples are likely to be due to recent tectonic deformation. Furthermore, the comparison of results from the four DEM's highlights a range of issues with DEM's collection methods and resolution.

This study concludes that geomorphic indices may provide an effective method to locate evidence of recent and large faulting events in New Zealand. However, this type of analysis is hindered by the resolution of digital elevation data available.

### **Oligocene carbonate sedimentology of the West Coast Rift System, Nile Group, West Coast, New Zealand**

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Oligocene carbonates associated with the West Coast Rift System outcrop along much of the western margin of the South Island of New Zealand. The carbonates are a heterogeneous succession of clastic-rich skeletal limestones that record accumulation across a series of narrow, interconnected, north-south trending, fault-controlled basins. The rocks are grainy to muddy wackestone to grainstone and floatstone composed of benthic foraminifers, coralline algae (rhodoliths), bryozoans, and echinoids with lesser contributions from quartz, glauconite, muscovite, and bivalves.

Lithologies can be subdivided into five geographic regions listed here from South to North: (i) Greymouth – Rapahoe, (ii) Punakaiki – Westport, (iii) Inangahua – Larry's Creek, (iv) Mohikinui – Little Wanganui, and (v) Karamea

– Kohaihai. Each region is defined by a distinct series of correlatable sedimentary successions. Boundaries between these regions are either abrupt lateral facies variations or related to a lack of exposure, which are thought to reflect syn- and post-sedimentary fault displacement. Together these five regions reflect sedimentation during a unique carbonate-rich, detritus-deficient episode (Oligocene) within the framework of a variably subsiding, topographically complex basin.

Palaeoenvironmental and palaeogeographic reconstructions of Nile Group limestones suggest a strong correlation between primary environmental factors, subsequent original sedimentology, and the degree and character of diagenesis during burial. For example, well-developed stylolites are diagnostic of inner shelf, bryozoan grainstone within the Nile Group. Neighbouring, contemporaneous wackestone and packstone, however, exhibit mere proto-stylotization. This relationship is proposed to explain, in part, the wide variety of Nile Group lithologies. Furthermore, this correlation may account for neighbouring and coeval strata with similar burial histories exhibiting distinct diagenetic features.

Palaeogeographic reconstructions are also expected to establish the existence and extent of Oligocene terrestrial environments associated with the West Coast Rift System, as well as the degree to which oceanography and tectonics influenced Oligocene limestone development within this depositional setting.

### **Distribution of potential reservoir and seal facies in the frontier Houtman Sub-basin, offshore northern Perth Basin, Western Australia: new insights from a detailed sequence stratigraphic study**

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The Perth Basin formed as part of an obliquely-oriented extensional rift system on Australia's southwestern margin during the Paleozoic to Mesozoic breakup of eastern Gondwana. The Houtman Sub-basin contains up to 14 km of Early Triassic to Late Jurassic sedimentary

strata and is situated in the offshore portion of the northern Perth Basin, located c. 200 km northwest of Perth.

A detailed sequence stratigraphic study was undertaken on the three wells in the Houtman Sub-basin: Gun Island 1, Houtman 1, and Charon 1. This study investigated facies variations between the wells to gain a better understanding of potential source, reservoir and seal distribution and to assist regional palaeogeographic reconstructions of the Perth Basin. The study focussed on the Early-Late Jurassic succession comprising the Cattamarra Coal Measures, Cadda Formation and Yarragadee Formation.

Wireline log character, cuttings, sidewall core and conventional core lithologies and palynological data were used to identify facies and paleoenvironments. Palynology for all wells has been reviewed, including new data collected by Geoscience Australia for Gun Island 1 and Charon 1. Facies stacking patterns were used to define systems tracts and subsequently ten third-order depositional sequences.

Collectively these sequences define a larger scale, second-order (supersequence) transgressive-regressive cycle. The Cattamarra Sequence Set forms a regional transgression which culminates in an extensive marine maximum flooding event within the Cadda Sequence Set. This is followed by the regressive highstand Yarragadee Sequence Set. The third-order sequences characterised here overprint this supersequence and control the local distribution of facies. The relative dominance of a facies may be enhanced or diminished depending on its position within the larger second-order supersequence; although both the dominantly non-marine Cattamarra and Yarragadee sequences record multiple, dinocyst-bearing, minor marine incursions, the transgressive systems tracts in the third-order Cattamarra sequences are better developed due to their position within the second-order transgression. Fine-grained facies deposited during one of these incursions may form a good intraformational seal to the thick highstand sandstones in the lower Yarragadee sequences which are excellent potential reservoirs.

## **Channeled viscoplastic lava dynamics**

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Lava from large volcanic eruptions often self-organises into localised channels, which can rapidly transport lava over large distances. The dynamics of lava transport through these channels (and particularly the dynamics of crust growth and a changing internal rheology) determine lava cooling rates; thus their dynamics form a crucial part of the large-scale problem of lava flow emplacement and extent. We present recent experimental, theoretical and numerical analysis which sheds light on the complex interplay between rheology and solidification in channeled lavas, and discuss how these general physical insights may be applied to field studies.

The experimental work used slurries of polyethylene glycol and kaolin as an analogue for lava, which flowed with a constant flux down an inclined channel under water. The water temperatures were varied to give three sets of complementary experiments: (i) isothermal, (ii) cooling, and (iii) solidifying flows. Isothermal flows, in which the slurries and water have the same temperature, were used as a base case for the study. A numerical scheme is used to infer flow depth, viscosity and yield strength from a known flow rate and measured surface velocities. Cooling experiments showed that thermal convection occurs in organised rolls aligned with the shear flow, but that unyielded regions are not broken up by the convective overturning. In the solidifying experiments a quasi-stable width of crust formed on the surface of the flow.

The degree of surface crust coverage and the transition between crust cover regimes is quantified in terms of a dimensionless parameter which characterises the relative importance of the strain and crust growth rates. We show that this parameter accurately predicts the crust distribution for both viscous and viscoplastic flows in the mobile crust regime, as well as the transition between tubes and mobile crust flows.



**Titanium-in-quartz geothermometry  
and sediment provenance in Western  
Southland basins**

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Sediment provenance studies are a valuable tool for solving geological problems and tracing detrital mineral sources. We are testing the titanium-in-quartz geothermometry (Wark and Watson 2006; Thomas et al. 2010) to “fingerprint” individual quartz grains as a tool for determining the provenance of clastic sediments. LA-ICP-MS is used to measure the concentrations of titanium (Ti) within quartz, which is proportional to its formation temperature. Quartz is highly ubiquitous and found throughout the stages of orogeny and basin development. Being able to “fingerprint” and trace individual quartz grains gives a way of quantitatively tracing them through these pivotal geological processes.

This study is part of a wider investigation of siliciclastic sediments of the South Island and in particular focuses on sources in Fiordland (a long-lived continental arc) and deposits of the adjacent Eocene to recent Western Southland basins. Determining the provenance of these sediments allows for a better understanding of basin geometry and geologic history as well as the tectonic evolution of their source(s). Results so far show the expected correlation between the Western Southland basins and the adjacent crystalline basement of eastern Fiordland. The results also tentatively show a correlation between age and temperature in the region. Samples analysed so far show distinguishable populations of quartz derived from separate source rocks, indicating the method is effective at “fingerprinting” quartz. A consistent low-temperature anomaly in granitic quartz has been identified and is being further investigated using independent geothermometric techniques.

**Terrestrial vegetation and climate  
reconstruction during the MIS 12-11  
transition recorded from 4 sediment cores,  
Hokitika canyon, New Zealand**

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Reconstruction of vegetation and climate for Marine Isotope Stage (MIS) 11 (420-360 ka) is of particular interest as this period is a possible past analogue for the natural progression of the Holocene and future climate. At present there are no published high-resolution, well dated, continuous palynomorph (pollen and spore) records of terrestrial vegetation change for MIS 12-11 from the New Zealand region. Reconnaissance sampling of the MIS 12-11 interval was carried out on four giant piston cores collected from the levee banks of the Hokitika submarine canyon, located c. 100 km from the central South Island. Previous work has shown that this marine setting can provide well-resolved continuous pollen records of vegetation and climate for the adjacent Westland region that enables direct comparison between marine and terrestrial proxies. The MIS 11 samples contain a diverse assemblage of dryland pollen dominated by podocarp-hardwood pollen and warm climate taxa broadly similar to Holocene examples for this region. Some variability in abundance and preservation quality between cores is apparent and these will be discussed along with a consideration of the pollen taphonomic pathways for this depositional setting.

Eventually with our reconstructed paleo-vegetation record we aim to be able to address the following: What was the duration and extent of warming for Westland during for the MIS 11 interglacial? Is there a difference in the timing of the MIS 12-11 termination between marine and terrestrial proxies? Is there evidence for when

the Westland beech gap formed, and under what climatic conditions did it form in? This paper presents preliminary findings from a new PhD investigation that will ultimately produce a long continuous mid-late Quaternary record of terrestrial pollen, vegetation, and climate for Westland, New Zealand.

**Planktic foraminiferal assemblages and sea-surface temperature record of the Subtropical Front in the Tasman Sea, Southwest Pacific, over the last one million years**

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Planktic foraminiferal assemblages in a composite section from two cores (MD06-2989/2986) off the west coast of New Zealand's South Island (42-43.5 °S) provide a 1 Ma (MIS 31-1) sea-surface temperature (SST) record (c. 3-4 ka resolution) in the Tasman Sea. A significant overall faunal change occurred near the end of the mid-Pleistocene Climate Transition (MPT) at c. 600 ka (MIS 15). Mean annual SSTs were estimated using the Artificial Neural Network (ANN) method. Glacial-interglacial (G-I) cycles in the MPT had c. 9 °C SST range, whereas in the post-MPT SST range was c. 6-7 °C. The SST and faunal changes imply that the Subtropical Front (STF) migrated c. 6° in latitude to lie just north

of the sites in MPT glacials (MIS 28-16), but only migrated 3-5° north in post-MPT glacials. These G-I latitudinal migrations of the STF west of New Zealand contrast with the situation east of New Zealand, where migrations of both the STF and Subantarctic Front (SAF) were prevented by the Chatham Rise and Campbell Plateau. Subtropical Water (STW) is inferred to have only flowed around the south of New Zealand (as it does today) during MIS 11 and the Late Pleistocene (MIS 5-1).

**The mid-Cretaceous granulite facies Glenroy Complex, SE Nelson: Was Cenozoic exhumation related to the restraining bend in the Alpine Fault?**

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The Western Fiordland Orthogneiss (WFO) is the largest suite of plutonic rocks intruded into the Pacific Gondwana margin crust during the final stages of arc plutonism prior to break-up of the supercontinent. Dextral motion along the Alpine Fault during the Cenozoic has offset Fiordland from the West Coast and Nelson regions, which contain associated Gondwana margin rocks. The Glenroy Complex in south-east Nelson is dominated by the two-pyroxene dioritic Woodham Orthogneiss. U-Pb zircon dating and whole-rock geochemistry indicates the emplacement age of the Woodham Orthogneiss is 125 Ma; in conjunction with its composition this indicates it is a correlative of the WFO.

Previous mapping shows the Glenroy Complex forms the lower-most fault-bound block in an east-dipping imbricate thrust system that has developed west of the largest S-shaped restraining bend in the Alpine Fault. Hence, it has been suggested the Glenroy Complex was exhumed during the Cenozoic due to shortening within this restraining bend. Unpublished

K-Ar dating of hornblende and biotite from the Woodham Orthogneiss yielded ages of 108 Ma and 112 Ma (Nathan et al. 2000), indicating cooling to c. 300 °C by c. 100 Ma. This is similar to the WFO, which was partially exhumed and cooled rapidly to c. 300 °C during mid-Cretaceous continental extension, following emplacement and subsequent granulite facies metamorphism in a shortening regime. Published low-temperature thermochronology suggests further cooling and exhumation of the WFO did not occur until the late Cenozoic when the rate of convergence between the Pacific and Australian plates increased. However, the Glenroy Complex may have been exhumed earlier due to its location adjacent to the restraining bend in the Alpine Fault. We are currently undertaking zircon and apatite fission track thermochronology to test this hypothesis. This will also provide constraints on the timing of development of the restraining bend in the Alpine Fault.

#### **Temporal evolution of the Darfield aftershock sequence prior to the Christchurch earthquake**

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We installed 13 broadband seismometers and a 1 Hz seismometer throughout the Canterbury region 8-20 September 2010, and removed them early January 2011. We use these stations and permanent GeoNet seismometers to examine the evolution of the aftershock sequence over time. Relocations are calculated in a 1-D velocity model using the double difference algorithm tomoDD. Shear wave splitting is calculated using the MFAST automatic processing package, and waveform cross-correlations are used to find families of similar events. Preliminary results from weekly

snapshots of the activity show that beneath the surface rupture lies a narrow E-W band, with a limb of seismicity along a north-south line at 171.2° longitude, all between 12 and 17 km depth. Near Christchurch, aftershocks are broadly distributed and shallower than along the Greendale Fault, with most from 8-13 km depth, corresponding with the shallow depth of the M 6.3 Christchurch earthquake. Throughout the study period, aftershocks were numerous east of the surface rupture, with similar seismicity rates beneath Christchurch as beneath the surface rupture, while seismicity to the west decreased more rapidly. Shear wave splitting yields fast orientations parallel to the regional stress in most places although at one station they appear to rotate with time. Two families of similar earthquakes have been identified based on cross-correlations of vertical components on Geonet stations CRLZ and MQZ. The S-P travel times for the family recorded at station MQZ arrive about 10 ms earlier for the earthquakes at the end of January and beginning of February than the ones in mid-September, suggesting either that the family is moving towards MQZ or else that the S velocity of some part of the path between the source and MQZ is getting faster relative to the P velocity.

#### **Historic activity at Ruapehu volcano a revised catalogue**

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In recent years there has been a stronger focus on risk calculations while evaluating things like the exposure to hazards. This is also been applied for people visiting active volcanoes, or working near them. These assessments to date have been based on published catalogues of activity. However these catalogues have been known to have shortcomings as new information has come to light about older activity, and also they tended to 'summarise' periods of activity.

To usefully calculate the frequency of occurrence of activity the catalogue needs to be as complete as possible for all eruptive activity from the volcano. In recognition of this a project was initiated to review the Ruapehu

data set and enhance its value for risk and hazard assessments. Data sets used for this review included historic newspapers, published scientific papers, GNS files and unpublished reports, annual reports of organisations to parliament, and other collections as they become known.

The revised catalogue is now near completion and several interesting observations are flowing through. For example the 1907 activity has usually been reported as 'crater lake steaming' where as it can now be shown that mud and rock was erupted covering the summit area and generating avalanches. Similar in 1936 and 1940, while in 1968 several moderate events occurred, some lahar producing, but these are 'lost' as precursors to larger 1969 eruption in many accounts. Any eruption producing a lahar is significant!

The challenge now is to utilize this catalogue, once minor issues like defining an eruption verses an eruption episode are solved, answering questions like "was the activity isolated or part of a sequence"? A further challenge is connecting this data set to the geological record to produce a longer eruptive record.

### **Cataclastic processes within the Alpine Fault Zone - an examination of particle size distribution and fracturing characteristics**

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Cataclastic particle size reduction is inferred to have occurred in brittle faults at all scales. It occurs as grains fragment, either *in situ* or accompanied by accompanying sliding and rotation, and results in the generation of characteristic cataclastic microstructures and particle size distributions. Fragmentation by different mechanisms represents the release of stored elastic strain energy within a fault zone; consequently previous particle size distribution studies have yielded information about the total energy released during co-seismic fracturing. However, the extent of cataclastic damage with

a fault zone has rarely been carefully examined in the context of earthquake history and total displacement. This study aims to examine this record in the cataclasite zone along New Zealand's Alpine Fault, where the slip history is reasonably well constrained. We are also interested to see if the mechanism by which grains fragmented can be linked to quantitative or qualitative grain shape description, as has been done in sedimentology and volcanology.

We have examined samples from the Waikukupa River, which provides a near continuous section of cataclasite on a now extinct strand of the Alpine Fault, and from drill core collected from Gaunt Creek during the Deep Fault Drilling Project (DFDP). The cataclasite varies in thickness and appearance between outcrop exposures and drill core. In both settings it displays a well-developed damage zone, which has been formed during repeated faulting events.

Preliminary work from the Waikukupa River yielded a two-part fractal distribution of grain sizes, with a lower D value for smaller grains and a higher D value with a larger range for larger grains. This is interpreted to result from fragmentation of a multi-grain aggregate. Initial examination of DFDP-1a drill core shows a well-cemented cataclasite with evidence of a weak foliation. Zones of cataclasite are observed; these have been cemented by late stage calcite in some places while calcite vein fragments are included in the cataclasite elsewhere. These microstructures illustrate the cataclasites formed by multiple episodes of shear localisation, cementation, and fragmentation. We will present a qualitative scheme for shape description within these materials.

**The relationship of Palaeozoic metamorphism and S-type magmatism on the palaeo-Pacific Gondwana margin**

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A massive pulse of granitic magma was rapidly emplaced into the once contiguous West Antarctic and New Zealand segments of the palaeo-Pacific margin of the Gondwana supercontinent at c. 371 Ma. In New Zealand, these Devonian S-type granitoids cover an areal extent of > 3400 km<sup>2</sup>, but the tectonic setting for crustal partial melting has remained unclear because most of the exposure represents either emplacement-level, or rocks that have been reworked during Cretaceous orogenesis. New petrologic data indicate that aluminous gneisses in the Bonar Range represent a rare portion of Devonian middle crust that preserves evidence for the initiation of crustal melting. The investigated rocks outline the tail of a clockwise P-T path that involved partial melting c. 670 °C, 5.1 kbar, deformation during the immediately following near-isothermal decompression, and then partial re-equilibration under deviatoric stress-free conditions. Syn- to post-kinematic growth of monazite establishes the timing of recrystallisation to a c. 16 Ma period that began at 374 ± 4.1 Ma. This age overlaps with the initiation of regional S-type granitic magmatism. Although estimated metamorphic conditions were insufficient for large amounts of melt to have been produced from Bonar Range pelites (calculated volumes are >10%), they do provide evidence consistent with widespread heating and partial melting in the deeper crust. This episode was contemporaneous with partial melting in Fiordland (New Zealand) and West Antarctica, although Mesozoic thermal and deformational events complicate the record in both those areas. The 1000's of km along-strike extent of crustal partial melting along this

portion of the Late Devonian Gondwana margin indicates that a continental-scale tectonic plate margin re-organisation took place at this time. The cause in the New Zealand segment was likely, but not unequivocally, an extensional tectonic regime with an elevated geothermal gradient caused by conductive heating from a shallowed lithospheric mantle.

**The hydration of the Pacific Plate: implications for the location and productivity of the Taupo Volcanic Zone**

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The Taupo Volcanic Zone (TVZ) is one of the most frequently active and productive silicic volcanic systems on Earth. The location and high productivity of the TVZ can be linked to the subduction water cycle, where hydration and subsequent dehydration of the subducting oceanic lithosphere is primarily accomplished by earthquakes. Analysis of regional and global earthquake catalogues indicates the location, geometry and deformation of the subducting Pacific Plate. Shallow intraplate earthquakes (e.g., ≤ 50 km) are predominantly normal dip-slip and coincide with the maximum curvature of the subducting plate and record plate bending. The magnitude and frequency of these shallow intraplate earthquakes are greatest where the overriding plate changes from oceanic to continental and decreases southwards along the margin. These high rates of seismicity associated with plate bending together with their proximity to oceanic fluids promote local hydration of the subducting plate east of the TVZ. Hydration of the subducting plate decreases to the south where 'bending' earthquakes are 100-200 km west of the trench and distal from oceanic fluids. The anomalously high heat flow and productivity of the TVZ is spatially associated with high rates of seismicity in the underlying slab at intermediate depths of 130-210 km. Intermediate depth seismicity is inferred to reflect dehydration embrittlement

of the previously hydrated slab. Dehydration of the slab crust provides insufficient fluid flux into the mantle wedge to induce 'wet' partial melting resulting in arc volcanism. In contrast, dehydration of the slab mantle correlates with the location and productivity of active North Island volcanic centres. South of the TVZ the subducting plate did not experience the same degree of hydration as further north and, as a consequence, expelled less fluid. In this model hydration of the subducting plate varies spatially and is an important determinant for the location of arc volcanism in the overriding plate.

#### **Statistical and structural analysis of the Dabbahu Rift (Afar, Ethiopia) using multiple remote imagery datasets**

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Over the past c. 30 Ma rifting of Africa and Arabia has resulted in the c. 300 km wide Afar Depression. The Red Sea arm of the Afar triple junction encompasses the subaerially exposed c. 60 km long volcanically and tectonically active Dabbahu magmatic segment, which is one of the few places where incipient seafloor spreading is observable on land. Normal faults and fissures in this region strike northwest-southeast, oblique to the direction of extension. Detailed structural maps have been constructed using three different resolution remote imagery datasets. These consist of high-resolution Light Detection and Ranging (LiDAR) data at 0.5 m resolution, Satellite Pour l'Observation de la Terre (SPOT) data at 6 m resolution, and Shuttle Radar Topography Mission (SRTM) data at 90 m resolution. A consistent method for manually picking faults was developed for each dataset utilising several topographic attribute surfaces (slope, aspect, aspect-slope, curvature, and hillshade) using quantitative criteria based on the accuracy and limitations of the data (vertical and horizontal errors).

Nodes for each structure were then defined depending on fault interactions, such as "i" for ends, "x" for crossing, and "y" for branching. The distributions of these nodal networks have been analysed to observe the nature of rifting in this region and have been examined for consistency between the datasets.

#### **Modelling of volcanic stress fields and temporal seismic variations at Mount Asama, Japan**

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Active volcanoes are dynamic systems that perturb the regional stress field in which they exist, by manner of both the weight of the volume of the mountain and the movement of large masses of magma under pressure. The resulting change in the crustal stress field is hypothesised to affect its seismic properties; in particular the degree and orientation of shear wave birefringence. Initial work into furthering the understanding of the link between volcanism-induced crustal stress and shear wave splitting is presented here. The focus of research is on the 2004 and 2008 eruptions of Mount Asama in Japan. Previous work has shown that a roughly east-west trending dike, with 0.8 m of opening, accompanied the 2004 eruption. This deformation has been modelled with finite element methods and we will constrain the surface deformation with existing GPS data. Preliminary results suggest a reasonable agreement between the stress model and measured surface deformation. Methods to model the effects of the resultant stress field on shear wave splitting are laid out.

Splitting measurements from earthquake data collected over the 2008 eruption are also presented, continuing on from previous work by Savage et al. (2010). Preliminary

measurements show changes in splitting fast direction at a few stations that coincide with GPS baselines and eruption times in 2008, but the relations are not as straightforward as they were for the larger 2004 eruptions.

### **Nannofossil biostratigraphy of Late Oligocene to Early Miocene sediments, Mangapehi Coalfield, New Zealand**

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The topic of complete inundation of the New Zealand landmass during the Oligocene is still a contentious one. The aim of this study is to construct a detailed biostratigraphy for the lower Te Kuiti Group to upper Mahoenui Group based on calcareous nannofossil assemblages. This data will be used to determine the timing of transgression across the King Country during the Oligocene, and to elucidate the paleoenvironment at that time.

Samples were obtained from two cores drilled at Benneydale in the Mangapehi Coalfield, both spanning the sequence between lower Te Kuiti Group and upper Mahoenui Group. In the Mangapehi coalfield, the Te Kuiti Group is comprised of a basal coal measure sequence, the Waikato Coal Measures, which unconformably overlie Mesozoic basement rocks. This sequence is dominated by carbonaceous mudstone and silty sandstone, with rare conglomerate and interbedded coal seams. Coal measures grade up into the Aotea sandstone, which is dominated by calcareous silty sandstone, with interbedded layers of sandy mudstone. The Mahoenui Group overlies the Aotea sandstone and is predominantly comprised of massive silty mudstone.

Simple qualitative analyses were carried out on nannofossil assemblages spanning the Late Oligocene to Early Miocene interval. The assemblages are dominated primarily by *Coccolithus pelagicus* and *Reticulofenestra*

spp. Other less common taxa include *Zygrhablithus bijugatus*, *Discoaster deflandrei*, *Sphenolithus moriformis*, *Pontosphaera multipora* and *Cyclicargolithus abisectus*, which are characteristic of the Oligocene. Two biostratigraphically significant taxa occur within the examined section. *Chiasmolithus altus* is present within Waikato Coal Measures and Aotea sandstone, which provides an age range of approximately 30-25.6 Ma. *Sphenolithus ciperiensis*, with a last occurrence datum at c. 24 Ma, has been identified within the Aotea Sandstone.

### **Seismotectonic significance of conjugate 'Andersonian' wrench faulting in the 2010-2011 Canterbury Earthquake Sequence**

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The 2010-2011 Canterbury earthquakes occurred about 100 km southeast of the fast-moving Alpine-Hope fault strike-slip system defining the Pacific-Australia transform boundary. Previously unrecognised faults concealed below alluvial cover and/or Neogene volcanics were activated within a wrench stress regime ( $\sigma_v = \sigma_2$ ) with horizontal maximum compressive stress  $\sigma_1$  trending  $115 \pm 5^\circ$ . Structural components of this upper crustal sequence include: (i) Subvertical dextral strike-slip ruptures trending c.  $085^\circ \pm 5^\circ$  including the 04/09/2010 rupture on the Greendale Fault associated with the  $M_w$  7.1 Darfield earthquake, (ii) A dilational stepover defined by a rhomboidal patch of distributed aftershock activity linking the eastern tip of the Greendale rupture to an ENE microearthquake lineament, (iii) Dextral-reverse slip on ENE-striking faults (e.g. the 22/02/2011  $M_w$  6.2 aftershock), (iv) Predominantly reverse-slip across northeast-southwest aftershock alignments, and (v) Sinistral strike-slip along SE-SSE trending aftershock lineaments lying  $50-70^\circ$  to the main east-west dextral structures, one of which hosts the 13/06/11  $M_w$  6.0 rupture which clearly cross-cuts earlier E-ENE structures.

The subvertical dextral and sinistral strike-slip faults striking  $\pm 30 \pm 5^\circ$  to inferred  $\sigma_1$  define a classic 'Andersonian' system of conjugate wrench faults, probably of low-displacement, either new-formed or optimally oriented for frictional reactivation in the contemporary stress field. Oblique-slip ruptures, on the other hand, likely involve reactivation of components of an inherited fault fabric.

Conjugate wrench faulting is significant because: (i) the conjugate relationship confirms the inferred regional  $\sigma_1$  trend, (ii) continued conjugate faulting implies that displacement weakening on neither of the strike-slip fault sets has yet reached the stage where it supplants the other, and (iii) mutual cross-cutting of faults from the two sets leads to the formation of contractional jogs impeding slip, rendering the immature fault system prone to high stress-drop rupturing. Control by the stress field rather than compliance with plate boundary kinematics suggests the 2010-2011 Canterbury is of intraplate character.

#### **Soil gas CO<sub>2</sub> concentrations and CO<sub>2</sub> fluxes in the Auckland Volcanic Field**

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Numerous studies have shown that anomalously high soil gas CO<sub>2</sub> fluxes and concentrations may be precursors to volcanic activity, and that faults or fractures can act as conduits for gases and magma to the surface. The Auckland Volcanic Field (AVF) is a dormant monogenetic basaltic field located in Auckland, New Zealand, on which there have been no previous studies of soil gas CO<sub>2</sub> fluxes or concentrations; atmospheric CO<sub>2</sub> is likewise not monitored. As part of the DETERmining VOLcanic Risk in Auckland (DEVORA) project, soil gas CO<sub>2</sub> fluxes and concentrations were measured

in seven transects spanning various settings (e.g., urban, rural, areas of known or suspected faults, areas of no suspected faults) in the AVF over four days in November 2010. There were two key goals for this pilot study: (i) establish a baseline soil gas CO<sub>2</sub> flux and concentration for the AVF, and (ii) attempt to detect subsurface structures such as faults that may act as a control on future vent locations.

During this study, 72 measurements of CO<sub>2</sub> concentrations ranged from 393 parts per million (ppm) to 10,140 ppm; 443 fluxes varied from 0 to 108.7 g.m<sup>2</sup>/d. Using a graphical statistical approach, two populations of CO<sub>2</sub> fluxes were identified. Both may represent the biological CO<sub>2</sub> production background flux in the AVF, with soil permeability as the main control. Differences between urban and rural fluxes are attributed to the infiltration of anthropogenic air into the soil in urban areas. No faults could be discerned using soil gas CO<sub>2</sub> fluxes or concentrations; however, there is a significant difference in fluxes between fault and no-fault transects. These results hint at interesting variations in soil gas CO<sub>2</sub> across Auckland; future work includes expanding the study area and identifying the CO<sub>2</sub> sources via  $\delta^{13}\text{C}$  analysis.

#### **Hydrothermal fluid flow along a ductile shear zone in the Greenland Group, Westland**

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The Greenland Group in Westland, which is dominated by a monotonous sequence of greywacke and argillite, also contains rare ductile shear zones. One shear zone, as yet unnamed, strikes northwards and dips steeply to the east. Spectacular winged porphyroclasts have formed about calcite and sulphide grains that have grown during deformation. Kinematic analysis of the shear zone fabric and porphyroclasts indicates an oblique sinistral sense of shear with east-side-down sense of motion. At the present orientation, this indicates that last motion on the shear zone corresponds to a high-angle extensional sense of throw. The



age of the shear zone is not yet known, but it is speculated to be Palaeozoic because it is parallel to local Palaeozoic fold hinges.

Structurally, the shear zone centre contains discrete brittle shears, and shear-parallel quartz veins that have formed after ductile deformation. A pressure solution foliation has developed parallel to the strike of the entire structure, and has, in places, been crenulated. Also associated with the shear zone are carbonate spots and visible sulphides including arsenopyrite, pyrite, and stibnite (ordered by abundance).

Petrographic observations and laser ablation inductively coupled plasma mass spectrometry analysis that this discrete brittle shear zone was a favourable pathway for hydrothermal fluids. Microscopic observations indicated multiple at least for styles of carbonate, with the most common carbonate type a Fe-bearing variety. The most common sulphides were pyrite and arsenopyrite, and there are tiny galena grains as inclusions within arsenopyrite. Minor framboidal pyrite has a high iron content and is depleted in most other minerals relative to other sulphides. Stibnite was seen in a hydrothermal breccia, with anhedral grains that appear to fill in cracks.

The apparent paragenetic sequence is: pyrite, followed by arsenopyrite-pyrite, then carbonate-quartz, and finally stibnite.

### **Geology of southern Victoria Land, Antarctica – QMAP22**

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A new 1:250,000 geological map and accompanying GIS dataset for South Victoria Land, Antarctica is in its final stages of production. The work integrates and summarises all previous geological studies in the Dry Valleys and Ross Island area. A comprehensive search and review of existing

geological maps, databases, research papers and geological theses has been completed and information compiled at 1:50,000 on 46 sheets. Limited new fieldwork was carried out in some areas in late 2008. A high quality 1:250,000 scale geological map will be published with a full colour illustrated explanatory book – the final map in the New Zealand QMAP series. A Web Map Service (WMS) of some of the draft map data has been made available, viewable through the OneGeology web portal (<http://portal.onegeology.org>).

Highlights of the new geological map include the differentiation of the Proterozoic high-grade Skelton Group metamorphic basement from four suites of Late Proterozoic to early Paleozoic Granite Harbour Intrusives granitic plutons. Extensive intrusion by the Ordovician Vanda Dike Swarms is also depicted. The Beacon Supergroup stratigraphic succession is depicted in terms of the Devonian Taylor Group and the Permian to Triassic Victoria Group, differentiated into 14 constituent formations. The Jurassic igneous Ferrar Supergroup sills and dikes that intrude across and close to the Kukri Erosion Surface are shown. The map shows for the first time the context of the Cenozoic volcanism (McMurdo Volcanics) of Mt Erebus/Ross Island and southern Ross Sea region with that of the Transantarctic Mountains. Structural features of the intervening Ross Sea Basin are shown together with the recent stratigraphic drilling sites. Considerable work has gone into characterising, rationalising and correlating till (moraine and drift) deposits based geomorphological criteria and the limited dating available to provide the first regional overview of glacial geology.

### **Ophiolitic Dun Mountain Belt rocks mined by Quaternary volcanic activity, Auckland, northern New Zealand**

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Xenoliths brought up by erupting volcanoes can provide information on: (i) the nature of the lithosphere traversed by the ascending magma, and (ii) aspects of the ascent mechanisms.

Magmas of the young (<200 ka) monogenetic Auckland Volcanic Field originated in the lithospheric mantle at a depth of c. 80 km and rose to the surface rapidly, each batch fractionating along a different trend (e.g., Smith et al, 2008). The field is underlain mainly by the Permian/Triassic Maitai terrane, which is the source of the Junction Magnetic Anomaly and a major gravity anomaly, marking the largest ultramafic massif of the Dun Mountain belt within New Zealand. It is flanked by Murihiku terrane in the west and Caples/Waipapa terranes in the east. These basement rocks are unconformably overlain by Early Tertiary Te Kuiti Group, Miocene Waitemata Group and various Pleistocene to Recent deposits. While lavas erupted by the Quaternary Auckland volcanoes commonly contain olivine-rich xenoliths, tuff eruptions in St. Heliers and Taylors Hill volcanoes in the north-eastern part of the field are unique in that they have brought up a diverse suite of crustal rock fragments dominated by basic schistose and non-schistose rocks up to 70 cm in diameter. Non-schistose rocks include Waitemata Group fragments, greywacke-type terrigenous clastics, basaltic volcanics and coarse-grained peridotites. The mafic schistose rocks have fabrics ranging from slightly foliated to banded, with the most highly deformed showing up to three phases of high temperature deformation, including formation of ductile shear zones. Irregular patches of polygonized feldspar indicate that the rocks were exposed to prolonged high temperature at a late stage. Metamorphic minerals are dominated by amphiboles, feldspar, and epidote, but there is also prehnite, clinopyroxene, garnet and some pumpellyite. Grade of metamorphism ranges from prehnite-pumpellyite to amphibolite facies. The terrigenous clastics are at a lower metamorphic grade, generally in the prehnite-pumpellyite facies range. One specimen of the metamorphic terrigenous clastics contains abundant calcite prisms identical to *Atomodesma* fragments in the Permian Maitai Group rocks of the South Island. All samples are cut by networks of cataclastic micro-faults generally post-dating several sets of different veins. A few prehnite veins postdate the cataclastic faults. We interpret this suite of rocks as fragments from schistose parts of the Dun Mountain Belt (shear zones?) and adjacent melanges, from the lower grade Maitai Group and the non-metamorphic Miocene Waitemata Group overlying these basement rocks. The metamorphism of the schistose mafic rocks

took place at a depth estimated to be less than 7 km. The pervasive cataclasite networks in the samples indicate that the magmas of these two volcanoes were mining a N-S- striking crustal fault zone within the brittle part of the upper crust.

**Reference:** Smith, I. E. M., Blake, S., Wilson, C.J. N., Houghton, B.F., 2008, Deep-seated fractionation during the rise of a small-volume basalt magma batch: Crater Hill, Auckland, New Zealand. *Contributions to Mineralogy and Petrology*, 155: 511–527.

### **Ground fissuring in foot-slope positions in the northern Port Hills**

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During the February 22<sup>nd</sup> Christchurch earthquake of  $M_w$  6.3, extreme vertical ground acceleration (c. 2 g) was experienced across the Port Hills of Christchurch. As a result of this event, extensive fissuring was observed along the loess/loess-colluvium foot- and mid-slopes of north-facing valleys near the location of the sub-surface fault rupture. This caused severe damage to many hillside properties, with fissures mostly less than 0.2 m in width extending segmentally for several hundred metres. The fissures are present in nearly all major valleys, occur at similar altitudes, and show a contour-parallel orientation. At many locations, the fissuring is accompanied by lateral compression features in the valley floor sediments.

Understanding the geotechnical mechanisms involved in the fissuring has implications for the safe occupation of these hillside properties, and it is vital that thorough remediation of the damage is conducted. Current hypotheses anticipate that the fissures have formed as a result of quasi-toppling failures in the low-tensile strength loess and/or through movement of a similar nature to riverbank lateral spreading. Occurrence of liquefaction in the valley floors would likely result in loss of toe support to the valley walls, providing the impetus for the fissure development.

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This project aims to explain the mechanism(s) of fissuring, and to develop suitable remediation techniques. To date temporary remediation has been achieved by infilling fissures with a mixture of bentonite and SAP20 gravels. The project is undertaking a comprehensive

engineering geological mapping of the global extent of the fissuring, detailed analysis of four case-study sites, and geotechnical soil testing of loess from these sites. Also included will be 2-D modelling of failure mechanisms, and study of groundwater and spring behaviour from piezometer data.

### **Seismic reflections and the focusing of the mantle wedge beneath an active continental volcanic arc - Withdrawn**

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Curvilinear chains of volcanoes that erupt above  $120 \pm 40$  km deep Wadati-Benioff zones are one of the most striking surface manifestations of plate tectonics. The prevailing view is that the magmas that feed these arcs are an end-product of fluid-assisted melting in the mantle wedge. Two key questions remain unresolved: (i) why is the line of an active arc so sharply defined? and (ii) where do parental mantle-derived melts pool and differentiate into the mafic and more felsic components that are so distinctive of continental magmatic arc systems? We present geophysical evidence for such a focused zone of melt below an active volcanic arc with a wide-angle seismic reflection study within North Island, New Zealand. The 120 km long seismic profile extended northwest-southeast from near Te Kuiti, across the TVZ and then 30 km southeast across the Kaingaroa Plateau. Nine large dynamite shots were fired into an array of 704 independent seismographs. Refracted and reflected phases were recorded. Deep seismic reflections with reversed polarity, and normalized amplitudes up to six times greater than those from the Moho, are the main indicators of partial melt accumulation. Other unusual attributes of the interface responsible for these reflections are its narrow width (c. 15-18 km), its flatness and its location in the upper mantle at a depth of 32

The aim of this presentation is to use an exhumed rift margin hanging-wall mini-basin of the Oligocene-Miocene Suez Rift, Egypt to reconstruct the spatio-temporal complexities of marine sediment dispersal pathways and processes. A high-resolution lithofacies study is presented and reveals a broadly coarsening-up system, dominated by coarse-grained, heterogeneous, lenticular beds. Interpretation of these data provides an opportunity to demonstrate that submarine drainages are dominated by multi-sourced, (earthquake-triggered) gravity flows that interact with complex steep faulted terrain and are modified by ongoing deformation. The upward-coarsening motifs suggest that rift-related faulting enhanced the delivery of sediment to the basin over time, by steepening slopes and exposing soft pre-rift lithologies. These results provide the best example yet studied of marine sediment dispersal pathways and processes from a submerged rift basin.

**Petrography and reservoir quality of sandstones from the Middle Miocene Tunanui Formation, northern Hawke's Bay**

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This report presents the results of a detailed reservoir quality study of the Middle Miocene (Lillburnian) Tunanui Formation from northern Hawke's Bay. The formation is interpreted as a series of stacked basin floor fans, deposited in a deepwater sub-basin, within the East Coast Basin. The main aim of the study was to investigate porosity-permeability and

petrographic variations within a single 1 m thick turbidite bed. Samples from other outcrops were also analysed, and the results of this study were compared with previous studies on the Tunanui Formation from throughout the region.

The sands are fine grained with no upwards-fining through the bed, apart from at the very top where fine sand is interbedded with siltstone, and are generally moderately well sorted. The sands are lithic-rich, and classify as litharenites or feldspathic-litharenites, with little variation through the bed, and have undergone little diagenesis, with minor pyrite and clay redistribution. Only in one sample did pore-filling ferroan calcite occlude most of the porosity. They have good porosity (25-29%) and moderate permeability (20-90 mD), with no trends through the bed, other than a slight drop at the very top. The only sample with very low poro-perm contained pore-filling carbonate cement. Their high porosity and limited diagenesis, despite being lithic rich, implies that the sands have undergone only limited burial.

Tunanui Formation sandstones from previous studies (both wells and outcrop), may be finer grained (silt to fine sand), but their detrital compositions are similar (litharenites, with some feldspathic-litharenites). The diagenetic histories of other Tunanui Formation samples are also similar to those from this study, the main difference being that the samples from two wells (Tuhara-1a and Waitaria-2) have undergone more compaction, due to deeper burial. Some implications for regional petroleum reservoir quality within the Tunanui Formation and its depositional setting are also discussed.

## The PETLAB database in 2011

**D.T. Strong<sup>1</sup>, N. Mortimer<sup>1</sup>, and S. Haubrock<sup>2</sup>**

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PETLAB is a nationally significant database operated by GNS Science. Data is contributed by GNS Science as well as Auckland, Waikato, Massey, Victoria, Canterbury, and Otago universities. The database contains locations, descriptions and analyses of rock and mineral samples collected by government, university and industry geologists. The majority of samples in PETLAB are from the New Zealand islands and EEZ, as well as Australia, Antarctica and further afield.

PETLAB is an exemplary rock catalogue and database, and an invaluable research tool for geoscientists, geoscience students, and rock hounds. In return for access to the wealth of sample information and data held in PETLAB, all users are encouraged to add their own sample records to the database. The database currently contains over 180,000 records; more than 52,000 records have analytical data. The easy-to-use web interface provides free access to sample and location data, and registered users can also access and download analytical data. Over 1000 people from all around the world use PETLAB annually (<http://pet.gns.cri.nz>).

Key recent improvements and upgrades to PETLAB that provide increased functionality for the end user include:

- Google Earth and new NZTopo50 background layers
- The ability to search by creating a map polygon
- A new Google-style quick search box
- The addition of three major datasets: DEVORA borehole data, NZGS Sedimentology Laboratory heavy mineral data, and INS R detrital zircon data.

At the poster display people will be able to have hands-on experience searching the database, and we will welcome any comments on PETLAB including requests for improvements.

## Overview of the Deep Fault Drilling Project, Alpine Fault, phase 1, DFDP-1

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The first phase of the Alpine Fault - Deep Fault Drilling Project (DFDP-1), was carried out in January and February 2011 at Gaunt Creek, South Westland, New Zealand. Two boreholes, DFDP-1A and DFDP-1B, were drilled to depths of 101 m and 151 m respectively. DFDP-1A cored a hanging wall mylonite sequence containing cataclastic zones that increase in frequency downward; 20-30 m of cemented and hydrothermally altered cataclastics; a >5 cm thick principal slip surface of ultracataclastic and gouge at 90 m; and footwall fluvial gravels to a total depth of 101 m. DFDP-1B cored a similar hanging wall sequence; encountered a principal slip surface with a thickness of about 20 cm at depth 128 m; then penetrated a footwall sequence of quartz and feldspar-rich, extensively altered and variably cataclastic rock to a total depth of 151 m that includes a significant fault at 130 m. A complete suite of downhole geophysical logs were collected and borehole observatories were installed. A brief summary of operations, preliminary data, and analysis of results is presented.

**Contribution of Warkworth 12m VLBI radio telescope to New Zealand geodesy**

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The Institute for Radio Astronomy and Space Research (IRASR) of Auckland University of Technology (AUT) launched the New Zealand's first and only research capable radio telescope (WARK12M) near Warkworth which is located 60 km north from Auckland 8 October 2008. We intend to use the WARK12M for both purposes of radio astronomy and geodesy. The WARK12M belongs to Australia and New Zealand SKA project and is providing valuable results in cooperation with Australian station. On the other hand, in the geodetic field the WARK12M became a network station of the International VLBI Service for Geodesy and Astrometry (IVS) and is participating in IVS regular sessions from the beginning of this year. The WARK12M mainly participated in IVS-R1 and IVS-R4 sessions as much as possible and is contributing to provide twice weekly Earth Orientation Parameter (EOP) results. In addition, we are coordinating the experiment together with Japanese VLBI station to provide ultra-rapid EOP result. We also intend to contribute to the geodetic and geophysical study in New Zealand. The WARK12M is collocated with a GNSS station (WARK) which belongs to PositionNZ network maintained by Land Information New Zealand (LINZ). The inter-technique (VLBI and GNSS) solution is capable of increasing reliability of the national geodetic infrastructure. Here we will introduce WARK12M and explain the great synergetic relationship between VLBI and GNSS that we aim in New Zealand and will show the first synergetic result at Warkworth. To determine the initial coordinate of our VLBI reference point, we conducted GPS survey in collaboration with the New Zealand Crown Research Institute GNS Science and LINZ. In addition, we intend to show the recent results and discuss about noise sources such as the Ocean Tide Loading or Atmospheric Loading to influence geodetic observation at Warkworth.

**Eruption dynamics of the Raventhorpe volcanic complex, South Auckland Volcanic Field**

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The 0.73 Ma Raventhorpe tuff ring is the largest in a closely spaced and overlapping six tuff ring/scoria cone complex in the central part of the South Auckland volcanic field (SAVF). The stratigraphically upper part of the tuff ring is exposed in an 11 m succession in which five facies (F1-5) have been identified. The lowermost part of the succession and the upper sequence above 6 m comprises planar bedded, alternating (5-300 mm), well sorted, fine to coarse, coarse ash beds (F1). Above this is a cross-bedded, moderately to well sorted, coarse ash to fine lapilli sequence (F2). A massive, moderately to well sorted, medium lapilli to block and bomb bed (F3) occurs from 1.1-1.5 m. From 1.5 to 6 m massive or crudely bedded, moderately to poorly sorted, coarse ash to medium lapilli (F4) alternates with horizontally bedded, moderately sorted, fine to coarse lapilli (F5). The succession represents a transition from ballistic fall and surge processes to surge dominated processes. The lower ballistic unit could exemplify an increase in magma ascent rates before the eruption moved into its final stages, demonstrated by the general fining in grain size.

The magma-groundwater interaction is an important dynamic in the evolution of Raventhorpe. The underlying Pliocene sand with shell horizons of the Kaawa Formation is >150 m thick in this area, shallowing slightly westward and thickening further south towards the St. Stevens Fault. This aquifer is thought to be a major control on phreatomagmatic volcanism of the central area of the SAVF. Evidence of the aquifer's importance comes from abundant xenocrysts of quartz, hornblende and plagioclase, most likely derived from the Kaawa Formation.

## Vertebrate survivors of Zealandia's Oligocene "Drowning"

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We challenge the theory that New Zealand's entire fauna originated after a supposedly complete drowning of Zealandia during the Oligocene. Molecular evidence and the morphological similarity to Australian neighbours indicate overwhelmingly that the ancestors of many recent New Zealand vertebrates dispersed to Zealandia after the Oligocene, either before human colonisation (e.g., Haast's eagle *Aquila moorei*, weka *Gallirallus australis*, tomtits and robins *Petroica* spp., long-tailed bat *Chalinobus tuberculatus*) or after humans settled (e.g., white-faced heron *Egretta novaehollandiae*, pukeko *Porphyrio melanotus*, silveryeye *Zosterops lateralis*). However, an increasing amount of evidence indicates that the ancestors of many other taxa arrived before the "drowning". A pre-"drowning" origin, based on both fossil and molecular evidence, is postulated for New Zealand frogs (Leiopelmatidae), tuatara (Sphenodontidae), New Zealand geckos (Diplodactylinae), moa (Dinornithiformes), adzebills (Aptornithidae), large parrots (Strigopidae), New Zealand wrens (Acanthisittidae), and possibly New Zealand pigeons (*Hemiphaga*). Additionally, molecular evidence supports a pre-"drowning" origin for many well differentiated taxa, e.g., kiwi (Apterygidae), several waders (*Coenocorypha*, *Anarhynchus*, *Thinornis*), New Zealand wattlebirds (Callaeidae), stitchbirds (Notiomystidae), the Mohouinae songbirds, and possibly New Zealand skinks (*Oligosoma*), New Zealand honeyeaters (*Anthornis*, *Prosthemadera*), and short-tailed bats (Mystacinidae).

Therefore a divergent range of New Zealand's recent vertebrates (amphibians, reptiles, birds, and possibly mammals) have ancient origins and there is little to suggest that the Oligocene "drowning" was complete or resulted in

widespread extinctions. For some taxa, e.g., skinks, the fragmentation of landmasses and habitats during the height of the Oligocene submergence may have driven an increase in speciation events.

## Probabilistic analysis of Okataina Volcanic Centre tephra fall hazard to Bay of Plenty agriculture

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The Okataina Volcanic Centre (OVC) is an active caldera complex in the eastern Bay of Plenty Region that has experienced nine plinian rhyolite eruptions, two explosive basalt fissure eruptions and one adjoining andesite-dacite dome-forming eruption in the past 26 ka. Each eruption occurred from multiple vents throughout the OVC area and generated an array of hazardous volcanic phenomena. The variability in eruption style and vent location at the OVC presents a challenge in developing a reliable volcanic hazards assessment. The new tool BET\_VH (*Bayesian Event Tree for Volcanic Hazards*) introduces a way to confront these challenges by integrating such variability into a volcanic hazard analysis through probabilistic evaluation of a range of likely eruption types, vent locations and outcomes.

BET\_VH can be customized to analyse any hazardous volcanic phenomenon and threshold of interest. Due to the Bay of Plenty's abundant agricultural activity, this study investigates tephra fall hazard on the basis of an accumulation threshold considered damaging to New Zealand agriculture. An extensive range of data from geological records, past studies, models and expert scientific opinion was collected for statistical input about the likelihood of eruption, eruption vent location, eruption type and the generation of tephra. A series of probabilistic tephra dispersal models were run using

TEPHRA2 software for statistical input about the likelihood of the tephra threshold being reached or overcome in areas throughout the Bay of Plenty for all eruption types and vent locations.

The resulting BET\_VH maps illustrate probability distributions in the Bay of Plenty Region for tephra fall reaching the agricultural threshold for specific OVC volcanic eruption scenarios within given time frames. The probabilities reveal important information about tephra hazard that could contribute to land-use planning and agricultural management practices and support a robust quantitative evaluation of volcanic risk in Bay of Plenty agricultural communities.

#### **Source of chalcophile and siderophile elements in Kermadec arc rocks**

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Most seafloor massive sulfide (SMS) deposits contain significant proportions of magma-derived chalcophile and siderophile elements (i.e., Au, Cu, V, Zn, Mo, Bi, Sb, As), which relate to the composition of associated (host) magmatic rocks. Compositional variability of the host rock therefore will have a strong influence on the composition of the SMS deposit. Our geochemical results, when combined with published data, show that mafic back-arc and arc front lavas are generally enriched in most chalcophile/siderophile elements, although depleted in Ag and Sn when compared to average mid-ocean ridge basalt. Elevated ratios of (Cu, Zn, V, Mo, Pb)/Yb, Ba/La, As/Ce and Sb/Pr indicate that these elements are mainly transported into the mantle wedge, beneath the arc, via aqueous fluids derived from the subducting slab. Ag and Sn contents, however, appear to be relatively immobile during dehydration of the subducting slab. Lower ratios of (Cu, Zn, Mo, Sb and Pb)/(MREE, HREE) in Havre Trough

basalts, when compared to Kermadec arc basalts suggests decreasing slab-related input into the mantle source region towards the back arc. Unusually high contents of most LILE, Ag, Sn, Mo, Th, LREE, MREE, Nb, Zr and Hf, and positive trends of (Sn)/Yb with Th/Yb, Hf/Y, (La/Sm)<sub>N</sub>, but low Sr/Y in dacites from the Brothers Volcanic Centre in the southern Kermadec Arc indicates Ag and Sn (and possibly Au) transport via a sediment-derived hydrous melt into the mantle wedge. The mobilization of Ag and Sn demonstrates that chalcophile and siderophile elements are added to the mantle wedge from the subducting slab, with a melt as the most effective metal carrier. Magmas generated through partial melting of a sub-arc mantle metasomatised by hydrous melts appear to play an important role in the formation of Cu-Au-rich arc-type SMS deposits, such as hydrothermal mineralization on Brothers Volcanic Centre.

#### **Distal volcanoclastic sedimentation as a record of the growth and development of the composite Ruapehu volcanic cone**

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Mount Ruapehu is one of New Zealand's highly active volcanoes with a well-documented record of historic activity and hazardous lahars. The current Mount Ruapehu composite cone and ring plain contain, between them, a record of the last c. 230 ka, although these two stratigraphies are currently only weakly correlated. The relationships between these records would provide a more complete understanding of the nature and frequency of past activity to robustly and more clearly outline the future behavior of the volcano. Volcanoclastic diamictons accumulating in distal river valleys around the volcano provide a wide perspective into the ancient volcanic history of Ruapehu allowing dating and interpretation of the style and magnitude of volcanism and cone collapse.



A stratigraphic sequence of volcanoclastic deposits in the Hautapu River catchment reveals a series of volcanic mass flow events representing an early episode of activity and instability on Ruapehu Volcano. The diamictites are exposed at an average topographic elevation of 700 masl around the Taihape-Mataroa countryside and are inferred to have been emplaced on the Greatford (110-120 ka) aggradational alluvial terrace correlated to oxygen isotope stage 7. The andesitic boulders in the area, previously identified as glacial tills, suggest that the proto-Hautapu River was located further to the west than is currently the case with deposits being contiguous to proximal Ruapehu ringplain areas. Sedimentologically, the *in situ* deposits display features and textures consistent with debris flow to hyperconcentrated flow, although some of the very large boulders present may indicate that debris avalanches also reached the upper catchment. The basal debris flow deposit, comprises sub-rounded andesitic boulders up to 4 m in diameter in an un-sorted clast supported framework, and represents a major mass wasting event related to instability on the volcanic edifice, such as a flank collapse induced debris avalanche. Transformation and dilution occurred downstream resulting in a debris flow. The availability of a large amount of unconsolidated volcanoclastic material on the proximal Ruapehu ringplain was remobilised in subsequent debris flows and hyperconcentrated flows. An overall increase in pumice clasts towards the top of the sequences indicates episodes of volcanic activity pre- or syn-laharic up until 22.6 ka B.P. where the overlying Kawakawa Tephra provides a minimum bounding age to the sediment package. The complex bedding of reworked deposits and unconformable strata is interpreted to indicate the development of a braided river system with an overall northwest-southeast flow direction through the Taihape township. Tectonic activity on the Whangaehu Fault and uplift in the Hihitahi area resulted in the catchment being cut off from the proximal Ruapehu ringplain around 22.5 to 14.7 ka ago, which prevented further deposition of lahars in this area. The existing deposits in the catchment were recycled into a series of younger flood terraces when the proto-Hautapu River cut down into the gradually uplifting underlying soft Tertiary sedimentary basin fill.

## The new Tongariro National Park (TNP) geological map

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With the recent completion of QMAP Taranaki and imminently Hawke's Bay, a need to publish a geological map of the central North Island volcanoes in greater detail and on one sheet of paper was identified. This 4-5 year project will integrate detailed volcanic stratigraphy, petrography and geochemistry (including existing and new Ar-Ar dating of lava flows) with glacial deposits on the mountain and sedimentary and debris flow deposits on the ring plain. We also intend to include the many active faults in the area, potentially leading to better constraint of the faulting history at the southern end of the Taupo rift.

The project is co-funded by DoC and is to be run in parallel with two PhD students through Victoria University, a PhD student from University of Canterbury, and collaboration with Massey University. Outputs of the project are a geological printed and digital map of the park likely at 1:80,000 scale and an accompanying bulletin by 2014. Samples will be lodged in the PETLAB database.

Digitising of an interpretation of geomorphic features in the park is underway. Reconnaissance-level fieldwork has so far been undertaken by GSL and DBT on the eastern side of Mount Ruapehu and on the northwest

flank. Main findings include many sequences of over thickened and textured lava that may have resulted from the interaction of lava with ice. Given the myriad of glacial features on the mountain, this is perhaps not surprising (although previously under-recognised). Other new findings include extensive andesitic pyroclastic deposits (possibly from flows) sourced from Ruapehu, many very young landscape-mantling lava flows (some of which have been subsequently glaciated), and evidence for very young glacial advance and retreat. Based on the types of rock in the lahar deposits there is potential to better link the older very large lahar bursts to past eruptive phases.

### **Western SAHKE: Crustal structure of the Wanganui Basin, New Zealand**

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Active source seismic data of deep crustal and lithospheric structure have recently been acquired in transects across the Southern Hikurangi margin, North Island, as part of a major international seismic collaboration (SAHKE). Wanganui Basin is of particular interest because currently the plate interface is thought to be locked and accumulating strain in this area and detailed knowledge of the plate interface and Moho geometry are vital to understanding this process.

I focus on analysing data from the western side of Lower North Island, in order to model crustal structure beneath Wanganui Basin. Here, clear seismic phase arrivals at offsets between 100 m and 200 km are recorded, and I interpret both crustal and upper mantle refractions and Moho reflections. These data define the detailed deep structure and geometry of the Australian Plate Moho and subducted Pacific Slab. In particular, arrivals from on land explosions show three clear reflections at 6.5 s, 8.7 s and 12.5 s (two-way travel time), that define the depth and

thickness of the Pacific slab. Offshore multi-channel seismic reflection data are used to constrain sedimentary velocities and basement geometry and also contain coherent arrivals at c. 14 s two-way travel time, interpreted as Moho reflections.

Two 2-D velocity models have been constructed that define the Pacific slab geometry and confirm the Australian Plate Moho deepens north to south through Wanganui Basin, from c. 30 km just south of Mount Ruapehu to c. 40 km at the latitude of Foxton Township. This makes the crust beneath Wanganui Basin, an area about 100 m below sea level, as thick as that beneath the Mount Cook area of the central South Island, where the average elevation is closer to 2000 m.

### **New Zealand and its neobiota**

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A popular school of thoughts holds that the characteristics of New Zealand's biota are the result of their having evolved in isolation from other biotas for some 80 million years; a product of plate tectonic activity causing intercontinental vicariance. This view emerged most strongly after recognition and acceptance of the tectonic mechanism, as it appears to provide an appealing elegant union between land surface and biota. However, it is obvious that New Zealand life is not biologically isolated from life elsewhere, and most biologists now recognise this. A possible partial solution to the problem of what lineages arrived in New Zealand, when, and how, emerged from the suggestion that the continental precursor of New Zealand, Zealandia may have been entirely inundated during the later Oligocene. If this were the case, then there would be no doubt that the entire biota of New Zealand had evolved from immigration (in the Miocene and later), just as is the case for many other islands. Proving submergence at some time in the past of all land in the immediate New Zealand region is difficult, and may be impossible, even though to date the proof of land persistence has also been lacking (or meagre). Understanding

New Zealand biogeography would be a little easier if it was known that New Zealand had emerged from beneath the sea at a given time, like the islands of Galapagos and Hawaii. Not knowing this simply enlarges the possibilities for evolution of the New Zealand biota, rather than constituting evidence that a Gondwanan vicariant history was important or even relevant. The major problem for biogeographic inference is that extinction obscures both the composition of the extant biota and the resolution of phylogenetic analysis. I will examine what we think we know about the modern biota of New Zealand and highlight issues with reconciling this with emerging evidence about geological history.

**Tectonic nails – plutons as markers of continental margin tectonism, with examples from the Victoria Range, Westland**

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We present a 1:50,000 scale geological map of the Victoria Range segment of the Karamea Batholith in the Buller Terrane. The area is largely comprised of granitic plutons of mid Paleozoic and Early Cretaceous ages. Garnet and sillimanite-bearing paragneisses represent metamorphosed Ordovician Greenland Group. The Paleozoic plutons are dominated by the “S”-type Karamea Suite with ID TIMS U-Pb ages of  $369 \pm 1$  Ma. Early Cretaceous plutons include the distinctively Kfeldspar-megacrystic Macey Granodiorite (Separation Point Suite; 126 Ma), and several plutons of the granite-granodiorite (Rahu Suite, type locality; 132-119 Ma).

Two instances of plutons as “tectonic nails” (Anderson 1996), whereby age and other characteristics of plutons can be used to constrain tectonic processes, are offered. Firstly, significant vertical motion of the crust appears to be associated with emplacement of Rahu Suite plutons at depths of c. 22 km (Al-in hornblende thermobarometry). Ambient temperatures at such depths might be expected to exceed 500-600 °C, but hornblende K-Ar

ages in Paleozoic diorites host rocks are not fully reset, suggesting only transient burial to 22 km. Secondly, the Carboniferous Maruia Pluton has characteristics of Ridge Suite, typically associated with Takaka Terrane. Its intrusion into Buller Terrane is consistent with intrusion through a terrane boundary that was *west-dipping* in the Carboniferous, allowing derivation from the Takaka Terrane source rocks and emplacement into the Buller Terrane.

All plutons exhibit some degree of tectonic foliation and the exposures may represent the lower plate of a metamorphic core complex. Mid Cretaceous exhumation may have been along a detachment fault now represented by steeply dipping mylonitic shear zone that currently bounds the batholith on its western margin.

**Dates and rates of the Karamea Suite ‘flare-up’ event and consequences for resolving the disconnect between plutons and volcanoes**

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Understanding how magma reservoirs grow has fundamental implications for resolving the apparent disconnect between the plutonic and volcanic domains. Of key significance is the duration and rates of magmatic processes that occur in both plutonic and volcanic magma reservoirs. Long-lived (up to 5-10 Ma) incremental emplacement of plutons and batholiths, as observed in plutonic systems worldwide, represent ‘steady-state’ magmatism, allowing for emplacement and solidification of a voluminous magma body, but with flux rates too low to allow formation of large magma chambers capable of producing caldera-forming events. This has led several authors to suggest a disconnect exists between plutons and volcanoes, with the volcanogenic period of a magmatic system dominated by waxing, high-flux magmatism, and the plutonic period representing the waning stages of a magmatic cycle.

The voluminous 370 Ma Karamea Suite granites of Westland, represent a magma reservoir formed during a period of elevated magma

flux under 'flare-up' conditions, and therefore may have fed explosive silicic volcanism at the surface. High precision CA-ID-TIMS U-Pb zircon dating reveal a short lived (c. 2 Ma) burst of 'S-type' silicic magmatism, followed by c. 10 Ma of minor I-type magmatism. What tectonic settings and crustal conditions are capable of producing such a short-lived pulse? The rapid production and accumulation of the silicic Karamea Suite magmas apparently required an elevated heat input from hot asthenospheric mantle, of which we see no direct evidence. Two tectonic models are hypothesized: (i) intra-arc extension as a result of slab roll-back, similar to the tectonic setting in the highly active TVZ, and (ii) thrusting of fertile continental lithosphere beneath an arc, followed by delamination and asthenospheric upwelling. O- and Hf-isotopes in zircon will allow us to better delineate the source characteristics and percentage of the mantle and crustal contributions, from which the two tectonic models will be tested by numerical modelling.

**Assembling a dacite in a continental subduction zone: case study of the Tauhara dacite**

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The genesis of intermediate magmas (andesites and dacites) in subduction zones remains a matter of debate as multiple crustal processes (fractionation, magma mixing, crustal anatexis, AFC) are able to account for such compositions. However, recent evidence suggests that magma mixing associated with chamber recharge (Reubi and Blundy, 2009; Kent et al., 2010) plays a prominent role. It is therefore important to assess the conditions and timescales involved in generating intermediate magmas. Mount Tauhara is the largest dacitic volcanic complex of onshore New Zealand. Its eruptives have a complex petrography including quartz, plagioclase, amphibole, orthopyroxene, clinopyroxene, olivine and Fe-Ti oxides that can only be the product of magma

mixing. As such, it offers an ideal opportunity to investigate the processes and timescales involved in assembling dacitic magmas from other melt compositions utilising whole rock, *in situ* and mineral specific analytical techniques by: (i) constraining the chemistry and relative proportions of the end-members involved in the mixing events, and (ii) estimating the timing of mixing and ascent prior to eruption. Whole rock major and trace element data and Sr-Pb isotope ratios define two separate linear arrays indicating that the dacites are generated by mixing of four distinct silicic and mafic magma end-members. Analysis of quartz-hosted melt inclusions reveals two separate rhyolitic end-members, whereas high-Mg# clinopyroxenes fingerprint a high-alumina basalt and an andesite as the two mafic end-members. Thermobarometry and diffusion timescale constraints from amphibole, clinopyroxene and quartz crystals constrain the mixing depth to between 9 and 13 km at temperatures of 900-950 °C, which occurred <6 months prior to eruption. The rapid ascent rates calculated from amphibole rims ( $\leq 2-3$  weeks) imply that almost complete homogenization of the deep magma chamber occurred within months of mixing of the silicic and mafic end-member magmas.

**Contributions from offshore seismic data to understanding the evolution of the New Zealand continent**

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Seismic data acquired for petroleum exploration of New Zealand's frontier basins gives insights into evolution of the New Zealand continent. Early development of New Zealand's sedimentary basins depended upon their location relative to the Gondwana margin. The basins can be grouped into four sets:

- A set along the subduction margin
- A belt of back-arc rift basins
- An intra-continental set.
- A Cretaceous pre-break-up set.

The marginal basins include the North Chatham Slope, Pegasus, the East Coast, Raukumara, and Northland Slope basins. Much of New Zealand's "basement" consists of sedimentary rocks deposited in environments from terrestrial to deep-sea trenches. Seismic data from the Pegasus Basin show a continuum from highly-deformed Torlesse rocks below the Chatham Rise through moderately-deformed rocks to flat-lying undeformed sedimentary rocks overlying the Hikurangi Plateau.

Basins developed by back-arc rifting include the New Caledonia, Taranaki, Canterbury and Bounty Trough basins. In Deep-water Taranaki, a large, Late Cretaceous delta prograded across an earlier rift succession. Rifting ceased around 105 Ma indicating that this basin developed in response to back-arc rifting relative to subduction at the Gondwana margin.

Intra-continental basins include the West Challenger, Pukaki, Outer Pukaki, and Great South basins, which may have originated during the Jurassic, as, apparently, did the Reinga/Northland, Deep-water Taranaki basins and Australia's Gippsland basin.

The Monawai, Bellona, Campbell, and Outer Campbell basins are closest to the Late Cretaceous rift margins and are likely to have been strongly influenced by pre-break-up rifting, during the early part of the Late Cretaceous.

The Western Southland, West Coast, and nearshore Taranaki basins are overprinted by post-break-up Cretaceous and Paleogene rifting, while the Tasman Sea was spreading. Basins in the northwest were overprinted by compressional structures in the Paleogene and other Northern basins were again overprinted during the Neogene further obscuring their early history.

## Refining the age of the Kawakawa/Oruanui tephra in New Zealand

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Kawakawa/Oruanui tephra (KOT) is a key chronostratigraphic marker for the Last Glacial Maximum in New Zealand. Age models at many paleoenvironmental study sites in the southwest Pacific region depend on an accurate age for the KOT.

More than 60 <sup>14</sup>C ages relating to the deposition of KOT have been published and range from ca. 20,000 to ca. 25,000 <sup>14</sup>C yr BP. One difficulty in establishing the accurate age has been a scarcity of high-quality, optimal organic material *directly* associated with the eruption. Another problem is that of anomalously young <sup>14</sup>C ages arising from contamination of some organic materials by post-depositional carbon. The

currently adopted age for the age of the KOT is  $22,590 \pm 230$   $^{14}\text{C}$  yr BP ( $27,282 \pm 709$  cal yr BP), based on an activity-weighted pooled mean age from only four small carbonised branch fragments, at separate sites, embedded within Oruanui ignimbrite emplaced during eruption. These fragments represent wood from short-lived plants killed during the eruption, whereas most other ages for the KOT are from tephra-fall sites and organic material less closely associated with the eruption and typically of wider age range.

Recent attempts to reproduce the key charcoal-based  $^{14}\text{C}$  ages and refine the calendar age have been undertaken through new analysis of organic matter from sites considered optimal for dating. These include new ages from pyrolysed plant material within the ignimbrite, intact and *in situ* plant remains, rapidly buried by distal tephra-fall deposits, and organic material from undisturbed lake sediment bracketing the tephra deposits. Results available thus far are compatible with existing tephrostratigraphic constraints on the KOT but are consistently younger than the currently adopted (calibrated) age estimate by c. 1800 cal yrs. We summarise and discuss these findings in light of refining the age of the KOT and the implications for correlating climate events within and beyond the southwest Pacific.

### **The use of 3D modelling to determine rockfall hazards on and around the Port Hills, Canterbury**

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Rockfalls are a major hazard in steepland areas as they pose a potential threat to lives, settlements, and infrastructure. The Christchurch Earthquake of February 22<sup>nd</sup>, 2011, highlighted the seriousness of rockfall hazards on and around the Port Hills which impacted on residential properties, infrastructure, and roads down-slope of boulder source areas and led to a number of fatalities. Rockfall hazard zones need to be delineated in relation to existing

and planned developments in order to avoid the problems experienced in Christchurch, and to inform planning decisions for future developments.

Rockfall data have been collected from Rapaki, a residential area that has experienced a particularly high amount of rockfall in the 2010-2011 Canterbury earthquakes. These data, by means of 3-D numerical modelling software (RAMMS Rockfall), will be used to calibrate a risk assessment model of the run out zone at Rapaki. The localised Rapaki site model will then be applied to other settlements around the Port Hills and possibly the whole of Banks Peninsula.

A prediction model can then be created based on data collected for each individual earthquake, such as the amount of rock released and run out distance for each peak ground acceleration experienced at the site during the 2010-2011 earthquakes. Interpolation between these events will allow prediction of severity of rockfall to be expected from the Port Hills for any given PGA.

Combining results of the calibrated 3-D model and prediction model will give a better understanding of rockfall hazards to residential or pre-residential areas, as well as infrastructure, on and around the Port Hills.

### **Surface rupture of the Greendale fault: lessons learnt, lessons to learn**

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The surface rupture of the Greendale Fault on the 4<sup>th</sup> of September is, and will be, a source of crucial information to understand various aspects of fault rupture, from the underpinning

science of fault mechanics to applied science. In this presentation, we will discuss some of the research and applied science where this new information will make an important contribution. The abundant, high quality field measurements obtained in the days to weeks after the rupture, together with airborne LiDAR, are currently being used to: (i) assess existing empirical relationships of earthquake magnitude versus fault rupture length and/or co-seismic displacement, for different levels of stress drop, (ii) generate a better understanding of the fault parameter uncertainties used in those relationships, (iii) understand the complexity of fault rupture and fault deformation width, an important aspect of fault zonation for urban planning and engineering design, (iv) calibrate and further benefit from the knowledge of fault deformation patterns gained from sand box analogue modelling, and (v) gain further insights into the complex tectonic setting of the Canterbury Plains. The occurrence of the rupture along an unmapped fault has also raised philosophical questions with respect to the National Active Fault database and highlighted the fact that the low seismicity areas of New Zealand can present a higher risk to the country than previously predicted.

#### **U-Pb dating of rhyolites from the eastern Coromandel Volcanic Zone**

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Previous geochronological studies of Coromandel Volcanic Zone (CVZ) rocks have dated mostly andesites using the K-Ar method. Few of the rhyolitic volcanics of the CVZ have been dated. In this project 16 rhyolite lavas and 5 rhyolitic ignimbrites were selected from the eastern CVZ to estimate their eruption ages as determined by U-Pb dating of zircons using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Some samples were also collected to determine the age of mineralisation of the rhyolitic host rocks, e.g., at

Broken Hills Mine and Wharekairauponga. U-Pb dating of zircon crystals is a useful method for age determination because most CVZ rhyolites contain zircon. Ages range from c. 11 to 3 Ma, i.e., Late Miocene to Late Pliocene. Some CVZ rhyolites contain zircons with Early Cretaceous ages, and are interpreted to be zircons inherited from the Mesozoic basement.

#### **Distribution of water related to flow banding and microlites in obsidian**

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Flow banding affects the bulk viscosity and strength of hazardous volcanic domes and lava flows. Flow bands are commonly micro- to centimeter scale structures defined by subplanar variations in microlite (crystals <100  $\mu\text{m}$ ) abundance and/or by higher porosities resulting from deformation and welding. Previous studies suggest microlites in flow bands are accumulated by strain (i.e., chemically passive) rather than forming *in situ*, thus, disconnecting the presence/formation of microlites as a major factor from processes such as second boiling and static pressurization.

Here, we measure water contents and speciation in flow bands and around crystals by using Fourier Transform Infrared Spectroscopy (FTIR) via a synchrotron IR source (Australian Synchrotron). High spatial resolution shows two distinct zones of water speciation associated with flow bands. Total water concentrations are slightly higher around flow bands containing microlites. Additionally, microlites including both plagioclase and amphiboles in the flow bands demonstrate hydration/dehydration halos suggesting an active synergy between crystal growth, hydration and flow banding. The data also show a shift in speciation from mainly hydroxyl groups to dominantly water molecules around areas of higher microlite concentrations.

Overall, this data illustrates that microlites in flow bands are active components that may be capable of altering the physical dynamics of a volcanic event.

#### **The distribution of water in collapsing foams of magma**

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The exsolution of volatiles and the formation of bubbles are the driving force behind any volcanic eruption. Following explosive eruptions, the bubbles in a magma foam collapse and the magma degasses non-violently creating a lava dome or plug in a conduit. These collapsed foams reduce permeability and can lead to repressurisation of the conduit. The nucleation and growth of bubbles have long been the main focus of research as they occur during magma rise and decompression. However, the collapse of bubbles and the formation of lava domes and plugs remain poorly understood. Here, we suggest two routes of bubble collapse: (i) the escape of gas through a permeable network of connected bubbles, and (ii) the resorption of gas into the melt. We used Fourier Transform Infrared Spectroscopy (FTIR) with a synchrotron IR source (Australian Synchrotron) to investigate the water concentration of glass around bubbles in samples from Mayor Island, New Zealand. Preliminary results show for the first time that there is a hydration rim of up to >0.1 wt% around bubbles. This shows that volatiles are not completely lost through a permeable network in collapsing foam but are also reintroduced into the melt. Our samples show strong banding without significant changes in microlite content. We propose the flow bands to be the result of incomplete foam collapse during flow that causes a measurable oscillating water distribution along the flow bands. This shows that strain can induce inhomogeneous degassing of magma and/or resorption of water around areas of bubble collapse. Future studies will allow estimations of time- and temperature-scales of bubble collapse in cooling magma.

#### **Slow slip events observed on the Hikurangi subduction interface in 2010/2011—two extreme end-member examples**

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2010/2011 was an active time for slow slip events (SSE's) at the Hikurangi margin. A repeat of the 2004/2005 SSE beneath the Manawatu region began in mid-2010, and is ongoing. As of mid-2011, the equivalent moment magnitude of that event had exceeded  $M_w$  7.0. Due to the increased density of GeoNet cGPS sites along the Hikurangi margin in recent years, the spatial and temporal evolution of slow slip in the 2010/2011 Manawatu event is much better constrained than for its predecessor 2004/2005 event. Nearly the entire Hikurangi subduction interface beneath the southern Hawke's Bay and Manawatu regions appears to rupture in SSE's implying that the physical conditions occurring along most of the interface in the central portion of the Hikurangi subduction margin boundary are those that promote SSE behaviour.

Before 2011, all SSE's documented at the Hikurangi margin occurred at the transition from interseismic coupling to aseismic creep, similar to SSE's at subduction margins elsewhere. However, during the last week of June 2011, several cGPS sites on the Wairarapa coast of the eastern North Island, located above the interseismically locked portion of the subduction interface began moving eastward by up to 15 mm over a period of two weeks. These displacements require up to 9 cm of slip over c. 100 km long region of the interface just offshore the Wairarapa coast, with an equivalent  $M_w$  of 6.7. The SSE was accompanied by a swarm of microseismicity ( $<M_L$  5) and both the cGPS data and the microseismicity suggest northward propagation (50-70 km) of the SSE over two weeks. We interpret that this event is occurring either: (i) at the up-dip unstable (seismic) to stable (aseismic) frictional transition, above the seismogenic zone where megathrust earthquakes are expected to nucleate, or (ii) within a "partially" coupled portion of the locked zone.



**3D velocity imaging of Hikurangi  
subduction beneath the Wellington Region,  
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We present first results from the Seismic Array HiKurangi Experiment (SAHKE). This joint project involving New Zealand, Japan, and US institutions aims to investigate the subduction zone fault characteristics beneath Wellington. Situated above where the Pacific Plate is subducting beneath the Australian plate at a rate of c. 42 mm/yr, the Wellington region provides a unique opportunity to investigate the frictional properties, geometry, and seismic potential of a shallow, locked megathrust fault. Here the coupled plate interface is 20-30 km deep beneath land and can be sampled with onshore-offshore data from 3 sides. SAHKE combines active and passive source data comprising 4 distinct data sets: (i) a dense temporary array of 50 seismometers with c. 7 km spacing augmented 25 regional network instruments to record 49 local and 45 teleseismic earthquakes over a four month period, (ii) these stations also recorded 69,000 offshore airgun shots from 17 lines crisscrossing two sides of the array, (iii) an additional coast-to-coast transect of 50 stations cutting through the temporary array recorded c. 2000 offshore shots on either side, (iv) 1000 stations with 100 m spacing along that same transect separately recorded 12 in-line, 500 kg onshore dynamite explosions. First inspection of the recent onshore shot gathers show excellent signal to noise and a band of three strong reflectors between 20 and 38 km at the western end of the profile. We combine shot and earthquake recordings to simultaneously invert c. 750,000 first arrivals for velocity structure and hypocenters in the densely sampled volume. First results from 3-D, Vp tomography and relocated hypocenters agree with previous studies and suggest the later weak signals are reflections from the top of the Pacific plate. Our improved velocity model provides a high-resolution geometry of the subducting plate to support interpretation of other phases identified in SAHKE shot gathers.

**Jetting behaviour during experimental  
thermal granulation of magma**

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Surtseyan tephra jets are mixtures of ash with bombs travelling roughly ballistic paths. Similar but smaller jets are generated by littoral magma-water interactions, confirming the general inference that surtseyan tephra jets are a characteristic product of explosive magma-water interaction, and suggesting that magmatic volatiles play no critical role. Surtseyan jets have been inferred to result from both intense fuel-coolant interactions, and from simple boiling of water entrained into rising magma, with little new information testing these two positions since the 1980's. In experiments, pouring magma into standing water has produced vigorous jetting of hot water as melt solidifies and undergoes extensive thermal granulation.

We present high-resolution hi-speed video of these jets, and infer that as thermal granulation takes place, a fracture network advances into the melt/glass body. Water invading the cracks at the rate of propagation is heated nearly instantaneously. Vapour produced at the contact expands and drives outward through cooled cracks, condensing as it moves to the exterior of the magma body where it is emitted as a jet of hot water. In ocean ridge hydrothermal systems diffuse crack networks induct cold water, which is heated and expelled in focused jets. Focusing of hot outflow in experiments, as at ridges, is inferred to result from thermoelastic closure of cracks near the one(s) feeding the jet. From the cooled products of our experimental runs, we know that thermal contraction produces a network of curved cracks with modal spacing of 1-2 mm, which separate domains of unbroken glass. It is during growth of this crack network that cold water enters, is vaporized, recondensed and driven out through other cracks as a hot-water jet. At larger scales, we suggest that intense jets of this sort may trigger explosive MFCI

capable of driving vigorous tephra jets in littoral interactions and surtseyan eruptions.

### **Development of three dimension geological models for hydrogeological applications in New Zealand 1996 - 2011**

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Three dimensional geological modelling techniques have been applied since 1996 with an aim to characterise the lithological and chronological units of New Zealand's many diverse aquifers. Models of property-scattered data have also been applied to assess physical properties of aquifers and the distribution of groundwater chemistry, including groundwater age, to inform an understanding of groundwater systems. These models, fundamental to understanding groundwater recharge, flow and discharge, have found many uses as outlined in this paper.

For example, groundwater allocation studies link 3-D geological models with groundwater budgets to assess groundwater available for allocation. This approach has been used for three studies in the Bay of Plenty region, the Hauraki Plains and Horowhenua.

Land use and groundwater quality is another common application. For example, the geological model of the Lake Rotorua catchment was used to assess groundwater flow paths between land use and the lake and to identify groundwater catchment boundaries which are crucial to the assessment of the effects of land use and lake water quality.

Models have been developed to understand the geology of coastal Holocene sediments as an important control on groundwater flow paths and the distribution of aquifers, springs and spring-fed streams. For example, a 3-D model of Christchurch City identifies that gravel lobes associated with deposition from the Waimakariri River are interfingered with relatively impermeable Holocene marine and estuarine sediments near the coast. Christchurch City

streams are closely connected with these gravel lobes (White et al. 2009).

Three-dimensional geological and property models provide important insights into groundwater systems and expansion of these models will continue in the future.

White, P.A. 2009. Avon River springs catchment, Christchurch City, New Zealand. *Australian Journal of Earth Sciences* 56(1) pp 61 - 70.

### **Shape Preferred and Lattice Preferred Orientation fabrics in mafic eclogites, D'Entrecasteaux Islands, Papua New Guinea; what deformation processes took place under high pressure and ultra-high pressure conditions?**

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Mafic boudins from the D'Entrecasteaux Islands, Papua New Guinea, preserve the youngest known (4-5 Ma) exposed Ultra-High Pressure (UHP) eclogite-facies rocks in the world. The deformation fabrics preserved in the boudins preserve a snapshot of peak metamorphic conditions as they are defined by (U)HP minerals (omphacite, garnet, rutile, phengite, quartz ± coesite) and were unaffected by later extensive recrystallisation and fabric development in the amphibolite-facies that took place after exhumation of the rocks to lower crustal depths. We seek to understand the deformational processes that were active at mantle depths such as direction and symmetry of ductile flow at that time. These results are of general interest as they may provide new insight into the tectonics of the UHP burial and unburied process. Zr in rutile thermometry and garnet-clinopyroxene-phengite barometry will be used to constrain peak temperature and pressure. 3-D Shape Preferred Orientation (SPO) fabrics are being measured for omphacite and quartz in 7 oriented samples. We hope to determine any foliation and lineation present and to characterise the strain orientation and shape

(e.g., constriction or flattening). For measuring SPOs, we are employing a semi-automated process in ArcGIS to identify grain boundaries and construct a grain boundary map for each of the two phases from multiple registered photomicrographs and Backscatter Electron (BSE) images. The grain boundary maps are input into the Matlab toolbox extension PolyLX to analyze the strength and orientation of the SPOs. Preliminary results suggest that a weak SPO is present for both quartz and omphacite. In addition, Electron Back Scatter Diffraction (EBSD) analysis has been used to measure Lattice Preferred Orientations (LPO) of the same two minerals. Preliminary results shows a unimodal concentration of [001] axes for both omphacite and quartz that developed as a result of slip parallel to the [001] direction in both minerals.

#### **Te Anau glaciations: complementary evidence from speleothems and moraines**

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This paper revisits and elaborates results published in the NZJGG by Williams (1996) concerning the glacial history recorded in Aurora Cave beside Lake Te Anau in Fiordland. Complementary records are provided by speleothems that grew during mild unglaciated intervals and lateral moraines over the cave that mark glacial events. The dated record comprises 33 speleothem <sup>230</sup>Th ages by TIMS and 22 minimum exposure ages by <sup>10</sup>Be on moraine boulders.

The first warm episodes recorded in the cave were from MIS 7/8 at  $273.21 \pm 9.80$  (2 $\sigma$ ) ka,  $214.37 \pm 1.84$  ka, and  $211.02 \pm 1.14$  ka. Between then and  $55.26 \pm 0.20$  ka (MIS 3) any younger speleothems that grew were scoured away, but then followed a 12.5 ka long interstadial until  $42.80 \pm 0.44$  ka, after which there was

a 6.7 ka glacifluvial event until  $36.06 \pm 0.29$  ka. Speleothem growth continued until  $33.43 \pm 0.13$  ka and then ceased, marking the start of the LGM.

The commencement of the LGM was dramatic with 630 m of ice accumulation over the cave in 1730 years, reaching its maximum depth by 31.7 ka. This represented the LGM culmination at Te Anau, because by the mid-LGM interstadial (24.4 - 22.7 ka, Williams et al 2010) the glacier surface had already ablated by 400 m and by 18.5 ka stood only 24 m above modern lake level. Revegetation of valley-side slopes permitted speleothem accumulation to commence again by  $16.43 \pm 0.47$  ka and it has continued uninterrupted into the Holocene.

Projected glacier profiles from the dated high terraces plus additional reconnaissance <sup>10</sup>Be ages on erratics help delimit the downvalley extent of the Te Anau glacier. This indicates that the Whitestone Till Member, previously ascribed to the Waimean (McKellar 1973), was deposited by the early LGM main advance.

McKellar, I.C. 1973. Te Anau-Manapouri District, 1:50 000, NZGS Misc Series 4.

Williams, P.W. et al. 2010. Int. J. Speleology 39(2), 99-112.

#### **Volcanic Ash Fall Impacts Working Group, thinking collaboratively acting globally**

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The Volcanic Ash Fall Impacts Working Group is an international consortium of multi-disciplinary geoscientists focused on understanding and mitigating the impacts of ash fall. The overall goals of this working group are: (i) more effective public ash fall warning messages, (ii) standardization where possible, of protocols

for ash fall data collection and analysis, (iii) creation of standard checklists of impact data to collect following eruptions, (iv) creation of ash impacts loss-damage functions for risk calculations, and (v) improving international ash fall impact data, image repository, and overall communications. The group was founded in 2008 in response to a growing need for international collaboration on ash fall science and impacts. The 2010 eruption of Eyjafjallajökull focused our attention on timeliness. Leading up to and following a successful first workshop in 2010 at COV6, significant progress has been made toward all goals. Improvements to warning messages include drafting of new message language, standardization of thickness terminology, and surveying of international volcano observatories. An international workshop of ash leachate experts discussing standardization of analytical protocols is planned for June 2011. A first draft of a post-eruption impacts checklist is complete. A prototype ash impacts database for capturing key impact data is nearly complete. A web-based citizen ash reporting system is complete and can be used as a template in any language/location. Modernization of an international ash hazards website (currently hosted by the USGS) is underway and will facilitate dynamic content and international collaboration and delivery of consistent hazard guidance worldwide.

**A decade on, what the St Bathans Fauna reveals about the Early Miocene terrestrial biota of Zealandia**

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We review the diversity and content of the St Bathans Fauna as now understood following 10 years of investigations. The St Bathans Fauna derives from the Early Miocene

Bannockburn Formation, a lacustrine unit in the Manuherikia Group, outcropping in various sites around St Bathans, Central Otago. This fauna is very diverse as follows: MOLLUSCA - 11 terrestrial and freshwater species in 6 families; CRUSTACEA – at least 1 species of crayfish; TELEOSTS – 15 species in 6 families, of which 12 (Galaxiidae 6, Eleotridae 4, Retropinnidae 2) were the principle fish inhabitants of paleolake Manuherikia; AMPHIBIA – *Leiopelma* (2 spp.) and a neobatrachian frog; REPTILIA – a crocodylian, a ?meiolaniid turtle, a sphenodontid, and at least 2 skinks and 2 geckos; AVES – minimally 38 species (dinornithiforms, diving petrel, waterfowl, raptors, herons, *Aptornis*, rails, waders, pigeons, parrots, owl-nightjars, swiftlets, and passerines; MAMMALIA – 5 bats (Mystacinidae 2 spp, fam. nov. 1 sp., a vespertilionid, 1 indeterminate), and a terrestrial species (order and family indeterminate).

The St Bathans Fauna offers overwhelming evidence refuting a total drowning of Zealandia during the Oligo-Miocene. (i) High endemism at all taxon levels with no species and only one genus, the global *Palaeolodus*, shared with Australia. Notably, there are no shared genera of anseriforms despite equivalent-aged lacustrine faunas dominated by waterfowl on both sides of the Tasman Sea. (ii) It has most of the iconic 'old endemics' of New Zealand long assumed of vicariant origin (e.g., sphenodontids, leiopelmatids, dinornithiforms), implying no such animals dispersed to New Zealand in the subsequent 16+ Ma. (iii) The endemic limpet *Latia*, a taxon highly unlikely to be able to disperse across oceans and with an ancient molecular based sister relationship to South American forms, is present. (iv) Extinction, in combination with dispersal of new lineages, has been a significant faunal modifier subsequently. Extinct lineages include major high level taxa e.g., crocodylians, turtles, neobatrachian frogs, swiftlets, palaeolodids, and several mammals.

## **Redox state of the Kermadec Arc and Havre Trough mantle and magmas**

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The mantle wedge in subduction zones is thought to be more oxidised than mantle beneath Mid Ocean Ridges as a result of oxidising fluids derived from sediments and/or hydrated, oxidised oceanic crust of the subducting slab. This more oxidised mantle has a profound influence on the composition of mantle derived melts and the mass exchange of elements between the Earth's mantle and surface, particularly elements that can exist in multiple valence states. Determining the oxidation state of the mantle from mantle melt derived material (i.e., basaltic glasses and mineral phases), however, can be difficult as secondary processes, such as fractional crystallisation, assimilation and degassing can alter the oxidation state of evolving magmas. One way to measure the oxidation state of more primary melt compositions (that are more representative of the source mantle than evolved melts) is through analysis of mineral phases and olivine-hosted melt inclusions that have had only minor modification by secondary processes.

As the  $K\alpha$  wavelength position of sulphur in electron microscopy is dependent on the oxidation state of the material analysed, the sulphur speciation of melt inclusions can be determined from the position of the S peak. Furthermore, as oxidation results in an increase in FeO(total) in plagioclase and a decrease in clinopyroxene, the oxidation state of the parental melt of these phases can be determined from FeO(total) contents in these minerals. Here, we present electron microprobe analyses of sulphur speciation in melt inclusions and pillow rim basalts and FeO(total) contents of plagioclase and clinopyroxene from the same pillow basalts to determine the redox condition of the Kermadec Arc and Havre Trough mantle. Through analysis of more evolved

compositions, any changes that occurred in the oxidation state of the evolving magma prior to its eruption can also be addressed.

## **Fault guided waves in the Darfield aftershock sequence**

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In the weeks following the 4<sup>th</sup> September Darfield Earthquake, an array of broadband surface seismometers was installed through the Canterbury region. Three of these (Dar6, Dar7, and Dar8) were aligned roughly along the newly re-exposed Greendale Fault. Seismograms from these sensors show several phases of interest. A vertical-dominant signal arrives between the P- and S-waves, and has been preliminarily identified as an S-P conversion, possibly from the base of the Quaternary sediments. Extraordinarily clear fault guided (Fg) waves are also present, the signal of which can be identified by large amplitude waves showing dispersion followed by a sharp cutoff, arriving after the S-wave. Typically only one phase is present, though occasionally a second phase can also be seen. These often appear on only one or two of the stations, indicating breaks in fault continuity. The amplitude of these signals may be up to c. 6 x the amplitude of any other waves present; therefore the potential damage in the areas exposed to these waves may be much higher than the surrounding region. Accurate mapping of the extent of these fault segments and their break points can be used to identify the extent of the areas at risk of increased shaking. This work may also have implications for other regions throughout New Zealand, in which waves could also become trapped and amplified within major faults.

**New insights into frequency of ash falls impacting the Auckland region in the Holocene: crypto-tephrostratigraphic record of tephra layers trapped in maar lake sediments**

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The city of Auckland is built on basaltic field called the Auckland Volcanic Field (AVF). The AVF consists of about 50 small monogenetic volcanoes on area 360 km<sup>2</sup> with eruptions extending back about 250,000 years. Despite the fact that there has been no activity in last 500 years, Auckland could be at risk of future activity. Coring of ancient lake sediments shows that volcanic eruptions in central North Island of New Zealand are also capable of producing ash falls in a city.

In new research, a 5.8 m core from Pupuke maar lake representing much of the Holocene was recovered. Four macro-tephra beds: Rangitoto (0.5 ka), Taupo (1.8 ka), Whakaipo (2.8 ka) and Tuhua (7.5 ka) were recognized and provide the age control. The core was subsampled at 1 cm intervals with a final number of 488 samples. The glass shards were extracted from the sediment and their concentration determined microscopically. Shards were also analyzed by electron microprobe to determine volcanic sources and individual eruptive events.

Cryptotephra record in Pupuke core revealed new ash sequences previously unknown in the Auckland area from Taupo, Egmont, and Tongariro Volcanic Centres and thus the study reassessed our knowledge about the recurrence of ash falls from the local and distal volcanoes. Based on new results Auckland region is affected by ash fall every 400 years. Taupo Volcanic Centre is the main contributor to ash falls over the past 10 ka. New calculated frequency requires attention from the city authorities, as we can expect aviation and minor utility disruptions in our lifetimes.

The study also highlights extensive upward reworking of the glass shards over time periods of 100-1000 years in a lake with a closed and limited catchment. For some sediment records, cryptotephra could be mostly artifacts of reworking rather than the signal of new ash fall events.

**A complex interplay of sediment erosion and deposition during the 18 March 2007 lahar at Mt. Ruapehu**

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The 2007 Ruapehu breakout-lahar reached its maximum sediment-carrying capacity at 22 km from source and continued to travel as fully-bulked lahar for at least another 40 km along the Whangaehu River. We focus on medial reaches, following attainment of the highest sediment concentrations (25-40 km) to evaluate sedimentary processes during the lahar passage by combining the depositional record with high-precision, pre- and post-event LiDAR topographic data and detailed observations of flow height, velocity and seismic energy.

LiDAR data reveal a broad alternating pattern of erosion and deposition along this sinuous river stretch with net-erosion dominating in straight sections and deposition mainly occurring on outer channel bends. The deposits comprise several discrete units that differ in grainsize, texture, thickness, and distribution depending on local channel conditions and time-variant flow rheology. The dynamic flow data show a rapidly rising watery bow-wave ahead of the lahar, which emplaced bedded, moderately-sorted medium sands on middle- to high-level banks. High flow velocity and turbulence promoted erosion in near-channel sites. Overlying massive, reversely graded, very poorly-sorted sandy gravels were deposited by the highly sediment-charged main lahar body. Decrease in stage height and retreat of the concentrated flow back into the channel ceased deposition on the upper banks and initiated near-channel accumulation of thick,

normally graded gravelly units at channel bends and a thin coarse sandy layer along straight sections. The final depositional stage was marked by bedded, moderately- to poorly-sorted sandy deposits in near-channel sites and initially on middle slopes, with pulses in the waning flow producing alternating layers of coarse and medium sands. The step-wise drop

in flow stage resulted in simultaneous erosion of the previously deposited sediments and successive cutting of terraces.

The 2007 event has provided more specific constraints on erosion and deposition rates and processes in relation to flow variations and local river channel morphology.

## Temperature structure of the Subtropical Front from seismic oceanography

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The Subtropical Front (STF) is an important oceanographic boundary that separates warm, saline subtropical waters from relatively cool, fresh subantarctic waters. In the vicinity of the STF, off the southeast coast of the South Island, several extensive sets of 2-D seismic reflection data exist, acquired during petroleum exploration initiatives in the Canterbury and Great South Basins. By reprocessing these data for seismic oceanography we have produced many interesting reflectivity images of the water column that provide detailed information on dynamic processes associated with the STF. The reprocessing includes simple modifications to gain, filtering, and velocity analysis in order to shift the focus of the seismic images from the sub-seafloor impedance contrasts, associated with rocks of varying density and velocity, to impedance contrasts within the water column, associated with water masses of varying temperature and salinity.

An important step in seismic oceanography is to “ground-truth” the seismic reflections to measured contrasts in ocean properties. In an oceanographic survey these properties, such as temperature and salinity, are measured directly using ship-deployed instruments such as conductivity-temperature-depth casts (CTDs) or expendable bathythermographs (XBTs). However, these measurements are not generally made during the course of a marine seismic survey. Our approach takes advantage of the abundance of satellite-derived sea-surface temperature (SST) data available. By calculating near-surface temperatures from the travel times of seismic first arrivals, we are able to make direct comparisons to surface temperatures from satellites and achieve the desired ground-truthing. Our images of water column reflectivity associated with the STF southeast of the South Island demonstrate how the interpretability of the seismic images is enhanced by linking visible reflections to contrasts in the extracted near-surface temperatures.

## Can graptolites provide a biological proxy for climate change in the Early Paleozoic?

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Planktic microfossils are sensitive indicators of ocean biogeochemistry, temperature, redox, nutrient flux etc., which in turn are related to ocean circulation patterns and climate change. In the Early Paleozoic, graptolites constituted the major component of the macrozooplankton and have the potential to perform a similar role to that of Cenozoic planktic microfossils. The graptolite clade spans the ‘Great Ordovician Biodiversification Event’ and one of the five great mass extinction events at the end of the Ordovician. But so far most attempts to detect *global* environmental change have been limited to the resolution achievable in biostratigraphic zonal schemes of groups such as graptolites and conodonts (0.68 – 1.5 Ma), too long to detect even the longest Milankovitch cycles (c. 0.4 Ma). Individual sections can yield high-resolution faunal change curves but through only short periods of time and for only local regions.

The CONOP method composites the species ranges from many local range charts into a single, global, sequence that spans the combined age ranges of all the local sections and which can be scaled to give a high-precision timescale. At the same time, a highly resolved graptolite macroevolutionary time series is produced. The first and last appearance events of over 2000 species give an average resolution of 30 ka for the Ordovician and Silurian periods against which to measure evolutionary rates. Species turnover and diversification rate curves indicate a major change in the late Ordovician from a relatively uniform background extinction rate to a highly volatile evolutionary turnover rate associated with climatic deterioration in the Late Ordovician and Silurian. A comparable change is seen in the  $\delta^{13}\text{C}$  curve, suggesting an environmental cause for both. The level at which the signal-to-noise ratio in our data becomes significant is still being investigated but promises to enable periodicities of 400 ka to be detected.



**Sediment dispersal pathways and processes from a submerged rift margin basin: Miocene Suez Rift, Egypt**

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Extension-induced landscape evolution has a primary control on sedimentary processes and architectures; driving sedimentation, controlling fluid pathways and creating sites of deposition. Well-documented Cenozoic terrestrial examples from the USA, Greece, and Kenya reveal reorganization of fluvial drainages around growing faults and folds; with related topographic tilting driving channel avulsion, re-incision, and abandonment. Associated lithofacies are complex, with coarse-grained, highly heterogeneous assemblages, forming coalescing deposits of alluvial fans, fluvial channels, soils, lakes and fan deltas.

Equivalent deep marine syn-rift strata have principally been described from regional outcrop and seismic-reflection datasets. Basin stratigraphies are highly influenced by tectonics, hinterland geology and relative sea level position. However, the stratigraphic resolution available is often inadequate to reconstruct detailed models of active sedimentary processes and pathways in submerged and partly submerged landscapes.

The aim of this presentation is to use an exhumed rift margin hanging-wall mini-basin of the Oligocene-Miocene Suez Rift, Egypt to reconstruct the spatio-temporal complexities of marine sediment dispersal pathways and processes. A high-resolution lithofacies study is presented and reveals a broadly coarsening-up system, dominated by coarse-grained, heterogeneous, lenticular beds. Interpretation of these data provides an opportunity to demonstrate that submarine drainages are dominated by multi-sourced, (earthquake-triggered) gravity flows that interact with complex steep faulted terrain and are modified by ongoing deformation. The upward-coarsening motifs suggest that rift-related faulting enhanced the delivery of sediment to the basin over time, by steepening slopes and exposing soft pre-rift lithologies. These results provide the best example yet studied of marine sediment dispersal pathways and processes from a submerged rift basin.

**Tainui Mooring Stone a key to understanding origins of Hauraki Gulf**

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A large boulder of silicified andesite breccia sitting on the foreshore at Whitford, Auckland, is well known in traditional Maori histories as the stone which the Tainui Canoe moored to when visiting Turanga Creek on his epic voyage from East Cape to Taranaki. The canoe came across from Coromandel to the Whitford area and the mooring stone is also inferred to have been transported across from its source area on the Coromandel. We argue that boulder was too large to have been transported on the Tainui canoe and that it is more probable that it and the accompanying suite of siliceous cobbles and pebbles found on the surrounding beach belong to the Puketok Formation and were transported across in a lahar-debris flow flood event(s) before the subsidence of the Hauraki Gulf. This is the third known exposure of the Pliocene (?Late Miocene) Puketoka Formation s.s.

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