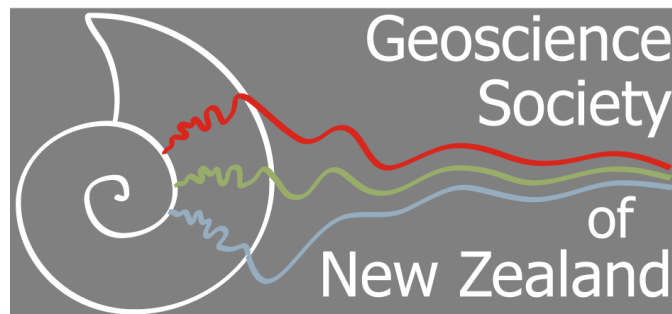


# Abstract Volume



## Geosciences 2019

24 - 27 NOVEMBER 2019, HAMILTON



**Miscellaneous Publication 155A**





# Geosciences 2019

24 - 27 NOVEMBER 2019, HAMILTON

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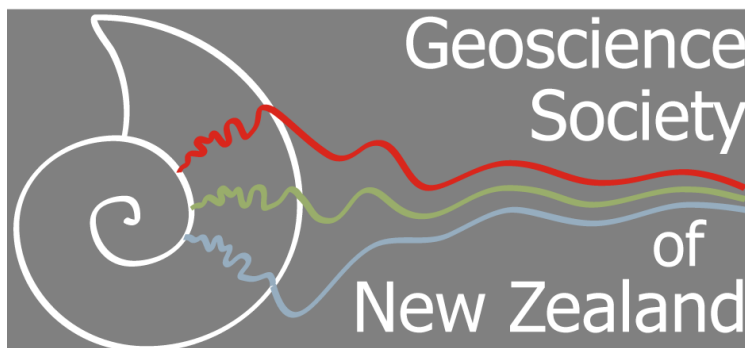
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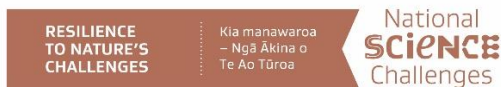
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Author A, Author B, Author C 2019. Title. In: Kamp, PJJ and Pittari, A eds.  
Abstract Volume: Geosciences 2019, Hamilton, New Zealand. Geoscience  
Society of New Zealand Miscellaneous Publication 155A. p 224.

Geoscience Society of New Zealand Miscellaneous Publication 155A

ISBN (online): 978-0-473-49900-6

ISSN (online): 2230-4495

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## LOW-FREQUENCY EARTHQUAKES ACCOMPANY DEEP SLOW-SLIP BENEATH THE NORTH ISLAND OF NEW-ZEALAND

**Florent Aden-Antoniow<sup>1</sup>, William B. Frank<sup>1</sup>, Calum J. Chamberlain<sup>2</sup>, John Townend<sup>2</sup>, Laura M. Wallace<sup>3,4</sup>, Stephen Bannister<sup>3</sup>**

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Slow-Slip Events (SSEs) have been observed along the Hikurangi subduction zone of the North Island of New-Zealand. They occur both in the shallow plate interface (<15km depth) and at the deeper end of the seismogenic- zone (>30km depth). Some slow slip events in New-Zealand are also accompanied by tectonic tremors, although tremor is not as common at the Hikurangi subduction zone compared to other subduction zones.

We present a systematically generated catalog of low-frequency earthquakes (LFEs) for the central Hikurangi margin. To detect preliminary LFEs from the continuous seismic data we used a Matched-Filter technique with template waveforms from the tectonic tremor catalog of Romanet & Ide (2019). The resulting detections were gathered as families and an innovative stacking technique was used to extract high-quality waveforms in order to build a set of LFE templates for a second Matched-Filter search.

The LFEs are organized into episodes of intense activity during deep M7 SSEs that occur absit every 5 years beneath the Manawatu region. One of our LFE bursts occurs during a small, deep SSE recognized at the central Hikurangi margin in 2008 (Wallace and Eberhart-Phillips, 2013). We expect that the other LFE episodes highlight small slow transients that have not yet been geodetically observed. In this presentation, we discuss the spatiotemporal evolution of LFEs in regard to potential aseismic transients that can be observed in the GPS data-set acquired by GeoNet.

## EARLY PENNSYLVANIAN (CARBONIFEROUS) SEDIMENT ROUTING TO THE OUACHITA BASIN (ARKANSAS AND OKLAHOMA, USA) BASED ON DETRITAL ZIRCON U-PB ANALYSIS

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Previous detrital-zircon U-Pb (DZ U-Pb) studies of Paleozoic sediments of the western US Laurentian margin document the widespread arrival of Appalachian-Grenville age populations (ca. 500-275 Ma and 1250-950 Ma, respectively) during the Carboniferous. However, pathways for continental-scale east-to-west sediment transfer remain unclear. This study presents ~3540 new DZ U-Pb ages from 12 samples from the Lower Pennsylvanian Jackfork Group and Johns Valley Shale of the Ouachita deepwater basin in Arkansas to delineate sediment provenance and paleodrainage systems that sourced these deposits, and how these results bear on the issue of large-scale sediment transfer from the Appalachians to the western Laurentian margin.

U-Pb age spectra indicate that sediment for the Jackfork and Johns Valley were derived from the Laurentian Appalachians to the east, and the midcontinent to the north. All samples display prominent Laurentian Appalachian-Grenville peaks, and also Midcontinent (ca. 1550-1300 Ma), and Yavapai-Mazatzal (ca. 1800-1600 Ma) age peaks. However, samples from the most northern, updip site, exhibit relatively modest Appalachian peaks and elevated Yavapai-Mazatzal peaks when compared with samples collected farther to the south and west. These differences are interpreted to indicate that at least two sediment-routing corridors, from the Appalachian foreland and the US midcontinent, fed the Ouachita basin. We conclude that Pennsylvanian sea-level fall, a contemporaneous shift to a humid climate, and collisional tectonics forced Laurentian sediment routing through at least two paleovalley systems, which sourced the Ouachita basin deepwater deposits.

The approximately north-to-south oriented paleodrainage systems of the US midcontinent, each at least  $10^5$  km<sup>2</sup> in area, physically barred fluvial sediment transport directly from the Central Appalachian orogen to the Western US, as did the Ouachita basin, which represents a terminal sink. Hence the Appalachian-like DZ U-Pb signal that has been recognized in the Western US likely did not come directly from the US Appalachians.



## **A NEW GEOMORPHOLOGICAL MAP OF TAURANGA CITY AND THE APPLICATION FOR NATURAL HAZARD ASSESSMENTS**

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The Tauranga Basin is approximately 40 km long and 15 km wide located between the Kaimai Range and current coastline. The geomorphology is shaped by a series of drowned river valleys, infilled with sediment derived from the erosion of voluminous Quaternary volcanic deposits. Other features include ignimbrite plateaus, alluvial terraces, volcanic domes, coastal dune complexes, flood plains and wetlands, capped by recent volcanic ash deposition. The landscape has since been modified by anthropogenic activity.

Tauranga is a rapidly expanding city, with development occurring across land of marginal quality and exposed to a range of natural hazards. Tauranga City Council has established a Resilience Project to identify natural hazards in the region. The project will enable a review of the city infrastructure and better understanding of the risk to infrastructure as well as to inform and manage future growth. The large sub-project – Liquefaction Analysis and Hazard Mapping – required the creation of a city-wide geomorphological map at 1:25,000 scale. Geomorphological analysis was performed by interpreting landforms and surface features; their origin, geology and geochronology. The analysis utilised published geological mapping, relevant literature and technical reporting; current and historic aerial photography; and Council hazard databases and GIS systems.

Key geomorphological terranes were defined including: land reclamation, active foredunes, fixed foredunes, wetland, harbour margin, alluvial flood plain and channels, alluvial terraces, ignimbrite terraces, and volcanic hills and ranges. The units and the resulting mapped layers were verified by geological and geotechnical data, and targeted field investigations.

The number, and variable nature, of terranes highlight the geomorphological complexity of the Tauranga Basin. Not only will the new geomorphological maps assist with the correlation of areas susceptible to liquefaction and ground shaking, they can be used to identify areas susceptible to other natural hazards including slope instability, soft ground, and flooding.

## WHAT LIES BENEATH? RECONSTRUCTING THE PRIMITIVE MAGMAS FUELING VOLUMINOUS SILICIC VOLCANISM USING OLIVINE-HOSTED MELT INCLUSIONS

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Understanding the origins of the mantle melts that drive voluminous silicic volcanism is challenging, as primitive magmas are trapped at depth and rarely erupt. The central Taupō Volcanic Zone (TVZ; New Zealand) hosts an extraordinarily productive region of rhyolitic caldera volcanism. Accompanying and interspersed with the rhyolitic products are minor amounts of basalt to andesite preserved as enclaves or as scoria in caldera eruption products and occurring as small monogenetic scoria cones between calderas. These mafic materials contain MgO-rich olivines (Fo<sub>79-86</sub>) that host melt inclusions (MI) capturing the most primitive basaltic melts fueling the central TVZ. Olivine-hosted MI compositions associated with large caldera eruptions (intra-caldera samples) contrast with magma compositions from the nearby, inter-caldera monogenetic centers. Intra-caldera MI from the modern TVZ caldera volcanoes of Taupō and Okataina have lower abundances of incompatible elements and total alkalis, reflecting distinct mantle melts. There is a direct cause and effect, with caldera-related silicic volcanism driven ultimately by basaltic magmas that have resulted from higher degrees of partial melting or a depleted source, along with distinct subduction signatures. Inter-caldera mafic eruptives are therefore unrepresentative of the feeder magmas that fuel nearby caldera volcanoes. The modern foci of voluminous central TVZ silicic volcanism are fundamentally determined by the degree of melting and flux of basalt from the underlying mantle. Inherited olivines and their MI thus provide a 'window' into the mantle dynamics that drive large TVZ silicic magmatic systems and may be a useful approach at other volcanoes that show evidence for mafic recharge.

## ALONG-STRIKE STRUCTURE OF THE HIKURANGI MARGIN FROM SHIRE SEISMIC REFLECTION DATA

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The Hikurangi subduction margin shows profound along strike changes in morphology, structural style and slip behaviour at the plate interface. We present preliminary interpretations of a ~500-km-long multichannel seismic (MCS) profile running coast-parallel along the full extent of the Hikurangi margin. These seismic data, MGL1708-007 and MGL1708-012, were acquired aboard RV *Marcus G Langseth* as part of the SHIRE experiment and were concurrent with OBS deployments and acquisition of the wide-angle reflection/refraction profile Line 3 (see Bassett et al., this meeting). With a 6,600 cu in source array and 12.6-km-long, 1008 channel streamer, the data were acquired at 37.5 or 50 m shot intervals (sequence dependent) to a 14 s TWT record length. As such, the MCS profile provides an excellent opportunity to seismically image the subduction interface offshore the Hikurangi margin at a depth of ~10-15 km and complex structure of the overlying upper plate accretionary margin. Observations will be compared with spatial distribution of slip behaviour the plate interface and other along-strike physical changes in the margin's structure and composition. In particular we will focus on features that may correlate with the slow-slip/locking along strike transition and a step in crustal velocities observed in preliminary analysis of the co-located wide-angle seismic data.

### 3-D SUBSURFACE GEOLOGY FOR THE DUNEDIN URBAN GEOLOGICAL MAP

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The GNS Science Urban Geological Mapping project is compiling suites of geological data products for selected urban areas in New Zealand. These products move beyond the traditional surface geological map, to embrace other geoscience information of relevance in urban, urban-fringe and prospective future urban expansion areas. These products may include surface geological maps, geomorphological maps, and some form of representation of subsurface geology in 3-D. Interpreted borehole data and subsurface geotechnical models may also form part of the product suite, where data density allows. Product suites have different content, tailored to the environment of each urban area. For example, the Christchurch urban geological map product (Begg et al. 2015; GNS Science Geological Map 3) included a geomorphological map over the coastal plain areas where Late Quaternary deposits conceal the older stratigraphic units. The Dunedin urban product does not include a geomorphological map because the geological form of the Dunedin area is well expressed in its hilly topography.

The Dunedin 3-D geological representation is based on structure contour maps for three key geological boundaries: top of the Otago Schist/base of Zealandia Megasequence; base of the Dunedin Volcanics, and base of Quaternary sediments. The structure contours have been used to generate a Leapfrog model, which greatly assists in visualisation of the subsurface geology. There is high interest in the Quaternary sediments under the low-lying South Dunedin plain, where frequent flooding is of growing concern to the community and authorities, in part caused by reduced drainage of surface and groundwater due to rising sea level and ground subsidence. Constructing a representative and robust 3-D model for South Dunedin's Quaternary sediments provides an important scientific foundation for planning and infrastructural responses to sea level rise.

## TRACKING THE DEMISE OF THE LAST GLACIATION IN THE SOUTHERN ALPS

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In the Southern Alps, application of surface-exposure dating using terrestrial cosmogenic nuclides (SED) over the past decade or so has produced comprehensive chronologies for moraine sequences in several major east-draining mountain valleys. While episodic advance and retreat of glaciers during the last glaciation resulted in some overprinting or removal of moraines, the withdrawal of ice at the end of the glaciation is well represented in the landform sequence, especially on the rain-shadow eastern side of the range, where geomorphic process rates are less than to the west and the land is mostly free of forest cover. The Pukaki, Ohau and Rakaia valleys were targeted by intensive SED studies to track the deglaciation. In each valley, terminal moraines were formed at ~18 ka, followed by rapid ice recession that, by ~17 ka, had seen each glacier trunk downwaste by hundreds of metres, with implied terminal recession of as much as 40% of the overall glacier length. The glacial moraine record implies an atmospheric warming of several degrees during the ~18 to ~17 ka interval. The paleoenvironmental impacts of this change are reflected to varying degrees of resolution in other New Zealand terrestrial paleoclimate proxies (Barrell et al. 2013 – QSR 74: 4-20) and registered most crisply at a lowland pollen record site in South Westland (Vandergoes et al. 2013 – QSR 74: 215-229) where subalpine shrub and grass taxa were replaced by full lowland temperate rainforest over that ~1 kyr interval. At about the same time, the Subtropical Frontal Zone shifted poleward to the south of NZ (Bostock et al. 2015 - *Paleoceanography* 30: 824-844), while substantial glacier recession and resurgence of temperate forest vegetation occurred in western Patagonia (Moreno et al. 2015 – QSR 122: 233-249). The last glacial termination in the austral mid-latitudes was rapid, sustained and of at least pan-Pacific extent.

## THE RELATIONSHIP BETWEEN FOREARC STRUCTURE AND GEODETIC LOCKING ALONG THE HIKURANGI MARGIN FROM SHIRE SEISMIC DATA

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Active source seismic data recorded by 49 Ocean Bottom Seismographs and a 12.7 km long streamer constrain crustal structure along a 530 km margin-parallel transect of the Hikurangi subduction zone. The subducting Hikurangi Plateau exhibits crustal wavespeeds of  $V_p$  5.0–7.0 km s<sup>-1</sup> over a  $12 \pm 2$  km thick interval and mantle wavespeeds increase from 8.0 km s<sup>-1</sup> to 8.5 km s<sup>-1</sup> at < 30 km depth. The subduction interface is located at 10-12 km depth. We observe a sharp along-strike transition in the forearc crustal structure. The northern half of the transect is characterized by ~4 km of basin fill (<3.5 km s<sup>-1</sup>) and forearc crustal wavespeeds are <5.0 km s<sup>-1</sup>. The southern half of the transect is characterized by wavespeeds that are 0.5 km s<sup>-1</sup> faster at all levels of the forearc crust. The transition zone is <10 km wide and is well correlated with a sharp north-to-south reduction in water-depth across the forearc trench-slope. It is also well correlated with the north-to-south increase in slip-rate deficit that marks the transition from a creeping megathrust in the north to an interseismically locked megathrust in the south. We will describe a range of physical and geological interpretations for the observed transition in crustal structure and its relationship the slip-behavior of the subduction interface.

## GREYMOUTH BASIN: EXTENSIONAL OR TRANSTENSIONAL RIFT?

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The Greymouth Basin is part of the West Coast-Taranaki rift system, a narrow rift active from the Late Cretaceous to the Paleocene along the western margin of Zealandia that overprinted more distributed extension related to mid-Cretaceous rifting from Gondwana. This comprises the 2<sup>nd</sup> phase of rifting of Strogen et al. (2017). Sedimentary facies in the Greymouth Basin indicate a rapidly-subsiding, narrow basin oriented NNE, 90 degrees to the earlier core complex extension of Gondwana rifting. Provenance analysis suggested strike-slip offset was necessary in order to bring granitic sources into range to be supplied to the Greymouth Basin (Ettmuller et al. 2006). Thus one model favoured basin extension as the result of transtension rather than orthogonal extension. A transtensional origin also fit well with the orientation of the basin relative to spreading centres and the opening of the Tasman Sea (Laird 1993). However, structural geologists find no evidence of strike-slip faults suggesting they were not a major part of the Late Cretaceous rifting (Nicol pers. comm. 2019). Counter arguments suggest evidence may have been overprinted, particularly in the Greymouth area, but to be hidden, fault segments would need to have been short relative to normal fault segments. New detailed sedimentary facies (Maitra 2019) and provenance analysis (Steadman 2017) in the Greymouth Basin indicates orthogonal extension with widening of the basin accommodated by new faults stepping north-westward as opening progressed. This could uplift granitic rocks explaining the influx of plutonic quartz and granite clasts in the younger units without calling on strike-slip offset. In addition, the facies analysis does not indicate any significant lengthening of the basin parallel to its axis as would be expected for a transtensional basin. So on balance, evidence from basin analysis in the Greymouth Basin indicates orthogonal extension rather than transtension for the West Coast-Taranaki rift system.

## NUMERICAL AND EXPERIMENTAL APPROACH TO MODELLING PYROCLASTIC FLOW GENERATED TSUNAMIS

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Globally about a quarter of deaths occurring due to erupting volcanoes have been caused by tsunamis directly associated with the eruption itself. Pyroclastic density currents (PDCs) are one of the key mechanisms that can generate these volcanic tsunamis. A well-known eruption of Krakatau volcano in 1883 produced massive pyroclastic flows that generated tsunami waves up to 35 m high and claimed over 36,000 lives. High temperatures, large velocities and complex density stratified internal structure of PDCs all have a significant effect on wave generation. The tsunami generation potential of PDCs is, however, poorly understood. Thus far, the phenomenon has been approximated in the same way as tsunami generation by fast-moving landslides or debris flows: an area which has been extensively researched. This methodology neglects many of the properties specific to PDCs, which could considerably affect the flow-water interaction. Using a combined numerical and experimental approach, this work aims to explore the effects of density stratification and high temperatures on the generation of tsunami waves by PDCs. Initial numerical experiments provide insight into how less-dense flows transfer energy to the water, in the absence of a dense underflow component. Despite their low density, large volumes of hot and fast-moving material can still displace significant amounts of water through a combination of shearing and pressure impulse mechanisms, analogous to a wind-wave problem. The numerical model will be validated by physical experiments, which will involve a heated fluidised granular column released from a reservoir into a water-filled flume. The internal properties of the flow, such as the size of particles and their density, will be explored. We will also investigate the thermal effects on wave generation as well as heat transfer within the flow. The combined numerical and experimental approach will lead to a better understanding of the mechanisms involved in tsunami generation.



## WIDESPREAD HYDROTHERMAL EFFECTS IN SOUTHERN TARANAKI BASIN – A POSSIBLE EXPLANATION

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In applying a systematic process to determine reliable vitrinite reflectance values from well samples, many ancillary reflective organic and inorganic particles, and fluidal fabrics, have been observed over wide geographic and stratigraphic ranges, in Taranaki and most other basins. These features include: fluidized silts featuring clouds of small sulphide crystals and fragments of coked carbonaceous material transported by fluidized sediments up fault planes; distinctive secondary microfabrics in siltstones and sandstones; hydrothermal mineral complexes comprising magnetite microveins, iron oxide and native metals; and hydrothermally microbrecciated fragments of an intrusive igneous lithology comprising altered microphenocrysts in an originally glassy framework. Notwithstanding these features, the enclosing strata have not been pervasively altered and contain organic and mineral phases consistent with a normal burial thermal history.

Smith et al (Advantage NZ 2014 Geotechnical Petroleum Forum) proposed that such features in samples from 22 southern offshore Taranaki wells indicate an episode of sub-surface hydrothermal fluid migration in the late Cenozoic, coincident with submarine arc volcanism further north (Mohakatino arc). The region also falls within the much wider geographic and temporal range of intra-plate mantle-derived magmatism. Late Cretaceous volcanic edifices can be observed in seismic data and some wells in the region, but the occurrence of hydrothermal features in strata as young as latest Cenozoic suggests that there may be a nascent intra-plate volcanic province coincident with the southern Taranaki Basin. The hydrothermal process is inferred to involve extremely volatile-rich fluid which has detached from a magma body, whose ascent may be stalled within the upper crust, creating sub-surface accommodation by a process akin to hydraulic fracturing.

Smith, Newman & Gavey  
Advantage NZ 2014 Geotechnical Petroleum Forum

VIRF

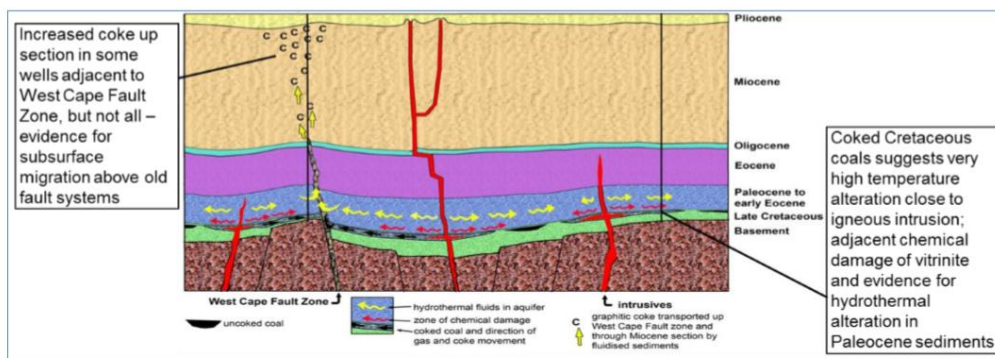


Figure 8: Possible formation and mobilisation of graphitic coke into shallow Miocene sediments via West Cape Fault Zone.

## NEW ASHFALL FORECASTS FOR NEW ZEALAND

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Ash is the volcanic hazard with the largest footprint and often the biggest overall impact. GNS Science and MetService have been working together on improving our capability to forecast ash deposition following a volcanic eruption in New Zealand. We present a project update showing visualisation prototypes for the new forecasts and future research and development plans.

The new ashfall forecasts are based on a combination of a modified version of HYSPLIT, a widely used atmospheric dispersion model that also models deposition, a New Zealand specific Numerical Weather Prediction model (NWP), and a suite of representative eruption modelling parameters. Currently, 24-hour forecasts are produced every 6 hours for several eruption scenarios at 10 New Zealand volcanoes. This is done on a best endeavours basis and we show current visualisation prototypes and outline possible pathways to fully operationalized forecasts.

Scenario based forecasts are instructive but not necessarily accurate as they fail to account for the large uncertainties in both eruption parameters and NWPs. Our future research will aim at computing probabilistic forecasts which combine distributions of eruption parameters with NWP ensembles. This will provide uncertainty estimates, facilitating decision making and mitigation actions that are based on these forecasts.

## **MINING AND MINERAL EXPLORATION: PUBLIC PARTICIPATION AT AN EARLY STAGE IN FINLAND, GERMANY AND SPAIN**

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The authors will present the project INFAC T on innovative exploration technologies that started in 2017, and will focus on the integrated part of stakeholder process which has taken place Europe-wide and at three reference sites in South of Spain, East of Germany and In North of Finland.

The process of stakeholder involvement aimed at informing and engaging with public about the research on mineral exploration and the data acquisition campaign with helicopter and ground geophysics. The main elements consisted of public hearings and workshops, meetings with mayors and representatives from the area, interviews with local stakeholders, and public events like “adventure day raw material research” as integrated part of the flight campaign in summer 2018.

Results show that this intense information and feedback process led to high acceptance and positive attitude in the reference regions, and a huge interest among the population for upcoming research activities. In 2019, as part of another data acquisition campaign with drones and ground geophysics, the researchers will conduct a new dialogue with the stakeholders and interact with locals.

The authors will show “lessons learned” when engaging with society and discuss how important information, active involvement and an intensive feedback is at an early stage of mineral exploration and mining. This presentation will contribute to the discussion about social aspects and community engagement in the area of resources.

INFAC T, a research project on exploration and mining, got a 5.6 Mio Euros funding for three years from the European Union ([www.infactproject.eu](http://www.infactproject.eu)). It will develop innovative exploration technologies and processes which are less invasive than classical methods, using new sensors attached to helicopters and drones, as well as ground geophysics. One important issue is gaining and maintaining acceptance of all research activities around exploration, public and decision makers.

[www.infactproject.eu](http://www.infactproject.eu)

Public acceptance, stakeholder engagement, public participation, mineral exploration

## **MAGMA IMAGED BENEATH THE ROTORUA AND OKATAINA CALDERAS WITH COMBINED LAND AND LAKE MAGNETOTELLURIC DATA**

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Over the past 5 years, GNS Science has acquired more than 350 broadband magnetotelluric (MT) measurements (with 2 km site spacing) to form a 60 km by 30 km array in the north-central part of the Taupo Volcanic Zone (TVZ). By recording small fluctuations in the Earth's natural magnetic and induced electric fields, and combining with a 3D inversion algorithm, these MT data are used to create images of subsurface conductivity. Because rocks that contain geothermal fluid, or that are partially molten are orders of magnitude more conductive than the same materials in a dry or cold state, MT data are useful for investigating thermal processes that drive both geothermal and volcanic systems. The land-MT array in the north-central TVZ encompasses the Rotorua, Waimangu and Tikitere-Taheke geothermal fields, as well as the Rotorua and Okataina calderas.

However, within this MT array, approximately 10% of the surface is occupied by the Te Arawa / Rotorua Lakes, which create significant gaps in the data coverage. These gaps reduce the resolution of subsurface conductivity models beneath the lakes, generated with land-MT data alone. For this reason, in 2018, GNS Science partnered with Bay of Plenty Regional Council, Te Arawa Lakes Trust, Mokoia Island Trust and Scripps Institution of Oceanography to measure MT data at 42 locations in lakes Rotorua, Tarawera, Okataina and Rotoiti. By combining the land and lake measurements, we have achieved uniform data coverage at 2 km spacing across the north-central TVZ. Initial results from this combined dataset improve earlier models and show a subsurface distribution of magma that is consistent with independent interpretation from geologic, petrologic, seismic and InSAR observations.

## **A NEW MAP OF NEW ZEALAND'S OFFSHORE SEDIMENTARY BASINS**

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We present a new map showing the distribution and extent of 24 sedimentary basins, primarily offshore within New Zealand's marine Exclusive Economic Zone (EEZ) and Extended Continental Shelf (ECS). The EEZ and ECS together cover ~5 800 000 km<sup>2</sup>. Sedimentary basins cover an estimated 1.74 million km<sup>2</sup> of that area, amounting to about 30% of the territory under New Zealand's jurisdiction. By contrast the land area of New Zealand's many islands total only ~268 000 km<sup>2</sup>. With such a large area of marine territory New Zealand is truly a maritime nation, and much of the geological history of New Zealand and Zealandia is therefore preserved within the post-mid-Cretaceous sedimentary successions within these offshore basins.

Significant advances have been made in mapping and understanding the geological history and architecture of New Zealand's offshore area during the past two decades, primarily driven by the UNCLOS programme and by exploration for petroleum resources. By far the biggest sources of new geological data have come from Government- and industry-led regional seismic data acquisition, in the form of 2D and 3D seismic surveys and deep drillholes, for petroleum exploration.

The distribution and extent of our sedimentary basins was refined during the multi-year GNS Science-led "Atlas of Petroleum Prospectivity" research programme. New digital structure and isochore maps have been developed, providing a regionally consistent assessment of sediment thickness and depth. Total sediment thickness is up to ~11 km in the deepest basins.

The entire suite of digital outputs from the APP programme are available for free download from <https://data.gns.cri.nz/pbe/>

## IHUNGIA FORMATION IN SOUTHERN HAWKE'S BAY: A RECORD OF PLATE BOUNDARY PROCESSES WITHIN THE EARLY HIKURANGI SUBDUCTION MARGIN

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A well-exposed deep-marine sedimentary succession of Duntroonian to Otaian (Late Oligocene to Early Miocene) age cropping out in the Toi Flat-Weber area of southern Hawke's Bay records an abrupt change in sediment provenance and tectonic regime. Light-coloured highly calcareous Oligocene Weber Formation (Mangatu Group/Waka Supergroup) is abruptly and unconformably overlain by dark-coloured terrigenous-dominated Early Miocene Ihungia Formation (Tolaga Group/Maui Supergroup). Most notably, some lowermost parts of the Ihungia Formation contain prominent extraformational olistoliths of centimetre to decametre scale, derived from the underlying Weber Formation. Benthic foraminifera reveal abrupt and significant changes in paleobathymetry across the Weber-Ihungia Formation contact, from lower-bathyal water depths (>1500 m) in the topmost Weber Formation (based primarily upon the occurrence of a good population of *Tritaxilina zealandica*), to middle bathyal (~800 m) depths in the basal Ihungia Formation (based upon the presence of *Vulvulina pennatula* and *Cibicides robertsonianus*). The abundance of planktic foraminifera also decreases abruptly across the contact, with 85% (near fully oceanic water mass) in the Weber Formation and less than 40% (outer neritic water mass) in the overlying Ihungia Formation. The paleodepth appears to further decrease up-section through the Ihungia Formation to upper bathyal and then outer shelf depths, and planktic foraminifera abundance also decreases to 15% (inner neritic water mass).

The onset of Ihungia Formation deposition and changes in sediment provenance within southern Hawke's Bay can be correlated to prominent Early Miocene lithological changes elsewhere in the East Coast Basin. Other examples include onset of Whakataki Formation deposition and associated emplacement of olistostromes in the southernmost Hawke's Bay and Wairarapa area, and deposition of the Puhokio Formation in coastal central Hawke's Bay. We attribute these changes in lithologies to the inception of subduction beneath eastern North Island and resulting creation of a rapidly uplifting and emergent hinterland to the west.

## **EXTENSIVE LANDSCAPE MODIFICATION FROM AN IMMENSE LANDSLIDE TSUNAMI IN TAAN FIORD, ALASKA, USA**

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On October 17<sup>th</sup>, 2015 a landslide in remote and undeveloped Taan Fiord, an arm of Icy Bay in southeast Alaska, USA, generated a tsunami with a high runup of 193 m. Extensive vegetation loss and surface modification in Taan Fiord was observed and documented during field surveys in Spring and Summer 2016. Although interest in the geomorphic signatures of tsunamis is high, most prior post-tsunami surveys are from earthquake-generated tsunamis with relatively low runup. As a result, the geomorphic signatures of high runup tsunamis and their potential for preservation remain relatively uncharacterized. Additionally, clear modifications described during post-tsunami surveys are typically ephemeral and unlikely to be preserved. Extensive modifications to several low gradient fan deltas within Taan Fiord make the fjord an excellent, and comparable, laboratory for characterizing geomorphic signatures from a high runup tsunami event. Geomorphic changes to the fan deltas in Taan Fiord from the tsunami include a complete uprooting and loss of vegetation over more than 0.6 km<sup>2</sup> of fan surfaces, formation of steep fan front scarps up to 10 m high on three fans, local alterations to fan topography, and formation of new channels from retreating tsunami flow. Prior to the Taan event, two of the fan deltas were heavily vegetated with deeply entrenched channels suggesting a longer-term stability. Following the events, these two fan deltas, while stripped of vegetation, maintained deeply entrenched channels and may preserve features of the tsunami modification for decades. As such, fan deltas may be a previously unrecognized location for preservation of tsunami signatures and fans in poorly monitored regions around the globe could hold evidence of previously unidentified high runup tsunami events.

## FIELD SURVEY AND PRELIMINARY MODELLING OF THE TSUNAMI GENERATED BY THE 22 DECEMBER 2018 ERUPTION OF ANAK KRAKATOA VOLCANO

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On December 22, 2018, an eruption and partial collapse of the Anak Krakatau volcano generated a tsunami in the Sunda Strait causing catastrophic damage and more than 400 deaths in Lampung (Sumatra) and Banten (Java). A survey team deployed from 4 to 9 February 2019 and focused on the islands in the Sunda Strait: Rakata, Panjang, Sertung, Sebesi and Panaitan. The team interviewed eyewitnesses, documented flow depths, runup heights, inundation distances, and impacts on the natural and built environment.

The largest tsunami impacts occurred on the steep shorelines of the islands within 5 km of Anak Krakatoa with maximum runup of 85 m on Rakata and 83 m on Sertung. On Sebesi Island, located 15 km northeast of the source, tsunami runup heights remained below 10 m. In contrast, tsunami heights of 10-15 m were observed on Painatan and in the Ujung Kulon National Park located 50 km to the southwest. The runup distributions on the islands encircling Anak Krakatau highlight the directivity of the tsunami source with volcano's collapse occurring towards the southwest. Inundation and damage were mostly limited to within 400 m of the shoreline given the relatively short wavelengths of the slump-generated tsunamis. A significant variation in tsunami impact was observed along the shorelines of the Sunda Strait with tsunami heights rapidly decreasing with distance from the point source. Preliminary numerical modelling using a 'hot start' initial condition with a dispersive Boussinesq-type numerical model satisfactorily reproduce the observed tsunami propagation patterns and measured wave amplitudes.

This event has lessons for New Zealand in that the tsunami caught locals off guard, this despite the history and a six-months of eruptive activity in the lead up. This highlights the need for community-based education and awareness programs as an essential life-saving tool in locales at risk from locally generated tsunamis.



## **CREATING LINKS IN THE LAB: A NEW INTEGRATED APPROACH TO INTERPRETING SCALE-DEPENDENT DATASETS**

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Earthquake occurrence is a problem with serious societal implications. Capturing the complex response of faults to tectonic loading under a broad suite of stresses, temperatures, and strain-rates is a major challenge faced when constructing realistic models of large earthquakes, aftershocks, and triggered seismicity. Current understanding of the seismic cycle relies heavily on information obtained on either (1) short timescales from historical earthquakes, seismic datasets, and geodetic surveys, or (2) extremely long timescales from uplifted and exhumed fault zones. Our research employs an integrated geological, geochemical and experimental laboratory approach to link these two scales. Using this novel combination of cutting-edge techniques, we aim to identify and quantify the key processes responsible for earthquake nucleation, rupture propagation and arrest, and fluid-assisted interseismic fault zone healing and sealing. In this presentation, we review recently published, ongoing, and new research on the processes that underpin the seismic cycle on the South Island's Alpine Fault, the Hikurangi Subduction Zone megathrust underlying the North Island and northeastern South Island, and the greywacke fault networks that crisscross both the North and South Islands.

## DEFORMATION CONDITIONS IN A HIKURANGI SUBDUCTION MARGIN FAULT ZONE CONSTRAINED BY CLUMPED ISOTOPE THERMOMETRY

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At the onset of subduction in the early Miocene (c. 25 Ma), the now inactive Hungaroa Fault Zone (HFZ) on the Wairarapa Coast accommodated large displacements (~4–10 km) as a thrust fault developed in Paleogene sediments. The HFZ is a mélange comprising deformed calcareous mudstones and marls. Within a 40 m-wide high-strain fault core, marls form lozenges embedded in a calcareous mudstone matrix. The lozenges and matrix contain evidence for fast-to-slow slip, including discrete faults, extensional veins containing stretched calcite fibers, shear veins with calcite slickenfibers, calcite foliation-boudinage structures, calcite pressure fringes, dark dissolution seams, stylolites, embayed calcite grains, and an anastomosing phyllosilicate foliation.

Extending these observations to active faults along the Hikurangi Subduction Margin requires constraints on HFZ deformation conditions. We report first formation temperature estimates from three calcite veins and one marl lozenge collected from the HFZ. Clumped isotope thermometry quantifies the thermodynamically dependent abundance of <sup>13</sup>C-<sup>18</sup>O bonds in the calcite lattice. Expressed as  $\Delta_{47}$ , our clumped isotope results from veins yield the temperature at which aqueous fluids precipitated calcite in the fault zone.

Analyses performed on three veins yield  $\Delta_{47}$  temperature estimates with uncertainties at the 95% confidence interval of: 80.7±8.1°C (HFZ9.6m, n=22); 82.4±9.1°C (HFZ18m-2A, n=23) and 83.7±9.6°C (HFZ18m-2B, n=21); 69.9±8.5°C (HFZ19.4m-A, n=20) and 68.7±6.3°C (HFZ19.4m-B, n=21). Calcite within a marl lozenge yields a lower temperature of 40.6±5.6°C (n=15), reflecting a surface formation temperature partially affected by solid state isotope reordering. Stable isotope  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of the samples indicate that the marl calcite precipitated in sea water and that the vein calcite precipitated from altered basin fluids with higher  $\delta^{18}\text{O}$  values. Our combined results indicate that, even at shallow crustal levels (<5–10 km depth, depending on thermal gradient), calcareous, clay-rich fault zones are fluid conduits that undergo fault slip at time-varying strain rates.

## **ENGINEERING GEOLOGY CHARACTERISATION OF ANTHROPOGENIC FILL SITES IN THE WELLINGTON REGION AND THEIR MODELLED PERFORMANCE DURING SEISMIC SHAKING**

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In the last 21 years, there have been four large failures (~1,000 m<sup>3</sup>) in anthropogenic fill materials in residential areas of the greater Wellington region. These fill sites are found in many parts of the Wellington region. As such, we investigated in detail two anthropogenic fill sites as part of the Stability of Land In Dynamic Environments (SLIDE) research project. SLIDE aims to improve the resilience of New Zealand's buildings and infrastructure through better knowledge of the behaviour of slopes under earthquake shaking or during significant rain events and to develop strategies for more robust remediation approaches.

We used remote sensing techniques, borehole investigations, geotechnical testing and numerical modelling to assess susceptibility to failure. This revealed that maximum anthropogenic fill thicknesses at both sites ranged between 20 and 30 m. The grain size distribution of the anthropogenic fills tested varied from sandy gravel with some silt to clayey gravelly silt sand. The shear strength of the anthropogenic fill obtained during shear box testing was of similar range to previously published values for colluvium filled fossil gullies in the Wellington region. Based on the site investigation and laboratory results, two-dimensional geotechnical cross-sections of the sites were generated to evaluate their potential performance during seismic shaking. A series of 9 actual and scaled earthquakes ground motions were assessed with results suggesting deformation ranging between 1 cm to 10's m. This study noted that several utilities are buried in the anthropogenic fills and that deformation during an earthquake may not cause the slope to fail but could damage waterlines, which in turn may destabilize the slope due to increase pore pressure in the hours to days after the earthquake. Empirical data and numerical runout back-analyses found that anthropogenic fill failures travel further than rock slides or debris avalanches of similar volume.

## **ZEOLITIC ERIONITE IN THE AUCKLAND REGION AND IMPLICATIONS FOR TUNNELLING AND EXCAVATIONS**

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Erionite is a naturally-occurring fibrous zeolite mineral originating in silica-rich volcanic eruptions, and is then later dissolved by water and recrystallized as zeolites, often in sediments. When aerosolised and inhaled, erionite fibres have health effects similar to asbestos exposure, including malignant mesothelioma (MM). In the USA, the carcinogenic properties of erionite are emerging as an occupational and public health hazard, in areas where erionite is found. Indeed, erionite-induced MM is thought to be particularly prevalent in the construction and quarrying industries, where erionite-bearing rock is disturbed. In New Zealand in 2015, the Government Chief Scientist reported that erionite was a more potent carcinogen than asbestos. Despite this, there are no established occupational exposure limits (OELs) for erionite in NZ or globally. In the Auckland region, erionite has been reported by geologists over the last five decades. It is present within the Early Miocene Waitemata Group, and is associated with highly-altered andesitic clastic material. Auckland's construction boom includes infrastructure projects such as the Waterview Tunnel and the City Rail Link (CRL), as well as excavations for high-rise building foundations. Most of these excavations are into Waitemata Group rock, and spoil is usually loaded onto trucks, transported by road and dumped as fill in former quarries. For example, the Waterview Tunnel created c. 800,000 m<sup>3</sup> of spoil (enough to fill 320 Olympic-sized swimming pools) that was excavated from the tunnels, which was trucked to, and filled, the disused Wiri Quarry in the residential area of Manukau. The current CRL project involves tunnelling through Waitemata Group rock, and the removal and disposal of 2 million tonnes of spoil, some of which will contain erionite. Thus, there is the potential for significant exposure of Auckland's population to erionite-bearing rock dust. A source-to-sink assessment of the health risks of such activities is required.

## **MASS TRANSPORT DEPOSITS FROM NORTHWEST NEW ZEALAND: WHAT CAN THEY TELL US ABOUT THE PAST AND FUTURE EVOLUTION OF ZEALANDIA?**

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Mass-transport deposits (MTDs) are gravity-induced slide and slump units that represent a major component of modern and ancient deep-water stratigraphic successions. The offshore Taranaki and Deepwater Taranaki basins in northwest New Zealand contain a thick Neogene–Recent sedimentary succession that lies adjacent to the current New Zealand plate boundary zone. The strata are extensively imaged in a large subsurface seismic dataset comprising 2D and 3D surveys and provide a distal record of the fundamental geological processes that have shaped our emergent continent. Here we present emerging results of a regional-scale study that examines the spatial and temporal distribution of large-scale MTDs from Neogene–Recent time. Individual MTDs from both seismic and coastal outcrops provide morphometric parameters, age, and lithology data that enable us to identify primary controls on MTD occurrence over a ~20 Myr time period. In addition, we examine the link between Neogene–Recent MTDs and the present-day by assessing the role played by the surface topography in controlling the evolution of local sedimentary systems. The most recent MTD identified occurred at c. 1.8 Ma in the Deepwater Taranaki Basin and involved the failure of an enormous volume of material (~ 3700 m<sup>3</sup>). We show that substantive topographic height and rugosity was created at the seabed which initially deflected incoming sediment, but with time was progressively covered and finally overtopped. Input of the covering sediments throughout the last 1.8 Myr has been non-uniform, and is linked to a series of tectonic pulses, forming compensationally stacked packages fed by slope and shelf canyons.

## MODELS OF SUBSURFACE RUPTURE OF THE HUMPS-LEADER FAULT SYSTEM DURING THE KAIKŌURA EARTHQUAKE,

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The Humps and Leader faults in North Canterbury both ruptured during the 2016 Mw7.8 Kaikōura Earthquake. The Humps Fault strikes east to east-northeast, is primarily right-lateral strike slip with up to 3m of displacement and terminates against the Leader fault at its eastern tip. The Leader Fault strikes approximately north-south and mainly accommodates oblique slip with components of up-to-the west and left-lateral slip. During the earthquake, slip on these two faults produced uplift of the Mt Stewart Range, which is bounded to the east and south by the Leader and The Humps faults, respectively. While the surface geometries and displacements of these faults during the earthquake are well documented, their sub-surface structure is less well constrained. In this presentation we use fault displacements (<4 m), uplift of the Mt Stewart Range (maximum ~5 m) and surface fault geometries during the earthquake to constrain the sub-surface structure of the faults beneath the range. We use ICP (iterative closest point) analysis and field observations to derive surface displacements which were employed in combination with elastic dislocation software (Coulomb 3.1) to model slip on possible configurations of subsurface faults. Models were run with a range of fault geometries and number of faults. Surface displacement across the Mt Stewart Range is more spatially distributed than for the sub-surface displacement modelled on The Humps and Leader faults alone. The best-fit elastic dislocation model has dips of 60° on The Humps (northwest dip) and Leader (west dip) together with rupture of at least one additional blind fault that strikes north-northeast, dips 60°southeast and terminates in the upper 3 km of the crust beneath the range. The addition of new blind faults suggests that rupture complexity and the number of faults involved in the Kaikōura Earthquake may have been greater than first thought.

## LONG -TERM RISK MANAGEMENT STRATEGIES FOR RHYOLITIC UNREST AND ERUPTION

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New Zealand's caldera volcanoes are capable of a diverse range of eruption styles and magnitudes. Their potential impact on society creates similarly diverse and some unique risk management challenges, such as volcanic unrest episodes through to hazards which will permanently alter vast landscapes. This PhD research is part of the ECLIPSE programme, investigating methods for assessing societal impacts from caldera volcanoes from pre- syn- and post-eruption, and identifying appropriate risk management strategies.

A key focus of the project will be comparative analysis of how Chile has managed several large silicic eruption in Patagonia, which has many natural, social, economic, and built environment similarities to the North Island of New Zealand. For example, the 2008 eruption of Chaitén volcano in Chile is the most recent global explosive rhyolitic eruption which caused severe proximal impacts, including pyroclastic density currents (PDC) destroying forest areas and secondary lahars (triggered by rainfall) within the Blanco River affecting the fortunately evacuated Chaitén town. Ten years after Chaitén eruption people are still living in a high-risk level zone with a high vulnerability despite government efforts and we can learn about this experience to extrapolate scenarios for analogical cases such as New Zealand volcanism. The concurrent ash cloud caused severe disruption to aviation in southern South-America, and considerable impacts of farming, touristic, public health and critical infrastructure sectors in both Argentina and Chile.

## WHERE DID YOU COME FROM WHERE DID YOU GO? WHERE DID YOU COME FROM, DENSITY FLOW? PRELIMINARY INTERPRETATIONS OF SEDIMENT TRANSPORT ON THE HAWKE BAY CONTINENTAL SLOPE

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Subaqueous sediment density flows, specifically turbidity flows are one of the most important processes for moving sediment in offshore and deep-sea environments. Turbidity flows may be initiated by several triggers including storm-induced waves, tsunamis, slope failures and earthquakes. The Hikurangi Subduction margin continental shelf provides a good example of an area which is highly reworked by these flows. Identifying turbidites in deep-sea deposits and identifying their provenance is therefore an important proxy for classifying sedimentation processes and sediment transport along the margin.

This presentation will show preliminary results from TAN1613 cores (1.52 – 4.5 m length) taken from the Hawke Bay continental slope at 1472 – 2264 m water depth. The continental slope is characterised by elongate basins separated by fault ridges which run roughly parallel to the coastline.

Three proxies and their use in identifying turbidite sequences and provenance are presented. Sedimentary structures, texture and quantitative grain size analysis are used as a preliminary assessment to identify turbidites. These interpretations are then investigated further using ITRAX XRF elemental ratios and foraminiferal studies that are used to infer the sediment provenance.

Grain sizes within these cores range from very fine silts to fine sands. XRF signatures which are used to further identify turbidites include Ca/Fe, Fe/Rb, K/Rb, Zr/Rb, Ti/Rb. Most turbidites which have currently been identified using grain size analysis have shown a provenance of at least 500 m water depth according to foraminiferal studies, however some of these depth ranges are as shallow as 100 m.

Provenance studies of turbidites is particularly important for understanding where sediment is coming from and where it moves along the shelf. By combining results from turbidite studies along the margin, the behaviour of sediment along the margin, including spatial and temporal changes may be identified, and may also contribute to paleo-earthquake records.



## HAZARD AND IMPACT SCENARIO DEVELOPMENT FOR SILICIC VOLCANOES IN NEW ZEALAND.

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New Zealand's caldera volcanoes of the Taupō Volcanic Zone (TVZ) in the North Island have typically been characterised as a low probability, high consequence risk for New Zealand. These volcanoes are capable of a broad and complex range of geophysical activity creating multiple hazards of variable intensity in both space and time. These can have diverse, complex and potentially severe impacts on society. Equally, the societal responses to such impacts, both potential and actual, can be equally diverse and driven by a complex variety of factors across social, cultural, economic, natural, and built environments – also sensitive to both space and especially time domains. One important tool for volcanic disaster risk management (DRM) is the development of scenarios, which can be used to illustrate one (of many) potential outcome(s) of a complex and/or uncertain system. By determining fixed values on otherwise uncertain inputs, it allows easier comprehension of how a complete event may unfold. The use of a suite of scenarios, based around a common framework, can allow exploration of the diversity of potential outcomes of the complex system, which partially addresses a key limitation of this approach. More recently the collaborative development of scenarios jointly by scientists and practitioners has been used to create products which are both credible (informed by robust scientific knowledge) and relevant (useful and useable for users), and so are legitimate – where the scenarios reflect the various stakeholders' different values and priorities (trusted by all and fit-for-purpose). This study is attempting to develop a modular, adaptable framework for the development of scenarios for New Zealand's caldera volcanic hazard risk within the ECLIPSE programme. The scenario development approach has used co-production methods to undertake a transparent and inclusive process which identifies the diverse range of potential stakeholder's, their respective requirements, and tailoring the scenario framework and scenarios to most effectively meet these requirements. This presentation will outline the process undertaken, the scenario framework, and present some of the scenario products.

## RELATIONS BETWEEN INJECTION AND ACOUSTIC EMISSIONS IN CRITICALLY-STRESSED WET SANDSTONE

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Injection-induced seismicity poses a risk to public safety, infrastructure and perception. Cases of wastewater disposal deep underground present the greatest seismic hazard such as in Colorado and Oklahoma, United States of America. Currently, relations used in risk assessment are based on injection volume and rate. However, the physical mechanism of fault initiation is known to be a reduction in the effective normal stress. Information of its components, the stress state and fluid pressure, are generally unavailable in the field. Perturbations of these can destabilise faults, triggering earthquakes due to the critically-stressed nature of the crust. The analogue between seismicity and acoustic emissions, the elastic waves that accompany microscopic damage observed in laboratory experiments on brittle materials, was first made through the perceived similarity between the magnitude-frequency relation of earthquakes and fractures during dry compression. Experimentation on Bentheim sandstone cores of 25 mm radius and 100 mm length was undertaken to establish quantitative relations between pore pressure and acoustic emissions. Wet sandstone was held at high differential stress and confining pressure to replicate crustal conditions and subsequently injected into while acoustic emissions were monitored. The stress state was determined from mechanical behaviour and acoustic emissions during compression. The injection pressure was stepped to allow pressure equilibration and acoustic emissions to cease before it was increased until macroscopic failure occurred below the minimum principal stress. The relations and solution to the one-dimensional flow of fluid in a bounded homogeneous porous medium will form an induced seismicity model to be calibrated to the catalogue of events. Model applications are in the inversion of rock properties and critical pressure, the proximity of optimally orientated faults to failure.

## **NEAR-REAL-TIME MATCHED-FILTERING FOR THE DEVELOPMENT OF DENSE EARTHQUAKE CATALOGUES DURING SEQUENCES OF SEISMICITY IN NEW ZEALAND**

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Conventional earthquake detection methods suffer significant degradations in completeness during high-rate sequences such as aftershock sequences or volcanic swarms. Missed earthquakes during the early periods of aftershock sequences can affect aftershock forecasts and hazard estimates. Missed events during volcanic unrest sequences can impact rate estimations, leading to the sequence being mis-characterized. Much recent work has addressed how matched-filters can be used to overcome some aspects of catalogue incompleteness during high-rate sequences, by detecting similar events using cross-correlation.

Here we describe the application of open-source (GPL v3.0) software to the near-real-time implementation of matched-filter earthquake detection. This software, named RT-EQcorrscan, is designed to listen to web-services and “spin-up” near real-time detection runs when events of interest occur, using a continuously updated database of historical seismicity as templates. We have deployed RT-EQcorrscan to react to New Zealand seismicity through various periods in 2019. In this presentation we will showcase some of the RT-EQcorrscan API, and examples of its application. We will also present some offline examples of improved aftershock catalogues throughout New Zealand to exemplify how this method can improve aftershock catalogues and forecasts built on them.

## **INCORPORATING MICROCRACKS INTO EBSD-BASED FINITE ELEMENT MODELLING OF THE ALPINE FAULT MYLONITES, NEW ZEALAND**

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Understanding wave velocities of the anisotropic Alpine Fault rocks is important for better fault plane imaging and locating earthquakes. Many factors complicate seismic wave velocities in fault zone rocks, such as mineralogy, mineral crystallographic preferred orientation (CPO), microstructure and porosity. While mineralogy and CPO are commonly incorporated into wave velocity modelling (e.g. effective medium modelling), microstructure and porosity are not, leading to erroneous velocity predictions. In this study, a numerical model is used to calculate P-wave velocities travelling parallel and perpendicular to the rock foliation. The numerical model takes two sets of data as inputs: electron back-scattered diffraction (EBSD) and synchrotron X-ray microtomography (micro-CT). Firstly, EBSD data were acquired from eight Alpine Fault rock samples that display the full range of typical mylonitic fabric: schist, protomylonite, mylonite and ultramylonite. The experiments provide phase maps describing the rock mineralogy, CPO and mineral distribution. The results show that samples are mostly composed of quartz, plagioclase and mica with a small fraction of garnet. Secondly, micro-CT data are analysed to investigate the rock porosity and pore dimension. The samples contain 2-5% porosity and the pore length ratio between primary (longest), secondary and tertiary (shortest) axis is about 1:0.4:0.2. Finite element modelling combines mineralogy, CPO and pore geometry to calculate elastic wave velocities. Preliminary analyses show that low aspect ratio pores significantly reduce the wave velocities and increase anisotropy. By adding 2% volume fraction of low aspect ratio pores, the modelled fast and slow P-wave velocity reduces from 7.5 and 5.3 km/s to 7.3 and 4.6 km/s while anisotropy increases from 35% to 45%. Future analyses aim to further explore the sensitivity to the input data (e.g. fracture volume, shape and mica orientation) and to invert for bulk rock porosity by comparing the numerical model results with laboratory velocity measurements at in-situ conditions.

## **A SEMI-AUTOMATED ADJOINT TOMOGRAPHY WORKFLOW APPLIED TO NEW ZEALAND'S NORTH ISLAND**

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Full waveform simulations performed on current tomographic models of New Zealand have been shown to exhibit substantial misfit between observations and synthetics; inverse methods that incorporate seismic energy which samples the shallow crust will lead to improved waveform fits, and consequently provide stronger constraints on subsurface structure. We develop a semi-automated workflow for full-waveform tomography using adjoint methods to allow for inversions with regional seismic observations; we seek to improve upon current tomographic models of the North Island of New Zealand, with particular emphasis on the Hikurangi subduction zone. To validate our methods, we perform a synthetic resolution test and recover a perturbation-checkerboard imposed upon a realistic velocity model. In parallel, we perform a tomographic inversion using observations of local seismic events recorded on New Zealand's regional broadband network, and with temporary broadband stations. Here we present the framework of our automated workflow, and results of initial inversions including data-synthetic comparisons, waveform improvements, and updated tomography models.

## LP OR VT SIGNALS? HOW SEISMIC WAVE ATTENUATION INFLUENCES VOLCANO SEISMICITY SIGNATURES

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A range of volcanic earthquake signals are detected at White Island, reflecting the dynamic rock deformation (Volcano-Tectonic (VT) earthquakes) and fluid resonance (Long Period (LP) earthquakes) processes within the edifice. These seismic signals may be distorted by wave propagation effects such as scattering due to heterogeneities and intrinsic attenuation due to fluids. Although fluid properties are known to be important for seismic wave propagation, how different fluid types in variable volcanic rocks influence volcano-seismic signatures is not well understood.

With in-situ ultrasonic wave experiments we quantify changes in wave velocity and attenuation ( $1/Q$ ) as a function of fluid stiffness, viscosity and rock pore network on White Island rocks. We find that the P-wave velocity and  $Q$  correlate with fluid viscosity and stiffness and inversely correlate with rock porosity and fracture volume. In gas-saturated fractured ash tuffs,  $Q < 10$ ; while in lava and tuff samples saturated with a viscous fluid,  $Q$  is as high as 100.

These experimental results are input as parameters for 2D wave propagation simulations through viscoelastic media at field scale. When a high frequency, VT earthquake is propagated through a low velocity, low  $Q$  medium - representing gas-saturated ash tuff - high frequencies are depleted over relatively short propagation distance ( $< 1.5$  km). The resultant seismograms resemble short-duration LP earthquakes. Scattering also alters the nature of seismograms. When the medium consists of a shallow low velocity, attenuative tuff, overlying a high velocity, high  $Q$  lava, long duration, low frequency signals are generated, resembling typical LP seismicity. LP and VT earthquakes are thought to represent distinct source processes. Our results suggest that wave propagation effects can cause VT earthquakes to resemble LPs in waveform and frequency characteristics at White Island, but likely also apply to other volcanoes with active hydrothermal systems with a high volatile content.

## **EVALUATING THE EFFECT OF DISCONTINUITIES AND TEXTURAL HETEROGENEITY IN VOLCANIC ROCK MASSES WHEN UPSCALING LAB SEISMIC VELOCITIES TO FIELD MEASUREMENTS.**

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Seismic investigations, including reflections and wave velocities, have long been used to assess characteristics of rock masses, as well as subsurface structures, magma, and areas of economic interest. We show that assessing primary seismic wave velocity of rock outcrops that include three-dimensional features such as caves, tunnels and arches provides a method to assess the impact of rock mass characteristics on primary seismic wave velocity. This research utilises 3-component geophones and hammer triggers at volcanic rock outcrops at Sumner Beach, Christchurch, New Zealand to obtain primary wave velocities in a variety of basaltic rock masses. Sumner lies on the northern portion of the Lyttleton Volcanic Complex and contains two coastal erosion features – Cave Rock and Cottage Rock. We mapped the different volcanic textures and used scanlines to assess the rock mass characteristics on the surface of the outcrops and inside the cave of Cave Rock. We created 3D models of both outcrops using structure from motion photogrammetry and located the mapped rock mass characteristics on the models using Leapfrog Geothermal. Measured field velocities of primary waves range from 2 – 3 km/s for Cottage rock and a small ridge on Cave Rock, both consisting of coherent lava with multiple fractures or a variety of textures with few fractures. For the remainder of Cave Rock primary wave velocities are slower, ranging from 1 – 2 km/s in rock masses with numerous large fractures and changes in texture. The next research steps will be measuring ultrasonic velocities of sample-scale lava, tuff and breccia from Sumner Beach in the laboratory. These velocities will be combined with the proportion of texture and rock mass characteristic changes along the field seismic ray paths in the Leapfrog Geothermal model to evaluate the influence of these variations on upscaling seismic velocity from the lab to the field.

## **INVESTIGATING HYDRO-ISOSTASY AS A DRIVER OF HOLOCENE SEA-LEVEL VARIABILITY IN NORTHLAND, NEW ZEALAND**

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Meltwater-driven ocean loading on the continental shelf is hypothesised to be a significant driver of spatial and temporal variability in Holocene sea-level (SL) changes around the New Zealand coast. The Northland peninsula is a key laboratory for examining the impact of meltwater loading on land deformation and SL variability in New Zealand: the coastline is convoluted with a variable-width continental shelf; the region is tectonically stable during the Holocene; was ice-free during the last glaciation; and contains a major sub-set of the population of SL index points from the New Zealand palaeo sea-level database.

Glacial isostatic adjustment (GIA) modelling for sites along the length of the peninsula predicts significant variability in Holocene SL changes over relatively short distances. This variability is the product of spatial variations in solid Earth deformation driven by postglacial meltwater loading on the continental shelf and is controlled by the width of the shelf. At the southern end of the peninsula modelling predicts ~1 m of subsidence during the Holocene. The amount of subsidence increases to the north, with the northern end of the peninsula predicted to subside ~12 metres during the Holocene.

New SL index points have been collected from Pakiri, Whananaki Inlet, Waikare Inlet, Whangaroa Harbour, and Hokianga Harbour, to supplement existing SL index points from the New Zealand database. Results from these sites indicate that meltwater loading drives variability in Holocene SL along the length of the peninsula, but that there is no variability across the width of the peninsula. GIA modelling predicts significant variations in SL history for the localities depending upon the ice model and Earth model parameters. These variations enable inferences to be made about ice histories during the deglaciation, and the rheological properties of the mantle beneath Northland.



### **3D GEOLOGICAL MODELLING OF THE LATE QUATERNARY HAMILTON BASIN AND REVEALING ITS SECRETS**

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3D Geological modelling developed from five successive stages of geotechnical investigations undertaken between 2008 to 2016 to inform the design of the Hamilton Section of the Waikato Expressway, a 23km long SH1 realignment east of Hamilton City, provided evidence for Quaternary faulting infilled with Late Pleistocene lacustrine and alluvial deposits.

The Hamilton Section runs from Lake Road Interchange in the north to the Tamahere Interchange in the south. The alignment chosen attempted to avoid the Holocene peat bogs and traversed the elevated and more geotechnically competent Hamilton Hills capped by Late Quaternary tephra beds and the Hamilton Ash Formation. Some 'Lowland' sections between the hills were unavoidable, these comprised deposits of the Hinuera Formation with minor Holocene swamp sections where drainage was limited.

Carbon dating of Lowland organic samples between 1 and 30 m depth confirm that the typical age of the Hinuera Formation is between 6,000 to 24,500 years before present. Underlying the Hinuera Formation, sediments encountered along the alignment included lake deposits and peat bogs in the north, and a widely distributed tephra bed and paleosol capping the Walton Subgroup in the southern part of the project. This paleosol, located near Morrinsville Rd (at 31m depth), was carbon dated to be 24,500 years before present.

Encountered only in the centre of the project area, underlying the paleosol, are deep channels infilled with thinly interbedded lacustrine silts and cross-bedded alluvial sands with a very thick massive sand unit. The localised deposits commonly occur adjacent to the Hamilton Hills, this potentially indicates sediments infilling basins located on the downthrown sides of faults cross-cutting the alignment prior to the deposition of the Hinuera Formation or older alluvial deposits.

## MID- PLEISTOCENE PALEOENVIRONMENTAL RECONSTRUCTION OF THE LARGEST FOSSIL FOREST IN AUCKLAND, NEW ZEALAND

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The mid- Pleistocene, fossil wood, palynology and sedimentology of a fossil peat bog in west Auckland is evaluated in order to reconstruct regional paleoclimate and paleoenvironments. Fossil wood compositions are highly unusual as they record a low diversity assemblage of cold adapted plants suggesting that the mid- Pleistocene climate of Auckland was much cooler and drier than today. The mid- Pleistocene pollen record consists entirely of extant pollen types which show prominent compositional shifts between *Fuscosopra*- dominated to podocarp and *Agathis*- dominated ecosystems. The Beach Road site in Te Atatu, Auckland details multiple transitions between stable mire and lake formation, with minor fluvial and marine components. The lowermost peat records the initiation of stable mire formation, which extended across the upper Waitemata Harbour. The pollen spectra from these peats records vegetation assemblages dominated by warm climate taxa such as *Agathis* and several different podocarps including *Dacrydium* and *Phyllocladus*, thus recording climatic conditions broadly similar to those recorded in the west Auckland region today. A prominent lacustrine phase marked a fundamental hydrological transition which is recorded by increases in wetland pollen taxa. As the lake evolved, fluvial inputs became greater, and the pollen spectra was dominated by cool, moist climate beech and podocarp forest which cycled with short lived, warmer conditions. Mires quickly developed over the lake which at first, is dominated by warm, frost free environments, succeeded by pollen indicative of cooler conditions. The results of this multiproxy paleoenvironmental investigation indicates that Auckland's mid- Pleistocene climate was characterised by warm, moist conditions which were punctuated by several cooler and drier phases. These cooler periods however, were probably not as cold as Auckland's climate during the last glacial maximum but were still significant enough to alter the dynamics of Auckland's paleoflora.

## THE INTERACTIONS BETWEEN PYROCLASTIC DENSITY CURRENTS AND TOPOGRAPHY: RESULTS FROM A FIRST LARGE-SCALE EXPERIMENT

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Pyroclastic Density Currents (PDCs) are hot mixtures of gas and particles travelling at high speed outwards from a volcanic vent. Understanding their interactions with topography is crucial to produce accurate flow hazard models, but the fundamental processes of gas-particle transport and sedimentation across topography remain largely unknown. This PhD project aims to understand how topography affects the turbulent and non-turbulent gas-particle transport, sedimentation and runout dynamics of PDCs through large-scale experiments and field work on the 232 AD Taupo Ignimbrite. Combining both research components, we aim to build a quantitative model linking deposit characteristics of ignimbrite deposits along topographic obstacles and PDC flow regimes. An initial PDC experiment without any topographic obstacles was conducted to determine the correct scaling similarity of the experimental PDC analogue to sustained natural PDCs, and to measure the characteristic length-scales of the largest coherent turbulence structures that develop and perpetuate inside the flow. These results together with geometric data of natural hill-shaped obstacles around volcanoes informed the construction of analogue obstacles that will be used in next experiments. This experiment also presents the first simulation and measurements (of velocity, particle concentration, turbulence intensity and temperature) inside a sustained particle-laden gaseous gravity current with natural high density contrasts between the flow and the ambient. We present data of the flow front kinematics of this non-Boussinesq flow, and link these to the spatiotemporally evolving flow-internal velocity, density and temperature structure. We show how the results of this analysis inform the scaling and positioning of experimental topographic obstacles in a systematic series of future experiments. We also present data of the temporal evolution of the experimental PDC deposit forming erosion and deposition features with massive, stratified and laminated bedforms.

## NEW ZEALAND NEOGENE CLIMATE: AN OVERVIEW

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The last major symposium on “The Tertiary Climate of New Zealand” was held at Victoria University of Wellington, on the 14<sup>th</sup> and 15<sup>th</sup> of August 1967.

The symposium was organized by the Victoria University of Wellington Geological Society and was chaired by Ian Devereux, the then President of the society. The presentations included talks by: *Norcott Hornibrook* (warm water benthic forams); *Tony Edwards* (calcareous nannofossils); *Graham Jenkins* (planktic forams); *Donald Squires* (corals); *Ian Keyes* (scleractinian corals); *Ian Devereux* (oxygen isotopes); *Paul Vella* (forams); *Ross McQueen*, *Dallas Mildenhall* and *Chris Bell* (fossil plants, spores and pollen); *Keith Lewis* (size of fossil animals); *Alan Beu* and *Phil Maxwell* (molluscs).

The proceedings of the symposium, including a summary of more than 8-hours of discussion were subsequently published in TUATARA Volume 16, Issue 1, April 1968.

Conclusions in relation to Neogene climate were:

- Landon Series: A definite cooling seems to have taken place at the beginning of this time although the extent of this cooling is not completely clear.
- Pareora Series: A warming again after the cooler Landon, with temperatures becoming marginally tropical especially in the North Island.
- Southland Series: A very warm period at the beginning which may be the warmest time of the Tertiary rather than the Pareora which has been accepted till now as the Tertiary temperature peak. A definite cooling appears to have set in almost from the beginning of this time.
- Taranaki Series: Cooling probably continued through this time also.
- Wanganui Series: The cooling of the previous times may have continued right through to the Pleistocene but there is some suggestion that the temperatures of the Pliocene were fairly uniform and about the same as today. It has been suggested though that the temperature fluctuations that are the feature of the Pleistocene may have begun in the Pliocene.

That was the state of knowledge 50-years ago, but what do we know now that we didn't know then?

## CENOZOIC CONTINENTAL TECTONICS IN NORTH-WESTERN ROSS SEA, ANTARCTICA

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The north-western region of the Ross has been subjected to several extensional events during the Cenozoic. New ocean crust formation in the Adare Basin off north-western Ross Sea (43 – 26 Ma) can be traced directly into the Northern Basin underlying the adjacent continental shelf, implying a continuity of emplacement of oceanic crust. Steep gravity gradients along the margins of the Northern Basin suggest that little extension and thinning of continental crust occurred before it ruptured and new oceanic crust formed, unlike most other continental rifts and the Victoria Land Basin further south. A pre-existing weak crust and localisation of strain by strike slip faulting may be factors allowing the rapid rupture of continental crust. A narrow ridge (Hallett Ridge) forms the eastern margin of the Adare/Northern basins. The subdued magnetic anomaly over most of the ridge indicates that it is continental. To the east are the older (60 Ma), but narrower, rifts of Central Basin and Central Trough. The deep water (2000m) of the Central Basin extends as far south as the Northern Basin to the west. It separates the Iselin Bank from the western Ross Sea continental margin. Gravity modelling indicates a thin crust (basement ~8km) with sharp margins, probably oceanic, underlying the central part of Central Basin. The rift continues south into the continental Central Trough graben. The Transantarctic Mountains form the western rift margin of the Ross Sea and traverse Antarctica, separating East from West Antarctica. They were primarily uplifted about 55 – 45 Ma, between the times of the extension episodes forming Central Basin and Northern Basin, along a major lithospheric boundary between the cold East Antarctica craton and warm mobile West Antarctica.

## **SUBDUCTION MARGIN RE-DEVELOPMENT FOLLOWING MASS-WEDGE FAILURE – RUATORIA RE-ENTRANT, NEW ZEALAND**

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The Ruatoria debris flow (RDF), located along the northern Hikurangi subduction margin, is one of the largest submarine failures observed globally (~3150 km<sup>3</sup>). Comprised of a blocky avalanche and mass-transport deposit associated with mass-wedge failure at ~170 ka, the RDF likely formed in association with seamount subduction and over-steepening of the margin. Following wedge failure and emplacement, the inner margin of the RDF has travelled ~9 km westward through plate convergence and has been partially accreted. Using high-resolution 30 kHz multi-beam swath bathymetry coupled with multi-channel seismic reflection profiles, we document the re-development of the deformation front across the blocky avalanche deposits and debris flow, and discuss implications for the shallow plate interface.

Localised thrust faults are identified propagating through the central zone of the RDF avalanche deposits, inducing folding of largely intact rafted wedge blocks. These faults appear active and are presently uplifting the central re-entrant region, indicating that the subduction deformation front has become re-established westward of the present-day regional subduction front. The subduction décollement is inferred to have propagated directly atop the Hikurangi Plateau volcanoclastic sequence beneath the RDF, with failure of the overlying wedge having likely destroyed the original interface slip surface. Within the RDF head-scarp, several large listric normal faults are clearly imaged in seismic profile, illustrating sequential wedge collapse and preservation of large, tilted sedimentary blocks detached from the shelf-margin. Some of these normal faults show signs of subsequent short-lived reverse re-activation, indicating localised contractional deformation of the upper sector of the re-entrant immediately after failure. These results provide new insights into seamount subduction processes and associated margin-scale mass-wasting events, and their effects on accretionary wedges.

## EXPANDING THE FOOTPRINT OF OROGENIC GOLD: TRACE ELEMENTS IN SULPHIDES

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The Macraes orogenic gold deposit in Central Otago, New Zealand was formed within the Otago Schist in the Early Cretaceous during long-lived subduction along the Gondwana margin. This gold deposit is primarily composed of refractory, sulphide-hosted gold with a minor component of quartz vein-hosted free gold. The mineralising fluids are thought to have originated through metamorphic dehydration of rocks and scavenged gold from the metamorphic pile. The gold-bearing fluid was subsequently focused, and gold and auriferous sulphides were deposited along shears of the Hyde-Macraes Shear Zone (HMSZ).

We make use of optical petrography, energy dispersive spectroscopy (SEM-EDS) and laser ablation-inductively coupled plasma-mass spectroscopy (LA-ICP-MS) to determine how trace elements behave with respect to each other within hydrothermal sulphides and with distance from a known ore zone in drill core.

With these data, we seek to allow exploration within a discontinuously mineralised structure to vector towards hydrothermal sulphides rich in gold rather than metamorphic sulphides and by extension, characterise distal and proximal hydrothermal sulphides.

Results so far show that sulphide-gold (within the sulphide structure) has a strong positive correlation with arsenic in pyrite and weaker correlations with copper, zinc and silver. Micro-nugget gold (discrete particulate gold within sulphides), however, appears to be more abundant in arsenic-poor regions of sulphides, suggesting that substitution of arsenic for sulphur in pyrite may promote incorporation of sulphide gold and prevent micro-nuggets from forming in high arsenic regions. When the concentrations of sulphide gold, arsenic, copper, zinc and silver are plotted against depth, there appears to be a systematic increase in concentration from distal to proximal sulphides around the ore zone.

## **GAS VENTING AT KEKERENGU RIDGE, OFFSHORE MARLBOROUGH - FAULT CONTROLLED VENT LOCATIONS AT AN OBLIQUE CONVERGENT MARGIN**

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Kekerengu Ridge, which forms one of the southernmost accretionary ridges on the Hikurangi Convergent Margin was the final area surveyed by the R/V Tangaroa survey TAN1808 as part of the HYDEE program of research. Kekerengu Ridge was found to be rich (> 50) in bubble columns, imaged by the multibeam sounder, reaching 150-250 m above the ridge seafloor. The bubbles are interpreted to contain methane escaping from a gas hydrate system highlighted in seismic reflection records by a regional Bottom Simulating Reflection (BSR), the likes of which are found throughout accretionary ridges further north on the Hikurangi Margin.

As found elsewhere on the Hikurangi Margin, gas ascent to the seafloor from the underlying BSR within the northern half of the Kekerengu Ridge is facilitated by existing faults, often tensional fractures, extending to near the ridge crest. The Southern Kekerengu Ridge is uplifted by underthrust elevated basement and seafloor. Faulting apparent in seafloor morphology of the southern ridge is sub-parallel to the direction of plate convergence, and oblique to the margin and ridge orientation. Gas vents cluster along these faults suggesting they act as conduits to the seafloor.

Gas venting at the seafloor is associated with carbonate mounds interpreted in collected TOPAS echosounder data. Clustering of carbonate mounds is not uniformly distributed throughout the sedimentary section, instead appearing concentrated on several horizons that may represent periods of fault activation at the local margin.



## **ANALYSIS OF THE ALPINE GARDENS LANDSLIDE AND MILL'S CREEK DEBRIS FAN, FOX GLACIER VALLEY**

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The Alpine Gardens landslide and Mill's Creek debris fan is a dynamic ~50 million m<sup>3</sup> landslide complex in the Fox Glacier Valley, West Coast. Alpine Gardens is currently one of New Zealand's largest actively moving landslides. Debris flows are sourced from the toe of the landslide, which travel down Mill's Creek and deposit on the debris fan at its confluence with the Fox River. This debris flow activity has resulted in the re-occurring damage to, and current closure of the roads and tracks within the Fox Glacier Valley, impacting the Fox Glacier township economy. We document and investigate the behaviour of the Alpine Gardens landslide, and the changing dynamics of the Mill's Creek debris fan via terrestrial laser scanning, airborne LiDAR, and aerial imagery. Our analysis reveals that the Alpine Gardens landslide is moving consistently as one "block" downslope. Change detection over various LiDAR epochs indicates that material is eroded from the slump section at the base of the landslide, and this material is then redeposited on the debris fan or washed further downstream. The active channel of Mill's Creek appears to be migrating and incising, with little material deposited between the toe of the landslide and the fan. To understand the controls on the movement mechanism of the landslide, we installed a continuous GPS monitoring station along with rainfall gauges on the landslide in February 2019 to monitor the movement of the landslide and associated environmental conditions. Initial analysis of this data suggests that the rate of movement of the landslide is closely correlated with rainfall, with significant accelerations in movement occurring after heavy rainfall.

## MODELLING INTERNAL TRIGGERING OF RHYOLITE ERUPTIONS BY GEOTHERMAL COOLING

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Magmatic geothermal systems extract heat and volatiles from deep magma bodies and transport these upward through the brittle crust. Sometimes, these same magma bodies evolve toward an unstable, overpressured state, precipitating a catastrophic caldera eruption. Understanding the deep coupling between magmatic and geothermal systems can help contextualise our near surface observations and plan for utilisation of the deep resource. In addition, insight into how the system transitions between convective and eruptive phases has implications for our understanding of volcanic hazard.

We have developed a lumped parameter thermomechanical model of a magma body that is being cooled from above by geothermal systems, and recharged from below by deep magma sources. The model tracks the evolution of temperature, pressure and magma composition, and includes parameterised descriptions of eruption, volatile leakage across a viscoelastic shell, and overlying geothermal systems. We have used this model to explore generic eruptive styles and to develop an approximation of the eruptive record of the modern Taupō Volcanic Zone (TVZ).

Our modelling suggests that magma bodies at 4 to 5 km depth in the TVZ are overlaid by a 500 m thick, permeable, viscoelastic shell. The timing and volume of eruptions are dominated by short intervals of sporadic magma recharge originating deeper in the crust. Long-term climatic modulation of rainfall driven geothermal systems has minimal impact on eruptive timing. However, under certain conditions, efficient geothermal systems can trigger an eruption by cooling a magma body too rapidly, resulting in gas exsolution that builds to a critical overpressure. These insights highlight the value of coupled magmatic-geothermal models, and suggest development of a magmatic reservoir simulator could shine new light on the complex physical interplays occurring deep in the TVZ.

## HIGH RESOLUTION IMAGING OF THE SOUTH HIKURANGI SUBDUCTION ZONE, NEW ZEALAND, USING 2-D FULL-WAVEFORM INVERSION

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Large quantities of fluids are predicted to be expelled from compacting sediments on subduction margins. Fluid expulsion is thought to be focused, but its exact locations are usually constrained on very small scales and rarely can be resolved using velocity images obtained from traditional velocity analysis and ray-based tomography because of their resolution and accuracy limitations. However, with recent advancement in computing power, the full waveform inversion (FWI) is a powerful alternative to those traditional approaches as it uses phase and amplitude information contained in seismic data to yield a high-resolution velocity model of the subsurface.

Here, we applied elastic FWI along an 85 Km long 2D multichannel seismic profile on the southern Hikurangi margin, New Zealand. Our processing sequence includes: (1) downward continuation, (2) 2D travel time tomography, and (3) full waveform inversion of wide-angle seismic data. In this presentation, we will present the final high-resolution velocity model and our interpretation of the fluid flow regimes associated with both the deforming overriding plate and the subducting plate

## THE APPLICATION AND LIMITATIONS OF HYPERSPECTRAL IMAGING FOR SURFACE ALTERATION MAPPING: A CASE STUDY OF PINNACLE RIDGE, MT RUAPEHU, NEW ZEALAND

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Diagnostic absorption features in hyperspectral data can directly correlate to a specific mineral, or mineral assemblage. As a result, hyperspectral data analysis is a growing field of mineral identification. However, it is unknown how accurate hyperspectral mapping can be for identifying alteration mineral compositions at the resolution required to describe structures such as intrusive systems, or whether it can accurately quantify the alteration present. Quantifying alteration on volcanoes is important for locating areas that are likely to fail, as this can lead to rockfall, landslide, or flank collapse events. For this study, laboratory and aerial hyperspectral data will be analysed for alteration surrounding an exposed intrusive system, Pinnacle Ridge. This ridge is located on the northern flanks of Mt Ruapehu and contains varying levels of hydrothermal alteration from argillic to advanced argillic assemblages. Point count analysis quantified 7.6 – 85.2% of alteration in thin sections from samples collected from the ridge. These values are consistent with published X-ray diffraction data from the area. Laboratory hyperspectral data was compared to the USGS spectral library to identify alteration absorption features in the samples. The results show strong kaolinite doublet absorptions near 1413 nm and 2205 nm or single absorptions near the same wavelengths, identified as either kaolinite/montmorillonite. Major goethite absorption near 500 nm is evident in almost all samples, with minor jarosite absorption at 2265 nm. This mineral assemblage suggests imprinting of weathering alteration over the hydrothermal alteration. A positive correlation between the reflectance values at band 2205 nm and the alteration percent provides a link between the spectral and spatial aspects of the alteration at Pinnacle Ridge. Our results encourage the use of hyperspectral image classification to identify areas of weathering and hydrothermal alteration relevant for hazard and geological mapping.

## CURRENT GLACIER EXTENT IN THE SOUTHERN ALPS MAY BE UNPRECEDENTED IN THE HOLOCENE

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Understanding pre-industrial or natural climate variability provides an important context for assessing the impact of anthropogenic climate change. However, detection and attribution of human impact on the climate system is limited by short instrumental climate records, especially in the Southern Hemisphere.

Mountain glaciers are sensitive climate indicators, thus geological records of their past variability offer the potential to augment instrumental records.

Here we present a new cosmogenic <sup>10</sup>Be chronology of glacier length changes from Dart Glacier in the Southern Alps. Prominent moraines deposited 321 ± 44 yr ago (n=11) and 7.8 ± 0.2 ka (n=5) show glacier advances during the Little Ice Age were smaller than during the early Holocene. This pattern of net Holocene glacier retreat is consistent with emerging data from other catchments in New Zealand and across the southern mid-latitudes. Measurements of <sup>10</sup>Be in bedrock surfaces uncovered by retreat of Dart Glacier over the last 3 centuries yielded no evidence for prior exposure, which is consistent with net glacier decline during the Holocene and may indicate a present-day glacial minimum for the interglacial. We use a suite of existing transient global climate model simulations to evaluate the likely drivers of glacier length changes during the present interglacial.

## **COASTAL ZONE MANAGEMENT, A CASE FOR INTEGRATING ECONOMIC IMPACT MODELLING AND ROBUST DECISION MAKING WITH SCENARIO PLANNING.**

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The availability of coastal natural capital to the environmental-economic system declines as sea levels rise, storms encroach, populations grow, and industries expand. Limitations in natural capital, particularly land supply, require society to adjust traditional ways of living to provide for the economic wellbeing of coastal communities. Scenario planning is useful in this regard as a strategic planning method that adjusts traditional mind-sets toward plausible future pathways. Groups develop different future scenarios and test the outcomes against a set of objectives. In this case, GIS analysis, economic impact modelling and Robust Decision Making are used to develop scenarios for coastal communities in order to plan for resilient futures through a managed retreat.

The development of scenarios in this PhD project involves three steps. First, GIS analysis compares current coastal hazard zone occupation and land-use zoning against projected hydrologic change. Second, economic impact modelling assessment through MERIT discovers the flow-on effects of asset exposure on household wellbeing, government expenditure, and industry performance. Third, Robust Decision Making in Python provides the analytical framework to process time-varying model outputs using a 'least regret' matrix. The study area focuses on the sub-regional coastal in Hawke's Bay. To date, scenario planning from model results have shown a significant deficit in natural capital, inadequate land-use zoning and a need for financial leadership from government to enable managed retreat. Current council long-term plans meet projected economic growth but fail to accommodate for coastal inundation. Converting more natural capital through new land-use zoning is useful, albeit expensive. Intensification of current land-use is, therefore, a priority over greenfield developments to preserve productive soils and lower the cost of borrowing capital. The central government is required to intervene as a 'direct investor' through climate bonds and climate leases due to the large scale, legal complexity and cost of adaptation.

## GLACIAL OVERDEEPEENINGS IN THE SOUTHERN ALPS: A REVIEW

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Glacial overdeepenings are closed topographic basins formed beneath glaciers by erosion of bedrock/sediment at the base of the glacier, while their size may be augmented by deposition of sediment at the glacier terminus. Understanding the processes and controls on their formation is important for predicting their occurrence beneath extant ice masses, which has implications for future hazards associated with deglaciation, as well as glaciological modelling of the future response of glaciers and ice sheets to climate change.

Here we review present understanding of the distribution, geometry of terrestrial glacial overdeepenings in the Southern Alps. We find >8000 overdeepenings are currently evident as lakes within the boundaries of the maximum late Quaternary ice extent in the Southern Alps. These lakes are predominantly small (<1 km<sup>2</sup>) and are most densely concentrated in the Southland region. Filtering by surface area, we find 52 overdeepenings >2 km<sup>2</sup>, which are more evenly distributed around the maximum late Quaternary ice limits. Bathymetric data is available for 36 of these large glacial lakes, which indicates depths up to ~450 m. Geophysical subsurface imaging and sediment cores indicate post-glacial sedimentary infilling of Quaternary glacial overdeepenings may be substantial (10s -100s metres) - especially in the central Southern Alps where high uplift and erosion rates enhance sediment fluxes. Southern lakes (e.g. Te Anau, Manapouri) may better reflect the true glacial overdeepening geometries due to lower rates of post-glacial sedimentary infilling.

The largest glacial overdeepenings in the Southern Alps preferentially occur in the former ablation zones and close to the termini of late Quaternary glaciers. This observation reflects the combined importance of subglacial water availability for basal sliding and proglacial outwash fan head sediments as important controls on overdeepening formation.

## COUPLED ATMOSPHERE-OCEAN TEMPERATURE CHANGES IN SOUTHWEST PACIFIC DURING THE ANTARCTIC COLD REVERSAL

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The thermal bipolar seesaw is the leading hypothesis to explain the millennial-scale temperature changes of the last glacial termination, which are of opposing sign between the polar ice cores. However, the spatial extent and temporal structure of these events outside of the high latitudes and thus, the climatic mechanisms responsible, remain poorly constrained. Here we address this shortcoming with quantitative constraints on the timing and magnitude of atmospheric and sea-surface temperature changes during the Antarctic Cold Reversal from the New Zealand region. Our new glacier-based air temperature reconstructions and foram-derived sea surface temperature record exhibit coldest temperatures within centuries of the onset of this millennial-scale event, followed by gradual warming prior to 13 ka. Placed in the context of Antarctic ice cores and the thermal bipolar seesaw hypothesis, our evidence for centennial-scale response at this far-field, southern mid-latitude location challenges the classic bipolar seesaw hypothesis by suggesting a teleconnection to the North Atlantic that is not modulated by their proposed Southern Ocean heat reservoir. Coupled atmosphere-ocean mechanisms operating north of the Antarctic Circumpolar Current, as indicated by recent climate modelling, provide a physical framework that may reconcile the different climate response times of the southern mid- and high-latitudes during the Antarctic Cold Reversal.



## THE HIKURANGI SUBDUCTION ZONE, THE BLIND (WO)MEN, AND THE ELEPHANT: NUMERICAL EXPERIMENTS TO EXPLORE INTERACTIONS BETWEEN RHEOLOGY, STRESS, AND FLUID PRESSURE THROUGH SPACE AND TIME

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Studies of the Hikurangi subduction margin have focused on the remarkable along-strike variations from south to north: the shallowing in interface locking depth and slow-slip, decrease in slow-slip duration, and transition from a wide low-taper wedge to a steep frontal wedge impacted by seamounts. Factors implicated in these along-strike changes include fluid pressure, interface fault strength, subducting plate morphology, and upper plate stress.

Coupled hydrological-mechanical numerical models can be used to test these potential controlling factors and show how they are inter-related. Models show that loading by overburden stress and compressive tectonic stress as material is accreted into the wedge leads to progressive sediment consolidation and porosity reduction, as also inferred seismically. Irregularities in megathrust geometry (e.g. subducting seamounts) modulate tectonic loading and fluid migration: lateral compression is enhanced in front of a seamount, and diminished above and seaward of it, creating a “stress shadow” that allows anomalously high sediment porosities to be preserved. Subduction of rough seafloor can also control sediment underplating, wedge morphology, and interface properties by creating thick packages of highly-sheared mélangé, promoting transient slip and stress states.

We consider how evolution of the Hikurangi subduction margin over the last few My could have altered its slip behaviour. In the south, the rapid progradation of the wedge may have caused a change in wedge mechanics, from slip along a primary splay fault connecting the interface to the seafloor, to more distributed shortening across a series of rapidly propagating frontal thrusts stepping upward from a weak décollement. In the north, subduction of rough seafloor dotted with seamounts has promoted diverse slip behaviour, with episodic frontal erosion, sediment subduction and underplating. Models, along with recent observations from drilling, suggest that multiple interacting factors can influence slip behaviour and margin evolution through time and space.

## MECHANICAL INTERACTIONS BETWEEN RIFTING, SILICIC MUSH AND INTRUSION OF MELT BODIES IN THE TAUPO VOLCANIC ZONE

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The geophysical and mechanical expression of melt bodies (such as dikes and sills) in an extensional environment such as the Taupo Volcanic Zone are affected by the presence of extensive crystalline silicic mush residing below or around the melt. The mechanical strength of partial-melt mush can be relatively high when crystal “lockup” occurs but can decrease abruptly when perturbed e.g. by heating events. The tensile strength (i.e. ability for mode 1 fracturing) of the mush zone affects the propagation of dike events. Numerical experiments show how tensile yielding and embrittlement are enhanced within the mush zone by high fluid pressures and/or very high strain-rates (e.g., due to the rapid influx of melt). Using a thermo-mechanical model, we investigate the stress perturbations caused by small to large magma intrusions within a crystal mush zone within rifting crust like the Taupo Volcanic Zone. A low-strength viscoelastic mush zone in the mid-crust can relieve overpressure generated by inflation of melt bodies provided rates of intrusion are slow compared to ductile creep rates in the mush. The degree to which stresses are relaxed in the mush also depends on where melt is residing relative to the mush (e.g., above or within it). Transient changes in rheology from ductile to brittle behaviour- promoted by fluid pressure and permeability changes- can create a patchwork of brittle-ductile deformation with a complex stress state. A sudden influx of material below the mush zone can cause reservoir heating, elevated rifting rates, and significant changes in physical properties.

## **MICRO-ANALYTICAL INSIGHTS INTO YOUNG RHYOLITIC ERUPTIONS FROM THE TAUPŌ VOLCANIC ZONE, NEW ZEALAND.**

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Large rhyolitic eruptions occur relatively rarely compared to other volcanic events, but potentially cause widespread damage. What we know about these eruptions principally comes from studies of their deposits, yet questions remain concerning how quickly their parental magmatic systems can mobilise from dormancy through to eruption. We are investigating the timescales on which New Zealand's two active rhyolite caldera volcanoes (Taupō and Okataina) operate, with the aim of providing estimates of how much warning we would receive prior to a future eruption.

To achieve this, mineral diffusion studies and volatile measurements in melt inclusions from a range of post-25.4 ka events at both volcanoes will be combined with detailed trace-element and isotopic work. These data will be used to build a fuller picture of Okataina's current magmatic system, which will then be used to interrogate how quickly Okataina may mobilise into eruption. Magma ascent timescales at both Okataina and Taupō (for which a full geochemical picture already exists) will then be assessed.

Initial results from Okataina melt inclusions show low CO<sub>2</sub> and a range of H<sub>2</sub>O values, augmenting existing magma storage depth estimates and providing a basis for investigating magma ascent rates. Initial whole-rock REE analyses show distinct variations between the Tarawera, Haroharo and Okareka Embayment vent zones of Okataina, and glass separates show distinctions between different eruptions. This, alongside initial Sr isotopic data and complex mineral zonation in Rotorua-episode minerals, suggests that the magmatic system beneath Okataina today may be highly complex, with multiple magma sources and a range of processes occurring within and between vent zones. Future work will involve further isotopic and glass analyses of Okataina's magma types, and diffusion-based timescales studies in minerals for each vent zone's youngest eruption, and in melt inclusions from a range of eruptions at both volcanoes to model magma ascent rates.

## RAYLEIGH WAVE MAPS OF THE CRUST IN THE AUCKLAND VOLCANIC FIELD FROM AMBIENT SEISMIC NOISE

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We used Rayleigh wave group arrival times and a transdimensional (reversible-jump Markov chain Monte Carlo) travel-time inversion to map the crust of the Auckland Volcanic Field. The resulting maps reveal two units demarcated along a boundary that aligns with the Junction Magnetic Anomaly. The higher-speed unit coincides with the Waipapa Terrane (higher metamorphic grade) than the Murihiku Terrane (lower metamorphic grade) with the lower-speed unit. The boundary between these units broadens and shifts WSW with increasing period, suggesting a westward dip.

The cause of the active Auckland Volcanic Field is still poorly understood. To improve this state of knowledge, we examine the structure of the crust in the Auckland Volcanic Field, using multi-component ambient seismic noise tomography. Ambient seismic noise tomography involves retrieving surface wave information from seismic noise and inverting for velocity structure. We produce more robust and better resolution models of the crust than previous studies by using multi-component ambient seismic noise, better tomographical method (transdimensional travel-time tomography), more seismometers, and many more inter-station paths.

We cross-correlated ambient seismic noise recorded on all components of 20 seismometers. We empirically found that the multi-component estimate of the Rayleigh wave signal with the greatest signal-to-noise ratio is the sum of the vertical-vertical and 90° phase-shifted vertical-radial and radial-vertical signals. We then performed frequency-time analysis (FTAN) on these signals to obtain Rayleigh wave dispersion data at periods 2-11s. Then invert the 1D Rayleigh wave group arrival times for 2D speed maps using a transdimensional travel-time inversion.

## **A MULTI-PROXY PALEOENVIRONMENT INTERPRETATION OF THE LAST GLACIAL CYCLE (CA. 117 KA) AND WAVELET ANALYSIS FROM LAKE KAI IWI, NORTHLAND, NEW ZEALAND**

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A 9.3 m lake sediment core was obtained from dune impounded Kai Iwi Lake in Northland, New Zealand and analysed with multi-proxy organic, physical index,  $\mu$ -XRF elemental data sets, and principal component analysis (PCA), which correspond to changes in precipitation associated with the South Westerly Winds (SWW) and El Niño Southern Oscillation (ENSO) variability. A well-dated chronology for the upper 3 m of core was established by  $^{210}\text{Pb}$ ,  $^{14}\text{C}$  and tephrochronology and used to extrapolate the age model for the remainder of the core using the estimated depositional age of the Lake Kai Iwi basin itself and an average sedimentation rate of 100 yr/cm. Results of the multi-proxy analysis indicate that the Holocene warm equivalent conditions of MIS 5e are not present in the Lake Kai Iwi core stratigraphy, consistent with an extrapolated basal age of 117 ka. PCA indicates that Component (PC)-1 represents detrital versus organic deposition, and PC-2 is associated with nutrient influx versus anoxic conditions in the lake. The cool periods of MIS 2 and 4 are apparent in the  $\mu$ -XRF data as having increased detrital influx in the form of Sr/Ca from marine derived sediments from the exposed continental shelf during low sea level. Warmer and wetter periods (MIS 1 and 5) are identified by increased Ti/K influx from catchment runoff and increased organic productivity as shown by Inc/coh and total organic carbon (TOC). The Lake Kai Iwi  $\mu$ -XRF data was converted to a 20 year time step time series and analysed with a Morelet wavelet to identify periodicities within the data. The wavelet analysis indicates periodicities of ~1000 years, ~2000-4000 years, and ~9000 years; possibly associated with Northern Hemisphere ice sheet dynamics, ~2400 year Hallstatt solar cycles, and a combination of a ~6000 year solar cycle and ~12000 year precession cycles respectively.

## POTENTIAL OF BURIED VOLCANOES AND ASSOCIATED SEDIMENTARY FACIES AS HYDROCARBON RESERVOIRS

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In recent years, unconventional hydrocarbon reservoirs have been discovered in and around volcanic rocks globally. New Zealand sedimentary basins host a large number of buried volcanoes that may be suitable targets for petroleum exploration. However, these systems remain underexplored due to a perceived complexity and limited number of studies that characterise their petrophysical properties such as porosity and permeability. The outcropping volcanoes of the Waiareka-Deborah monogenetic volcanic field provide excellent exposures to study analogues of petroleum reservoirs formed with and around volcanic cones. Eocene to Oligocene submarine shelf edifices comprise tuffs, pillow lavas, and reworked volcanoclastics surrounded by cool-water carbonates including karsted limestones and well sorted grainstones. The wide range of rock-types and facies provide an opportunity to test the petrophysical properties that can infer reservoir quality for the Waiareka-Deborah volcanoes and enclosing sedimentary rocks. We tested 57 cores for porosity and permeability aiming to understand which rocks are likely to provide the best reservoir properties. In addition, we described 35 thin sections to analyse which parameters control these properties such as microfractures. Preliminary results show that tuffaceous rocks (which comprise the majority of the volcanic cones) have low porosity (~14%) and permeability (~0.39 mD), due to intense secondary calcite precipitation. However, numerous vertical calcite veins and hydrothermal alteration are proof of ancient permeable fluid pathways. Karsted carbonate surfaces have 10-30% porosity and fit into low (0.0047-22.28mD) and high (166.14-647.87mD) permeability groups (depending on the micritic content) therefore, providing both potential reservoirs and seals. Pillow lavas and their limestone matrix were both 3-22% porosity and 0.01-5.7mD and 0.003-0.0202mD respectively providing a seal facies. Seismic facies determined from these properties can be compared to seismic imagery of potential ancient monogenetic volcanoes buried in the Canterbury Basin and elsewhere. These results provide further understanding of offshore volcanoes and their prospective reservoir properties.

## “DARK AGES” IN THE HISTORY OF WHALES AND DOLPHINS

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Whales appeared in the global record at about 50 Ma. The early archaic forms were amphibious, but whales later became pelagic, reaching Zealandia and the Southern Ocean about 40 Ma. Pelagic cetaceans (whales, dolphins) have an increasingly informative record up to the Pleistocene, offering many insights into evolutionary and ecological history. There are some notable gaps or “dark ages” in the record, however, with unexpectedly sparse assemblages that stand out in comparison with more diverse assemblages in adjacent stages. Of note are the international Rupelian and Aquitanian stages, both with low species-diversities reported in the Paleobiology Database, PBDB. Such drops in diversity could reflect collecting effort, preservational rarity linked to facies (with large whales more likely pelagic than neritic), and uncertain dating through lack of age-diagnostic microfossils. Yet, the Aquitanian was also a time of marked turnover and modernisation, judging from the cetacean record from immediately adjacent stages. Our studies of New Zealand Cetacea include both previously named and new species particularly from the upper Otekaike Limestone, Gee Greensand and Mt Harris Formation of southern Canterbury basin. The incoming of planktic foraminiferan *G. connecta* is used as a proxy for the base of the Aquitanian which spans roughly upper Waitakian to middle Otaian. Taxa of note are: dolphins – *Otekaikea*, *Papahu*, an archaic kentriodontid, and 5-6 unnamed species of probable platanistoids (including one species convergent with modern beaked whales – an offshore deep-diver?); a shark-toothed dolphin (*Tangaroasaurus*); baleen whales – eomysticetids, 3+ species of *Mauicetus*-like balaenopteroids, and a probable right whale. This southern Zealandia assemblage is remarkably diverse in terms of species and inferred lifestyles. The baleen whales are notably abundant, suggesting nearby high-productivity feeding grounds.

## TRANSFORMING RURAL VALUE CHAINS IN THE 'TOP OF THE SOUTH', NEW ZEALAND

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Exposure to risks and hazards—including earthquakes, floods, snowstorms, and the current and anticipated impacts of climate change—have significant implications for rural regions throughout New Zealand. Agriculture and tourism make a vital contribution to local economies, but are sensitive to disruption and can be slow to recover. The vulnerability of rural regions in the 'Top of the South' was highlighted during and after the 2016 Kaikoura-Marlborough-Hurunui earthquake, which coincided with the effects of drought in North Canterbury, and was followed by extreme weather in autumn 2017. Rural communities, producers and businesses faced immediate and longer-term logistical, economic, and social challenges caused by these events, including damage to critical infrastructure and lifelines, and supply chains. The cascading and compounding effects of disruption affected flows of agricultural products and tourists, necessitating flexible and adaptive response mechanisms. Drawing on insights from ongoing qualitative research in the region with wine producers, tourism stakeholders and sheep and beef farmers, we discuss empirical examples highlighting the distinctive dynamics of disaster response mechanisms and recovery trajectories. Results show emerging reorganisation and redesign of rural value chains, with implications for further transformation, driven by enhanced social capital, strengthening of key relationships and growing diversification.



## USING PH-CONTROLLED SEDIMENT LEACHING EXPERIMENTS TO ASSESS THE BIOTOXIC IMPACTS OF OCEAN ACIDIFICATION: A PROOF OF CONCEPT.

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Anthropogenic activities in and around the marine environment cause disturbance and chemical contamination to sediments. These activities, including human-induced ocean acidification, can potentially harm the environment and the local biota. As a direct consequence of climate change, increased CO<sub>2</sub> in the atmosphere is projected to decrease the pH of ocean surface water by 0.3 units by 2100.<sup>1</sup> It is currently uncertain to what degree the reduced pH could affect coastal and marine sediments through dissolution of minerals and desorption of metals.

Current standard elutriate methods can only determine potential ecotoxicity of disturbed sediments over a 1 – 2 hour period. These offer no pH control or insights into when chemical equilibrium may be reached, consequently limiting our understanding of how dissolved metals will be released into the environment with decreasing pH. In order to assess long term effects over different pH ranges a unique sediment leaching column apparatus has been further developed as a part of an MBIE Smart Ideas project 'Crustaceans as Indicators for the Marine Environment' (CAIME).

To investigate the effects a lower pH could have on the disturbance of sediments, a sandy mud estuarine sediment sample was doped with Cu. The sediment was leached in ambient pH and 0.5 units below ambient pH. The final leachate for each experiment was then tested for response in algae and blue mussel larvae to investigate their function in a more acidified ocean. The results show that with pH reduced by 0.5 units, the concentration of dissolved Cu in the leachate increases by up to 30%, and ecotoxicity tests showed significant mortality effects in all experiments. This work demonstrates that the effects of ocean acidification on ecotoxic element leaching from sediments could be significant in the future, with increased mortality of organisms compared to their current, higher pH, environment.

1. IPCC. Summary for Policymakers. In: Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Nicolai M, Okem A, Petzold J, Rama B, Weyer N, editors. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Internet]. Forthcoming 2019. [cited 2019 Sept 30]. Available from [https://report.ipcc.ch/srocc/pdf/SROCC\\_FinalDraft\\_FullReport.pdf](https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_FullReport.pdf)

## EVIDENCE FOR VOLCANIC ERUPTIONS IN SPELEOTHEMS — THE TAUPŌ 232 ± 10 CE RECORDED IN A NEW ZEALAND STALAGMITE

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This study examined whether New Zealand speleothems preserved the 232 ± 10 CE Taupō eruption (VEI 7). A stalagmite, TR-990218B (TR-B), from Te Reinga Cave in the eastern North Island was subjected to various geochemical techniques to search for evidence of the eruption, which deposited ~10–20 cm of volcanogenic material over the cave site. High-precision uranium-series ages revealed a significant increase in growth rate shortly after the eruption (a factor of ~4 for ~35–40 yr). Trace element profiles obtained by laser-ablation-inductively-coupled-plasma-mass-spectrometry exhibited two concentration peaks in S at 214 ± 27 CE (lasting ~7 yr) and 243 ± 23 CE. Field-emission-scanning-electron-microscopy with energy-dispersive-spectroscopy observations at 214 ± 27 CE revealed particulate/colloidal material with elevated Si, K, Na, Mg, Al, S, Cl, and Ti contents, but not consistent with rhyolitic cryptotephra. High-resolution stable C–O isotopic analyses show decoupling for ~11 yr from 214 ± 27 CE, as compared to other parts of the stalagmite record. These observations strongly suggest TR-B preserved a fingerprint of the Taupō eruption. Growth rate increases can be ascribed to: (1) de-vegetation above the cave site due to ashfall, which perturbed normal evapotranspiration processes, and thus increased water flow into the cave; (2) the enhanced acidity of the percolating groundwater (due to increases in inorganic/organic acids) increasing karst dissolution and subsequent delivery of Ca (for stalagmite growth) into the cave; and (3) regenerating vegetation as new plant root systems and bacterial colonies thrive on surplus nutrients in the soil enhancing carbonic acid production, and thus stalagmite growth. Lower Mg/Ca ratios at this time can also be accounted for by these processes, as a decrease in prior-calcite-precipitation due to evapotranspiration decrease above the cave (i.e., effectively causing wetter conditions) would increase stalagmite Mg/Ca ratios. Moreover, this process is consistent with stable isotope decoupling, due to vegetation destruction above the cave site. The patterns in S can be explained by volcanically sourced aerosols being deposited above the cave and then by immediate leaching from the volcanic ash deposited above the cave, which persisted for more than ~20 yr due to biogeochemical cycling. In summary, this study suggests that New Zealand speleothems preserve evidence of volcanic eruptions, which can be used to refine eruption ages using U-series dating techniques and also assess the nature and duration of environmental change produced by eruptions.

## REDOX-SENSITIVE METALS AND $^{238}\text{U}/^{235}\text{U}$ ISOTOPE RATIOS IN FURLO BLACK SHALES: CONSTRAINING REGIONAL AND GLOBAL REDOX CHANGES RELATED TO OAE 2

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The understanding of how the complex ocean-atmosphere system responds to climate disruptions is vital for the prediction of modern-day climate change, in particular the expansion of de-oxygenated marine areas or 'dead zones'. To deconvolve dead zone expansion, extreme climatic disturbances from Earth's past can be investigated, which serve as analogues for future climate change scenarios. One of the most extreme climatic perturbations of the Mesozoic Era occurred during Oceanic Anoxic Event 2 (OAE 2), which took place around the Cenomanian–Turonian boundary (~94 Ma). The event is associated with the widespread deposition of organic-rich black shales and ocean de-oxygenation, affecting ocean basins worldwide. Although OAE 2 has been well studied, the evolution, extent and timing of ocean anoxia remain poorly constrained. A novel palaeo-redox tracer is given by the  $^{238}\text{U}/^{235}\text{U}$  isotope system however, the degree to which black shales reflect the marine U isotope signature is not well understood. Here, we present data of an extensive suite of palaeo-redox tracers, including U isotopes, from Furlo in Italy. We utilise black shales deposited before and during OAE 2 to unravel mechanisms controlling the offset in U isotopes between black shales and ambient seawater and to broadly characterise the progression and extent of oceanic redox conditions during OAE 2. The overall results of this study suggest that black shales are a reliable U isotope archive for studies of past ocean redox conditions, provided the prevalence of extremely reducing conditions during deposition and the negligibility of other local influences on U isotope fractionation between seawater and sediments.

## A NEW SPECIES OF FOSSIL *SCUTUS* MONTFORT, 1810 (GASTROPODA) FROM NEW ZEALAND

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A new fossil species of the molluscan genus *Scutus* is reported from four late Oligocene to early Miocene (Waitakian to Altonian) localities in the South Island. Specimens were collected from Mount Harris Formation at Sisters Creek, Hakataramea Valley and the Beach Road section south of Oamaru; from Chatton Formation at Mataura River, near Brydone township and from Curiosity Shop Sandstone at Cavendish quarry, Blands Bluff, Mt Somers. Living New Zealand *Scutus breviculus*, commonly called “shield shells”, are found at low tide (down to 20 m) in crevices and under rocks and feed on brown and green algae including *Hormosira* and *Ulva* as well as some red algae.

This is one of the oldest records of *Scutus* globally and these algal grazers likely inhabited very shallow rocky substrates in sub-tropical waters surrounding Zealandia during this time. The holotype of *Scutus petrafixus* Finlay, 1930, is re-examined because its age and collection locality are uncertain; it has been reported as being collected from a late Eocene or Miocene locality near Oamaru. Lithology and microfossils suggest it is possibly from glauconitic limestone at All Day Bay, Kakanui (Waitakian). The New Zealand species documented here significantly expand our understanding of the fossil record of this shallow-marine molluscan lineage, and by proxy, also indicate the presence of very shallow rocky shore environments around southern Zealandia in the late Oligocene and early Miocene.

## **RAMPED PYROLYSIS RADIOCARBON DATING AT THE RAFTER RADIOCARBON LABORATORY**

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Rafter Radiocarbon Laboratory at GNS Science is the oldest continuously operating radiocarbon laboratory in the world. Dedicated to upholding state-of-the-art capabilities, our scientists are constantly improving and adding to our available research techniques for collaborative research projects and commercial services. Most recently, we have developed a Ramped Pyrolysis system to improve radiocarbon measurements of Antarctic and other sediments that may be difficult to date. For example, in marine detrital sediments, the presence of reworked carbon may obscure depositional age. This technique exploits the thermochemical stability of distinct organic carbon pools present in a given sample to obtain a more accurate picture of carbon age distribution of a total sample relative to its components. More diagenetically altered carbon is more thermochemically stable, therefore the more refractory carbon can be isolated from authigenic carbon. In collaboration with the Rosenheim group at University of South Florida, Rafter Radiocarbon Laboratory has established this technology in New Zealand. This method achieves an intermediate step between bulk and compound-specific radiocarbon analysis, giving more accurate information without the cost and additional challenges associated with compound-specific radiocarbon dating. This analysis can provide more reliable chronologies particularly for detrital sediments where traditional bulk radiocarbon dating is often precluded. Our initial Ramped Pyrolysis system is currently being optimized through collaborative Antarctic research. The primary source of uncertainty in ramped pyrolysis is the blank contamination due to the small sample size of individual splits. Establishing and understanding this uncertainty is a primary focus of current development.

## WHAT FORCES MOVE TECTONIC PLATES?

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The movement of tectonic plates is a fact scientifically accepted, but the driving mechanism of plates is still controversial. It is still not clear what forces are behind these movements. Majority of scientists believe that one of the primary forces behind plates movement is thermal convection. Others mention such culprits as *“Centrifugal momentum”, “gravity”, “volcanos”, “glaciers”, “ridge push and slab pull”...*. None of the above reasons is precisely explained from a mechanical point of view leaving many questions unanswered. This paper undermines the credibility of previous assumptions and offers a new hypothesis. Earthmoving through the universe is subject to accelerations and these accelerations multiplied by mass equals force ( $F = ma$ ). The Earth is not a heterogeneous object; therefore, its rotation is not balanced. This unbalanced rotating and oscillating movement of the Earth through the universe create accelerations. This paper explains where these accelerations come from and also discuss the role of Earth Tidal and Lithosphere-Asthenosphere coupling/decoupling in the movement of Tectonic Plates. The analysis presented in this paper are based only on current and accepted scientific facts and fundamental laws of physics.

## **PALEOSEISMOLOGY OF THE HYDE FAULT AND IMPLICATIONS FOR EPISODIC FAULT ACTIVITY IN THE OTAGO RANGE AND BASIN PROVINCE**

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The 55 km long Hyde Fault is one of the more significant of several NE trending reverse faults within the Otago range and basin province that accommodate ~3 mm/yr of plate convergence east of the Alpine Fault. Previous studies have demonstrated episodic earthquake occurrence on the Pisa, Dunstan and Akatore Fault within the province, with indications that neighbouring faults may have experienced surface rupturing earthquakes at different times. We present the results of the first paleoseismic trenching undertaken on the Hyde Fault. We selected two sites for trenching, 11 km apart, on fault scarps across alluvial fan surfaces, identified in LiDAR elevation data and confirmed in the field. The trenches were excavated to ~ 5 m depth. Moderately-dipping reverse fault planes have offset and deformed alluvial fan sediments, and stratigraphic and structural relationships provide evidence at each site for at least two surface-rupture displacement events, with possible indications of a third event preserved at one of the sites. Preliminary interpretation of OSL dates indicates Late Pleistocene age for the ruptures. These results are discussed within the broader context of episodic earthquake occurrence observed elsewhere in the Otago region, considering in particular how crustal deformation may be partitioned in time and space such that a few faults may accommodate the bulk of the regional strain budget at any given time. Finally, we discuss the implications for incorporating paleo-earthquake data obtained from a small number of events into seismic hazard assessments.

## FROM SUBSURFACE TO OUTCROP – A DEEP-WATER TURBIDITE ANALOGUE CASE STUDY FROM THE EAST COAST BASIN, NEW ZEALAND

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The offshore Titihaoa-1 well was drilled in 1994 to test the petroleum potential of late Paleocene Waipawa Formation and Oligocene–Miocene sandstones. The oldest rocks encountered were late Early to mid-Middle Miocene (Clifdenian–Lillburnian) deepwater thin-bedded turbidites (equivalents to the outcropping Early Miocene Whakataki Formation), through which a borehole image log (resistivity) was acquired. The Titihaoa-1 dataset, combined with outcrop, seismic, and biostratigraphic studies, provides a valuable opportunity to correlate onshore observations of a thin-bedded turbidite succession with similar rocks in the subsurface, enhancing our understanding of fractures, *in-situ* stress, petrophysical, and depositional properties at local and regional scales.

Structural data obtained from the Titihaoa-1 image log show a general NE–SW fracture strike orientation, with a minor NW–SE trend. Many faults, also with a NE–SW strike, have <1 m displacements. Thin-bedded units visible on the image log are interpreted as dominantly interbedded fine sandstones and mudstones that display a NW dip trend, while adjacent shore platform outcrop studies of the Early Miocene Whakataki Formation indicate dips to the NNW. Sediment dispersal directions from the subsurface data have a general northerly direction, consistent with paleocurrent directions measured in outcrop suggesting that beds were deposited by north-flowing turbidity currents. Biostratigraphic analysis of Titihaoa-1 rocks suggests the strata were deposited in lower bathyal water depths, consistent with interpretations for the lithologically similar deep-marine accretionary slope turbidite succession encompassed by the Whakataki Formation. Few *in-situ* stress features have been identified from the image log. An inferred NW–SE  $S_{Hmax}$  for the studied interval in Titihaoa-1 is perpendicular to the modern plate boundary, while the imaged faults are sub-parallel to the boundary, suggesting a complex stress regime.



## **TSUNAMI FORECASTING WITH ASSIMILATION OF TSUNAMI DATA ON DENSE ARRAYS: THE 2009 DUSKY SOUND, NEW ZEALAND, TSUNAMI**

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Tsunami warnings in New Zealand rely on first locating and determining size of a large earthquake and then using precomputed simulation results to estimate the size and timing of the resulting tsunami. In cases where a dense array of offshore pressure gauges is available, a new “data assimilation” method can be applied to estimate the tsunami using the observations of pressure changes. Here we apply the data assimilation method to the tsunami generated from the 2009 Dusky Sound, New Zealand, magnitude 7.8 earthquake and determine a rapid and accurate estimate of the tsunami wave arrival time and size along the west coast of New Zealand. The earthquake occurred during the 1-year deployment of the Marine Observations of Anisotropy near Aotearoa (MOANA) OBS network.

We use tsunami waveform inversion applied to Deep-ocean Assessment and Reporting of Tsunamis (DART) offshore pressure gauge and coastal tide gauge data to estimate the fault slip distribution of the Dusky Sound earthquake. The tsunami from this fault slip estimate is then used as a reference to measure the forecast accuracy from different approaches to forecast the tsunami threat in New Zealand’s tsunami warning zones.

A good match was found between forecast from the data assimilation method and observed tsunami waveforms at the Charleston tide gauge station on the west coast of New Zealand's South Island. However, this method gives only accurate forecast along the west coast of New Zealand because the offshore pressure gauge network is located off the west coast of the South Island. While an advantage of the data assimilation method is that no initial condition is needed, we find that our forecast is improved especially along the south and east coasts of the South Island by merging tsunami forward modelling from a rapid W-phase earthquake source solution with the data assimilation method.

## **AMPHIPODS AS BIOMONITORS OF MARINE COASTAL ENVIRONMENTS: A CHATHAM ISLAND CASE STUDY**

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Biomonitoring applied to New Zealand's coastal marine environments may aid in understanding and monitoring biochemical changes resulting from human activities such as mining, urban development, trawling and ocean acidification. Crustaceans such as amphipods take up potentially toxic trace metals into their bodies, and hence become recorders of the bio-available fraction of metals in their environment. Abundant in coastal marine environments, amphipods consume a wide variety of foods and are of importance to the food web as the metals they may take up are magnified up through the food chain.

The marine estate is of great cultural and economic significance to Chatham Island. Three marine algal-dwelling amphipod species, together with associated algae, sediment and water samples, were collected from five diverse coastal locations around Chatham Island to evaluate the use of amphipods as biomonitors. The locations were selected from different geological substrates, to evaluate potential natural variations, and with different historical usage to test for potential anthropogenic variations. The amphipod specimens were analysed for >30 trace elements including metals of known potential ecotoxicity (e.g. Cd, Cr, As). The effect of specimen size in influencing the bioaccumulation of the trace elements was evaluated, and for most metals appears to be insignificant for the three species studied here. Comparing across the five sites, consistent patterns of different trace metal enrichments are observed in the different species, showing that quite different trace metal profiles are entering the food chain via these animals in different parts of the island.

## A HIDDEN VOLCANO IN THE SOUTH AUCKLAND VOLCANIC FIELD: KARAKA VOLCANO

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Intraplate monogenetic volcanic fields litter the upper western North Island. Four geographically-related fields, approximately 38 km apart, young northwards from Raglan to Auckland. The South Auckland Volcanic Field (SAVF; 1.56–0.51 Ma) is older and more weathered than the Auckland Volcanic Field (AVF; active since 200 ka) across the Manukau Harbour. Located between the two fields and overlying the Late Pliocene to Mid Pleistocene pumiceous fluvial deposits of the Puketoka Formation is the newly discovered Karaka Volcano. Although local residents had referred to a volcanic landform in the area, it was in 2018 that evidence for a volcano based on geomorphology, a magnetic anomaly, weathered surficial deposits and water bore data was reported.

This talk will present the recent findings of the volcano-sedimentary geology of the Karaka volcano based on two new drill cores and a complementary resistivity survey. One drill core intersected an upper 6 m blanket of Hamilton Ash Formation and a lower 7 m succession of interbedded dark brown organic-rich silts, grey silts to sands and distal tephras. The lower succession is consistent with lacustrine or palludal sediments associated with a crater lake that had been inferred from lithologic and groundwater information from a nearby water bore within the geomorphic tuff ring. The second drill core, located on the central high point of the volcanic landform, intersected an upper ~6.5 m of brown and red clay, and a lower 9.5 m of volcanic ash coarsening downwards to basaltic lapilli ash deposit with a lithic-rich matrix, that represents a phreatomagmatic phase in the upper part of the volcanic sequence. No recognised volcanoes are within 5 km of this site so it is unlikely that this pyroclastic deposit came from elsewhere, despite its isolated location outside of the predefined margins of the SAVF and AVF. The weathering and thick distal composite ash succession that mantles this volcano is consistent with a SAVF age.

## **PASSIVE TREATMENT FOR ELEVATED FE IRON AND AS ARSENIC IN CIRCUM-NEUTRAL MINE AFFECTED WATER**

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OceanaGold's Globe Progress Mine, located near Reefton in New Zealand, is a hard rock gold mine which ceased operation in 2015 and is now in the closure phase. During operations an active water treatment plant was used to remove contaminants before release offsite. As the mine transitioned into closure, a site-wide water balance model based on sampling data identified the need for treatment of various water sources for arsenic and iron. Field trials were established in order to determine the most appropriate passive treatment option for post-closure. The trials consisted of four bioreactors in 15,000 L water tanks with different mixtures of organic media, including mussel shells and biosolids, which treated the combined underdrain water. A vertical flow reactor (VFR) was also trialled, which utilises oxidation of iron rich water to co-precipitate metals onto a non-reactive fine gravel bed, which then allows for adsorption of arsenic onto the ochre layer in which the precipitates form. Water from the combined tailings and PAG (Potentially Acid Generating material) Cell underdrains (median chemistry: 440 g/m<sup>3</sup> SO<sub>4</sub>, 1.66 g/m<sup>3</sup> As, and 29.5 g/m<sup>3</sup> Fe) was fed through the bioreactors at different hydraulic retention times (HRT). Although results were variable, they showed that removal of arsenic was greater in tanks with biosolids, with about 80% removal at 24h HRT. All tanks showed sulphate removal increased with HRT and tanks with biosolids removed approximately 10% more sulphate at all HRT. Water from the waste rock underdrain (median chemistry: 580 g/m<sup>3</sup> SO<sub>4</sub>, 0.16 g/m<sup>3</sup> As and 7.65 g/m<sup>3</sup> Fe) was fed through the VFR. Results from this showed iron removal above 90% and arsenic removal above 80% consistently at a 24h HRT. These results showed a VFR could remove adequate iron and arsenic with a small footprint and was deemed appropriate as a full-scale system.

## FORAMINIFERAL PROXIES FOR DISTINGUISHING DISPLACED TURBIDITE SEDIMENT AND IN-SITU HEMIPELAGITE

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Along the Hikurangi margin of New Zealand, turbidites are being investigated by paleoseismologists as potential proxies for the timing of major earthquake shaking events. Accurate dating of these turbidites is essential for possible correlation of deposits generated by the same earthquake event and potential identification of megathrust ruptures along a considerable length of the plate boundary. In the absence of tephra horizons, radiocarbon dating of large planktic foraminiferal tests is the next best option, but these need to be recently dead and not downslope-displaced mixtures of tests of older ages.

We have developed a relatively simple methodology using fossil foraminifera to distinguish between displaced or taphonomically-altered faunas and those that accumulated in-situ and contain tests suitable for dating. This methodology has three elements:

1. a comparison of the size distribution of the foraminiferal tests in the fossil fauna with modern in-situ bathyal-abyssal faunas;
2. use of a transfer function developed from a modern analogue database of modern in-situ faunas from around New Zealand that relates planktic foraminiferal % in a fauna to the water depth of deposition;
3. determining the relative abundances of six bathymetric groups of benthic foraminiferal genera in each fossil sample and using these to identify displaced tests and their bathymetric provenance or mixing.

This methodology has been tested on a number of core samples along the Hikurangi margin with initial results suggesting that only a small proportion of the sediment in the turbidite depocentres is in-situ hemipelagite and suitable for dating. Most displaced turbidite sediment contains a significant proportion of tests derived from depths shallower than 400 m.

**\*WE REQUEST THAT OUR FIRST NAMES BE RETAINED IN THE AUTHORS LIST AND IN THE PROGRAM AS AN AID TO ANY LATER COMMUNICATION FROM INTERESTED PARTIES.**

## IMAGING THE PLATE COUPLING AT THE HIKURANGI SUBDUCTION MARGIN, NEW ZEALAND

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Inter-plate coupling along the Hikurangi subduction margin along the east coast of North Island changes from weakly or partially coupled in the north to locked in the south. In the last 10 years magnetotelluric (MT) measurements have been carried out along the east coast to image the electrical resistivity at the depth of the subduction interface. These results show that there is a good correlation between the resistivity and strain rate determined geodetically. In the northern part of the subduction margin, we see a dipping electrically-conductive zone above the subduction interface which we interpret to be fluid- and clay-rich sediments within the subduction interface shear zone. A more resistive patch within this zone correlates with a similarly sized area of contractional strain seen in the GPS data. The resistive patch is interpreted as a fluid- and sediment-starved region of the subduction interface which is more strongly coupled. In the central part of the margin, where the transition from a partially-coupled to a locked interface occurs, the resistivity at the depth of the interface increases from north to south. Here, the upper plate is more conductive where the strain is extensional and resistive where contraction is occurring.

## UPPER-PLATE HETEROGENEITY ALONG THE SOUTHERN HIKURANGI MARGIN, NEW ZEALAND

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Active-source and passive seismic data are used to build a 3-D P-wave model for southern North Island, New Zealand, where the Pacific Plate subducts beneath the Australian at a rate of c. 41 mm/yr. Our analysis reveals an abrupt along-strike transition in overthrusting plate structure within Cook Strait. Contrast in properties ( $V_p$ ,  $V_p/V_s$ , and  $Q_s$ ) likely reflects the degree of deformation in the Australian plate, where the Alpine-Wairau and Awatere faults mark the northern boundary of a terrane that has undergone  $>50^\circ$  of clockwise vertical-axis rotation since the early Miocene. Heterogeneity of the crustal transition is likely associated with changes in frictional and elastic properties that may impact elastic stress accumulation and may also inhibit southward propagation of megathrust earthquakes. Low connectivity of faults in Cook Strait is consistent with the heterogeneity we observe and may promote complex earthquake triggering by lateral stress loading during earthquakes or slow slip events.

## **SHEAR WAVE VELOCITY STRUCTURE ALONG HIKURANGI FOREARC FROM CONVERTED WAVES**

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Compressional (P-) and shear (S-) waves are seismic body waves that travel through the interior of the earth. S-wavespeeds ( $V_s$ ) are slower than P-wavespeeds ( $V_p$ ).  $V_p/V_s$  ratio is a diagnostic property of a rock's degree consolidation and porosity. Typical  $V_p/V_s$  ratios of consolidated sediments and crystalline rocks are in the range 1.6 - 1.9 and unconsolidated sediments are in the range 2.0 - 4.0. The Hikurangi subduction margin, offshore of the east coast of North Island of New Zealand, displays along strike variations in subduction-thrust slip behavior (stick-slip in the south to aseismic creeping in the north) with episodic slow-slip events. This contrast has been hypothesised to be caused by spatial variations in porosity, potentially linked with elevated pore pressure. Ultra-long duration of seismic ground motion observed in the northern Hikurangi margin has also been linked with an extremely low  $V_s$  accretionary wedge. A better understanding of  $V_s$  structure is crucial to gain further insights into these phenomena.  $V_p/V_s$  ratios between 1.7 - 1.9 have been obtained from seismic tomography studies for the east coast of North Island and delay times of P- and S-waves recorded on ocean bottom seismometers (OBS) offshore in the Northern Hikurangi Margin. P to S converted waves can determine  $V_p/V_s$  more directly than tomographic methods, and the uncertainties can be more readily quantified. We identify converted S-wave arrivals from airgun shots on radial and transverse components of OBSs, considering their angle of incidence, ellipticity, linear moveout and absence on hydrophone component. These identified converted waves are forward-modeled by ray-tracing using the  $V_p$  model to derive the  $V_s$  model along the Hikurangi Forearc. We obtain  $V_p/V_s$  ratios of 2.0 - 2.5 for the sediments overlying the basement and 1.70 for the basement in the southern Hikurangi margin, consistent with typical values for unconsolidated and consolidated sediments.



## **GEOLOGICAL MAPPING FROM AERIAL SURVEYS USING LIDAR FROM AN ONBOARD-PILOTED AIRCRAFT SURVEY AND DIGITAL SURFACE MODELS FROM A REMOTELY PILOTED AERIAL SYSTEM**

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Data acquired by aerial surveys is an essential supplement to traditional ground-based geological mapping and provides spatial intelligence that could not otherwise be gained in a safe and timely manner. Aerial photography and Light Detection and Ranging (LiDAR) data collected by traditional onboard-piloted aircraft as well as remotely piloted aerial systems (RPAS, also known as drones) provide rich geological and topographical data. Here, we report on two New Zealand case studies employing these methods. A LiDAR survey near Murchison obtained from a piloted aircraft was used to create a digital terrain model (DTM) of the ground surface from reflected light pulses that penetrated the tree canopy of this densely vegetated region. Advanced terrain analysis showed moderately dipping bedding planes intersecting a deeply-incised topography in Paleogene-age sediments that revealed a folded 3D structure. We were able to trace lithological contacts from the data, measure many structural attitudes of bedding, and resolve the plunging geometry of the Tutaki Syncline. At Crawford Knob, near the Franz Josef Glacier, we used a RPAS consisting of a quadcopter fitted with a digital camera and GPS navigation to map geological features in the Alpine Schist lithologies. The aircraft was flown between 2 and 100 m above the ground providing real-world image pixel sizes (ground surface distance) of 0.7 to 40 mm, a significant (up to 400x) increase in resolution compared to traditional aerial photography. Structure from motion was used to create digital surface models (DSM) and detailed orthophotographs of outcrop exposures. These data were used to undertake remote structural measurements of faults and foliations using a semi-automated technique in 3D modelling computer software, and to map lithological units using GIS software. Results have been correlated with field observations. While some limitations were found, the RPAS survey provided geological data in locations that were previously inaccessible.

### **3D GEOLOGICAL MODELLING OF THE UPPER HUTT BASINS TO PROVIDE AN UNDERSTANDING OF LOCAL GROUND SHAKING HAZARD**

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To improve our understanding of the local seismic hazard in Upper Hutt City and surrounding areas we first need to understand the geometry of the subsurface basins, thickness and density of sedimentary deposits, and fault structures underlying the city. Utilising the wealth of geological data in the area, modern computer software, geophysical surveys, surface and subsurface data such as Light Detection and Ranging (LiDAR) and a new borehole database, we have developed a three-dimensional (3D) geological model. The model comprises seven Quaternary geological packages deposited into basins of eroded Rakaia and Kaweka terrane rocks. The Quaternary sediments are each distinguished by their sedimentary, geotechnical and geophysical properties. The model uses a single-sided fault-bound structure for sediments infilling the Upper Hutt, Witako and Mangaroa Valley basins. Borehole data and geophysical surveys, particularly from those holes that reach or surveys that interpret basement rock, were used constrain the basin geometry. From the 3D model, depth to basement and sediment thickness maps have been created, and using measured shear wave velocity ranges for sediments in Wellington, a 3D velocity model for the basins has been derived. The velocity model has been used to calculate site period maps that can be used as an indicator of the local ground shaking characteristics and potential. This model that can easily be tested by collecting and evaluating the horizontal to vertical spectral ratio (HVSR) and other geophysical data. The subsurface geometry of the Upper Hutt basins is complex and is less well understood than other basins in the Wellington region due to limited and dispersed datasets. More data such as borehole testing and geophysical surveys would be of benefit to future studies. Improved understanding of the basin geometry to inform us of local ground shaking hazard is an important adjunct for city planning and building construction.

## LITHIUM MINERAL POTENTIAL MODELLING IN THE TAUPO VOLCANIC ZONE

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Lithium is considered a clean-technology element due to its importance to the green technologies sector. In recent times, the consumption of lithium has increased substantially because of rising global demand for lithium-ion batteries. To date, no targeted exploration for lithium from hard-rock sources has been undertaken in New Zealand, and consequently there is a dearth of data available to assess the potential for lithium mineralisation. We have applied a mineral systems approach to mapping the lithium mineral potential in the Taupo Volcanic Zone (TVZ) based on a model for a hydrothermally altered rhyolitic lacustrine sediment-hosted (HARSH) deposit. The mineral systems model is based on international examples, and can be defined by four components: (1) ore source, mapped using fractionation indices and rock type; (2) fluid and focusing mechanism, mapped using current geothermal activity, presence of faults and fluid chemistry; (3) trap, mapped using known location of lacustrine sediments, presence of clay minerals and specific lithological units; and (4) surface expression, mapped using spring and groundwater chemistry and rock, stream and soil pathfinder and ore elements. Data were extracted from geological mapping and geo-analytical databases as well as sourced from various mineral reports and scientific publications. Additionally, 189 new geochemical analyses were undertaken that targeted drill core samples (specifically targeting lacustrine sediments) from legacy geothermal and epithermal exploration holes. Several samples had lithium concentrations >400 ppm, which until now was the highest published lithium concentration within a hard rock sample throughout the TVZ. The four mappable criteria listed above were combined using an expert-weighted, fuzzy logic spatial modelling approach to generate a lithium mineralisation potential map for the TVZ. This model depicts areas within the Mokai, Tauhara, Wairakei, Rotokawa, Ngatamariki, Ohaaki (Broadlands), Waiotapu and Rotorua active geothermal fields as having the highest potential for lithium mineralisation from a HARSH deposit.

## CHARACTERISING FLUID FLOW PROCESSES ASSOCIATED WITH FAULTS, GAS HYDRATE SYSTEMS AND COLD SEEP LOCATIONS IN THE SOUTHERN HIKURANGI MARGIN

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The Hikurangi Margin is New Zealand's largest gas hydrate province, with bottom simulating reflections abundant in water depths of >600 m. There is widespread evidence for active fluid flux across the region in the form of hydro-acoustic flares and observations of cold seep fauna and methane derived authigenic carbonates at the seafloor. Observations from seismic reflection profiles indicate that there is a significant relationship between extensive subsurface faults, the formation of concentrated gas hydrate deposits, and the location of cold seeps at the seafloor. However; the interconnectivity of the processes of deformation, fluid migration and hydrate formation is not yet fully understood.

Newly acquired 2D seismic data reveal numerous gas flow pathways and fault structures associated with concentrated gas hydrate deposits. In addition, we use multibeam bathymetry and backscatter data, combined with water column imaging, to investigate the distribution and characteristics of seafloor seeps. Underwater images also reveal extensive cold seep communities associated with venting sites, at a scale that was previously unknown in this region. The aim of this study is to characterise seep-related acoustic features in the sub-surface and water column and investigate their link with underlying tectonic features. We focus on several locations on the southern Hikurangi Margin, offshore Wairarapa, where concentrated hydrate deposits have been identified within accretionary ridges, in combination with active seafloor seeps. Integrating multiple seismic datasets, bathymetric data and seafloor observations allows us to characterise these dynamic systems. Results of this study will contribute to a better understanding of the distribution and formation of hydrate accumulations and associated fluid flow processes and is therefore a significant area of research with implications offshore New Zealand and elsewhere worldwide. Determining the distribution of hydrates is critical in evaluating their role in the carbon cycle, their potential contribution to hazards such as slope failure, and understanding the influence of fluid flow in fault movement.

## LITHOSPHERIC STRENGTH IN NEW ZEALAND FROM THIN-SHEET MODELLING

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We model the stress field driving lithospheric deformation in New Zealand by solving the stress balance equations in the context of a viscously deforming thin sheet for the deviatoric stresses and effective viscosities averaged over the thickness of the sheet. We inverted for the stress and viscosity fields according to the Flesch *et al.* method, using the gravitational potential energy field from crustal structure and topography and either a long-term strain rate field inferred from Quaternary faulting or a short-term field from GPS velocity measurements. Deviatoric stress magnitudes were found to be in the range 0-35 MPa, with mean values of  $13 \pm 1$  MPa, comparable to earthquake stress drops.

Gravitationally induced stresses account for approximately half of the full deviatoric stress. Effective viscosities are  $0.5-5 \times 10^{21}$  Pa s in the deforming zone, with an approximately inverse relationship between strain rate and viscosity.

Future work will improve on this by further developing the Haines and Sutherland method, which uses a faulted thin sheet to model lithospheric dynamics including stress and fault strengths. The method is two-part with a dynamics-derived *a priori* solution and a kinematic *a posteriori* solution which includes observations. The *a priori* parameters can be adjusted, based on the attained solutions, to better fit the observations and other constraints and the model inverted again. We will use this method combined with topography, fault slip-rates, and other observations to model stress and fault strength in the South Island.

## **ACOUSTIC INVESTIGATIONS OF POCKMARKS AND SUBMARINE GROUNDWATER DISCHARGE IN GASEOUS MUDDY SEDIMENTS**

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Submarine groundwater discharge into coastal areas is a common global phenomenon and is rapidly gaining scientific interest due to its influence on marine biology and the coastal sedimentary environment, and its potential as a future freshwater resource. We conducted an integrated study of hydroacoustic surveys combined with geochemical porewater and water column investigations at a well-known freshwater seep site in Eckernförde Bay (Germany).

The location and distribution of pockmarks in this area have been the focus of many studies since their discovery in 1966 including numerous investigations of their geochemical, geological and geophysical behaviour. Despite several intense and extensive research campaigns (e.g. Sub-GATE/CBBL) their internal morphology and structure presented in this study were poorly constrained to date. With recent advances in shallow high-frequency multibeam echosounder methods combined with highly accurately positioned sediment cores, we can provide new insights on the influence of shallow gas and freshwater on the formation and internal morphology of the pockmarks. We show that high-frequency multibeam data can be used to detect free shallow gas in areas of enhanced freshwater advection in muddy sediments. Intra-pockmarks, forming due to ascending gas and freshwater, pose a new form of 'eyed' pockmarks revealed by their acoustic backscatter response. Our data suggest that in muddy sediments morphological lows combined with a strong multibeam backscatter signal can be indicative of free shallow gas and the subsequent advection of freshwater.

## BEYOND 2°C: LESSONS FROM EARLY PALEOGENE ZEALANDIA

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If the current trajectory of carbon emissions continues, the Earth will likely transition through the 2°C warming threshold by 2040. Under a high growth/low mitigation scenario, much of the planet will experience Eocene-like climate conditions by 2100. Therefore, there is value in comparing high CO<sub>2</sub> climate model projections with climate data from the Paleogene (66 to 23 Ma). Although some boundary conditions were different, Paleogene climate provides a means to validate climate models in relation to climate sensitivity, meridional temperature gradients, carbon cycle feedbacks, biodiversity and biological productivity, broader regional climate impacts, and more.

In the late 1960s and early 1970s, studies of foraminiferal biogeography and the emerging science of oxygen isotope palaeothermometry established the broad trends in Paleogene climate for the Southwest Pacific. Progressive warming through the early Paleogene culminated in a prolonged period of peak Cenozoic warmth in the Eocene, prior to pronounced cooling in the earliest Oligocene due to the onset of major Antarctic glaciation. A pioneering study by Graham Jenkins identified four pulses of subtropical warmth in the Eocene, anticipating the discovery of Eocene “hyperthermals” by 30 years.

From the late 1990s, GNS Science researchers have worked with local and international collaborators to identify the local expression of global climatic and biotic events in the early Paleogene, including the Paleocene-Eocene thermal maximum (PETM) and the early Eocene climatic optimum (EECO). Some lessons learned include: mid-Paleocene circulation and temperature gradients are comparable to present day despite different boundary conditions; anomalous warmth during the PETM and EECO suggesting major southward expansion of tropical waters; relatively stable floral and faunal assemblages during the early Paleogene suggesting resilience of terrestrial and marine ecosystems; climate model-data comparisons suggesting that climate sensitivity may increase as CO<sub>2</sub> increases, implying that current projections underestimate the level of future warming under high growth scenarios.

## DECIPHERING SOUTHWEST PACIFIC EOCENE TEMPERATURE PROXY MISMATCHES

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Researchers within the Deep-time model and data intercomparison project (DeepMIP) have recently outlined the recommended methods for generating temperature estimates from geological archives and compiled available temperature data for the latest Paleocene and early Eocene. These methods and data allow us to revisit the reasons for mismatches between Eocene temperature estimates from marine and terrestrial proxies for the southwest Pacific region. Super-warm early Eocene temperatures derived from marine proxies have been difficult to reconcile with cooler modelled temperatures and are 10–15°C warmer than temperatures derived from terrestrial proxies. Although the DeepMIP team expressed reservations about deriving temperature estimates from brGDGTs in marine sediments, we find a correlation between mean annual air temperature (MAAT) estimates derived from the MBT-CBT proxy and new estimates derived from bioclimatic analysis (BA) of pollen and spore assemblages in the marine mid-Waipara section, both of which indicate that MAAT was no warmer than 20–22°C during the early Eocene climatic optimum (EECO) in mid-latitude Zealandia (46°S). In contrast, estimates for peak sea surface temperature (SST) derived from Mg/Ca ratios and TEX86 (BAYSPAR) at the same locality range from 27° to 34°C, respectively. We contend that three factors explain these offsets: (1) a 2–3°C cool bias in MAAT due to greater seasonality and an altitudinal effect; (2) a summer bias in all SST proxies of ~4°C; (3) a “Red Sea” effect on TEX86-derived SSTs (~4°C higher than other SST estimates where TEX86 > 0.75). In summary, revised estimates for peak Eocene warmth in Zealandia are consistent with warmer simulations from the current generation of Eocene climate models, with mean annual temperatures of ~24–25°C and summer temperatures of 28–29°C. The BA-derived temperature record helps peak EECO warming in the mid-Waipara section: abrupt warming occurs at ~52 Ma and gradual cooling begins at ~49.5 Ma.



## CHARCOAL LAYERS IN THE SAND: PREHISTORIC LANDSCAPE MODIFICATION IN THE MANAWATŪ SAND COUNTRY

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The Manawatū sand country is the largest area of coastal sand dunes in Aotearoa-New Zealand. It has a long history of human habitation. Recently, excavations in the vicinity of Foxton, associated with a major roading project, revealed the existence of distinctive, charcoal-rich layers below the surface on some of the dunes in the area.

The dunes investigated lie within an area mapped as the Foxton Phase (dated at 1500 – 6500 cal yrs BP). The number and thickness of the layers varied considerably within the 10 hectare excavation area, with some dune faces having as many as 10 layers (ranging in thickness from a few centimetres, to up to 30cm or more), and other dune faces having none at all. As far as we are aware, this phenomenon has not been formally reported in the literature from anywhere else in Aotearoa-New Zealand.

The irregular distribution within the excavation area suggests that these layers are not the result of natural fires, but instead represent human activities. This is supported by radiocarbon dating, indicating they formed within a short period during the 15<sup>th</sup> – 16<sup>th</sup> centuries. It is our interpretation that these layers represent deliberate and selective firing of the landscape to encourage the growth and regeneration of aruhe (bracken fern, *Pteridium esculentum*), used by Māori as a source of carbohydrate. This supported by palynological data, specifically the presence of *Pteridium* spores within the layers.

While the idea of prehistoric bracken fern cultivation is not novel, these layers do represent an important new avenue of physical evidence for human presence within sand dune landscapes in Aotearoa. Future developments within the sand country will therefore need to consider how natural and cultural elements of the landscape are distinguished and in some cases such distinctions may not be appropriate or even possible.

## **MAKING THE MICRO MACRO: USING 3D PRINTED POLLEN MODELS FOR TEACHING**

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3D printing is a potentially transformative technology for education. 3D printers are now readily accessible, affordable, and the cost of materials are minimal. The combination of 3D scanning technology and 3D printing allows the production of scale models: microscopic objects, such as microfossils (pollen, foraminifera, diatoms) can be made large; and very large objects (such as megafaunal fossils) can be made small. Plus rare or very fragile specimens can be duplicated and made available for handling, with little risk to the original. Furthermore, the relatively low cost of 3D printing means that class sets of scale models can be generated with little departmental outlay.

But what impact do these models have on students' learning? This presentation will use palynology as a case study example of how 3D printed models can enhance students' learning experiences. Palynology has been crucial to unravelling the Quaternary vegetation and climate history of Aotearoa-New Zealand, and therefore is a common component in undergraduate and postgraduate earth science and geography programmes at Universities in New Zealand and worldwide. Students are typically required to become familiar with the morphology of a variety of pollen types. Pollen grains are three-dimensional objects, and may feature intricate surface patterning and complex aperture arrangement. However, students often struggle to appreciate pollen grain morphology when viewing them in 2D, as seen under a basic transmitted light microscope in the teaching lab environment, and this can make pollen identification daunting.

Discussions with, and survey responses from, students enrolled in a 3rd Year Quaternary Biogeography course at Massey University have indicated that 3D models provide a number of benefits which serve to support and enhance the more 'traditional' ways of learning pollen morphology. The ability to hold and manipulate a physical model facilitates deeper engagement with pollen morphology concepts.

## **DEVELOPING A MAJOR AND TRACE ELEMENT GEOCHEMICAL REFERENCE SET FOR NEW ZEALAND QUATERNARY RHYOLITIC TEPHRA DEPOSITS**

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Tephrochronology is the principle whereby volcanic-ash (tephra) deposits are used as stratigraphic marker horizons (isochrons) for linking, dating, and synchronizing deposits and events in the geological or archaeological record. It relies on tephra deposits being unequivocally correlated, commonly through geochemical characterisation of constituent glass shards, a technique called “fingerprinting”.

Most previous studies have generally provided limited glass-shard-derived geochemical data, mainly major element concentrations. Moreover, such analyses are often presented as means and standard deviations, limiting the potential to extend correlations to new deposits and to apply statistical correlation techniques. Recent studies have shown that trace element concentrations in glass shards can provide a more discerning fingerprint tephra deposits where major elemental analyses are too similar to allow them to be distinguished. Therefore, the development of a full geochemical reference set for many of the most widespread Quaternary-aged tephra deposits in New Zealand will provide a valuable asset for a wide range of future correlational and chronological studies. Here we present the details of our proposed study. We will target the commonly found distal tephtras derived from the large rhyolitic eruptions of the Taupo Volcanic Zone (TVZ) (together with some eruptives of Tuhua/Mayor Island) including the most recent (Kaharoa, ~1314 AD) through to some of the earliest (e.g. Pakihikura, ~1.63 Ma). The glass shards will be extracted and analysed for major elements using the electron probe microanalysis; with the same shards analysed for trace elements using laser ablation inductively coupled plasma-mass spectrometry. Both analytical techniques will be undertaken at Victoria University of Wellington. These will be the first trace element analyses of glass for many widespread tephtras in New Zealand. As well as generating valuable data for stratigraphic and chronological studies, the data will also provide insight into the geochemical evolution of the large rhyolitic eruptions of central TVZ.

## TOWARDS A COMPREHENSIVE TEPHROSTRATIGRAPHIC FRAMEWORK FOR QUATERNARY RHYOLITIC VOLCANISM IN NEW ZEALAND: EMPLOYING CRYPTOTEPHRA METHODS TO FIND THE HIDDEN ERUPTIONS.

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The Taupo Volcanic Zone (TVZ) is currently one of the most active volcanic systems on Earth. Thought to have initiated ca. 1.6 Ma, it has produced numerous supervolcanic eruptions. However, our understanding of the eruptions from this system are skewed towards the last 61,000 years due to the preservation bias of proximal, younger, larger deposits. Therefore, a high percentage of the TVZ eruptive history is unknown; thus, existing magnitude-frequency models may underestimate the recurrence of the TVZ eruptions. Macro- and crypto-tephra deposits situated downwind of the TVZ (onshore and offshore eastern New Zealand, ~50 – 200 km from source) offer the potential of augmenting the existing record of volcanism. However, the disjointed nature of tephra horizons in the terrestrial record, coupled with large uncertainties in dating methods, mean that producing a comprehensive record from onshore deposits is challenging. In addition, existing offshore marine cores are either proximal ( $\leq 250$  km) and short ( $<6$  m,  $\leq 30$  ka), or long but distal and therefore only preserve the largest events. To resolve these limitations, we present preliminary results from a new, combined onshore- and offshore-study.

Macroscopic tephra deposits identified within 4 new, long cores, recovered from land-proximal (~200 km) marine sites, are analysed for their major elements compositions. These are then correlated to well-defined onshore marker horizons, to provide a robust chronological framework for the cores. In order to develop an efficient way to determine the location of the cryptotephra deposits within the cores we investigate identification methods using novel core scanning techniques (photographic and X-ray density imagery, magnetic susceptibility and density measurements, and elemental profiles by X-ray Fluorescence). We present the components of the scan data that highlight the macroscopic tephra horizons, then use these and semiquantitative petrography to locate potential cryptotephra horizons. They will then be analysed for major, and where possible trace element compositions, to allow correlations to be made. This will produce a comprehensive overview of the eruptions from the TVZ, and result in a database of geochemically referenceable, stratigraphically constrained tephra marker horizons for Quaternary eruptions of New Zealand.

## **COUPLED ERUPTIONS IN THE AUCKLAND VOLCANIC FIELD: ARE WE UNDERESTIMATING THE THREAT TO OUR CITY?**

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Volcanic fields are pervasive across the globe and are made up of tens to hundreds of small-scale volcanic centres. Each centre is considered independent, formed by a single eruption of a single magma batch. However, recent research has proven this concept too simplistic; multiple magma geochemistries have been identified in a single centre, and the existence of “flare-ups” in eruptions have been observed through improved chronologies. This evidence implies a potential for multiple eruptions occurring close in space and time – a concept currently overlooked in hazard and risk modelling.

Coupled eruptions, those occurring  $\leq 1$  km and  $\leq 1$  kyrs apart, are identified in the Auckland Volcanic Field; 20 (38%) of 53 show this relationship. We discuss the attributes that characterise their relationships through spatial, temporal, and geochemical analysis. There are two structural controls on the location of the couplets; (1) interaction with the Dun Mountain Ophiolite Belt (DMOB) providing a pathway between the crust-mantle boundary and shallow crust, and (2) NNE-SSW trending faults in the shallow crust (Murihiku and Waipapa terranes) providing a route to the surface. The temporal relationships show repose periods of  $\leq 50$  yrs for most centres. Geochemical results split the coupled centres into two groups; (1) couplets showing a consistent, systematic geochemical evolution from the first eruption to the second eruption, and (2) couplets that have the same geochemical signatures. The geochemical relationships for group 1 and 2 couplets are attributed to variabilities in partial melting linked to differing heterogeneous mantle sources.

We conclude that coupled eruptions are indeed linked both spatially, temporally and geochemically, and are not uncommon in the AVF. This has major implications for hazard and risk models of a future eruption, which has the potential to migrate laterally on a potentially predictable trajectory.

## GEOMETRY CAUSES TEMPORAL CLUSTERING OF GREAT EARTHQUAKES ON A TRANSFORM PLATE BOUNDARY FAULT

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Minor changes in geometry along the length of mature strike-slip faults may act as conditional barriers to rupture, terminating it in some instances and allowing it to pass in others. This hypothesis remains largely untested because paleo-earthquake data that constrain spatial and temporal patterns of fault rupture are generally too incomplete. Here we develop earthquake records from lake and near-fault swamp records that encompass the last 18 earthquakes along ~320 km of the Alpine Fault in New Zealand, with sufficient temporal resolution and spatial coverage to reveal along-strike patterns of rupture extent. The paleo-earthquake record shows earthquake terminations tend to cluster in time near minor along-strike changes in geometry. These terminations limit the length to which rupture can grow and produce two modes of earthquake behaviour characterized by phases of major (Mw7-8) and great (Mw>8) earthquakes. Physical simulations of the seismic cycle produce synthetic earthquake catalogues that closely resemble our observations. Spatial and temporal clustering of rupture terminations is caused by heterogeneous stress states that evolve over multiple seismic cycles in response to along-strike differences in fault strike of 7° and dip of 30°. These geometric complexities exert a first-order control on rupture behaviour that is not currently accounted for in fault source models for seismic hazard. Our work demonstrates that simple physics-based models with sufficient computation efficiency to run on 3D fault networks relevant for seismic hazard can replicate complex real world fault behaviour. When combined, the paleoseismic record and physics-based simulations allow us to forecast not only the probability of Alpine Fault rupture within the next 50 years, but also the likely magnitude and spatial extent of the next earthquake. Our new understanding has implications for future Alpine Fault research, managing the hazard poised by the fault and modelling seismic hazard beyond the 'one fault, one earthquake' paradigm.

## REPEATING EARTHQUAKES AROUND THE RAUKUMARA PENINSULA, NORTH ISLAND, NEW ZEALAND

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Repeating earthquakes can provide useful insights into fault-zone processes operating at seismogenic depths. Characterising these processes is important for seismic hazard analysis and for understanding interactions between different types of seismicity. We have conducted an exhaustive search of the New Zealand national earthquake catalogue to identify well-correlated events. We first clustered the catalogue by distance, before undertaking initial correlation analysis of each cluster to search for potentially repeating events. From this initial nationwide catalogue of possible repeaters, we focused on clusters surrounding the Raukumara Peninsula, North Island. The Raukumara Peninsula has experienced a range of transient deformation phenomena during the last decade, including repeated slow-slip and moderate shaking caused by nearby large earthquakes. In our work to date we have focused on refining the criteria used to identify and classify repeating earthquakes in New Zealand, and these criteria will be used in future searches in other regions. We have targeted earthquakes recorded by GeoNet between 2004 and 2018, which provides the longest-duration data-set from continually running seismic stations and allows for the comparison of waveforms at multiple locations. In order for events to be identified as repeating, we require their waveforms to have a cross-correlation and/or coherence of at least 0.96, at two or more stations. Additionally, precise relative locations of all the events were computed to confirm overlapping source locations. Once repeaters were identified, we constructed a catalogue of event locations and magnitudes for each repeating family around the Raukumara Peninsula. This has revealed that the events are predominantly occurring in the upper plate, at depths shallower than 15km, rather than along the subduction interface. Repeating earthquakes can now be added to the diverse range of seismic phenomenon already observed in this region.

## AMOUNT AND WIDTH OF SURFACE RUPTURE ALONG THE SAN ANDREAS FAULT IN THE 1906 SAN FRANCISCO EARTHQUAKE, SAN FRANCISCO PENINSULA, CALIFORNIA

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The location, surface displacement amount, and rupture width of the **M7.8** 1906 San Andreas fault (SAF) surface rupture was evaluated at two locations on the San Francisco Peninsula as part of an assessment of the surface fault rupture hazard to buried gas pipelines. Fault location and width evaluations were based on the interpretation of 1906 post-earthquake observations, review of 1906 historical photographs and topographic maps, measurements from a fault-offset tunnel reoccupied in the 1920s, stereo aerial photographs from the 1940s to early 2000s, swath bathymetry published in 2010, and LiDAR from 2014. At the Upper Crystal Springs Reservoir, reconstructions of the 1906 fault rupture in the 1980s had at least two 1906 coseismic surface ruptures. This analysis confirms that the 1906 SAF surface rupture at the Upper and Lower Crystal Springs dam was on a single, northwest-striking (N36°W) fault located within the Franciscan Complex rocks and had a right-lateral displacement estimated at  $2.68 \pm 0.18$  m. The SAF rupture width was about 6.1 to 10 m in rock, increasing to 11 to 14.6 m at the dam surface. Analysis of 1906 photographs confirms the absence of significant secondary fault displacement for the 1906 rupture at this location. At a location about 10 km northwest, post-earthquake surveys, georeferencing of 1906 maps and 1940s aerial photographs reveal a total of 5.15 m purely horizontal right-lateral displacement distributed across a 366-m-wide zone that includes two discrete surface ruptures and 1.83 m to 2.13 m of deformation distributed across a 128-m-wide zone to the northeast of the main 1906 surface trace. The analysis at these two locations confirms that detailed post-earthquake documentation of the location and amount of surface fault rupture and the wider deformation zone is not only critical to understanding earthquake source mechanics but can also support future engineering analysis for critical infrastructure.



## THE 2019 TAUPŌ SEISMIC SWARMS: MAGMATIC, TECTONIC OR BOTH?

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Taupō volcano, New Zealand, hosted Earth's most recent supereruption (~25.4 ka) and at least 28 smaller eruptions have occurred since. Geochemical analysis of erupted magmas suggests that a substantial magma reservoir, capable of producing significant eruptible volumes, exists beneath the present-day composite caldera, now infilled by and concealed beneath Lake Taupō. Taupō thus poses a large potential hazard to New Zealand's population and economy, yet relatively little is known about unrest in the magma system and how it interacts with the regional tectonics. The Taupō region lies within an area of active rifting (ca. 8 mm/yr) and is seismically active. In 2019, Taupō has been exceptionally seismically active, with several seismic swarms consisting of many hundreds of individual earthquakes. In particular, in September a seismic swarm was initiated by magnitude 5.2 earthquake, the largest that has occurred in the region for at least 35 years. Through the detailed analysis of earthquake locations, moment-tensor solutions, waveform frequency content and comparisons with petrologically constrained depths to the magma system, we can distinguish between tectonic- and volcanic-related activity. Earthquake locations illuminate the presence of newly identified faults and deforming magmatic features in the mafic recharge zone of the rhyolite mush system. Moment-tensors reveal that a large proportion of the 2019 seismic activity is directly driven by deformation within the Taupō magmatic system, and that this system is interacting with tectonic structures. Our work provides new constraints on this active volcanic system and important insights into non-eruptive volcanic unrest at Taupō volcano.

## VELOCITY CHANGES IN COOK STRAIT FOLLOWING THE 2016 KAIKŌURA EARTHQUAKE

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In the last ten years, decreases in relative seismic velocity have been observed after numerous moderate to large earthquakes in many settings (Napa Mw 6.0, Darfield Mw 7.1, Tohoku Mw 9.0). We present ambient noise velocity variations associated with the 2016 Kaikōura earthquake measured on 12 permanent GeoNet seismic stations surrounding Cook Strait. Although station-paths crossing Cook Strait are subject to a complex internal noise field, we recover robust cross-correlations. All three station-channels are used to calculate 9 component cross-correlations. Cross-component pairs have broadly similar trends to the vertical component (ZZ) cross-correlations, and we present results of stacking all 9 components. Shallow velocities in the top 10 km (0.1-1 Hz) decreased 0.04% at the time of the earthquake and a gradual recovery took place over at least two years. The small magnitude of the change is unsurprising given the long inter-station path lengths and our interest in the fringes of the fault rupture (Cook Strait). We model seasonal change on the order of 0.02% to more clearly identify tectonic changes and we investigate signals of other moderate earthquakes in the time series between 2015 through 2018. The effect of variations to the definition of the “reference time” period that is used to measure relative velocity changes is also examined.

## **DYNAMIC SITE CHARACTERISATION OF THE WAIKATO BASIN USING PASSIVE AND ACTIVE SURFACE WAVE METHODS**

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Despite the relatively low seismicity, the impact of a moderately large earthquake is expected to be high in the Waikato region when its fourth-largest regional population and economy and high-density critical infrastructure systems are taken into consideration. Furthermore, Waikato has a deep soft sedimentary basin, which increases the regional seismic hazard due to trapping and amplification of seismic waves and generation of localised surface waves within the basin. This phenomenon, known as the “Basin Effect”, has been attributed to the localised damage in numerous historic earthquakes, including the 2010-2011 Canterbury earthquakes. To quantitatively model the basin effect and improve the understanding of regional seismic hazard, we developed a preliminary model of the fundamental site period ( $T_0$ ) and the depth-to-basement model of the Waikato Basin using the Horizontal-to-Vertical (H/V) spectral ratio technique and existing petroleum exploration logs in the region. Currently, we are refining the basin model using deep shear wave velocity profiles obtained by surface-wave based geophysical methods across the Waikato basin. The newly developed seismic velocity model of the Waikato basin will enable a better understanding of the regional seismic hazard and help estimate the level of damage across the region for a given earthquake scenario.

## **A FIELD - BASED UNIVERSITY ENTRANCE QUALIFICATION UNDERPINNED BY EARTH SCIENCE.**

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Te Aratika Academy are delivering an NCEA Level 3 programme which builds upon the benefits of field based studies to integrate Earth Sciences accreditation with Physical Education, Geography, Biology, Technology and Mathematics.

In addition, research on exoplanets is integrated with Physics so that E&SS becomes the foundation subject for a comprehensive STEM based pathway to a University Entrance qualification.

The University Entrance pathway has 14+ credits in E&SS, 14+ in Combined Science and 14+ in either Physical Education or Geography (both of which leverage off the field based work and the use of ArcGIS).

Additional credits needed to complete University Entrance includes Achievement/Unit Standards in Mathematics, Infrastructure and Science.

Field work focuses on locations in the Kaweka Ranges, Heretaunga Plains and Tongariro National Park - providing opportunities for learners to acquire tramping/navigational skills and learn DoC hut etiquette.

The NIWA SHMAK\* resource is used to conduct a series of Investigations around the measurement of water quality in the Kaweka Ranges and at numerous locations downstream as waterways pass through farmland and vineyards on the Heretaunga Plains.

Field work within Mangatepopo Valley and tephra observations in the vicinity of Waihohonu Hut assists with the determination of the age of Ngauruhoe.

Detailed discussion about radiocarbon dating provides a pathway into Modern Physics which is further developed within the Space module when considering how spectra, gravitational lensing, and Doppler shift are used to discover exoplanet properties.

Peer reviewed ubiquitous eLearning and field trips form the basis of delivery with numerous practical options. There is a genuine intent to align with Matauranga Māori and create meaningful relationships between science and māori.

The NCEA Level 3 Standards assessed include:

AS91410, AS91411, AS91412, AS91415, AS91522, AS91525, AS91527, AS91601, AS91500, AS 91501, AS91504, AS91505, AS91430, AS91431, AS91432, AS91433, AS91483, US8096, US27388, US27500

\*Stream Health Monitoring and Assessment Kit

## CRUCIAL METALS OF ZEALANDIA'S ULTRAMAFICS; NI, CO, CU & ZN IN EXPOSED MANTLE ROCKS

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As technology advances towards clean energy production, the demand for crucial metals—often called ‘critical elements,’ ‘green metals’ or ‘clean tech minerals’—is more paramount than ever before. This study aims to investigate several of these targeted elements, Ni, Co, Cu and Zn, as they exist in surface exposures of lithospheric mantle rocks within Zealandia.

While primary extractable concentrations of crucial metals unequivocally reside in ore deposits, Earth’s mantle is an important reservoir for crucial metal retention and eventual distribution into the crust. New Zealand hosts a unique array of exposed deep-Earth ultramafic bodies. Utilising a suite of Zealandia continental and oceanic mantle rocks at varying degrees of chemical enrichment and metasomatic alteration, we explore Ni, Co, Cu & Zn in peridotites, pyroxenites, chromitites and serpentinites. This study investigates crucial metals by measuring whole rock concentrations, element-mapping in-situ samples, and analysing both major mineral phases (olivine, pyroxenes and spinels) and samples’ fine sulphide and alloy mineral sites. Synthesising SEM, LA-ICP-MS, Synchrotron XFM, and bulk rock chemistry by ICP-AES, informs the investigation into the residence and abundance of Ni, Co, Cu & Zn in Zealandia ultramafics from whole rock to mineralogical scales.

Bulk rock data reports crucial metal concentrations as high as 2900ppm Ni (ophiolitic dunite), 213ppm Co (ophiolitic chromitite), 230ppm Cu (serpentinite), and 280ppm Zn (ophiolitic chromitite). SEM analyses identify fine metallic mineralisation as predominantly Ni-Fe and Cu sulphides, and rarely Ni-Fe alloy phases, which occur as varied species and often contain minor or trace Co. XFM element maps show that spinels host the highest concentrations of Zn, and chromite spinels are specifically enriched in Co; olivines are relatively enriched in Ni, and Ni-sulphides tend to be associated with olivine preferably over other available phases, while Cu-sulphides tend to be associated with orthopyroxene, or spinels when orthopyroxene is absent.

## **THE NCTIR PROJECT – RESPONSE, RECOVERY AND RESILIENCE OF THE NORTH CANTERBURY TRANSPORT CORRIDOR**

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The 14 November 2016, M7.8 Kaikoura earthquake severely damaged the North Canterbury region. The earthquake resulted in significant ground shaking triggering widespread landslides, extensive coastal uplift on multiple faults, and a locally sourced tsunami. The earthquake caused significant damage over a very large area, closing both State Highway 1 and the Main North Rail Line between Picton and Christchurch.

The North Canterbury Transport Infrastructure Recovery (NCTIR) was set up by the government under the Hurunui/Kaikoura earthquakes Recovery Act 2016. The scope of the NCTIR project included reconnection of the road and rail links from Kaikoura to Picton, which provide critical transport routes for freight and tourism industries to Kaikoura as well as vital access for many local communities.

Reconnection of the transport corridor included:

- Immediate response to remove debris from the transport corridor and temporarily repair/reinstate other damaged assets
- Design, construct risk mitigation works to meet the requirements of KiwiRail and the NZ Transport Agency
- Maintenance of the safety of the public and workforce throughout
- Improvements to the future Resilience of the transport corridor

The aim of this presentation is to provide an overview of the engineering geological aspects that were considered and assessed on the journey in the NCTIR project from Response, to Recovery, and then to improvement of Corridor Resilience, and the lessons learnt along the way.

## TIMING (PIRIPAUAN) OF THE END OF CRETACEOUS SUBDUCTION IN NEW ZEALAND

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Setting aside the tectonic development of the modern plate boundary through New Zealand, arguably, the next most important tectonic problem is the Cretaceous timing of the end of subduction along the New Zealand sector of Gondwanaland. Unlike the beginning of subduction, its end is characterized by cessation of tectonic activity (e.g. magmatism, accretionary wedge progradation) and a transition to subsidence and retrogradation (stratigraphic onlap).

In this talk I will re-assert evidence for the end of subduction during the Piripauan Stage around 86 Ma based on: (i) new radiometric age data (zircon U-Pb and fission track) from the youngest part of the accretionary wedge (Pahau subterrane and Pahaoa Group), (ii) reinterpretation of the formation of the unconformity between “basement” and overlying slope basin deposits in Raukumara Peninsula, and (iii), the timing and magnitude of 90-85 Ma uplift and erosion from fission track modeling of data from basement samples from the accretionary wedge in Raukumara Peninsula.

In this context, mid-Cretaceous shortening in the forearc region is concurrent with extension in the arc terrane, as is the case currently in North Island, in contrast to the notion that the whole of the New Zealand platform went into extension at 100 Ma. In relation to the timing of docking of the Hikurangi Plateau with the accretionary wedge, the only evidence upon which we can rely is that it was there at c. 86 Ma.

## ELASTIC AND MAGNETIC PROPERTIES OF HYDROTHERMALLY ALTERED VOLCANIC ROCKS

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Hydrothermal alteration processes often predispose volcanic edifices to catastrophic collapses and affect eruption dynamics. Seismic and magnetic field data are used to monitor and study the internal structure of volcanoes but interpreting how rock alteration manifests in geophysical signals still remains a challenge. To address this challenge, we aim to create a laboratory dataset of both the measurable petrophysical properties of variably altered volcanic rocks and their corresponding elastic and magnetic geophysical signatures. To create this dataset, we are using one hundred representative samples of variably altered volcanic rocks from the surface outcrops and ballistics of White Island (Whakaari) and block and ash flow and debris avalanche deposits of Mt. Taranaki.

Our initial measurements show that samples from White Island contain secondary minerals characteristic of acid-sulphate type alteration. Their ambient connected porosities range from 2% to 72.9%, P-wave velocities ( $V_p$ ) from 2.2 to 4.9 km/s and S-wave velocities ( $V_s$ ) from 1.4 to 2.9 km/s. Although,  $V_p$  and  $V_s$  follow a general inverse trend as a function of connected porosity, deviations in this trend due to mineral densities seem to be controlled by the amount and type of alteration minerals present in the samples. Furthermore, results of magnetic properties show that the samples from White Island have relatively lower mass specific susceptibility (ranging from  $-0.005 \times 10^{-6}$  to  $7.2 \times 10^{-6} \text{ m}^3/\text{kg}$ ) compared to less altered samples from Mt. Taranaki (ranging from  $0.3 \times 10^{-6}$  to  $33.5 \times 10^{-6} \text{ m}^3/\text{kg}$ ). The intensity of Natural Remanent Magnetisation of these samples range between 0.006 A/m to 66.11 A/m. Ongoing work aimed at quantifying the intensity of alteration of these samples will provide further insight into their magnetic mineralogy.

Our laboratory-based dataset will aid interpretation of field-scale seismic and aeromagnetic data acquired over stratovolcanoes in New Zealand and around the world.



## CHARACTERISTIC OF FAULT FORM IN THE FOCAL AREA OF THE 2016 MW7.8 KAIKOURA EARTHQUAKE INFERRED FROM HIGH PRECISION AFTERSHOCK DISTRIBUTION

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On November 14, 2016, an earthquake with Mw7.8 occurred in northeastern South Island, New Zealand (Kaikoura earthquake). The main characteristic of this earthquake is that the rupture process was complex involving many faults. Previous studies (e.g., Clark et al., 2017) pointed out that the aftershocks are strike-slip or reverse faulting and occurred on more than 20 faults in the focal area of this earthquake. Previous studies have relocated aftershocks using double-difference techniques and found multiple fault segments (Mouslopoulou et al., 2019; Lanza et al., 2019). However, more precise fault geometry than the preceding studies is required to consider relations between co-seismic fault behaviour and observed surface breaks. In this research we analysed seismograms observed at seismic stations including temporary stations deployed close to the rupture area before the mainshock. We adopted the double-difference earthquake relocation algorithm (Waldhauser and Ellsworth, 2000) and time-domain waveform cross-correlation (Poupinet et al., 1984) to determine precise hypocenter locations.

The results show that the scattering of the hypocentres was reduced compared to those without the temporary station data and the depths are concentrated around 15 km. The major alignment of the aftershocks was oriented northeast-southwest, and it was connected to small clusters of about 10 km on a side. From aftershock relocations we identified 10 or more faults. The arrangement of aftershocks was consistent with the seismic focal mechanisms.

## HISTORICAL SURFACE RUPTURE OBSERVATIONS CONFIRM RELATIONSHIP BETWEEN CURVED SLICKENLINES AND THE DIRECTION OF RUPTURE PROPAGATION

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Temporal changes in slip direction are common during large-magnitude earthquakes and are preserved as curved slickenlines on fault surfaces. Spudich et al. (1998, *BSSA*) used the curvature of slickenlines from the  $M_w$  7.2 Kobe earthquake to infer the magnitude of shear traction on the Nojima fault surface. Aside from this pioneering work, the potential link between curved slickenlines and the dynamics of earthquake rupture has received little attention. Following the  $M_w$  7.8 Kaikōura earthquake, we observed curved striae up to 6 m long on exposed surfaces of the Kekerengu fault. Using simulations of spontaneous dynamic rupture on a vertical strike-slip fault, we show that temporal changes in rake are driven by vertical stresses along mixed-mode rupture directions produced within the process zone. We demonstrate that slip-path convexity is sensitive to the direction of rupture propagation (Kearsse et al., 2019, *Geology*). Our hypothesis is consistent with the convexity of slickenlines on both the Kekerengu and Nojima faults, and the known rupture direction during those events. If proven robust, this theory will provide a tool for geologists to extract rupture direction from the paleo strike-slip earthquakes. We test our hypothesis with geological data (both historical and contemporary) that document changes in slip direction during a surface-rupturing earthquake. We incorporate events such as the  $M_w$  7.9 Wenchuan,  $M_w$  6.6 Fukushima, and  $M_w$  7.1 Ridgecrest earthquakes. To investigate relationships between slip path convexity and the direction of rupture propagation, we require mainshock hypocentres for each event. By expanding our previous simulations to include dip-slip earthquakes, we show that slip path convexity at the free surface during dynamic rupture is sensitive to the rupture direction for all faulting mechanisms. This generalized hypothesis is supported by available geological and seismological data, providing necessary validation for earthquakes geologists seeking to constrain paleo rupture direction from geological observations.

## A CONDUIT FILLED WITH HYDROTHERMAL BRECCIA AND SELF-CLOSING CRACKS RECONSTRUCTED FROM BALLISTICS FROM WHAKAARI (WHITE ISLAND)

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Ballistics from hydrothermal eruptions are varied in physical properties hinting at an origin from a complex hydrothermal eruption conduit. Hydrothermal eruption conduits are dynamic systems where pressures frequently exceed critical failure thresholds, generating earthquakes, transmitting fluids, and necessitating the systematic study of transiently permeable fractures. We collected ballistics of lava, ash tuff, and lake sediment with varying degrees of alteration, veining, and brecciation from the hydrothermal eruption of Whakaari in 2016. Many samples were progressively altered and veined from outside inwards with anhydrite, silica polymorphs, sulphur, and alunite. We measured connected porosity, uniaxial and tensile strength, and permeability at a range of confining pressures. We additionally created tensile fractures in select samples and measured their cracked permeability over a range of confining pressure. Our results show a large range of connected porosity, permeability, and strength. In contrast, the cracked samples show a consistently high permeability with a much smaller range of permeability at low confining pressure. The permeability of the cracked unaltered samples decreased by less than an order of magnitude as a function of increasing pressure up to 30 MPa. However, the cracked altered samples show a permeability that progressively decreases by up to three orders of magnitude with increasing confining pressure.

Textural evidence in the ballistics depicts a conduit composed of a polyolithic hydrothermal breccia, with extensive evidence of tensile and explosive fracture and hydrothermal cementation. The permeability of our altered ballistics is significantly lower than surface rocks, illustrating that mineral precipitation in the conduit has blocked pores and cracks. The creation of cracks close to the surface dramatically increases permeability, however deeper in the conduit these cracks are easily closed by confining pressure on elastic timescales. Precipitation within a fractured breccia combined with episodic opening and closing of cracks can offer explanations for outgassing and unrest that last minutes to months.

## SHORT AND LONG TIMESCALES OF MAGMATIC PROCESSES AT WHAAKARI/WHITE ISLAND

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The last major eruption episode at Whakaari/White Island occurred between 1976 and 2000, with further activity sporadically occurring since then. During that main episode, eruptions alternated between strombolian and phreatomagmatic activity largely covering the main crater floor in scoria and ash. The longevity of the eruption is not well understood and to explore the controls on the eruption episode, we take advantage of a sample suite collected soon after each event. In this way, we aim to explore the connection between geophysical and geochemical monitoring data collected at the time to seek ways of constraining these signals to magmatic processes at depth.

Recent analysis of scoria from this eruption episode reveal clear magma mingling between a relatively minor mafic component into a dominantly andesite-dacite. We also observe variable states of resorption of olivine phenocrysts, together with near-ubiquitous reversely zoned pyroxene (both clinopyroxene and orthopyroxene); all petrographic signals of repeated mafic injections. Seemingly fuelled by repeated mafic inputs, we set out to use diffusion chronometry to quantify the timescales of magma interactions prior to discrete events. Based on our initial results, we find that timescales extracted from both olivine and pyroxene vary between a few days to a few months, in a generally bi-modal distribution. Despite the uncertainty in these data, we show that these timescales possibly represent reservoir and in-conduit magma mingling. Our results show the utility of diffusion chronometry to discriminate magmatic processes and their relation to monitoring data.

## RECONSTRUCTING SEA-LEVEL RISE FROM NEW ZEALAND'S SUBSIDING COASTLINES

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Globally, sea-level rise has shown a substantial increase in rate across the twentieth and twenty first centuries, from  $1.2 \pm 0.2$  mm/yr over 1901-1990, to  $3.3 \pm 0.4$  mm/yr since 1993 (around New Zealand, rates of 4-5 mm/yr have been directly measured by satellites between 1993-2011). The dynamic tectonic setting of New Zealand exacerbates the regional expression of this in many locations. Notably, around the capital city of Wellington, plate coupling has led to net subsidence of the land of 2.2mm/yr since the year 2000, though the lack of concordance between GPS-recorded subsidence and long-term tide gauge records suggests that this rate has not been consistent across the past century. To provide a longer-term context to the current tectonic motions observed during the twenty-year long GPS record, this ongoing study uses salt-marsh microfossil assemblages to reconstruct sea level in tectonically subsiding and ambiguous parts of New Zealand. Work has begun at Pauatahanui salt marsh near Wellington, where two surface transects have been taken and their foraminiferal assemblages counted. From these data, transfer functions will be created and cores taken for use in generating a high-resolution sea-level reconstruction for the region from the 1855 formation of the marsh to the present.

## OCEAN ACIDIFICATION IN THE INDUSTRIAL ERA: BORON ISOTOPE-PH PROXY RECORDS FROM PACIFIC MICROATOLLS

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Ocean acidification has caused a reduction of  $\text{pH}_{\text{sw}}$  (seawater pH) altering the ability of many organisms to calcify. As instrumental records of  $\text{pH}_{\text{sw}}$  only exist for the past three decades, geochemical proxies such as the  $\delta^{11}\text{B}$  (boron isotope ratio) of tropical corals have been utilized. However, physiological modification of a coral's internal  $\text{pH}_{\text{cf}}$  (calcifying fluid pH) complicates the application of this proxy. Corals of the genera *Porites* growing on intertidal reef flats often form microatolls when their vertical growth is limited by minimum water level at spring tide. The enhanced preservation potential and accessibility makes them promising paleoclimate recorders.

This study explores the potential of microatoll  $\delta^{11}\text{B}$  for  $\text{pH}_{\text{sw}}$  reconstructions aiming to apply the proxy on microatolls from sites spanning the full range of Pacific Ocean  $\text{pH}_{\text{sw}}$  (Kiritimati Island, Arno Atoll and Rarotonga). First,  $\text{pH}_{\text{cf}}$  upregulation was quantified by comparing highly resolved  $\delta^{11}\text{B}$  data obtained with LA-ICPMS in one annual growth band of a coral from Kiritimati Island with synchronously recorded environmental data. Second, 20<sup>th</sup> century  $\delta^{11}\text{B}$  records from Kiritimati Island were constructed, from corals growing on reef flats as well as on the fore reef.

Results showed that on a seasonal scale reef flat  $\text{pH}_{\text{sw}}$  remained stable equalling offshore  $\text{pH}_{\text{sw}}$ . Similar, coral  $\text{pH}_{\text{cf}}$  revealed only minor fluctuations around a year-round stable value. Both suggest that microatoll  $\delta^{11}\text{B}$  can potentially track ocean  $\text{pH}_{\text{sw}}$ . Multi-decadal  $\delta^{11}\text{B}$  records from Kiritimati Island recorded differing  $\text{pH}_{\text{sw}}$  trends with acidification towards present but also  $\text{pH}_{\text{sw}}$  constantly higher than modern observations. While the first indicates the microatoll recorded open ocean conditions, the latter might be a result of locally insufficient flushing of the reef flat. Nevertheless, the findings suggest that industrial era  $\delta^{11}\text{B}$ - $\text{pH}_{\text{sw}}$  records can be constructed from Pacific microatolls.

## **EFFECT OF THE KAIKŌURA EARTHQUAKE ON STRESS IN AND AROUND THE RUPTURED REGION: A NOISE CROSS CORRELATION APPROACH**

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The earthquake cycle is governed by the build-up and release of shear stress on fracture planes. Measuring this process is difficult. The Kaikōura earthquake was a complex earthquake with a large aftershock sequence. Stresses can close and open fractures and pores, which change the seismic velocity and movement of fluids in those pores can change the pore fluid pressure, affecting the stress. The purpose of this study is to measure the temporal variation in seismic wave velocities before and after the 2016 M7.8 Kaikōura earthquake using nineteen short-period three-component seismometers deployed by the Japanese Crustal Dynamics project. The short-period network used has been collecting data since 2011 and a time period from 2012-2018 will be used to determine the temporal changes in seismic velocities.

Ambient noise cross correlations are used to determine the temporal variation of the seismic wave velocities in the Kaikōura region. Noise cross correlations determine temporal velocity variations by computing the relative velocity changes between a reference noise cross-correlation and moving stacked noise cross correlations. A python package, MSNoise, is used for most of the processing. Preliminary data analysis has shown there was a velocity decrease as a result of the 2016 Kaikōura earthquake. Currently more data are being processed to determine more accurately the degree of change. Determining these velocity changes will help understand more about the earthquake cycle and how stress and velocity changes are related.

## **THE SOUTHERN TARANAKI BASIN IN FOUR DIMENSIONS: STRUCTURAL AND SEDIMENTOLOGICAL CHANGE AND RAPID PETROLEUM SYSTEM EVOLUTION**

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The southern Taranaki Basin has recorded over 80 Myrs of structural and sedimentological change. Permeable reservoir rocks were deposited in a range of environments. Deformation along major fault zones such as the Cape Egmont Fault Zone (CEFZ) controlled the deposition of coaly source rocks and the formation of structural traps. It has been proposed that some of these traps did not form before Latest Miocene inversion, which would require generation of hydrocarbons, migration, and charge occurring over only a few Million years. This challenges common concepts on petroleum migration and the transmissibility of major fault zones.

To better understand the evolution of southern Taranaki Basin and the impact on petroleum systems, we have mapped up to 20 horizons at a regional scale and at high resolution in the central part of the basin using 3D seismic data and petroleum exploration wells. A total of 100 faults were mapped along the CEFZ to control horizon offsets. Depth converted horizons and faults were imported into PetroMod™ basin modelling software. The model was further subdivided to incorporate facies distributions mapped from seismic data. Paleobathymetry and eroded section were reconstructed using decompacted mapped horizons and iteratively calibrated to burial histories at well locations and reconstructed shelf geometries. Shale gouge ratio evolution through time was estimated for the CEFZ. The model was then used to reconstruct the evolution of the basin and to predict petroleum generation and migration.

The resulting models reconstruct subsidence and the response of sedimentary systems through time. The models illustrate how fault transmissibility and carrier bed permeability, as well as the architecture of sedimentary strata around major faults, have impacted fluid migration. Results suggest that petroleum migration can occur rapidly, even in tectonically complex regions, and that areas of high fluid transmissibility exist along and across major fault zones.



## **DEFINING THE BASAL UNCONFORMITY OF THE WAITEMATA-NORTHLAND BASIN OFFSHORE AND ONSHORE**

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The Waitemata Basin has a complex history of sedimentation, deformation and subsidence due to its tectonic evolution. On the west coast of New Zealand lies the interconnected Northland and Taranaki basins, separated from the Waitemata Basin by the exposed landmass of the Auckland region. This study focuses on visualising the regional basal unconformity of Early Miocene Waitemata Strata across the onshore Waitemata Basin and offshore the Northland Basin that are hypothesised to have been part of a single Early Miocene depocentre. The study aims to gain insight into the Waitemata Strata's depositional setting through the identification of slope characteristics and topographic features. Definition of the Waitemata Strata basal unconformity is achieved through the combination of offshore 2D seismic analysis using 'Petrel' software and Qmap outcrop interpretations. Data has been sourced from pre-existing offshore industry 2D seismic surveys and from GNS science. The initial slope on which the Waitemata Basin formed has since experienced deformation, yet with the aid of Petrel's surface interpolation tools it may be possible to visualise some of its initial characteristics. This surface will form the baseline for the rest of this study, which aims to develop a regional 3D interpretation of Waitemata Group strata.

## THE VOLCANIC GEOLOGY OF TAUPŌ VOLCANIC ZONE: 1:120,000 SCALE MAP AND BULLETIN

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We present the draft 1:120,000 scale map of the volcanic geology of Taupō Volcanic Zone, which will be published in 2020. The map will be printed on two sheets and covers the whole zone from Ruapehu to Whakaari. It will be accompanied by an approximately 100 page richly illustrated bulletin. The map incorporates our 1:60,000 scale geology map recently published for Tongariro National Park (TNP) and the 1:250,000 scale volcanic geology within the regional QMAP Rotorua sheet, along with parts of the Waikato and Hawkes Bay Sheets. The scale is chosen as a compromise between those of the two existing map series. The TNP geology has been generalised and updated with new work on Tongariro volcano. The QMAP geology has been substantially refined and updated to take advantage of new LiDAR coverage throughout the Bay of Plenty Region and in parts of the Waikato Region, new mapping and data acquired in the last 10 years and new theses and publications over that time. The bulletin will incorporate a unified stratigraphy, new and updated diagrams for TVZ evolution, an eruption sequence narrative and new photography. The detailed spatio-chronological legend on the map will utilise a full pallet of colours highlighting on the volcanic units' diversity. The two map sheets can be joined together for wall presentation, but with each sheet aiming to be a manageable physical size when used in the field.

## LESSONS FROM FIELD-EXPERIMENTAL STUDIES OF HYDROTHERMAL ERUPTIONS IN THE TAUPO VOLCANIC ZONE

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Steam-driven eruptions caused by explosive vaporization of water in host rock are common hazards in geothermally active areas, such as the Taupo Volcanic Zone (TVZ). At many of the geothermal fields exploited for renewable power generation, the risks from hydrothermal eruptions are huge. As such, understanding the conditions that lead to these eruptions is vital for proper mitigation and risk planning. This can be done through a combination of understanding the hydrothermal breccia deposits left behind by past eruptions and understanding the petrophysical properties of the rocks through which these eruptions take place.

This combined field-experimental approach was applied to three locations within the TVZ: Lake Okaro, Waimangu Volcanic Valley, and the Champagne Pool at Waiotapu Thermal Wonderland. Respective breccia units in each location were correlated between outcrops using breccia grain size and componentry, supported by recognisable tephra marker beds. To complement field study, erupted lithologies within the breccia representative of the exploded host rocks were analysed for their petrophysical, textural, and petrological properties in relation to alteration type/intensity, and served for reconstruction of the dynamic properties and eruption depth(s). Breccia samples were then rapidly decompressed from elevated pressure-temperature conditions using the fragmentation bomb at LMU, mimicking hydrothermal eruptions triggered by sudden perturbation of the hydrothermal system (e.g. seismic induced fracturing of shallow/cap rocks). Experiments allowed us to further explore eruption-controlling parameters as geological variation, rock alteration, and water/steam pressure. Moreover, fragmented particles were recovered for analysis and comparison to field settings. Results show that experimentally-produced sizes and componentry can be compared to the breccias found in the field in order to determine the conditions under which past eruptions at within the TVZ.

## ENGINEERING GEOLOGICAL CHARACTERISATION OF THE VERA RUBIN RIDGE, MARS

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To date, evaluation of Mars surface rock has typically been limited to surface geophysical testing, allowing estimations of modulus and compressive strength. NASA and ESA affirmed the importance of Mars exploration by establishing the international MSR Objectives and Samples Team (iMOST). One of the goals (iMOST, 2019) is that soil and rock sample return would permit geotechnical characterization of surface materials. This would allow iMOST to refine engineering designs and aid architectural decisions. Thus, characterisation of rock mass properties, such as joint width, spacing, angle, surface roughness and state of weathering has yet to be undertaken. These rock mass properties are critically important for any greenfield site development and are precursors to construction works. We applied the Geological Strength Index (GSI) to the characterisation of rock mass properties on Vera Rubin Ridge, Mars. The GSI allows the estimation of rock mass strength and rock mass deformation modulus (via Hoek-Brown failure Criterion) and is based on the description of rock structure and block surface condition. GSI can be applied (conservatively) using outcrop or core photographs, different to other rock characterisation approaches that typically require in situ testing. We used site photographs NASA Curiosity Mars Rover's mast camera, in the vicinity of the Vera Rubin Ridge (VRR). Also known as Hematite Ridge, this is a linear topographic feature along the northern foothill perimeter of Mt. Sharp in Gale crater. The outcrop is characterised by laminated siltstones. Defects along bedding planes are the most laterally pervasive rock mass defects, inclined in some areas. They can dip in multiple directions, and so can be both favourable and unfavourable to slope stability. Several cross-cutting joint systems also occur, some of which are infilled. Intersection of joint systems creates blocky outcrop and producing a range of GSI values.

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## **THE MOST VIOLENT PHREATOMAGMATIC EXPLOSIVE ERUPTION OF THE ARXAN-CHAIHE VOLCANIC FIELD (ACVF) IN NE CHINA, COULD ALSO BE ONE OF THE YOUNGEST?**

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The Arxan-Chaihe Volcanic Field (ACVF) covers approximately 2000 km<sup>2</sup> with at least 46 vents identified so far in an area located on the border between Mongolia and China. Tongxin Volcano lies in the north-eastern corner of ACVF, and its eruptive products cover an area of about 10 km<sup>2</sup>. In the east flank of the volcanic edifice, there are two outcrops (Site 1 and Site2) that represent the proximal deposits dominated by pyroclastic density current-dominated successions. In the north-western section lava spatters crop out and an additional large outcrop seemingly positioned under the deposits of Site 1, provides the core of fields observations and initial analytical works on the deposits. On the far south of the proximal pyroclastic units, approximately 6 km away, typical distal primary pyroclastic deposits are mapped still in a total thickness of in metres scale. The primary deposits of the Tongxin Volcano are unconsolidated ash and lapilli with abundant country rock fragments in the whole size spectrum of clasts indicating effective phreatomagmatic fragmentation and successful cratering processes. New mapping revealed that the primary pyroclastic density current deposit that dominates the succession with some pyroclastic curtain deposits are more widespread than originally thought. In addition, reworked pyroclast-fans are filling the rugged mountainous terrain and forming flat-topped intra-mountain basin fills indicating that the original volume of the tephra must have been significantly larger than what preserved today. The lack of erosion-resistant capping units, the general climatic conditions and the region general geomorphology together suggest that Tongxin Volcano must be a young volcanic landform having still large volume of its easy to eroded tephra rim and blanket reasonable well preserved typically under rock-fall screes from the basement hill tops. The scattered preserved primary pyroclastic deposits, however indicate a dynamic landscape evolution of the region that is presented here.

## **ENIGMATIC SUPRA-SUBDUCTION ZONE DACITE VOLCANOES IN NORTHERN NEW ZEALAND: EVIDENCE FOR ERUPTION OF SUBDUCTION-MODIFIED MANTLE MELTS FACILITATED BY THE HAURAKI RIFT?**

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The dacitic Little Barrier volcano in the Hauraki Rift east of Auckland and three dacite-rhyolite domes near Whangarei in Northland (Opuawhanga, Parakiori and Hikurangi) are anomalously young (1-4 Ma) with respect to the adjacent Coromandel (12 – 18 Ma) and Northland (16 – 23 Ma) arc volcanism with which they are associated. These volcanoes are also geochemically distinct from lavas of comparable SiO<sub>2</sub> content of the Northland and Coromandel volcanic regions, being richer in Zr and poorer in Rb and Ba, and having very non-radiogenic isotopes. Several samples also display intriguing Ce-anomalies in their REE patterns. One explanation for their unusual geochemistry and ages is that they might represent small degrees of partial melt of subduction-modified mantle or lower crust due to extension on the Hauraki Rift, which is typically thought to be amagmatic. We present whole rock major and trace element and Sr, Nd and Pb isotope data as well as major and trace element mineral data to explore the petrogenesis of these volcanic rocks. Regardless of their origin, we suggest these dacites represent a magma association that is different from the other arc and intraplate volcanic associations in northern NZ, and that a better understanding of them may shed light on the nature of the Hauraki Rift, as well as the termination of subduction-related volcanism in the Northland and Coromandel arcs.

## **ANALYTICAL MODELLING OF TSUNAMIS GENERATED BY UNDERWATER VOLCANIC ERUPTIONS**

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Underwater volcanic eruptions are one of the source mechanisms that can generate volcanic tsunamis. Although infrequent, such tsunamis have accounted for almost 25% of those killed directly by volcanic eruptions since 1000 A.D. The 1952 eruption of Myojinsho volcano, Japan, resulted in tsunami waves up to 92 cm that destroyed a surveying boat of the Japan Hydrographic Department killing 31 people. The 4.7 m high waves generated by the 1965 eruption of Taal volcano in the Philippines devastated villages on the lakeshore and killed 190 people. The destructive potential and unpredictability of such waves highlight the need for improving our understanding of the phenomena.

The present work is based on the mathematical model of Duffy (1992), who analysed surface waves generated by an underwater point-source volcanic eruption. We extend this work by modifying the source model to include time dependence and periodic effects. We explore how the free surface elevation depends on the geometrical parameters of the eruption and compare the efficiency of the wave generation of the following sources: an instantaneous source with a finite duration of the eruption, a pulsating source and an exponential source. The generated wave fields are compared to the waves generated by a vertical deformation of the seafloor. We find a similar pattern present in the wave fields produced by all the impulsive mechanisms, with waves generated by pulsating and exponential sources approaching those generated by an instantaneous eruption. Moreover, a beating behaviour is observed in waves generated by an instantaneous eruption of finite duration, similar to the beats present in tsunami records from 1952 Myojinsho eruption. Finally, we show that the size of the volcanic crater, relative to the water depth, impacts the resulting waves much more than its vertical position in the ocean.

### **References**

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## PALEOEARTHQUAKES RECORDED BY MARINE TERRACES IN THE NORTHERN AND CENTRAL HIKURANGI MARGIN

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A compilation of past subduction earthquakes along the Hikurangi Subduction Margin (Clark et al., 2019) highlights the potential of post-7000 yr coseismic marine terraces to record past subduction earthquakes, but the terrace record is frequently complicated by the influence of nearshore upper plate faults. We summarise completed and ongoing work at several sites in the northern and central Margin and current interpretations on the implications for Hikurangi Margin seismogenesis.

Paleoseismic trenches were excavated at Puatai Beach and Pakarae River mouth, northeast of Gisborne. Surveying, radiocarbon dating and tephrochronology were used to obtain uplift-per-events of  $2.9 \pm 0.5$  m (Puatai Beach) and  $2.0 \pm 0.5$  m (Pakarae River mouth) and paleoearthquake ages of 1770–1710, 1100–910 and 420–250 cal. yr BP (Puatai Beach) and 1490–1290 and 660–530 cal. yr BP (Pakarae River mouth). The paleoearthquake ages don't match between these two sites (nor with ages from other northern Margin sites), suggesting uplift here is primarily driven by a local, upper plate fault. Re-examination of submarine bathymetry and seismic data reveal a complex network of offshore faults that may be secondary structures above a feature at depth, such as a subducting seamount.

Preliminary terrace Lidar mapping and radiocarbon dating at Clifton, Ocean Beach and Waimarama, southeast of Napier confirm that a single terrace is preserved between Clifton and Ocean Beach, the 2300-2000 cal. yr BP Kidnappers terrace. Multiple terraces are preserved at Waimarama, including the Kidnappers terrace at the north end of the beach. Preliminary dislocation modelling suggests offshore upper plate faults could be responsible for the uplift, and the ages suggest the recurrence intervals are much longer than those in the north. The Kidnappers terrace age doesn't match any subsidence events at Ahuriri Lagoon, providing further evidence that the marine terraces may not record subduction earthquakes.

Clark, K., Howarth, J., Litchfield, N., Cochran, U., Turnbull, J., Dowling, L., Howell, A., Berryman, K., Wolfe, F. 2019. Geological evidence for past large earthquakes and tsunamis along the Hikurangi subduction margin, New Zealand. *Marine Geology* 412: 139-172, doi: 10.1016/j.margeo.2019.03.004.



## CO-SEISMIC STRUCTURAL EVOLUTION OF LARGE-MAGNITUDE STRIKE-SLIP GROUND RUPTURES (“MOLE TRACKS”)

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Many studies address the structural evolution of strike-slip zones developed in previously intact rock, soil, sand, clay, or other materials—both natural and experimental. Most observe segmented synthetic Riedel (R) faults early in the slip history, and infer eventual localisation of slip into through-going (Y) faults. We use the “natural laboratory” provided by the Kaikoura Earthquake along the eastern Kekerengu Fault to understand how ~9-11 m of dextral-slip was accommodated co-seismically near the surface by deformation of clay-rich materials capped by grass-bounded turf. We undertook field work and analysis of immediate post-earthquake drone orthophotography. Our work indicates that ground deformation initiated with slip on *en echelon* shear-extension fractures (hybrid Riedel faults, “R<sub>h</sub>”) striking ~26° clockwise (CW) to the main fault trace, and spaced at ~2-3 m. Subsequently, coherent “rafts” bounded by R<sub>h</sub> faults rotated CW by (mean)  $27 \pm 8^\circ$  about a vertical-axis, in so doing accommodating ~1/3 of the total displacement. As they rotated, the rafts were internally shortened and also cut by younger fissures striking (on average) ~25° CW to the R<sub>h</sub> faults. The fissures fragmented the elongate rafts into smaller blocks, and these typically have rotated CW by ~30-40°, as a further 10-25% of the total displacement was absorbed by distributed deformation. The balance of the displacement was accommodated by discrete slip on one or more, in part younger, Y faults, the effect of which was locally to destroy the earlier-formed “raft-and-block” fabric. Predictions of our model are: 1) final fault-perpendicular shortening of the zone is greater than the imposed contraction (heave); 2) local uplifting of mounds, even on a strike-slip fault; and 3) opening of fissures between (and within) the mounds. Mound elevation is predicted to decrease as slip becomes transtensional—reducing to zero for only a ~10° obliquity of displacement relative to the fault strike.

## CHARACTERISING BASALTIC TEPHRAS ERUPTED FROM MID-HOLOCENE MOUNTS GAMBIER AND SCHANK, SOUTH AUSTRALIA, AND ASSOCIATED SOILS (ANDISOLS)

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Intraplate Holocene alkali-basalt volcanoes of southeast South Australia form the western extension of the Newer Volcanic Province of Victoria. The isolated Mount Gambier (MTG) and Mount Schank (MTS) complexes comprise intricate maar and cone structures built over eruptive fissures. The two complexes are situated ~10 km apart and erupted ~5 ka. Eruptions were primarily phreatomagmatic with abundant tephra deposits and subordinate lava flows. Recent petrological studies of MTG have focused on whole-rock lava compositions but analyses of glass and crystals from tephras were not reported. The tephras contain both “exotic” crystalline material, derived from underlying limestone and calcareous dunes, and juvenile basaltic material. Ash at MTG contains considerable quartz, sponge-spicules, chert, calcite, lherzolite, and phytoliths (~80%), together with volcanic crystals of forsterite, plagioclase (including labradorite), clinopyroxene (mainly diopside), and Fe-Ti oxides, and comparatively low amounts of glass (<20%), much of which is altered. Ash at MTS contains much less exotic material (quartz, sponge-spicules, phytoliths) and has higher glass content (~50%), most unaltered, along with volcanic crystals as at MTG. Major elements (normalised) in glass shards from MTG- and MTS-derived tephras are notably high in silica and alkalis: mean SiO<sub>2</sub> at MTG = 49.62 ± 0.55 wt% and Na<sub>2</sub>O + K<sub>2</sub>O = 8.54 ± 0.61 wt% (n = 21); mean SiO<sub>2</sub> at MTS = 49.72 ± 0.86 wt% and Na<sub>2</sub>O + K<sub>2</sub>O = 8.72 ± 0.71 wt% (n = 18). Most shards are phonotephritic. In contrast, MTG lavas are basanitic to trachybasaltic, indicating that the host melts were more evolved than previously known. “Extra” SiO<sub>2</sub> occurs at MTG because of the more abundant xenolithic silica polymorphs. Soils on MTG and MTS tephras are globally-rare Xerands: clay fractions at MTG are dominated by layer-silicate minerals (notably with no halloysite), whereas clays at MTS are less variable and dominated by allophane and ferrihydrite.

## DEVELOPMENTS AND CHALLENGES IN PALEO-ICE SHEET MODELLING TO CONSTRAIN PAST SEA LEVEL

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To more accurately project the future contributions of the Antarctic and Greenland Ice Sheets to global sea level in a warming climate, reconstruction of sea levels of past warm periods and transitional climate states is a useful exercise in understanding relevant processes and controls on ice sheet sensitivity to changes in climate. Numerical ice sheet models are an important tool for estimating the individual sea level contributions of both ice sheets, and these models have improved tremendously over the past decades.

While early iterations of 3D thermo-mechanical ice sheet models were run at relatively coarse resolution, state-of-the-art models are now capable of reproducing modern observations with advancements in the simulation of ice streams, grounding-line mechanics, and ice-ocean interactions. Despite these successes, challenges remain in precisely quantifying the impact of specific processes in the simulation of past sea level contributions of ice sheets, including marine ice cliff instability (MICI), sub-ice shelf melting, and the evolution of basal friction. Contributing to these challenges are the spatial and temporal limitations of the paleoclimate record and the high uncertainty of past sea level reconstructions.

Ice sheet modellers have used different approaches to address these issues, and the wide range of simulated ice sheet responses to climate forcings of the mid-Piacenzian warm period (3.2-3.0 Ma), the Last Interglacial period (129-116 ka), and the last deglaciation (21-0 ka) have highlighted the existing sources of uncertainty. In particular, the Antarctic Ice Sheet is highly sensitive to ocean thermal forcing and subglacial topography, whereas the Greenland Ice Sheet is highly sensitive to changes in surface mass balance. Paleo-constraints that can aid in reducing these uncertainties in climate forcing and subglacial conditions may improve model-data agreement and lead to better model consensus of future sea level projections.

## HOW PYROCLASTIC FLOWS OUTSMART GRANULAR FRICTION DURING VOLCANIC ERUPTIONS

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Granular-fluid flow and gas-fluidization traditionally constitute key processes in the investigation and modelling of violent volcanic and non-volcanic mass flows on Earth and other planets. These include phenomena such as pyroclastic flows, and avalanches of rock and snow. Amongst these natural gas-particle flow phenomena, pyroclastic flows constitute the most lethal volcanic process known. Causing more than fifty percent of volcanic fatalities globally, these hot mixtures of volcanic particles and gas exhibit an astonishing fluidity. This allows them to transport thousands to millions of tonnes of volcanic material across the Earth's surface over tens to hundreds of kilometres, by-passing rough and tortuous terrain with flat and upsloping surfaces. Here we give an account for the natural flow characteristics and hazard impacts of these flows to highlight a long-standing research question: how do pyroclastic flows attain their characteristic mobility? The fluidity of pyroclastic flows is attributed to an internal process that effectively counters granular friction. Aspects of this enigmatic fluidity have been variably explained by vertical gas escape, high internal gas pore pressure, acoustic fluidization, dynamic fragmentation, among others. However, the violence of real-world flows has precluded direct measurements, so that none of these processes has been quantitatively validated.

Here we show, through large-scale experiments and numerical multiphase modelling, that pyroclastic flows generate their own air lubrication. This forms a near-frictionless basal region. Air lubrication develops under high basal shear when air is locally forced downwards by reversed pressure gradients and displaces particles upward. We demonstrate that air lubrication is enhanced through a positive feedback mechanism, explaining how pyroclastic flows are able to propagate over slopes much shallower than the angle of repose of any natural granular material. This discovery necessitates a re-evaluation of hazard models that aim to predict the velocity, runout and spreading of pyroclastic density currents.

## CHANNEL EROSION AND AGGRADATION FROM EXTREME RAINFALL IN STEEP CATCHMENTS – THE 2017 ROXBURGH DEBRIS FLOWS

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On 26<sup>th</sup> November 2017 a localised thunderstorm cell over the hills behind Roxburgh, Otago, produced up to an estimated 180mm of rain over a three-hour period. Four catchments experienced severe flooding and sediment movement (debris flows or hyper-concentrated flows), resulting in significant sediment deposition across SH8 and within Roxburgh township<sup>1</sup>. As part of hazard mitigation efforts, we seek to quantify the topographic controls on sediment sources and deposition across the four catchments.

The catchments (2.5-6.3km<sup>2</sup> in area) span up to 1km of relief, with broad low-relief headwaters, transitioning to confined channels which descend steeply towards the Clutha River. At range-front outlets, lower gradient (0.05-0.1) alluvial fans have accumulated upon abandoned river terraces.

Debris flows most commonly initiate on steep slopes as a landslide which mobilises and travels down-channel entraining sediment. In Roxburgh, sediment was nearly exclusively sourced from within the active channel bed, or from channel bank erosion. Comparison of the onset of contiguous channel erosion between catchments displays a strong inverse relationship between catchment area and channel slope, suggesting a critical stream-power control on the onset of channel bed erosion. Steeper (0.15-0.35) mid-profile channel reaches were scoured and stripped of fine sediment, leaving exposed bedrock, a matrix of large boulders, and undercut banks. These mid-channel sections supplied the bulk of sediment mobilised in the event.<sup>2</sup> Consistent across all catchments, when channel gradients decreased below ~0.12 sediment aggradation overwhelmed existing channels, filling valley floors, and flows avulsed in unconfined reaches.

Comparison of topography before and after the event reveals localised channel erosion of up to 5 m, generally along the steeper channel reaches, with corresponding aggradation of up to 3m downstream. Landslides were tightly coupled to channels and concentrated along the steeper reaches. Several deep-seated landslides have moved after the event, likely a delayed response to toe slope erosion.

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<sup>1</sup> Dellow GD, Jones K, Rosser BR. (2018). Hazard and risk assessment of the Roxburgh debris flows of 26th November 2017. Lower Hutt (NZ): GNS Science. 35 p. GNS Science consultancy report; 2018/65.

<sup>2</sup> Golder Associates (2019). Management and Reduction of Debris Flow Risk in Roxburgh, Otago – Geomorphological Assessment Report. 131 p

## **AN END-USER PERSPECTIVE: THE IMPORTANCE OF NATURAL HAZARD RESEARCH THAT MEETS LOCAL GOVERNMENT NEEDS AND IS ACCESSIBLE TO ALL**

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Regional Councils, in collaboration with district councils and civil defence emergency management, are responsible for providing natural hazard information and guidance to communities. This information is used to inform new development, property purchases and natural disaster preparedness. Regional Councils can and do use natural hazard information of varying scales and accuracy. However, the information that really makes a difference in terms of reducing exposure and therefore risk, is that which directly informs development through district and regional plans. This information needs to be spatial, robust and accurate to large scales. We see regional and district councils as the 'on the ground' end-users of natural hazards research. Yet local government is often excluded from end-user consultation, or has little representation. Improved collaboration is required so research can directly inform the occurrence of development and, increasingly, retreat. Councils do not have the resources to meet all of their research needs alone.

Natural hazard research and data should be available and accessible to all. To achieve this goal, the Waikato Regional Council (WRC) has significantly improved the accessibility of natural hazards information in the Waikato. The [Waikato Regional Hazards Portal](#) displays spatial natural hazard data held by WRC and others in an ArcGIS StoryMap, with interactive layers, and supplementary information and links. This portal is intended to be a one-stop-shop for natural hazard information in the region, and data will be available to download via the [Waikato Data Portal](#). The updated [Coastal Inundation Tool](#) builds on the 2016 tool to improve usability and context. The project was in collaboration with two other regional councils, and the tool and accompanying documentation will be freely available to any council that wishes to develop a tool for their region. Shared projects such as this allow the pooling of ideas, reduced costs and improved consistency nationwide.

## THE NEW 1:50 000 SCALE GIS DATASET AND MAP OF THE HYDE-MACRAES SHEAR ZONE, OTAGO, NEW ZEALAND: A PROGRESS REPORT

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The Hyde-Macraes Shear Zone host a globally significant orogenic gold resource, and this shear zone and adjacent faults are important to the understanding of Zealandia's tectonic history. A significant amount of investigation has occurred since the last published geological map sheet of the area was released in 2001. These data include onshore petrography and chemistry (soil, whole rock and mineral) studies, structural mapping, structural contour modelling, mineral exploration work and airborne and ground-based geophysical surveys. The shear zone and nearby Waihemo Fault are predicted to extend offshore, data have been acquired from shipborne surveys by government, industry or university groups. Exploration and mining also continues apace along the onshore segment of the Hyde-Macraes Shear Zone, with open-pit mining extending northwest to Coronation North pit from the initial Round Hill pit, extended underground workings at Frasers and exploration to the southeast and northwest along the shear zone. With knowledge of these important structures still a strong focus amongst explorers and researchers, it is opportune to record the state-of-the-knowledge both for understanding the tectonic development of Zealandia and to aid mineral exploration for comparable structures in Otago and elsewhere. A collaborative effort to collate geological data will be led by GNS Science and supported by OceanaGold Corporation, Hardie Pacific, University of Otago and others. The area to be covered will extend from offshore the coast near Palmerston in the east, to the Maniototo in the west, encompassing active areas of exploration along the inferred extension of the shear zone, including around the Cap Burn Fault. The intention is to produce a geographical information system (GIS) dataset product, a printable map, cross-sections and accompanying text by 2020 that will be of value to researchers and explorers focussed on understanding structures within the Otago schist and the mineralisation of precious metals.

## **DETECTION OF S-WAVE REFLECTORS BENEATH AFTERSHOCK AREA OF THE 2016 KAIKOURA EARTHQUAKE**

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S wave reflectors in the crust may be caused by structures such as existing fluid or magma. Especially, fluid around an earthquake fault could play an important role for initiation of the earthquake rupture as a mechanism for reducing fault strength. The reflector generates reflected phases from incoming seismic waves from an earthquake hypocentre and we can observe the signals on seismograms. The location and geometry of the reflector can be determined from the travel time of the reflected phases. For detecting the reflection phases, we need to observe at stations located close to the hypocentre because of the small lapse time of the reflected phases due to a reflector in the crust. In this study, we attempted to detect reflected waves in observed seismograms at the seismic stations in and around the 2016 Kaikoura earthquake (Mw7.6). Seismic records were obtained from the permanent GeoNet stations as well as from seismic stations deployed before the Kaikoura earthquake in the northern South Island. We applied reflection seismology techniques to the data obtained by the network. We used seismograms with smaller epicentral distance than 30 km and obtained normal move-out sections for each station. We detected several reflectors in the mid and lower crust from the sections. The reflectors may relate to the faults of the Kaikoura earthquake and to the subducting slab beneath the South Island.



## STRESS TENSOR INVERSION IN FOCAL AREA OF THE 2016 MW7.8 KAIKOURA EARTHQUAKE, NEW ZEALAND (3)

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We study spatio-temporal changes of the stress field surrounding the 14 November 2016 Kaikōura earthquake rupture in the northern South Island of New Zealand. Data from 51 temporary and 22 permanent (GeoNet) stations were used, from the time period March 2011 through December 2017. We derived focal mechanisms using the HASH (Hardebeck and Shearer, 2002) method to estimate the stress field before and after the main shock. We used the SATSI (Hardebeck and Michael, 2006) method for stress tensor inversion. By using the Kagan angle between the main shock fault model of Hamling et al. (2017) and each focal mechanism, we remove aftershocks with the same orientation and slip vectors as the mainshock. The bound on the value of the Kagan angle that I consider to be close enough to define the aftershocks to remove is 40. We perform the stress tensor inversions on the remaining aftershocks. The stress regime after the main shock in the areas near the London Hills Fault and near the Kekerengu fault is strike-slip with an SHmax orientation of N100E to N110E, which is almost the same as for the stress regime before the Kaikōura earthquake (e.g., Balfour et al., 2005; Sibson et al., 2012; Townend et al., 2012). In the southern area near the hypocenter of the main shock, the obtained stress tensor inversion indicates reverse faulting with a similar SHmax orientation, while sigma2 and sigma3 are equivalent. As a future study, we plan to increase the number of focal mechanisms to determine a stable stress tensor for the region near the hypocentre prior to the mainshock.

## **A WINDOW INTO MAGMATIC TIME (340 – 25 KA): HOW MAGMA SYSTEMS REORGANISED BETWEEN SUPERERUPTIONS IN THE NORTH TAUPŌ AREA**

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How magma systems evolve and assemble eruptible melt-dominant magma bodies, and how magmatic/volcanic systems behave in between supereruptions, remain unresolved questions in volcanology. The Taupō Volcanic Zone (TVZ) has hosted four of the ten Quaternary supereruptions (>450 km<sup>3</sup>, magma) known worldwide. The surficial volcanic record from Taupō volcano extends from the Whakamaru Group eruptions at 349-339 ka to ~1.7 ka. It is thought Taupō volcano began erupting in this time period along with the Maroa volcanic centre but burial by younger deposits and insufficient age data means that much of this early history is unknown. We are analysing volcanic products to understand how magma systems in the north Taupō area were organised in time and space in between the two youngest TVZ supereruptions; Whakamaru (~349 ka) and Oruanui (~25 ka). This research builds on existing tephrostratigraphic data and localities with new analytical data, improved geochronological constraints by dating of eruption units and extension of pre-existing geochemical datasets. Surficial eruption products are also correlated to drillhole formations newly dated in geothermal fields (Wairakei-Tauhara, Ngatamariki, Rotokawa) to look at patterns of rift-related subsidence in the area. Preliminary <sup>40</sup>Ar/<sup>39</sup>Ar dates imply that the Western Dome Belt, dating from as old as approximately 480 ka, is in part, a pre-existing linear dome complex pre-dating the Whakamaru caldera formation. Why should smaller eruptions shortly precede or follow a larger supereruption? The volumes and diversity of the magmas produced in this limited area over a ~300 kyr period is unusual globally and the results of this work have global implications into the magmatic workings of large rhyolitic volcanoes.

## THE ANOMALOUSLY OLD BUSH STREAM ROCK AVALANCHE AND ITS IMPLICATIONS FOR LANDSLIDE INVENTORIES

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Dated rock avalanche deposits in the Southern Alps are all of Holocene age, likely because older deposits are buried or eroded rapidly in New Zealand's dynamic landscape. Without recognition of age-bias, these young ages might lead to spurious inferences about heightened landslide activity during the Holocene. This study of a rock avalanche in a tributary catchment of the glaciated Rangitata Basin in Canterbury, demonstrates that older landslides do exist, and are found in the rare environments that have conditions favourable for preservation. The rock avalanche, referred to as Bush Stream Rock Avalanche, was mapped and dated. Mapping was done in the field and from photogrammetry. Four boulders on or near the deposit were sampled for in-situ Be-10 cosmogenic nuclide surface exposure age dating. The morphology of the head scarp and deposit of the rock avalanche are distinct from the surrounding landscape, much of which appears to be glacial in origin. The rock avalanche travelled almost 4 km, with a volume of 70 M m<sup>3</sup>, and appears to have temporarily blocked Bush Stream. The dated boulders suggest an age of 15-20 ka, making this avalanche possibly the oldest known alpine rock avalanche in New Zealand, and one that fell early on in the regional deglaciation. Deep depressions (i.e. kettle holes?) in the deposit are indicative of runout over glacier ice (or dead ice), but the glacier must have been small and probably dying. The results suggest that the climate of the small basin, in the lee of the Two Thumb Range, is relatively dry, dampening glacial and fluvial activity here and favouring preservation of the Bush Stream Rock Avalanche. Other events like this may have occurred but are not preserved, thus hampering efforts to understand the frequency and causes of large slope failures in highly dynamic alpine environments.

## SCALES OF GEOCHEMICAL VARIATION AMONG CROSS-ARC BASALTIC STRATOVOLCANOES IN NORTH ISLAND: THE ALEXANDRA VOLCANIC GROUP

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Back-arc volcanism is the product of complex interactions between flux-derived island arc basalt (IAB) and decompression-related ocean island basalt (OIB) magmas. Erupted products are typically more mafic, alkalic and geochemically diverse than in the arc, and provide an important window into distal subduction processes and OIB melt generation. The Alexandra Volcanic Group (AVG) in western North Island is a prime example of a basaltic back-arc volcanic field. The field (1100 km<sup>2</sup>, 55 km<sup>3</sup>, 2.74–1.6 Ma) erupted transitional high-K (IAB) and subordinate intraplate (OIB) magmas along a 60 km 'cross-arc' chain oriented perpendicular to the Hikurangi subduction zone. Spatio-temporal variations in lava geochemistry along the cross-arc thus provide direct insights into the diminishing role of the slab and increasing influence of mantle-derived (OIB) magmas in back-arc volcanic fields. Here we present a comprehensive new dataset of elemental (major and trace) and isotopic (Sr-Nd) data for Pirongia, the largest basaltic stratovolcano in the AVG and North Island. We examine volcanic-geochemical variation at scales ranging from regional (North Island), to cross-chain (Alexandra Group) to intra-edifice (Pirongia), in the context of newly established volcanic stratigraphy. The AVG basalts derive from two contrasting magmatic sources (forming IAB and OIB respectively) with marked isotopic variability (<sup>87</sup>Sr/<sup>86</sup>Sr: 0.705420–0.705370). Mixing of IAB and OIB magmas is an intrinsic process across the back-arc, with the OIB isotopic signature becoming more prevalent in lavas with increasing depth to the slab. IABs sampled along the cross-arc reveal north-westward enrichment of key incompatible elements (K<sub>2</sub>O, Nb/Zr and La/K) that reflect increasing slab depth and (likely) waning intensity of partial melting. Late-stage (1.6 Ma) lavas from Pirongia have distinct high-K compositions that record lower-degree partial melting of deeper parts of the mantle wedge that occurred following migration (~40 km southeast) of the Pacific Plate during the 400-kyr hiatus of the volcano.

## **IMPACT OF TEPHRA FALL TO BUILDINGS ON AMBAE ISLAND, VANUATU FROM THE 2017-2018 ERUPTION PERIOD OF MANARO VOUI VOLCANO, AMBAE ISLAND, VANUATU**

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Volcanic hazards can cause a multitude of impacts to society, often over various temporal and spatial scales. Assessing societal impacts from volcanic hazards is an important contribution of the scientific community's role in disaster risk reduction efforts, particularly for informing impact and risk assessments which can be used to forecast potential future impacts. Despite sustained efforts over the past two decades, global research on volcanic impacts has often focused on economically developed and/or large populated areas exposed to volcanic hazards, with few studies focused on volcanic impacts to Small Island Developing States (SIDS), such as in the Pacific. There is also limited consideration of the impacts to society from multi-phase eruptions through time, particularly the compounding nature of multiple hazard impacts and the influence of dynamic mitigation strategies on impact through an eruption crisis. The 2017/2018 explosive, multi-phase eruption of Manaro Voui volcano, Ambae Island, Vanuatu provided an opportunity for scientists to record the impact that the eruption had on Ambae's built environment. This research used field and photographic surveys, tephra falls, to record the damage that both traditional (made of bamboo and thatch) and non-traditional (made of milled timber and/or cinder block) buildings sustained from tephra fall. Damage sustained by buildings was described according to a 'damage state' framework, customised for this case-study. Complete collapse of traditional buildings was observed from ~40 mm of tephra fall, though some buildings exhibited no damage in areas with ~200 mm of tephra fall. The effectiveness of rapidly implemented mitigation methods to reduce building damage and maintain building habitability was also evaluated. Results from this research represent the first empirical dataset for traditional Pacific buildings damaged by tephra fall and contribute towards the limited, global empirical data available for tephra fall building damage, improving the current evidence base in forecasting future volcanic impacts.

## COMBINING SLOPE STABILITY AND MASS FLOW MODELS TO FORECAST DEBRIS AVALANCHE HAZARD AT MT. RUAPEHU

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An effective hazard assessment for volcanic flank instabilities relies on the delineation of source areas and the likelihood of collapse (i.e. assessment of slope stability), and estimations of the run-out, velocity and impact of these collapses. Recently acquired geophysical and geotechnical data of the Mt. Ruapehu edifice has reduced the uncertainty in identifying flank collapse source areas. However, the range of potential collapse volumes, locations and triggering mechanisms still presents significant difficulties in forecasting the potential impacts of slope failures at Mt. Ruapehu. Numerical mass flow models can be used to simulate debris avalanches, but it is infeasible to simulate all potential collapse scenarios to estimate the hazard. To ease the computational burden, we have developed a methodology that uses a reduced subset of potential slope failures through dimensional reduction and space-filling sampling techniques. Using debris avalanche simulations of this subset, a comprehensive mapping of debris flow impacts across the entire input space can be developed using statistical techniques. This mapping provides an efficient mechanism for understanding flank collapse hazards across a large spectrum of potential scenarios. This presentation will outline our framework for assessing and forecasting debris avalanche hazards including the integration of remote sensing surveys with geotechnical measurements, identification and modelling of slope failures, and development of the impact forecasting model.

## **MULTI-ATTRIBUTE SEISMIC ANALYSIS FOR VOLCANIC FACIES IDENTIFICATION: KORA VOLCANO, TARANAKI BASIN**

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The study of volcanism in sedimentary sequences has attracted attention since volcanic reservoirs have become targets for hydrocarbon exploration. However, the characterization of volcanic lithofacies in the subsurface is a difficult task, which is mainly attributed to their complex structural characteristics and extreme lateral variations. Seismic facies analysis is a technique that combines classification algorithms and seismic attributes to generate maps of reservoir heterogeneity, which reveal the distributions and geometries of seismic facies. In this study, multi-attribute seismic analyses, based on artificial neural network methods, were applied to characterize stratigraphic and structural features of the Miocene Kora stratovolcano, which is buried by more than 1000m of sedimentary strata in the Taranaki Basin. In our analysis a 3D post-stack seismic reflection volume was first inverted to acoustic impedance using a supervised artificial neural network framework, a genetic inversion technique, which employed well log data to quantitatively predict acoustic impedance from seismic amplitude. Seismic attributes (including acoustic impedance, RMS amplitude, and instantaneous phase), were used as input for an unsupervised neural network method, a self-organizing map, to classify the main seismic facies of the Kora volcanic edifice. To construct a structural framework enhancing the identification of faults and fractures, an ant-track seismic attribute analysis was conducted after pre-conditioning of the post-stack data. The interpretation of seismic facies were used to map the distribution of different igneous rock types and to reveal the internal structures of geobodies in the basin fill sequence. Sills, lava flows, volcanic conduits, flanks, normal and radial faults have been interpreted based on time slice and seismic-blending techniques. The interpretation of seismic facies and the structural framework of the Kora volcanic system contributes to the analysis of volcanism in sedimentary basins, increasing knowledge for prospecting and reducing geologic uncertainty during the seismic identification of volcanic system components.

## THE RISE OF A GIANT: USING CLUMPED ISOTOPES TO CONSTRAIN THE HYDROLOGIC HISTORY OF LAKE BONNEVILLE DURING THE LGM

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New geochemical constraints and climate modelling are reshaping our understanding of the conditions requisite for establishing large lakes in the Great Basin region of Western North America. During global ice ages, lakes expand dramatically across the region, but rapidly retreat, become hypersaline, and often disappear altogether during interstadial intervals. At the Last Glacial Maximum (~21,000 years ago), Lake Bonneville was the largest lake in Western North America, reaching a maximum surface area of nearly 50,000 km<sup>2</sup>. The hydrologic factors associated with transgression of shorelines are not fully understood; previous studies have hypothesized that increased summer or winter precipitation coupled with reduced summer evaporation led to the growth of these lakes. Most proxies provide an estimate of effective precipitation (precipitation minus evaporation), but cannot resolve either parameter independently. Here, we apply carbonate clumped isotope thermometry to constrain surface water temperatures at Lake Bonneville and reconstruct evaporation and precipitation using an isotope mass-balance approach. Multiple types of lacustrine carbonate were evaluated, including aragonitic gastropod shells, marls, and tufa, encompassing transgressive and highstand conditions between ~25 and 15 ka. Reconstructed water paleotemperatures were applied to estimate summertime and mean annual air temperatures using lake-atmosphere transfer functions. Results indicate a mean annual air temperature depression of 8-10 °C below modern values at Lake Bonneville during the LGM. Reconstructed evaporation, derived from clumped isotope constraints upon temperature and  $\delta^{18}\text{O}$  of lake water, was 75 percent below modern values, while precipitation over the lake was determined to be 21 percent above the modern rate. These results highlight the consequential role that temperature depression plays in facilitating a positive hydrologic balance, suggesting that Lake Bonneville grew primarily a result of lower evaporation.



## **SYNTECTONIC CARBONATE VEINS REVEAL LATE OLIGOCENE INITIATION OF EMPLACEMENT OF THE EAST COAST ALLOCHTON, NEW ZEALAND**

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Carbonates associated with fluid expulsion along the evolving Hikurangi margin have been studied in both active and ancient settings. Here, a unique set of syntectonic calcite veins are described for the first time in an outcrop of the Tikiore formation. Veins occur within the lower parts of the succession, including those within the Ngaterian and Arowhanan stages. Petrographic, trace metal, and stable isotope techniques are used to identify the timing and conditions of vein growth. Multiple brecciation and fluid events can be inferred from samples, where there is some evidence of disruption of primary calcite veins. Oxygen and carbon isotope and trace metal results indicate a fluid chemistry consistent with a minimally modified brine of marine origin. Some degree of seismically induced pumping enabled rapid migration of fluids at, or near, calcite saturation. Vein growth occurred at temperatures significantly below peak burial conditions, which were in excess of 100 °C, based upon vitrinite reflectance measurements of organic materials in the surrounding sandstone. Based upon calcite-fluid oxygen isotope equilibrium relationships, and constraints upon modern connate brine  $\delta^{18}\text{O}$  (i.e. Giggenbach et al., 1995), the inferred temperature of calcite growth is  $22 \pm 15$  °C. Radiogenic U-Pb constraints of calcite age indicate veins formed circa 27 Ma. Together, these results are consistent with vein formation during a period of rapid exhumation and deformation associated with the emplacement of the East Coast Allochthon and initiation of subduction along the Hikurangi Margin.

## MONITORING AND IMAGING THE TAUPŌ VOLCANO: A NEW SEISMOMETER NETWORK AROUND THE LAKE

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The Taupō Volcanic Zone (TVZ) supervolcano system is the most active area of silicic volcanism in the world. Taupō Volcano is the site of Earth's most recent supereruption (Oruanui, 25.5ka). The area continues to be active; there have been 28 eruptions at Taupō Volcano since Oruanui, most recently the Taupō eruption in 232AD. The substantial, but poorly constrained, magma reservoir beneath Taupō poses a significant unknown risk to New Zealand. The area under the lake has been particularly seismically active in 2019, including the largest earthquakes under the lake in the last 55 years. The current national GeoNet network of seismometers has relatively little coverage around Lake Taupō. This limits our ability to monitor and interpret seismic activity that could be a precursor to eruptive activity. To increase the coverage, we are deploying 13 additional broadband seismometers around the Lake Taupō area for a two year period. Recorded data will be used to detect and locate earthquakes with greater accuracy. First arrivals picked from waveforms recorded close to Lake Taupō will allow better constraints on focal mechanisms for earthquakes under the lake, and help identify the type of event that caused the earthquake. Tomographic techniques will also be used to image the current state of the magma reservoir, and to develop a crustal velocity model for the Taupō region. As part of the ECLIPSE project, we will work to combine inferences from the new data with other geochemical, geological and structural constraints, and share our results within the geosciences community and beyond.

## TRIGGERING OF LANDSLIDES IN SENSITIVE SOILS, BAY OF PLENTY, NEW ZEALAND.

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Omokoroa Peninsula in Tauranga Harbour is surrounded by ~ 30 m high coastal cliffs formed in Quaternary, halloysite-rich, sensitive tephra deposits. Flow-slides in these deposits are common, and generate long run-out debris flows. Cyclones Debbie (3/4 April 2017) and Cook (13 April 2017) generated considerable landslide activity, with 26 new landslides observed. Elevated pore water pressures provide the primary trigger for these landslides (Kluger *et al.*, in press), however, none of the landslides following Cyclone Debbie coincided with the peak of the pore water pressure (01.00 am, 5 April 2017). Rapid pore water pressure dissipation occurred and 66% of the pore water pressure had dissipated when the first landslide was observed (11.00 am). Landslide activity continued for a further 36 hours. Borehole inclinometer data indicates that the borehole casing sways in response to the solid Earth tide, indicating magnification of Earth tide movements in this soil profile. Comparison of the predicted Earth tides for 5/6 (Debbie) and 13/14 April 2017 (Cook) shows that all of the landslides for which adequate timing data exist occurred near the point of zero velocity on the Earth tide cycle. Analogous to Northern Hemisphere sensitive soils we infer a progressive failure mechanism for our soils. Lowered effective stresses at peak pore water pressures initiate failure, but pore water pressures rapidly dissipate, halting fracture development. Earth tides provide the mechanism for driving further progressive failure. Global failure thus occurs after peak pore water pressure, with the delay duration depending on the magnitude of the Earth tides and the soil characteristics.

Kluger, M.O., Jorat, M.E., Moon, V.G., Kreiter, S., de Lange, W.P., Mörz, T. Robertson, T., Lowe, D.J., in press. Rainfall threshold for initiating effective stress decrease and failure in weathered tephra slopes. *Landslides*, accepted 16 September 2019.

## THREE-DIMENSIONAL CO-SEISMIC ACCOMMODATION OF ~9 M OF DISPLACEMENT THROUGH A “MOLE-TRACK” STRUCTURE IN A STRIKE-SLIP EARTHQUAKE

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The 2016 *Mw* 7.8 Kaikoura earthquake provided a rare opportunity to understand ground deformation during a large magnitude strike-slip earthquake. During the earthquake, a backfilled paleoseismic trench (excavated 10 months prior) was displaced ~9.1 m dextrally along a section of the Kekerengu Fault striking 063. Both halves of the trench were re-excavated and re-logged following the earthquake to uncover a post-earthquake cross-section of the fault zone. Analysis of pre- and post-earthquake trench logs, photography, and high-resolution digital surface models at this site allow us to resolve where and how the ~10 m of slip was accommodated in 3D. Fence posts surveyed both before and after the earthquake indicate a transpressive displacement vector trending 065. Our results show that deformation was distributed across a 2.5 – 4 m zone; within which, turf broke along inferred Riedel faults into semi-coherent blocks that rotated clockwise by 10-15° to accommodate about 35 – 60% of the total strike-slip (dependent on the initial orientation of these faults). At the same time, blocks were shortened by 1 – 2 m perpendicular to the fault, contrasting the 0.32 m of contractional displacement of the transpressive slip vector. Cross-cutting relationships in the trench indicate that deep ground fissures were later overridden by thrust sheets of squeezed material as the earthquake progressed. Deformation at the same site during the previous three paleoearthquakes was very different to 2016, involving repeated subsidence without the raising of a moletrack. This temporal change in ground deformation style may be attributed to; 1) clockwise rotation of the displacement vector by ~10° from slight transtension to slight transpression in 2016; and/or 2) historical introduction of exotic grasses promoting the formation of a cohesive turf mat in the soil.

## **SIMPLIFYING COMPLEXITY: A TECTONIC MAP OF ZEALANDIA/TE RIU-A-MĀUI**

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A c. 1:8M scale Tectonic Map of the continent of Zealandia/Te Riu-a-Māui is being created as a GNS Science poster product. The purpose of the poster is to (1) visually describe the present day geotectonic framework of our continent and its surroundings, (2) promote public and educational awareness of Zealandia, especially its 95% offshore part, (3) inspire further research.

For regional context, the map takes in eastern Australia, the Solomon Islands, Samoa, and the Southern Ocean south of Macquarie Island. The principal map colours are keyed to the type of crust, and Zealandia is intentionally front and centre. Zealandia is subdivided into Western Province basement, Eastern Province basement and Zealandia Megasequence sedimentary basins. The area surrounding Zealandia shows oceanic crust, intraoceanic volcanic arcs and Large Igneous Provinces. Linear features on the map include active and inactive spreading ridges, oceanic crust isochrons, fracture zones, major faults, plate and microplate boundaries, the limits of the subducted Hikurangi Plateau, and contours on crustal thickness and the depth of subducting slabs. GPS-derived plate and microplate motions (Australian Plate fixed) are drawn. Zealandia's cargo of c. 500 volcanoes is symbolised to show Holocene, Pleistocene and older volcanoes, and subduction-related, hotspot track, and intraplate volcanism.

Hopefully, there's something familiar and something new for everybody on this map. The intent is to make the poster product and its data layers as widely available as possible, including in Geographic Information System format via a web server.

## HOW TO COPE WITH INCREASING EROSION ISSUES DUE TO MORE FREQUENT HEAVY RAINFALL EVENTS IN SUB-CATCHMENTS IN THE UPPER WAIKATO?

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A series of high intensity rainfall events occurred from the 12 December 2018 to early January 2019 near Tiverton Downs Road in Broadlands, Reporoa.

Slips and soil erosion processes have accelerated in gully systems as a result to these events in the Te Hau and Kaiwhitiwhiti Stream Catchments. This included extensive tunnel gully, gully head and streambank erosion over ephemeral and perennial waterways. Consequently, there was property damage and some infrastructure loss.

With the rainfall events having a high spatial variability, it was difficult for weather forecast providers to forecast precipitation at the local level. Therefore, there was some uncertainty to how the catchments would respond to the forecasted rainfall events. Similar weather events have happened in the past (2013/2014) and it is an ongoing problem for residents.

No measurements or systems are currently in place to estimate the amount of sediment loss into the surrounding waterways. However, there are three monitoring cameras set up in erosion prone areas, which capture a time-lapse of any earth movements.

The geology of the Tiverton Downs area presents mainly soil from the Holocene (<10,000 yrs). These deposits include mostly ash content, but also comprise unconsolidated, very soft to stiff intermixed peat, silt, sand and gravel. This type of soil has poor cohesive properties, making it particularly susceptible to erosion, especially during heavy rainfall.

After outlining the rainfall events and some of its consequences, this paper describes the methodology put in place by Waikato Regional Council to assess and mitigate erosion hazards and provide remedial options to the community of Tiverton Downs.

## SOFTWARE ENGINEERING FOR MULTI-SCENARIO MODELLING AND MACHINE LEARNING IN TSUNAMI SCIENCE: DO WE NEED IT?

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Tsunami research is largely relying on numerical simulation of tsunami wave propagation and coastal inundation because tsunami events are much rarer than earthquakes or other natural hazard events. This lack of real world examples also is responsible for a comparably large level of uncertainty around the tsunami phenomenon.

Uncertainty in tsunami modelling is assessed predominantly using the Monte Carlo approach, typically requiring large numbers of scenario simulations over a diverse parameter space. These parameters include, for example, source magnitude, geo location, geometry, non-uniform distribution of slip as well as variations in bathymetry close to the source.

Such large number simulation projects not only require a robust approach to creating them reproducibly and reliably, but also are computationally expensive and often take a significant amount of time to run, even on high performance computers. For the latter reason machine learning techniques are coming increasingly in to focus to help speed up multi-scenario assessments.

I will be presenting a multi scenario tsunami simulation framework (tsunami API) and it's use for inundation mapping, tsunami forecasting and the generation of machine learning data sets. I will discuss and demonstrate how useful engineered science software tools can be and why we should strive to create more of them, preferably in the open source space.

I will discuss examples from a multi-scenario tsunami modelling study for Christchurch, the results of which have been used to update the Christchurch tsunami evacuation zones, show example use of machine learning to predict on shore inundation extents and the use of the framework for tsunami forecasting.

## ARE MILANKOVITCH CYCLES EVIDENT IN THE GAMMA RAY LOGS OF LATE OLIGOCENE MIXED SILICICLASTIC-CARBONATES OF TIKORANGI FORMATION, TARANAKI PENINSULA, NEW ZEALAND?

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We evaluate whether gamma ray well logs from the Late Oligocene (Early Waitakian/late Chattian) Tikorangi Formation, onshore Taranaki Basin, North Island, New Zealand, preserve a record of astronomical forcing. The formation in the studied wells (Ngaere-2, Wahapa-2 and -5) is a deep shelf/slope, mixed siliciclastic-carbonate succession deposited in outer neritic to bathyal depths at paleolatitudes of c.45°S. It is composed of cool water, highly calcareous siltstones (high gamma), very fine to fine siliciclastic muddy packstones (intermediate gamma), and winnowed very fine to fine grain-dominated packstones and grainstones (low gamma). Gamma ray and sonic logs calibrated to core samples designate four lithofacies based on percent carbonate by Hood et al. (2003; NZJGG 46:363-386). Log-transformed and detrended gamma ray logs were tuned using minimal tuning methods (405 kyr long eccentricity cycle or, where absent, the c.100 kyr short eccentricity cycle) with sedimentation rates tested statistically against astronomical forcing. Both untuned and tuned data show well developed long- and short-term eccentricity, obliquity, and a weak precessional forcing. The floating time scale was tied to an absolute time scale via published biostratigraphy (Morgans and Waghorn 1999; GNS Science Report 99/18, 63 pp.), the La2004 eccentricity solution, an ODP inverted  $\delta^{18}\text{O}$  record, and the Mi-1 isotope event at c.23 Ma. The high gamma siliciclastic-prone units are mainly associated with higher sea level and warmer and wetter phases, whereas the cleaner carbonates developed during slightly lowered (<40 m) sea levels and cooler and drier phases. Tectonic deformation of the seafloor, local uplifts, resedimentation events, and seafloor currents probably account for subtle differences in the resulting gamma ray log records. The evidence for Milankovitch-scale spectra in the Tikorangi Formation suggests that comparable orbital forcing could be an important depositional control on the facies types and their architecture in other New Zealand Oligocene sedimentary sections.



## **GEODIVERSITY MAPPING AS A TOOL FOR GEOHERITAGE MANAGEMENT AND PLANNING**

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Current geoconservation practices face the problem of conflicting interests with rapidly increasing demand for urban development. Support for decision making in geoconservation could benefit from a more accurate spatiotemporal synthesis of available information on the outstanding value of abiotic nature. Practitioners developed in past decade diverse methods for quick identification of high diversity geologic and geomorphologic areas. However, the lack of a general consensus of defining the “unit” of significant values raise complex problems in the process of geodiversity mapping. Questions such as “What the outstanding element of geodiversity for geoheritage conservation is?” or “How to align land use planning with geoheritage promotion?” are basic questions waiting to be answered.

This paper aims to create the first step towards developing a robust scientifically based geoheritage value quantification to define geodiversity for the Quaternary Auckland Volcanic Field. Geoheritage is a multidisciplinary field that involves the mission of education and raised public knowledge of Earth Sciences through geotourism. Auckland Volcanic Field is one of the best examples to demonstrate how to categorize, cluster and quantify volcanic geodiversity useful for a diverse array of stakeholders.

Geodiversity is the variety of the geologic and geomorphologic features in the world and that moved us to plot geodiversity as taxonomic richness of a geographic area to best measure geoconservation priorities. Input variables were chosen for their strong links with geoheritage value to classify low to high geodiversity elements.

The meta data and map together form the basis of directing geoconservation and related activities to an optimal level that satisfies diverse interests of stakeholders.

The geodiversity map must underpin all further assessments where the different objectives for regional planning can step in. It serves as a base map that ensures that our evolving knowledge on monogenetic volcanism is well represented and translated to a comprehensive story that generates a broader public interest.

## **VOLATILES IN THE HIMU MANTLE COMPONENT AND THE EFFICIENCY OF DEHYDRATION DURING SUBDUCTION**

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Pillow basalts have been collected from the flanks of Rurutu and Tubuai in the Austral Islands, South Pacific by submersible. Whole rock radiogenic isotope and trace element chemistry of these samples suggests that the basalts were generated from a HIMU mantle component derived from an ancient subducted slab that was entrained and mixed with the depleted asthenospheric mantle. Sixteen glassy rims from the same samples have been analysed for major elements (including S and Cl) by EPMA, trace elements by LA-ICP-MS, and H<sub>2</sub>O and CO<sub>2</sub> by FTIR to constrain the volatiles in the magma sources, the volatiles in HIMU and the efficiency of subduction-related volatile-loss in the HIMU component. H<sub>2</sub>O ranges from 0.62 to 2.44 wt%, S 612 to 1889 ppm, Cl 151 to 538 ppm, while CO<sub>2</sub> is below detection (<20 ppm). The highest H<sub>2</sub>O contents may reflect late-stage hydration and are oversaturated at the depth of collection, the low H<sub>2</sub>O contents (11 samples 0.62-0.96 wt%) are undersaturated, and there is a positive correlation between the H<sub>2</sub>O contents of all chips and their incompatible element concentrations. Cl also correlates strongly with incompatible elements, while S correlates positively with FeO and Cu, but not with incompatible elements, suggesting sulfide saturation. Using H<sub>2</sub>O/Ce and Cl/Nb the Rurutu source contains 299 ppm H<sub>2</sub>O and 7 ppm Cl, and the Tubuai source contains 222 ppm H<sub>2</sub>O and 3 ppm Cl. Using the isotopic compositions to estimate the contribution from HIMU to the Rurutu and Tubuai sources, the H<sub>2</sub>O content of the HIMU component is 1,644 ppm in the Rurutu source, and 2,765 ppm in the Tubuai source. Thus, assuming oceanic crust entering a subduction zone contains 20,000-30,000 ppm H<sub>2</sub>O, the HIMU component in the Rurutu source has been ~92-95% dehydrated and ~86-91% dehydrated in the Tubuai source.

## MICROPHYSICAL MECHANISMS BEHIND GIANT EARTHQUAKES AND SEISMIC SUPERCYCLES

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Field observations suggest that natural fault zones are commonly heterogeneous in their composition, exhibiting alternations of frictionally stable and unstable materials (defined nominally to a reference plate velocity). This complexity prevents a simple interpretation of seismological observations based on laboratory results. We investigate the seismic cycle behaviour of heterogeneous faults of which the rheology is governed by a microphysical model for fault rock deformation. We focus on the occurrence of frictional instabilities in which the entire fault fails in a single event ('T-instabilities'), rupturing through both stable and unstable fault segments, as opposed to instabilities that rupture only a part of the fault. A model T-instability may be analogous to giant ( $M_w > 9$ ) earthquakes occurring in subduction zones, and so uncovering the processes that govern this type of events may provide useful insights for seismic hazard assessments. We study the occurrence of T-instabilities in complex heterogeneous fault systems, in which the fault zone geometry and microphysics are based on geological observations of exhumed faults and laboratory interpretations of friction. We found that the emergence of T-instabilities in these simulations is governed by a rheological transition that occurs within nominally stable segments of the fault, rendering large parts (or the entirety) of the fault unstable and causing initially stable segments to propagate dynamic ruptures rather than arresting them. In turn, this rheological transition is driven by an accumulating slip deficit which raises the average stress on the fault near a critical level at which the transition occurs. This makes T-instabilities time-predictable on the basis of the seismic moment accumulation rate. T-instabilities in the model are thought to be analogous to giant earthquakes in nature, and so the proposed mechanism for T-instabilities offers a microphysical interpretation for the origin of multi-segment ruptures and megathrust earthquakes.

## QUANTIFICATION OF ORGANIC CARBON TRANSFER TO THE DEEP-SEA BY THE KAIKŌURA EARTHQUAKE TURBIDITY CURRENT

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The November 2016 M<sub>w</sub>7.8 Kaikōura earthquake caused intense local and regional ground shaking, resulting in a significant failure of materials in the Kaikōura Canyon and other canyon catchments along the NE Marlborough-Cook Strait continental margin. These mass failures generated a turbidity current that swept down the Hikurangi Channel, transporting and depositing material at least 700 km away from source. It is estimated that 850 metric megatons (Mt) of material were removed from the Kaikōura Canyon, transferring ~7 Mt of organic carbon to the deep-sea (Mountjoy et al. 2018). Bulk carbon content and stable isotope analysis of sediment cores sampled within twelve months of the earthquake have better quantified the contribution made by remobilised sediments from Kaikōura Canyon as well as other canyon catchments. Radiocarbon <sup>14</sup>C measurements of the organic matter in these turbidite sediments indicate a consistent age of 1-2 kyr, suggesting that the material mobilised during the earthquake was largely from Holocene deposits, perhaps staged mostly in the upper parts of the canyon where the highest erosion rates occurred (typically 10-30 m of vertical incision) and/or incorporated into the turbidite flow as it progressed down the Hikurangi Channel into the deep-sea. The relative contribution of terrestrial organic material to the turbidite deposit has also been quantified using compound-specific stable isotope analysis of fatty acids and by meta-barcoding of DNA in deep-marine sediments, the latter undertaken for the first time in the New Zealand region. The Kaikōura earthquake turbidite deposit offers a potential template for fully quantifying the partitioning of organic carbon during such episodic events and for understanding the importance of deep-sea turbidites as 'lateral' organic carbon sinks in the global carbon cycle.

Mountjoy, J. J. et al. (2018). Earthquakes drive large-scale submarine canyon development and sediment supply to deep-ocean basins. *Science Advances* 4.

## TESTING THE VERACITY OF TURBIDITE PALEOSEISMOLOGY USING THE KAIKŌURA EARTHQUAKE-TRIGGERED TURBIDITE

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To better understand earthquake reoccurrence and hazard, records of ancient earthquakes spanning millennia are routinely generated using seabed turbidite deposits, inferred to be synchronously triggered by strong ground motions over large geographic areas. However, the use of turbidites for paleoseismology is underpinned by untested hypotheses due to the dearth of verified earthquake-triggered turbidite deposits produced by well-characterised earthquakes. The aim of our short voyage in October 2019 is to use the unique opportunity provided by the widespread occurrence of the 2016 Mw7.8 Kaikōura earthquake-triggered turbidite to determine whether synchronous turbidite deposition can be reconstructed from the sedimentary record alone. Our presentation will summarise provisional insights gleaned from a RV *Tangaroa* voyage in October 2019 that will densely sample along and across the axis of submarine canyons that preserve turbidite deposits triggered by the Kaikōura earthquake. Planned detailed laboratory characterisation of the turbidites will include high-resolution core imaging, texture, densitometry, down-core physical properties and geochemical characterisation combined with radioisotope-derived chronology. Through repeat coring at historical sites and future coring campaigns we hope to also quantify the impact of biological mixing on the Kaikōura event deposit to determine its likely preservation potential in the geological record. Our results should provide the first robust test of turbidite paleoseismology.

## FUNDAMENTAL GEOLOGICAL SKILLS ARE ESSENTIAL

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Geological mapping during the early 20<sup>th</sup> century focused on mapping the location, distribution and extent of economic resources, including coal and gold. One can only admire the skill, maps and accompanying documentation of those early geologists. Geological mapping and stratigraphy are no less important for 21<sup>st</sup> century geoscientists. The basics of rock and mineral identification together with field mapping experience are essential tools that every geoscience undergraduate student should expect to acquire. Geological mapping requires an ability to understand the landscape. Many environmental problems are landscape related with an underlying geological control, for example soil erosion processes. Simple mapping techniques such as good stratigraphic descriptions and measuring the dip and strike of beds are key to solving many problems. We need to find ways to increase students' time in the field participating in fundamental geology. Furthermore, mapping should be taught consistently throughout undergraduate courses, forming the backbone of a practical education that prepares students for real world problems faced in the workforce.

Recent work on the hydrogeology of the Rangitikei (Rees et al. 2019) demonstrates the benefits of applying a traditional geological approach to understanding a modern day problem. New Zealand's primary economy and reliance on conventional agriculture is driving landuse intensification, erosion and freshwater pollution. The ability to match landuse with landuse capability relies on our ability to understand landscapes, how they operate and how management practices can be targeted to protect our natural resources. Local geological mapping projects provide baseline information including structural and stratigraphic frameworks that place engineering and environmental studies into context.

The role of geology is important. Undergraduate geoscience courses focussing on mineralogy skills coupled with geological, including landscape, mapping ensure young geoscientists are well prepared to solve problems in the natural environment.

## **A STUDY OF VERY LONG PERIOD VOLCANIC EARTHQUAKES AT WHAKAARI/WHITE ISLAND, NEW ZEALAND**

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Whakaari/White Island volcano has produced three eruptive phases and various volcanic earthquakes for the past decade. One type is very long period (VLP;  $f = 0.03\text{--}0.1$  Hz) earthquakes which are often recorded prior to eruptions, and are thought to be related to fluid mass transport beneath volcanoes. VLP signals at Whakaari have been recognised since 2007 when a broadband sensor was first installed. Previous studies of Whakaari VLPs examined the source characteristics using seismic data from only a few days. This study aims to estimate the link between long-term VLP activity and eruption dynamics, and to assess the ability of VLPs to forecast eruptions.

Most Whakaari VLP events had repetitive and similar waveforms implying stable source process. We investigate VLP families for the period of 2007–2017 and analyse their temporal variations, source locations and mechanisms. To detect volcanic VLP events, we apply semblance and template matched filters and use a hierarchical clustering algorithm for a cluster analysis. We classify VLP activity into two major families and possible subfamilies depending on cluster threshold. One of the main families commonly occurred during the observation period and contains two of the three eruptive phases, while the other family was dominant during quiescence phase. We locate their source positions by a waveform semblance method revealing that most events occurred around 1 km depth. The source mechanisms are determined using moment tensor inversion, and results suggest a correlation between characteristics of VLP families and volcanic activity at this volcano. We expect that continuous monitoring of the VLP types will allow empirical analysis that leads to statistical assessment of probability of eruption.

## NEW ZEALAND, THE NATURAL LABORATORY: USING SPELEOTHEM FLUORESCENCE TO INVESTIGATE SOIL DOM EXPORT IN A PRE-HUMAN CONTINENT

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Soils store a greater mass of carbon than terrestrial vegetation and the atmosphere combined, meaning that changes in soil carbon storage can have a large effect on the global carbon budget. Dramatic increases in surface water dissolved organic matter (DOM) have occurred recently across the UK, Western Europe and parts of North America, and are attributed to loss of carbon from soils. Because these increases occurred on continental scales, the drivers must be broadly distributed. Yet, because the onset of DOC monitoring coincided with many broad environmental changes (temperature increase, land-use change, atmospheric S deposition), the causes of the DOM increase are hotly contested. Long-term (centennial-millennial) reconstructions of DOM under pre-human conditions, but during periods of changing climate, can help to disentangle the causes of heightened DOM export, and provide a natural baseline to contextualise contemporary monitoring data of DOM concentrations in terrestrial waterbodies.

This project focuses on New Zealand, a geographically isolated archipelago located in the Pacific Ocean. Unlike the Northern Hemisphere, NZ had no human inhabitants until the 13th century, and was not subject to 20th century industrial-scale atmospheric S deposition. However, NZ has undergone notable climatic and environmental changes through the past 14,000 cal. year BP.

In this study, 3D EEM fluorescence was used to measure humic-like DOM concentrations in modern dripwaters and within three flowstones (secondary carbonate deposits) from three caves distributed along a 7° latitudinal gradient. Our fluorescence data is shown alongside high-resolution trace-element measurements, with a focus on ratios of Mg/Ca (a proxy for effective meteoric precipitation above the cave), as well as comparison with other palaeo-environmental records.

The findings of this study imply that temperature and landscape response (in the absence of anthropogenic impacts) plays an important role in soil C export, and that speleothems are reliable recorders of such changes.



## SEAFLOOR POCKMARKS ON THE CHATHAM RISE: THEIR POSSIBLE LINK TO GLACIAL CYCLES AND THE SUBDUCTED HIKURANGI PLATEAU – AN OVERVIEW ON CURRENT HYPOTHESES

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Over 50,000 km<sup>2</sup> of the seafloor on the Chatham Rise and Bounty Trough is covered by pockmarks, which are usually thought to be caused by sudden escape of fluids and gas. Echosounder and seismic data furthermore reveal wide-spread buried pockmarks that appear to have been formed repeatedly near glacial-stage maxima. Pockmark distribution seems bathymetrically controlled, with smaller pockmarks occurring between ~500-700 m water depth and larger ones in water depths of >800 m. Formation of these pockmarks is enigmatic. Some of the buried pockmarks appear to be stacked, often at a slight offset, underlain by positive-polarity reflections, and aligned with structures that promote fluid escape. These patterns are compatible with repeated release of fluids from deep sources and precipitation of authigenic material. We present recently developed hypotheses for formation of these wide-spread pockmarks. Pronounced  $\delta^{14}\text{C}$  anomalies during the last glacial termination, around the time of formation of the most recent pockmarks, indicate release of significant amounts of geologic carbon. The pockmark fields coincide with the extent of the Hikurangi Plateau. We hypothesize, pockmark formation is linked to repeated release of CO<sub>2</sub> that originates from carbonates on top of the Hikurangi Plateau. We will discuss this hypothesis, open questions e.g., related to the “valve” mechanism controlling repeated release, as well as possible alternative mechanisms for pockmark formation.

## TERRESTRIAL HOT SPRING ANALOGUES FOR THE ORIGIN OF LIFE? THE ROLE OF MIXING ZONES IN HOT SPRINGS AT TIKITERE, LAKE ROTOKAWA, PARARIKI STREAM, AND WAI-O-TAPU, NEW ZEALAND

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In recent years, new geologic, chemical, and computational evidence supports the hypothesis that life originated on land in hot springs, rather than the currently favoured deep sea hydrothermal vents. This has profound implications for the search for life on Earth and beyond. Here, we will present new mineralogical and geochemical data from modern terrestrial hot springs in the Taupō Volcanic Zone, New Zealand in order to assess whether mixing zones between different geothermally influenced environments and chemistries are locales for concentrating elements that may be building blocks for the origins of life.

Sample sites were selected based on the presence of mixing zones between distinct source pools or water bodies (thermally influenced creeks). Geochemical and mineralogical analysis of sediments and thermal waters from hot spring sources and mixing zones at four sites in the Taupō Volcanic Zone are being used to characterize the ionic concentration and rates and composition of mineral precipitation, with sediment and fluid results compared to organic signatures.

Modern siliceous hot spring deposits develop as mineral precipitates out of the thermal waters, building up layers of sinter that preserve the physicochemical conditions of the thermal pools and discharge aprons, as well as the settings of the organisms living there. The effects of fluid alteration and metamorphism on ancient hot spring deposits change the original fluid signatures and textural environmental signals. However, modern hot springs can be used as a guide to interpreting ancient hot springs such as in the 3.5 Ga Dresser Formation, Pilbara Craton, Western Australia. Understanding the chemistry and chemical energies of active hot spring systems and their mixing zones will enable evolution of these systems as incubators for ancient life on Earth, as represented by the Dresser system, as well as for the origin of life.

## USE OF UAV FOR GEOTECHNICAL ASSESSMENT

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Adoption of innovative technology for carrying out geotechnical inspections has traditionally been sluggish across the industry. There has typically been very little difference to how geotechnical professionals carry out inspection work since the industry began: measurement, record observations, take photos etc. The use of Unmanned Aerial Vehicles (UAVs), however, is 'taking off' in this space, and starting to be recognised as best practice for the geotechnical industry.

Historically, geotechnical inspections of geohazards, e.g. landslips, would be limited by access constraints, availability and resolution of aerial photography. Use of UAVs allows capture of aerial photography from any available perspective. Capturing a view of the area upslope of the geohazard is of particular importance. For large scale features, use of a UAV can save huge amounts of time, costs, as well as reduce risks of needing to access marginal areas of site.

The Beca geotechnical team is taking advantage of the use of UAVs to capture data as part of their services to manage geohazard risks in the Coromandel region. The team have now carried out multiple flights of geohazard sites. Each flight typically records hundreds of photos. Use of software that utilises photo-stitching and photogrammetry allows generation of a 3d model. This can be analysed in detail from the comfort of the office. Depending on photo quality, and resolution, a well-developed 3d model can have millimetre accuracy.

Better visibility of the features of a geohazard allows for better assessment, and better management of risk. Development of a 3d model also means no longer rifling through photos from a site visit, more accurate sketches, elevations and cross sections of geological and geotechnical features, and a great visualisation tool to show to clients/stakeholder. Interpreting the 3d model below ground allows seamless transition into geotechnical and geometric design.

## **VOLCANISM OF 'MIDDLE EARTH': THE NORTH ISLAND VOLCANIC LANDSCAPE BETWEEN 3.0 AND 0.9 MA**

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The Taupo Volcanic Zone (TVZ), in particular the young, northeast-trending volcanic arc that has been active for the last 340 kyrs, is the latest manifestation of the ever-changing Late Cenozoic central North Island volcanic landscape. The young TVZ, since c. 200 ka, has been synchronous with intraplate basaltic volcanism in the Auckland Volcanic Field. This talk reviews our current knowledge and ongoing research on earlier volcanic landscapes active from 3.0 to 0.9 Ma, which span the end of long-lived arc volcanism of the Coromandel Volcanic Zone to the early TVZ. Three volcanic landscape configurations are defined across this timespan. The first phase saw the focus of rhyolite volcanism at the Tauranga and Kaimai volcanic centres (2.95–1.95 Ma), which was dominated by domes and local pyroclastics, and accompanied by an andesitic stratovolcano. The large-volume Waiteariki Ignimbrite (2.09 Ma or 2.25 Ma), which also occurs in the Tauranga-Kaimai region, was erupted from a yet-unidentified source vent. Contemporaneous transitional basaltic volcanism occurred in a back-arc setting along the Alexandra Volcanic Lineament (mostly 2.7–1.9 Ma), where the earliest known intraplate field of western North Island was also established (Okete Volcanics, also 2.7–1.9 Ma). The second phase (1.9–1.6 Ma) is characterised by dispersed andesitic stratovolcanism at Maungatautari (1.8 Ma), Titiraupenga (1.89 Ma), and Pureora (1.60 Ma) in the southern Waikato, along with other buried andesites in geothermal drill holes and a 1.89 Ma silicic ignimbrite of unknown source. This was synchronous with a shift in intraplate volcanism northward from Okete to Ngatatura (1.8 Ma), northern Waikato. The third phase was marked by rhyolitic explosive volcanism at the Mangakino Volcanic Centre (1.6–0.9 Ma), sporadic arc front andesites (e.g. Hauhungatahi, 0.9 Ma) and brief rejuvenation of back-arc volcanism (Pirongia, 1.6 Ma), alongside further northwards migration of intraplate volcanism to South Auckland (1.59–0.51 Ma).

## EVIDENCE OF LARGE EXPLOSIVE VOLCANIC ERUPTIONS FROM NEW ZEALAND IN ANTARCTICA

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Abrupt volcanogenic cooling of the Earth - “volcanic winters” - has been documented after historic eruptions, but the impacts of the largest known events remains highly speculative. Scientific drilling of sediment and ice cores has recovered Antarctic palaeoclimate records that provide a unique opportunity to determine how and at what rate the climate system components of Antarctica and the Southern Ocean respond to, moderate and control the effects of rapid change induced by volcanic (super)eruptions. In order to better understand volcanic-forcing on climate, this study seeks to identify the products of large eruptions from the Taupō Volcanic Zone of New Zealand within Antarctic ice cores at two key intervals during inter-glacial and glacial periods (1800 and 25,400 years ago). Previous research has attributed a positive non-sea-salt-Sulphur (nssS) spike at ~232 C.E. in Greenland and multiple Antarctic ice cores to the Taupō eruption. However, in the absence of volcanic glass shards for geochemical verification this assignment remains speculative. The primary aim of this study is to locate glass shards produced by the Oruanui and Taupō eruptions. Preliminary analyses of nssS, electrical conductivity and particle counter data obtained from the South Pole (SPICEcore) and West Antarctica (WAIS-Divide) have identified depth intervals for the eruptive signatures of interest, with promising results. Ice from these selected intervals will be melted and its contents subsequently examined via SEM for the presence of glass shards for analysis of major and trace elements. Following the chemical identification of volcanic glass from the Taupō and Oruanui eruptions it will be possible to refine existing age models, provide insights into atmospheric ash transport and examine the water isotope record to better understand volcanically-induced climatic responses and recovery times.

## WHAT DROVE RAPID TERRESTRIAL PALEOENVIRONMENTAL CHANGE IN LATE CRETACEOUS NEW ZEALAND?

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The Waipounamu Erosion Surface is a heterolithic unconformity expressed throughout the greater New Zealand region. It represents a short intense episode of non-marine erosion and can be interpreted as a Late Cretaceous subglacial floor. Removal of several kilometres of overburden can be inferred from the presence of authigenic pumpellyite in the mid Cretaceous non-marine Momotu Supergroup, which was clearly deposited, buried, incipiently metamorphosed then exhumed within a short span of Cretaceous time.

Momotu Supergroup sediments record a temporal transition from fluvial and lacustrine sedimentation to deposition of laterally-extensive boulder breccias. The transition from continuous fluvial sedimentation to episodic non-precipitation driven deposition from bouldery hyperconcentrated debris flows is expressed regionally and suggests that a pluvial climatic regime was superseded by an episode of semi-aridity.

Bouldery Momotu sediments probably represent jökulhlaup or glacial lake outburst flood (GLOF) debris deposited into the proglacial environment soon before regional glacial erosion. Aridification can be accounted for by windy periglacial conditions.

Paleoenvironmental and paleoclimatic changes archived by Cretaceous terrestrial sediments of the Momotu Supergroup can be explained coherently in terms of nucleation of small ice caps that periodically generated GLOFs before coalescing to form the voluminous wet-based or polythermal Cretaceous ice sheet beneath which the Waipounamu Erosion Surface developed.

However, controls on terrestrial paleoenvironmental change in Late Cretaceous New Zealand and in particular the drivers of the brief destructional event that formed the enigmatic Waipounamu Erosion Surface are poorly understood.

Cooper, Price and Reay (2018, *NZJGG 61*: 444-460) have proposed that New Zealand's Late Cretaceous magmatism, tectonism and metamorphism were driven by a hitherto-unrecognised episode of eastward-directed late Cretaceous subduction. This subduction was plausibly also the driver of uplift-driven climatic deterioration and consequent rapid Momotu sedimentation, associated burial metamorphism, and regional glacial denudation represented by the Waipounamu Erosion Surface.

## TSUNAMI HAZARDS OF THE ROSS SEA, ANTARCTICA

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We consider the effects of tsunamis on Antarctica and the potential for tsunamis to be generated there, with focus on the Ross Sea region. Historically, there have been few tsunamis reported in Antarctica, which may in part be due to the continent being sparsely and recently populated. We summarise what has been recorded in relation to only a handful of events. As part of a study to inform planning for a redevelopment of Scott Base, we used numerical modelling to establish the sensitivity of the Ross Sea region to distant-source tsunamis caused by earthquakes on the Pacific Rim. Tsunamis can transmit energy over long distances, this energy is typically concentrated in a 'beam' that starts perpendicular to the fault which causes it and is further modulated by seafloor topography. We demonstrate that the Ross Sea is particularly sensitive to tsunamis generated on the coast of southern Mexico. A large earthquake on the south Mexico coast could produce a much larger tsunami than any historical tsunami in Antarctica. The coast of Antarctica, and the Ross Sea in particular, is fringed by seasonally-variable floating sea ice and permanent floating ice shelves. We consider the effect of ice on tsunami propagation and, using information on historical tsunamis in 1868 and 2011, consider what impact a tsunami can have on the stability of ice shelves. We also consider the potential for locally generated tsunamis, including those that might be caused by mapped faults in the Ross Sea; these are associated with rifting in McMurdo Sound but may also be activated by isostatic rebound. Other sources, such as landslides, volcanic events, and ice-calving events are considered, and we discuss the possibility that these may become more active with changing climate and ice-retreat.

## INTRODUCING THE NATIONAL GEOHAZARDS MONITORING CENTRE TE PUNA MŌREAREA I TE RŪ

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The National Geohazards Monitoring Centre Te Puna Mōrearea i te Rū (NGMC), based at GNS Science's Avalon campus, launched on December 12, 2018. The establishment of the NGMC represents a significant step forward in New Zealand's capability to monitor and respond to the geohazards that impact its people. Here, we will show how the NGMC has grown from the initial business case through to the design, build and launch of the centre. We will present key developments and statistics from our first year in operation, illustrate the impact of the NGMC on how geohazard information is analysed and reported and unveil some of our plans for the near future.



## THE NATIONAL GEOHAZARDS MONITORING CENTRE: OPERATIONS AND EVENT RESPONSES

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New Zealand's National Geohazards Monitoring Centre Te Puna Mōrearea i te Rū (NGMC) is unique in the world, in that it monitors and responds to the four primary geological perils: earthquakes, tsunamis, volcanoes and landslides. Manned 24/7 with a tight-knit team of dedicated Geohazards Analysts (GHAs), who work closely with support staff and experts from GeoNet and GNS, the NGMC constantly buzzes with activity. In a significant geohazard event, the NGMC escalates into response mode and works to rapidly provide information to the Ministry of Civil Defence and Emergency Management (MCDEM) to help inform decision making. Between events, the GHAs maintain live geohazard monitoring using a number of different tools and systems, produce various daily reports, review and improve standard operating procedures, undertake further training to improve their skills and knowledge, participate in event-response exercises and other portfolio work. In this presentation, representatives from the NGMC will discuss how the NGMC operates day-to-day, and what happens during event responses.

**THE ANCIENT DNA REVOLUTION: HOW OUR UNDERSTANDING OF THE IMPACTS OF THE QUATERNARY ICE AGES, AND HUMANS, ON NEW ZEALAND'S BIODIVERSITY IS RAPIDLY CHANGING.**

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The Quaternary has been a dynamic period of New Zealand's geological history, first with the Pleistocene glaciations, and later human arrival. The arrival of humans resulted in the loss of 50% of our unique biodiversity due to hunting, habitat destruction and predation by introduced predators. New Zealand is unique in that the often confounding effects of humans and climate change can be clearly separated, and studied in isolation. The arrival of humans and the consequent extinctions occurred at a time of relative climatic stability. New Zealand's rich Late Quaternary fossil record, spanning the past 60,000 years, and the recent archaeological record, contain the remains of many of New Zealand's extinct avian species. The advent of ancient DNA, combined with morphological analysis and radiocarbon dating, has revolutionised our understanding of how our unique biodiversity responded to climate change and human impact. In this talk I'll review the current state of the field and how ancient DNA has revolutionised our understanding of this dynamic time.

## **QUATERNARY GEOLOGY AND HYDROGEOLOGY OF THE POUREWA SUB-CATCHMENT, RANGITIKEI, NEW ZEALAND**

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The Pourewa Stream is a tributary of the Rangitikei River in the lower North Island of New Zealand. The stream dissects a portion of the onland Whanganui Basin, characterised by cyclic Late Miocene-Quaternary shallow-marine sedimentary units deposited throughout eustatic sea level fluctuations. Issues regarding sub-catchment water quality and supply have been raised following ongoing landuse change and associated demand for freshwater. Nitrogen loss from farms due to leaching of nitrate into the subsurface has increased in conjunction with landuse intensification. Concerns around the availability and long-term sustainability of freshwater resources have initiated research into the sub-catchments groundwater system. The aim of this study is to (1) map the hydrogeology of the study area at 1:25 000, (2) collect and analyse representative samples of key hydrostratigraphic units, and (3) develop a conceptual hydrogeological model. Results suggest the area is characterised by a series of vertically stacked fine- and coarse-grained sedimentary units that correspond to aquitard and aquifer units. Individual units display lateral and vertical variations in key hydrogeological parameters, including high permeability zones that act as preferential subsurface flow pathways. Hydraulic conductivity, effective porosity and permeability generally decrease with age, reflecting progressively greater depth of burial and level of diagenesis. Depositional environment and resultant facies dictate sedimentological properties, exerting an important control on the ability of a unit to store and transmit water. Organic carbon, illite and glauconite present within the hydrostratigraphic succession indicates natural attenuation of nitrate within the local groundwater system is taking place. High permeability Late Quaternary fill represents the most productive regional aquifer. The close relationship between Late Quaternary fill and surface water bodies results in susceptibility to pollution and over exploitation. In contrast, the Quaternary marine basin fill is characterised by lower hydraulic conductivity, longer residence times and therefore, a greater ability to attenuate nitrate.

## CHARACTERISING THE QUATERNARY STRATIGRAPHIC INFILL OF DUNEDIN

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Beneath the surface of the low-lying densely populated suburbs of Dunedin and the adjacent Otago Harbour is an extensive record of past sea-level change over the Quaternary. In this investigation, we use a combination of seismic and sedimentological techniques to identify and constrain paleo sea-levels within the subsurface geology of Dunedin and Otago Harbour.

Seismic imaging of sediments within Otago Harbour was used to track sea-level high-stand sedimentary units throughout the subsurface, identified by contrasts in the physical properties of the sediment, causing strong visible reflections. The seismic images were used to propose and track representative sedimentary horizons, allowing comparison with sediment cores collected as part of the New Zealand SeaRise programme in early 2019 and from the Edgar Centre in South Dunedin in 2016. We have mapped five distinct horizontal sedimentary reflections observed within the paleo-valley sediments, that coincide with observed changes in lithology within both the New Zealand SeaRise and Edgar Centre cores. XRF data collected from cores indicate changes in depositional environment as well as provenance. Radiocarbon ages from the Edgar Centre Core produce age constraints for the upper 20 m, with the lower 25 m being past the dateable age range. These ages cover the two shallowest horizons observed within the seismic record. Additional dating of the SeaRise cores will help constrain these processes further.

We present several distinct horizontal sedimentary reflections observed within the paleo-valley sediments, that coincide with observed changes within the New Zealand SeaRise and Edgar Centre cores. By combining seismic and sedimentological techniques we can better understand the processes involved in the stratigraphic infill of Dunedin.

## #CLIMATEEMERGENCY – WHAT IS IT AND WHAT DOES THE FUTURE HOLD?

### **James Renwick**

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The Paris Agreement on climate change commits the countries of the world to take action to hold global warming to “well below 2°C above pre-industrial levels” and to pursue “efforts to limit the temperature increase to 1.5°C above pre-industrial levels”. A recent report from the IPCC (Intergovernmental Panel on Climate Change) stated that to stop global warming at the lower end of the Paris Agreement range (1.5°C), global emissions of carbon dioxide would need to halve by 2030 and get to zero by 2050. On that basis, many national and regional government agencies have declared a “climate emergency”.

As the climate warms, the occurrence and intensity of many weather and climate extremes increase. This leads to greater risk of economic, infrastructure and social damage. Hence, the sooner global warming is contained, the lesser the cost to human society. However, the geological record suggests that there is no “point of no return” where climate change goes “out of control”, as has been suggested by some commentators. Human activity has caused the bulk of the changes observed over the past century or two and it will be human activity that defines the amount of future change.

This presentation will give an overview of the current state of the climate system and will discuss what would be required to stop global warming at 1.5 or 2 degrees C above pre-industrial, including what motivates calling the situation an emergency. It will outline some of the risks for different levels of warming, and the potential for surprises, informed in part by the geological record. Looking further ahead, it will touch on what would be required for the long-term sustainability of humanity.

## A HYDROCHEMICALLY GUIDED LANDSCAPE CLASSIFICATION SYSTEM FOR MODELLING SPATIAL VARIATION IN MULTIPLE WATER QUALITY INDICES: PROCESS-ATTRIBUTE MAPPING

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Spatial variation in landscape attributes can account for much of the variability in water quality relative to land use on its own. Such variation results from the coupling between the dominant processes governing water quality, namely hydrological, redox, and weathering and gradients in key landscape attributes, such as topography, geology, and soil drainage. Despite the importance of ‘process-attribute’ gradients (PAG), few water quality models explicitly account for their influence. Here a processes-based water quality modelling framework is presented that more completely accounts for the role of landscape variability over water quality – Process-Attribute Mapping (PoAM). Critically, hydrochemical measures form the basis for the identification and mapping of effective landscape attributes, producing PAG maps that attempt to replicate the natural landscape gradients governing each dominant process. Application to the province of Southland (31,824 km<sup>2</sup>), New Zealand, utilised 12 existing geospatial datasets and a total of 28,626 surface water, groundwater, spring, soil water, and precipitation analyses to guide the identification and mapping of 11 individual PAG. The ability of PAGs to replicate regional hydrological, redox, and weathering gradients was assessed on the accuracy with which the hydrochemical indicators of each dominant process (e.g. hydrological tracers, redox indicators) were estimated across 93 long-term surface water monitoring sites (cross-validated R<sup>2</sup> values of 0.75–0.95). Given hydrochemical evidence that PAGs replicate actual landscape gradients governing the dominant processes, they were combined with a land use intensity layer and used to estimate steady-state surface water quality. Cross-validated R<sup>2</sup> values ranged between 0.81 and 0.92 for median total nitrogen, total oxidised nitrogen, total phosphorus and dissolved reactive phosphorus. Models of particulate species *E. coli* and total suspended sediment, although reasonable (R<sup>2</sup> 0.72–0.73), were less accurate, suggesting finer-grained land use, landscape attribute, and/or flow normalised measures are required to improve estimation.

## LATE QUATERNARY GEOLOGY AND GEOMORPHOLOGY ALONG THE WAIKATO RIVER FROM CAMBRIDGE TO THE NARROWS

### Late Quaternary Hamilton Basin development

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A geological model was developed to assess liquefaction and ground stability risks to future urban growth and infrastructure adjacent to a 2km length of the Waikato River, to the west of Cambridge. The model provides evidence of the complexity involved in cycles of deposition and erosion of Late Quaternary alluvial sediments and volcanic soils, and variations in the level and location of the Waikato River.

The Waikato River is typically within a 25m to 50m wide incised channel between terraces that step down from the overlying Hinuera Surface. The general geological sequence comprises Late Pleistocene Hinuera Formation alluvium (Piako Subgroup) below the plains and upper terraces, older Piako Subgroup lacustrine and alluvial deposits near the surface on lower terraces and river banks, Late Pliocene to Mid Pleistocene Walton Subgroup tephra, ignimbrite and alluvial deposits in the lower portion of the river banks. Holocene age Taupo Formation pumiceous alluvium was encountered in portions of the lower terrace and within tributary gulley's . River bar and channel geomorphic features were also identified on the lower terrace potentially due to re-entrenchment of the Waikato River after the Taupo eruption and subsequent breakout flooding approximately 1800 years ago.

Both the river channel and overlying terraces are not as wide at the Narrows gap at the west of the site. Walton Subgroup materials were encountered high up the river banks and at the surface of some of the terraces to the north of the Narrows. The narrowing of the river channel is potentially due to constraining by more competent Walton Subgroup soils in a 'buried paleo-hill' to the north. Faulting has been postulated to account for some of the river bank geomorphic features and the palaeo-hill. Evidence that the river terraces were formed due to large scale mass movement was not identified.

## VOLCANIC PROCESSES AND EMPLACEMENT MECHANISMS OF THE 1.6 MA NGAROMA ERUPTION

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The Taupo Volcanic Zone (TVZ) on the North Island consists of at least eight caldera complexes, the earliest being the Mangakino Volcanic Centre (MVC), which lies west of the modern NNE-SSW trending volcanic arc basin. The 1.6 Ma Ngaroma eruption is the first known rhyolitic eruption of the TVZ, and textural and compositional variations recorded throughout the Ngaroma ignimbrite provide insight into pre-eruptive processes and post-emplacment mechanisms. The research presented here is based on field mapping and facies analysis of this ignimbrite around the Ngaroma township in southern Waikato, and follow up petrographic and geochemical analysis.

The ignimbrite is up to 40 m thick and is intensively devitrified and vapour-phase altered in the field area. It typically comprises 10-20 %, up to 40 % pumice (wispy lenticulite; grey elongate; chalky) and up to 7 % lithics (greywacke-argillite, andesite, rhyolite), and <2 % crystals (plagioclase, orthopyroxene, opaques). Two primary facies (lithic-rich and lithic-poor facies) and four subfacies (based on alteration colour and texture) have been identified and are presented in five stratigraphic logs, which vary both vertically and laterally and reflect both syn- and post-depositional processes.

Petrographic observations and mineralogic analyses involving optical microscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD) record high concentrations of sanidine and cristobalite, resulting from significant post-emplacment devitrification and vapour phase alteration. Although very little glass is preserved, the intensity of alteration, in terms of textural overprinting is variable; the ignimbrite matrix varies from a eutaxitic texture comprising (a) visible, well-formed, but devitrified glass shards, typically 300 to 800  $\mu\text{m}$ , to (b) a fine-grained, homogenous, optically unresolvable medium; the latter can be resolved under SEM and comprises intergrown <3  $\mu\text{m}$ -sized K-feldspar (sanidine), nano-crystalline silica (cristobalite  $\pm$  tridymite), and pores.



## THREE-DIMENSIONAL ARCHITECTURE AND RESERVOIR POTENTIAL OF A LAVA FLANK, NE LYTTLETON VOLCANO, BANKS PENINSULA

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Increasing commercial interest in volcanic deposits is demanding a better understanding of the petrophysical properties that control the formation and distribution of volcanic reservoirs. We characterise the northeast portion of Lyttleton Volcano, Banks Peninsula to understand how permeability and porosity vary with the three-dimensional architecture of volcanic facies and increasing distance from the eruptive centre. The lava units are described according to the proportion of fractures and vesicles, the mineralogy, flow textures, and alteration degree, and their relationships with each other. The lava pile is formed by intercalation of 0.5 to 12 m thick sheet `a` flows. Proximal to the eruptive centre, coherent fractured lavas predominate, while brecciated facies are dominant in the medial zone. A slight decrease in the underlying slope controls the facies variation.

Field matrix permeability in the brecciated facies ranges from  $2 \times 10^{-14}$  to  $1.8 \times 10^{-13}$  m<sup>2</sup>. Laboratory measurements of porosity in the coherent fractured lavas range from 0.5 to 15%, and matrix permeability varies from  $10^{-20}$  to  $10^{-15}$  m<sup>2</sup>. Highly porous (17 and 25 %) and permeable ( $4 \times 10^{-15}$  and  $2.4 \times 10^{-15}$  m<sup>2</sup>) samples correlate with microfracturing and dissolution textures. To estimate the effect of macrofractures (>0.065 mm aperture), an equivalent permeability is calculated using the fracture frequency and aperture described in the field. Macrofractures increase the matrix permeability by six orders of magnitude ( $2 \times 10^{-13}$  to  $5 \times 10^{-9}$  m<sup>2</sup>).

Our results indicate that the reservoir properties of the lava flank are principally controlled by the mechanisms of emplacement and growth of the lava flows. The proximal facies to the eruptive centre, present a low matrix permeability and are mainly control by fracture networks. In contrast, the medial zone predominates facies with higher matrix permeability and rare fractured. This study demonstrates that the detail architectural and petrophysical analysis can be used as a prospective tool for geofluid extraction.

## THE ECLIPSE PROGRAMME - REDUCING UNCERTAINTY AROUND FUTURE UNREST AND ERUPTION IN THE CENTRAL TAUPŌ VOLCANIC ZONE

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New Zealand's central North Island is home to the world's most frequently active system of rhyolitic calderas. The volcanic lakes, domes, and geothermal systems that stretch from Taupō to Tarawera are the surface expressions of this super-sized underground magma system. Every few years to decades, this caldera volcano system becomes restless, causing swarms of earthquakes, ground deformation and disturbance of hydrothermal systems. Every few hundred years (highly variable, but on average), this unrest leads to a volcanic eruption. These eruptions may be small or very large, and in the largest examples can have devastating impacts on people, the environment, and economy. Much more likely in the near future is unrest, yet there remain great uncertainties about the causes of unrest and the factors that make an unrest event occasionally lead into eruption. ECLIPSE (Eruption or Catastrophe: Learning to Implement Preparedness for future Supervolcano Eruptions) is a 5-year multi-institutional research programme funded by the New Zealand Ministry of Business, Industry and Employment (MBIE) Endeavour Research Programme ([www.supervolcanoes.nz](http://www.supervolcanoes.nz)). Research in the ECLIPSE programme investigates the underground roots of the volcanic system to identify what conditions cause it to become restless or erupt and aims to better define the tipping point when unrest leads to eruption. Experimental and numerical modelling methods are being developed for consequent hazards and impacts in today's society. Through deep partnership with GeoNet, tangata whenua, the community (including schools) and emergency management groups, ECLIPSE research will also explore ways in which we can enhance resilience to these events. This presentation will summarise the key milestones of the ECLIPSE research programme over the last 2 years, and outline our directions for the future.

## **BOOTS, HAMMER AND COMPASS: NAVIGATING FIELDWORK IN OUR CHANGING LANDSCAPE**

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Zealandia: a continent largely submerged except for the rise of an accretionary orogen that provides a window for direct geoscientific observation. From Hochstetter, Hector and Haast to Wellman, Suggate, Isaac and Cox, geologists have explored this landscape with boots, hammer and compass. The bulletins and maps that underpin our understanding of subaerial Zealandia were generated by geologists with a sense of adventure and fortitude. Primary data were hard won and the insights drawn were exceptional, particularly before the advent of remote sensing. Much has changed since Wellman deduced the Alpine Fault. In this address, I review the context of field geology in New Zealand from the first few decades of colonisation to today, a time of extraordinary social and environmental change. This review focuses on the impact of our disciplinary history and changing technical and political landscape on our social license to operate and our ability to maintain field capability.

## THE ORIGIN OF MAGMA ENCOUNTERED DURING DRILLING OF THE HYDROTHERMAL DRILL-HOLE KJ-39, KRAFLA, ICELAND.

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In July 2008, drill hole KJ-39 encountered magma at 2865 metres below the surface while drilling into the geothermal system within the Krafla central volcano, north-eastern Iceland. The magma was returned to the surface as quenched glass. In June 2009, the better-known IDDP-1 drill hole, located 1 km north of KJ-39, also intercepted rhyolitic melt and partially molten felsite rich in quartz, plagioclase and alkali feldspar. Because of the proximity of the two drill holes, we investigate whether the magma encountered in KJ-39 is from the same source as IDDP-1. This will have important implications for the dimensions of the magma chamber and thus future geothermal drilling operations. Major elements, S, Cl and F have been measured in KJ-39 glass chips using electron probe micro-analysis (EPMA) and H<sub>2</sub>O and CO<sub>2</sub> have been measured in different chips using Fourier-transform infrared spectroscopy (FTIR). The KJ-39 chips have a striking range in composition from andesitic to rhyolitic, SiO<sub>2</sub> 58-79 wt% and all are brown (in contrast to the colourless and brown, 74-78 wt% SiO<sub>2</sub>, glass from IDDP-1). In KJ-39 there is a group containing 0.76-1.20 wt% H<sub>2</sub>O, and two chips with much higher H<sub>2</sub>O contents of 4.49 and 6.26 wt%. S contents range from below detection to 1157 ppm and show a strong negative correlation with SiO<sub>2</sub>. In contrast, IDDP-1 contain 1.4-2.5 wt H<sub>2</sub>O % and 11-75 ppm S. Major elements for the KJ-39 glass give low totals (90-95 wt%) despite Smithsonian rhyolite standard VG568 having totals of 98.7-99.1 wt% under the same conditions. Continued EPMA analysis of the high-H<sub>2</sub>O chips is planned to determine whether the low totals are related to H<sub>2</sub>O content. The implications of the differences between the KJ-39 and IDDP-1 glasses will be discussed in this presentation.

## **SEDIMENT PROVENANCE ADJACENT TO THE AUSTRALIAN–PACIFIC PLATE BOUNDARY: PRELIMINARY RESULTS FROM THE MURCHISON BASIN**

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Regional tectonic events are recorded in Cretaceous–Cenozoic sedimentary basins across Zealandia by widespread changes in sediment texture and composition that may reflect changes in sediment provenance. In our study we build on earlier provenance work through acquisition of new mineralogical, geochemical and geochronological data for Cretaceous–Quaternary sandstones in the West Coast and Taranaki basins, central Zealandia. Murchison Basin lies immediately west of the Alpine Fault and is, therefore, ideally placed to have recorded Australian–Pacific plate boundary evolution through the Cenozoic. Previous work in this area demonstrates an influx of Caples Terrane metasedimentary clasts in the middle Miocene, interpreted to reflect plate boundary shortening and Pacific Plate exhumation. We present new petrographic and U–Pb detrital zircon age data for Murchison Basin sandstones to further investigate these provenance changes. Petrographic data show that the sandstones display a range of compositions from arkose to feldspathic litharenite. Samples of the Eocene Maruia, and Miocene Mangles and Longford formations from the northern Murchison Basin are relatively enriched in quartz and K-feldspar compared to Miocene–Pliocene Rappahannock Group samples collected in the south of the basin. Lithic grains are dominated by igneous rock fragments in samples of the Mangles and Longford formations, whereas metamorphic lithics dominate in Maruia Formation and Rappahannock Group samples. These compositional differences may reflect greater proportions of plutonic detritus in sandstones from the northern part of the basin. We suspect that the metamorphic lithics in the Eocene Maruia Formation sample were locally derived from Ordovician Greenland Group basement, while those in the Rappahannock Group samples were sourced from the Permo-Triassic basement terranes east of the Alpine Fault. Forthcoming detrital zircon U–Pb ages will enable these two hypotheses to be tested and provide further invaluable provenance information.

## **Influence of pre-existing basement fabric on the formation of rift fault systems in the Great South Basin**

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Basement terrane boundaries constitute pre-existing crustal-scale discontinuities that can exert a strong influence on the architecture and evolution of many rift basins. The Great South Basin (GSB), offshore of South Island, is a Cretaceous rift basin underlain by several NW-trending metasedimentary and (meta)igneous basement terrane boundaries. The basin experienced three rift phases during the mid- to Late Cretaceous. Interpretation of newly available seismic data in the basin indicates two main sets of normal faults during the rifting which trend NE and NW. Northeast trending faults are the dominant set, with secondary NW trending faults reactivating pre-existing basement fabric. In particular, faults initially nucleated along the Brook Street, Dun Mountain-Maitai and Murihiku terrane boundaries. Pre-existing basement fabrics represent zones of weakness that locally promoted localisation of NW faulting and retarded the propagation of NE faulting during early rifting (c. 105 Ma). With continued rifting during c. 101–83 Ma, the influence of basement fabric gradually diminished and NE fault trend become dominant and wide spread across the GSB. The number of active faults with NW trends reduced from ~50 at c. 101 Ma to ~7 faults by the end of rifting (c. 83 Ma), and the maximum fault displacement along these faults decreased from ~1300 to 120 ms TWT over the same period. Fault activity significantly reduced after c. 83 Ma and displacements were primarily accruing on parts of the NE-trending structures with little activity on NW faults or reactivated basement terranes.

## **SIMS AS A TOOL FOR OBTAINING SR ISOTOPES IN MAGMATIC PLAGIOCLASE: A CASE STUDY AT OKATAINA VOLCANIC CENTRE, NEW ZEALAND**

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Plagioclase, an abundant igneous mineral, readily responds to fluctuations in crystallization conditions and therefore serves as an ideal recorder of magmatic processes. While high spatial resolution compositional analyses are possible for plagioclase, high spatial resolution isotopic analyses more limited and often exceed 100  $\mu\text{m}$ . Thus, we investigated the potential of multi-collector secondary ion mass spectrometry (MC-SIMS) as a tool for obtaining Sr isotopic ratios in plagioclase. MC-SIMS permits high spatial resolution analyses of isotopes ( $\sim 12 \mu\text{m}$  in this study), consequently improving the temporal scale at which fluctuations in crystallization conditions can be recognized. Plagioclase selected for analysis was extracted from two young, dome-building rhyolitic events from the Okataina Volcanic Centre (OVC) in New Zealand, each representative of its respective intra-caldera volcanic centre (Kaharoa from Tarawera, Rotoma from Haroharo). Results of MC-SIMS analyses were matrix effect-corrected via linear modelling versus An contents, in addition to  $^{87}\text{Sr}/^{86}\text{Sr}$  obtained via laser ablation inductively-coupled plasma mass spectrometry (LA-MC-ICP-MS). Corrected MC-SIMS  $^{87}\text{Sr}/^{86}\text{Sr}$  had an average  $2\sigma$  uncertainty of  $\pm 0.0008$  per spot, and were homogeneous in Okataina plagioclase at high spatial resolutions. Average LA-MC-ICP-MS Sr isotopic ratios of plagioclase from both intra-caldera volcanic complexes (Tarawera  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7056$  and Haroharo  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7054$ ) indicate similar magmatic sources and comparable assimilation and fractional crystallization processes across the OVC. General plagioclase homogeneity reveals no significant changes in crustal or mantle contributions to the system during the majority of plagioclase crystallization. Moreover, lack of fluctuations of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in crystal rims advocate limited interaction (i.e., volatiles and heat versus mass) between the silicic resident magma and the mafic eruption-triggering magma. The MC-SIMS method can be used to detect open-system, short- and long-lived events that occur in magmatic reservoirs where  $^{87}\text{Sr}/^{86}\text{Sr}$  differences are significant.

## GEOTHERMAL SYSTEMS IN THE TAUPŌ VOLCANIC ZONE THROUGH EARTHQUAKE ANALYSES

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In partnership with Mercury NZ Limited, Victoria University of Wellington postgraduate students have used seismic data from New Zealand's geothermal fields to determine the structure and geomechanical properties of several geothermal systems in the Taupō Volcanic Zone, including Rotokawa, Ngatamariki and Kawerau.

Double difference earthquake locations reveal that under Kawerau the majority of seismicity is shallower (4 km maximum depth) than in the surrounding regions (6-7 km). This suggests that the major heat source is situated beneath the centre of the field and that at levels deeper than 4 km the ground is too hot to support brittle failure.

Between 2012 and 2015, matched filter methods doubled the number of earthquakes detected in Rotokawa and Ngatamariki to about 9000. Focal mechanisms of ~1000 of those events were inverted to determine the stress field. At Ngatamariki, the new locations exhibit a strong spatio-temporal association with borehole drilling and stimulation. High b-values (a measure of the ratio of the numbers of small to large earthquakes) occur in areas with elevated pore fluid pressure and broad distributions of fractures. Focal mechanism inversion yields a normal faulting stress state with a NW/SE axis of minimum compressive stress ( $S_3$ ), but distinct regions vary from the average. Shear wave splitting yields NE/SW fast directions, consistent stress-aligned cracks under NW/SE extension. Changes in delay time and  $V_p/V_s$  ratios correlate with changing volumes of production. Noise cross-correlations revealed changes in isotropic shear velocity, with faster velocities in regions of injection, and gradual increases in shear-wave velocity from 0.06% to 0.08% over a year. Yet it remains difficult to distinguish the effects of rainfall changes and production. Abrupt decreases in velocity by as much as 0.07% in Ngatamariki immediately after regional and local earthquakes returned to normal over a period of several weeks.



## DOES SIZE MATTER? USING OSTEOLOGY AND ANCIENT DNA TO RECONSTRUCT EXTINCT SPECIES DIVERSITY IN NEW ZEALAND'S LARGE GECKOS

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New Zealand's extant herpetofauna is characterized by high species-level diversity, driven in-part by the repeated formation of allopatric barriers (i.e. mountain-building, glaciations, strait formation and volcanism). Consequent phylogeographic structure provides a useful tool for both understanding and calibrating geologic/climatic events. However, centuries of anthropogenic disruption (i.e. cryptic extinctions) have obscured true evolutionary patterns, necessitating incorporation of sub-fossil material into existing analyses.

Duvaucel's gecko (*Hoplodactylus duvaucelii*) is a large, monotypic species part of a wider radiation of New Zealand geckos (Diplodactylidae), originating prior to the Oligocene marine transgression. Sub-fossil evidence (comparably large cranial/post-cranial bones) suggests '*H. duvaucelii*' was previously widespread across mainland New Zealand, with subsequent range contraction to predator-free offshore islands. This study aimed to reconstruct prehuman diversity in extinct, mainland '*H. duvaucelii*' using bone morphology and ancient DNA.

Geometric morphometrics (landmark-based statistical shape analysis) was used to compare 3-dimensional micro-CT scans of sub-fossil gecko maxillae to a reference ontogenetic series (which exhibits species-specific morphometric clustering). Additionally, complete mitochondrial genomes were sequenced from a variety of isolated skeletal elements using state-of-the-art DNA extraction, library preparation and hybridization capture techniques and compared to both published and generated modern datasets. Integrating these aforementioned datasets has enabled robust species delineation of *H. duvaucelii* and identification of fine-scale population structuring, in addition to assigning taxonomic affinity of cryptic species.

## EXTRA-TERRESTRIALS VISIT AUCKLAND; CHARACTERISATION OF THE 2004 AUCKLAND METEORITE

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On June 14<sup>th</sup> 2004, a 1.3 kg meteorite crashed through the roof of a house in the Ellerslie suburb of Auckland. Although this meteorite is now on public display in the Auckland Museum, little is known about it because it is coated with a polished black fusion crust that formed as it passed through Earth's; however, three internal fragments provided by Auckland Museum reveal it to be a high-iron (H group) ordinary chondrite composed of Mg-rich olivine, enstatite, diopside/augite, albitic plagioclase, merrillite, troilite, kamacite and taenite. This class of meteorites provides valuable information about planetary building blocks because the parent body (where the meteorite came from) was internally warmed enough to experience thermal metamorphism but not enough to undergo chemical segregation into a core, mantle and crust. Thus, the bulk chemical composition of this 4.56 billion-year-old rock is broadly a snapshot of the solar nebula from which it formed. However, the chondrules (melted dust particles in the solar nebula) that occur in such meteorites have been almost entirely replaced by olivine, pyroxene and plagioclase. The original iron metal and Fe-sulphides – which would have precipitated from the cooling solar nebula gas – have melted and coalesced to form metamorphic grains. The equilibrated mineral textures are indicative of petrologic type 5 thermal metamorphism, which indicates that this meteorite was probably excavated from deep within the interior of a parent body. Although yet to be fully characterized, there is little initial evidence for shock metamorphism (e.g., melting/solid-state collapse of plagioclase, or melt veins), which suggests that this rock was some distance from the impact site that resulted in parent body fragmentation.

## **INVERSION HISTORY OF THE NORTHERN TASMAN RIDGE, TARANAKI BASIN, NEW ZEALAND: IMPLICATIONS FOR PETROLEUM MIGRATION AND ACCUMULATION**

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The northern Tasman Ridge in the southern Taranaki Basin is an entirely sub-surface inversion structure that hosts some of New Zealand's largest oil and gas field discoveries. Contiguous 3D volumes and 2D seismic reflection data tied to 26 exploration and production wells delineate 5250 km<sup>2</sup> of the northern Tasman Ridge enclosing the Maui, Maari and Manaia petroleum fields. Isopachs and structural restoration of Late Cretaceous to Pleistocene time equivalent horizons constrain the development of positive and subsequent negative inversion, extension and regional tilting. Positive inversion occurred 8–6 Myr ago synchronously along the northern Tasman Ridge with the magnitude of inversion decreasing northwards. Inversion anticlines across the Maui high were open to the northeast until the mid-Pliocene when negative inversion and extension were initiated. Pliocene–Recent footwall uplift along the Cape Egmont Fault has tilted the Manaia and Maari inversion anticlines down to the north and accentuated structural closure across the Maui high towards the present. In a fill to spill scenario, this tilting resulted in spill points of the Maari structure changing from southwest into the Manaia structure to southeast towards the greater Tasman Ridge c. 2 Myr ago. *As an oral presentation in the Understanding Zealandia - Lithosphere Structure and Deformation symposium*

## MICROSTRUCTURAL EVOLUTION OF THE MANTLE BENEATH WEST OTAGO AND ITS RELATIONSHIP TO THE ALPINE FAULT

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We will present a microstructural study of harzburgitic xenoliths from different locations in West Otago, to constrain the relationship between the Alpine Fault and the West Otago mantle evolution. Non-mylonitic samples can be divided into equigranular and coarse-grain types based on the microstructural details. Olivine in equigranular-grain samples have weak crystallographic preferred orientations (CPO). Olivine in coarse-grained samples have stronger A-D type ((010) [100] and/or (010)/(001) [100]) dominant CPO. The mylonitic samples have fine olivine and orthopyroxene grains, with orthopyroxene distributed through the samples. Mylonitic samples, have a weaker olivine CPO than coarse-grained samples. Mylonite CPOs are mostly A-type (010) [100]). The co-existence of non-mylonitic and mylonitic peridotites suggests that the West Otago mantle includes localized zones that have experienced higher stress and higher strain rate deformation. Work in East Otago suggests that mantle microstructures in the east of the South Island pre-date the initiation of the Alpine Fault. The non-mylonitic harzburgites in West Otago have some subtle differences and greater variety compared to the East Otago xenoliths, but are sufficiently similar that we interpret these as being formed before the Alpine Fault. Once the Alpine Fault was activated, the faster simple shear strain lead to partial mylonitisation. The weaker CPOs and dispersed orthopyroxene suggest that grain size reduction during mylonitization lead to increased significance of grain boundary sliding and phase mixing. The weaker CPOs of the mylonitic samples has an interesting implication: that is that the seismic anisotropy attributed to the Alpine Fault may not relate to CPOs formed during Alpine Fault deformation but instead to re-oriented older CPOs.

## ACTIVE SEDIMENTARY PROCESSES IN A DETACHED CANYON ON THE WILKES-ADÉLIE LAND CONTINENTAL MARGIN, EASTERN ANTARCTICA

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Marine sediment cores were collected from the slope of the Wilkes-Adélie Land continental margin of Eastern Antarctica. The proximity of the margin to the East Antarctic ice sheet on the Antarctic continent has resulted in an oceanographic environment that is strongly affected by the differences in glacial (extended ice sheets over the continental shelf) and interglacial conditions (retreat of the ice sheet to the coast). Marine sediments found on the margin are heavily influenced by these environmental changes as they impact the sedimentary processes that lead to their deposition. In this honours study, sediments from core TAN1302-44, obtained by the crew of the *RV Tangaroa* during the TAN1302 Marine Science Cruise in 2013, were characterised using a range of methods including core logging, X-ray images, grainsize data (including end-member modelling) and microscope analyses. These analyses were supplemented by micro-XRF and magnetic susceptibility measurements. These characterisations were used to assist in the identification and reconstruction of depositional regimes on the margin. Three distinct sedimentary facies were identified. The first facies consists of massive, structureless silt beds, which are rich in IRD's, biogenic silica (high Si/Al) and bioturbation; these are interpreted as hemipelagic sediments deposited during interglacial periods. The second facies is composed of thin, laminated beds of silt, sand and clay, marked by an almost complete absence of bioturbation and biologically-derived sediments; these have been interpreted as glacial deposits, with the laminae forming as a result of the reworking of glacially-derived sediments by contouritic bottom currents. The third facies is represented by a normally-graded bed of fine sand to silt, which is interpreted as a turbidite deposited during an interglacial stage. These variations in the sedimentary characteristics have implications for understanding changes in the sediment sources and ocean circulation in an East Antarctic marine setting.

## DUAL-DRIVEN FAULT FAILURE IN THE LOWER SEISMOGENIC ZONE

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Frictional instability leading to fault rupture may be driven by increasing either differential stress or pore-fluid pressure within the rock-mass, or both. Geological evidence (from hydrothermal vein systems in exhumed faults) together with geophysical information around active faults supports the localized influx of near-lithostatically overpressured hydrothermal fluids, derived from prograde metamorphism at greater depths, into lower portions of the crustal seismogenic zone at depths of c. 10-15 km (c.  $250 < T < 350$  °C a prehnite-pumpellyite metamorphic environment). This is especially true of compressional-transpressional tectonic regimes which cause crustal thickening and dewatering and are better at containing overpressure. Extreme examples are associated with formerly rifted crust undergoing active compressional inversion where existing faults are poorly oriented for reactivation. 'Fault-Valve' action is likely widespread in such settings with failure driven by a combination of rising fluid pressure in the lower seismogenic zone lowering fault frictional strength, as well as by rising tectonic shear stress – *dual-driven fault failure*. Localized overpressure affects rupture nucleation sites, but dynamic rupturing may extend well beyond the regions of intense overpressuring. Postfailure, enhanced fracture permeability along fault rupture zones promotes fault-valve discharge during the aftershock period, increasing fault frictional strength before hydrothermal sealing occurs and overpressures begin to reaccumulate. The association of rupture nucleation sites with concentrated fluid overpressure is consistent with selective invasion of overpressured fluid into the roots of major fault zones and with irregular spacing of major vein systems along exhumed brittle-ductile shear zones. Given its transpressional setting, the severe misorientation of fault components for reactivation, and the chain of elevated  $V_p/V_s$  anomalies underlying the surface rupture zone in the mid-crust (Eberhart-Phillips and Bannister, 2010: *Geophys. J. Int.* 182, 73-96), it seems likely that fault failure leading to the 2016 **M** 7.8 Kaikoura multi-rupture was dual-driven.

## SPATIOTEMPORAL RELATIONSHIPS BETWEEN TWO CLOSELY-SPACED STROMBOLIAN-STYLE VENTS, YASUR, VANUATU

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Strombolian eruptions involve explosions of gas bubbles through ponded/stalled mafic magma in near-surface open-vents. They repeatedly eject incandescent ballistic lava bombs, along with ash and gas, often from multiple vents. These vents often appear independent of one another, even if only <100 m apart. Determining any systematic variation in vent activity and underlying processes behind it requires careful monitoring setups. Here, using high resolution thermal, seismic and visual observations, we detail a case of systematic transition of volcanism from one vent to a second newly formed one. This is shown by a decline in explosive power and frequency from the first vent, alongside an increase in both of these parameters at the new vent. This process is driven by the transfer of magma and volatile flux within a shallow branching conduit system. Waning of activity at a vent corresponds with a shift from bomb-rich to ash-rich explosion types, showing an increase in magma viscosity (cooling and stagnation within the conduit). By contrast, waxing in explosive activity accompanies a greater proportion of bomb-rich explosions. The two vents observed here also produced 'paired explosions', caused by the rupture of a single gas pocket before the upper conduits split pathways to vents. Paired explosions are seismologically similar to single Strombolian-style explosions and they share a common low frequency component (0.06-1 Hz). The surface manifestation of paired eruptions may show a brief temporal offset between vents, if they have a different conduit length, diameter or tortuosity. This may also reflect differences in the viscosity state of the magma in each conduit. Offset times may last up to 45 seconds when one vent displays very-ash-rich activity that is indicative of high magma viscosity and gas trapping.

## SPATIOTEMPORAL VARIATIONS IN ERUPTION STYLE, MAGNITUDE AND VENT MORPHOLOGY AT YASUR VOLCANO, VANUATU: INSIGHTS INTO THE CONDUIT SYSTEM

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Using visual, seismic, SO<sub>2</sub>-gas, and thermal infrared data collected over three months, we observed systematic variations in the steady-state and persistently-active Strombolian-style eruptive activity of Yasur volcano, Vanuatu. These reveal insights into the relationship between explosion magnitude and style with shallow conduit and magmatic conditions and geometry. The analysis revealed multiple timescales of eruptive behaviour change, with short fluctuations of 2-5 days occurring within longer ten to 20 day-long cycles. The most powerful explosions were clustered in periods of 2-5 days, ejected ballistics up to 500 m height and had explosion frequencies of ~70-80 events hr<sup>-1</sup> and often coincided with increased SO<sub>2</sub> flux. Powerful activity is indicative of high magma and volatile flux maintaining hot conduit pathways filled with mobile magma. The least powerful and lowest frequency explosive phases produced ash-dominated Type 2b and 3 eruptions (i.e., with progressively higher ash content) indicative of low magma and volatile flux with cooling and stagnant magma near the top of the conduit, and/or a thick cap of debris covering the vent. The eruptive behaviour of the three major vent zones (A&B in South Crater and C in North Crater) was recorded, and statistical modelling was applied to understand the relationships between the vent zones and conduit geometry. Results show that the South and North craters have a complex relationship that suggests North and South conduits are separated at significant depths where changes to either craters are based on the separation of magma and volatile flux into one or the other pathways preferentially. Zones A and B in the South Crater have an alternating relationship, swapping between periods of active-inactive, or powerful-weak. This could show that magma and volatile flux is channelled preferentially to either one or the other pathway, likely due to periods of temporary conduit blockage followed by clearance.



## IN SITU LASER ULTRASONIC MEASUREMENTS FOR UNDERSTANDING THE ELASTIC PROPERTIES AND TEMPERATURE DEPENDENCE OF ALPINE FAULT ROCKS IN THE SHALLOW CRUST

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Understanding the elastic properties of fault rocks yields insight into the processes and behaviour of the fault, including its structure and mechanical properties. Additionally, accurately imaging the subsurface structure of a fault with seismic waves in the upper crust requires a careful consideration of elastic anisotropy. This is especially true near the Alpine Fault in New Zealand, where rocks are highly anisotropic in the shallow crust (>20%).

In this study, we aim to understand how the anisotropic properties of Alpine Fault rocks vary with depth and proximity to the fault in the shallow crust. We investigate five rocks from schist through to cataclasite at effective pressures up to 16 MPa, representing the lithology approximately 2 km laterally from the principal slip zone (PSZ) and the subsurface conditions to 1 km in depth. Using our newly developed high-pressure laser ultrasonics methodology, we obtain over 90 independent estimates of P-wave velocity at different angles to the foliation. We find that away from the PSZ, anisotropy is controlled by aligned micas and microfractures are randomly oriented. As we approach the PSZ, aligned microfractures become the dominant cause of anisotropy at shallow crustal depths.

We also present initial results from experiments investigating the temperature dependence and nonlinear behaviour of the elastic properties of Alpine Fault rocks. An observed 5% decrease in P-wave velocity for an 80°C increase in temperature suggests that the temperature dependence of Alpine Fault rocks is significant. Moreover, experiments investigating the nonlinear recovery of the elastic properties of Alpine Fault rocks after a disturbance (i.e. “rock healing”) have potential implications for the mechanical properties of the fault following an earthquake.

## THE KIMBREA CUTTING: A CLOSER LOOK AT THE GEOLOGY OF THE HAMILTON HILLS

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Recent urban development in the Hamilton Basin has exposed geological features that were once hidden beneath poorly consolidated sediments. These features have posed new questions about the geological history of the Hamilton Basin and any potential seismic hazards within the basin. The construction of the Waikato Expressway created a 230 m long by 14 m high road cutting in the hills of Kimbrea, Hamilton that exposed a complex series of geological structures. The structures consist of nine large major fractures and multiple minor fractures that offset and deform bedding within the Walton Subgroup (WSG), the Kauroa Ash, and even the Hamilton Ash. However, this presentation will focus on the WSG and Kauroa Ash. Standard geological mapping techniques were employed to investigate these features such as mapping contacts, measuring offsets, and measuring the orientation of structural features. There are four distinct layers in the WSG, and a distinct paleosol and sequence of tephra in the Kauroa Ash that aid in the identification of offset and deformation at the site. One important layer is a purple-grey clay marker bed that occurs at the top of the WSG and has an unconformable contact with the overlying Kauroa Ash. Offset measurements taken from the base of the purple marker bed range between 3.98 m and 29.2 m with normal movement dominating. Seven of the major fractures strike NE-SW, two strike NW-SE, and one strikes W-E. When examining the dominant orientation of these fractures against the geomorphology of the Hamilton Basin it appears that the hills within the basin have a similar orientation. Given these similarities it is possible that the Kimbrea site provides evidence that the hills in the Hamilton Basin are formed from structural influences rather than erosional.

## PALEOENVIRONMENTAL RECONSTRUCTION OF AN EARLY MIOCENE DEPOSITIONAL ENVIRONMENT AT MATHESONS BAY, AUCKLAND, BASED ON THE SKELETAL COMPOSITION OF COOL WATER CARBONATES.

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Early Miocene basal Waitemata Group strata that outcrop at Mathesons Bay, Auckland, consist of nine lithofacies, representative of various depositional environments. Falling within the Cape Rodney and Pakiri formations, the lithofacies were unconformably deposited upon an irregular, highly-eroded Mesozoic Waipapa Terrane basement during marine transgression. Lithofacies generally consist of conglomeratic units that comprise of granule to boulder sized clasts reworked from Waipapa Terrane lithologies and supported within a matrix of calcareous sediments. Petrographic analysis of these calcareous sediments under optical microscope indicates sparite and microcrystalline calcite alongside numerous skeletal bioclasts.

This presentation will present a petrographic analysis of the lithofacies and the implications these have on reconstructing depositional paleoenvironments. Particular focus is placed on the skeletal carbonate component and the sedimentology of the lithofacies, which were studied to determine sediment genesis and transport processes. Using the classification system for non-tropical carbonate deposits devised by Hayton *et al.* (1995) as a foundation, the skeletal assemblage of each lithofacies was identified, based on dominant bioclastic components. Benthic foraminifera, coralline algae, brachiopods, bryozoans and molluscs dominate the basal sequence, indicating Rhodalgae and Bryomol assemblages of shoreface and inner-shelf environments. This is supported by extensive horizons of encrusting macrofossils including *Crenostrea* and rhodolith pavements that cement substrate in many of these units, indicating a low likelihood of transportation and supporting shallow depositional conditions. Contrastingly, lithofacies higher in the sequence are dominated by planktonic foraminifera, indicating a Nannofor assemblage characteristic of bathyal depositional environments.

Complimentary taxonomic and taphonomic analyses of macrofossils help to constrain the range of environments indicated by skeletal carbonates, and provide greater context to sedimentological data observed in thin section. Upon completion, this study will contribute toward a more comprehensive paleoenvironmental reconstruction of Mathesons Bay that aspires to improve understanding on the history of tectonics and sedimentation in the Waitemata Basin.

### References:

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## **ENGINEERING GEOPHYSICAL INVESTIGATION OF COSEISMIC LANDSLIDES FROM THE 2016 KAIKŌURA EARTHQUAKE**

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Globally, landslides cause many thousands of deaths each year and damage built environment infrastructure, costing billions of dollars to repair, resulting in thousands of people being made homeless and the breakdown of basic services such as water supply and transport. In New Zealand, landslides tend to be triggered by rainfall or by earthquakes, and if the effects of landslides are to be mitigated and avoided then the causes of landslide activations, and importantly, re-activations, need to be understood. Overseas, 3D and 4D electrical resistivity tomography (ERT) is used to monitor moisture and associated pore water pressure changes due to rainfall, as part of slope failure early warning systems. However, in New Zealand, there is a paucity of even 2D geophysical surveys of landslides, thus the effectiveness of using methods such as ERT to survey landslides is yet to be fully evaluated. Here, the aim was to trial the use of 2D ERT to better understand the morphology and internal structure of two large New Zealand coseismic landslides: (1) Seafront Landslide in the Clarence Valley; and, (2) Leader Landslide in the Leader Valley. An inverse model of resistivity was produced to interpret subsurface features such as the failure surface, internal structure, lithological variations and hydrology. The acquisition process allows for comparisons to be conducted between common electrode configurations and determination of their effectiveness for landslides of this type. Results indicate that as with overseas, ERT could prove a useful tool in monitoring the moisture content of large landslides, as part of an early warning system. Interpretation could be improved further with the application of other geophysical methods such as MASW and GPR, as well as direct testing in boreholes (i.e. piezometers).

## MONITORING SLOPE FAILURES ALONG THE SOUTHERN KAIKŌURA TRANSPORT CORRIDOR, NEW ZEALAND

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On the evening of 14 November 2016, a magnitude (Mw) 7.8 earthquake struck North Canterbury. The earthquake ground motions caused widespread damage of housing and infrastructure throughout North Canterbury, and damage to the road and rail infrastructure within the South Kaikoura Transport Corridor (SKTC). Coseismic landslides covered and destroyed parts of the State Highway 1 (SH1) road and rail transport corridor. Post-earthquake aftershocks and significant rainfall events further mobilised the shattered and de-stabilised greywacke rock mass and paleo-landslide debris slopes. The SKTC was then affected by over 40 separate landslides that have impacted either the rail corridor, the road corridor, or both. A number of different landslide types associated with the earthquake occurred along the SKTC, including shallow translation slides of existing paleo-landslide debris and rotational slumping. Rockfalls were driven by wedge, planar or toppling failure from greywacke bluffs above the SKTC. Following the 14 November 2016 earthquake, further landslides occurred due to significant rain events associated with storm activity such as cyclone Gita, Cook, and Debbie. These resulted in large (debris volume >30k m<sup>3</sup>) translational debris slides, and significant debris flows, mobilising colluvial materials deposited within gullies, for example. This project characterised and quantified slope failure rates and processes at selected sites along the South Kaikoura Transport Corridor, using multi-temporal analyses of digital elevation data, extensometer data, and land deformation monitoring using GPS receivers. Thus, several datasets and techniques are used in a comparative approach. Results provided an opportunity to better understand the dynamics of surficial landslide movement at each site, and provide information on the morphological and volumetric changes of each landslide. This was undertaken through UAV aerial image acquisition, and the use of DEM's constructed from UAV-SfM image processing and LiDAR acquisition. This provided an important monitoring of near-surface movement, important for risk management along the transport corridor.

## ZEALANDIA-WIDE PALINSPASTIC PALEO GEOGRAPHY FROM THE MID-CRETACEOUS TO PLIOCENE

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We present a series of Zealandia-wide paleogeographic maps covering the mid-Cretaceous through to the Pliocene, utilising new data from regional studies carried out as part of the 'Atlas of Petroleum Prospectivity' (APP) programme. These include detailed paleogeographic maps from northern Zealandia (Reinga-Northland, Taranaki and West Coast basins) and southern Zealandia (western Southland and Canterbury-Great South basins) as well as more regional maps covering less data-rich frontier regions such as the Campbell and Challenger plateaux, Lord Howe and Chatham rises, and New Caledonia Basin and Bounty Trough.

The maps produced tectonically reconstruct Zealandia at each time step, in a paleomagnetic reference frame (earth's spin axis), rather than in a rigid present-day configuration. This was achieved using a structurally based block model to retro-deform the continent and plate boundary. This block model is relatively simple for the main regions of northern and southern Zealandia, but breaks central Zealandia, particularly the East Coast-Marlborough region, into numerous fault-bounded blocks that reflect the complex Neogene deformation associated with the Hikurangi subduction margin and its southward transition into the Alpine Fault. For this reason, paleogeographic maps for the greater East Coast region were produced using primary paleoenvironmental data in their reconstructed position. This marks a major advance on previous attempts to produce maps for the East Coast in present-day configuration. These maps were combined with those from other regions to produce Zealandia-wide maps. Production of these reconstructed paleogeographic maps provides an important test of tectonic reconstruction models. Areas where paleogeographic maps become problematic or unrealistic may highlight regions and/or times where reconstruction models may require further refinement.

## **S-WAVE REFLECTORS BENEATH THE EARTHQUAKE SWARM IN THE YONEZAWA – KITAKATA AREA, NE JAPAN**

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Shear wave reflectors in volcanic regions and inland earthquake source area has been reported for decades. In the NE Japan, S wave reflectors was interpreted as fluid which was dehydrated from melt [e.g., Hasegawa et al., 2005] and, it was pointed out that crustal fluid may be involved in the mechanism of inland earthquake occurrence. Further understanding of crustal fluid is necessary.

In the Yonezawa - Kitakata area, NE Japan, a earthquake swarm occurred 7 days after the 2011 off the Pacific coast of Tohoku Earthquake because frictional strengths were estimated to have changed due to fluid diffusion [e.g., Okada et al., 2015]. In this study, we will obtain the spatial distribution of the S wave reflectors in Yonezawa - Kitakata area. We used data from the permanent stations by Hi-net and the temporary seismic network deployed by Group of the aftershock observations of 2011 off the Pacific coast of Tohoku Earthquake. We used the hypocentre locations determined by the Double Difference method using the temporary observation data.

First, we carefully picked arrival time of the S wave reflected wave manually. For eight observation stations – earthquake clusters pairs which were able to confirm the S wave reflected wave remarkably, the travel time of the seismic wave was converted to the depth as in Inamori et al. (1992) for the reflected S wave to be remarkable. Next, using the read travel time, the mirror observation stations were calculated by grid search [e.g., Horiuchi et al., 1988]. From the equation of the reflector obtained by this method, the strike/dip and the location of the reflection point for each hypocenter were obtained. As a result, the reflectors are located from the lower part of the source region to the depth of 10 - 20 km below it.

## **GEOLOGICAL INVESTIGATION OF THE OHUI EPITHERMAL AU-AG PROSPECT USING APPLIED GEOPHYSICAL AND GEOCHEMICAL METHODS, HAURAKI GOLDFIELD, NEW ZEALAND.**

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The Ohui tenement is a low-sulphidation, high-temperature, Adularia-Sericite epithermal prospect located within the eastern coastline of the Coromandel Volcanic Zone, forming one of the 50 Au-Ag deposits within the broader Hauraki Goldfield area. This project assessed the economic viability of the Ohui epithermal deposit, specifically looking into the Staircase exploration target defined by the tenement parameters characterized by OceanaGoldLtd. Historic and recent data-sets include geological field mapping, lithological composition of drill-hole OHD030 within the Staircase target, local geochemical analysis, small-scale geophysical methods, and large-scale geophysical methods. The results of these applied techniques are combined within the interpretation to constrain areas that imply gold deposition. The coalescence between new results produced throughout this project and existing data-sets obtained from OceanaGoldLtd is used to evaluate prosperity of the Staircase target and to create an interpretative model of the Ohui tenement gold locations and depositional types. Based on the data analyses, we concluded that there is little gold mineralisation that has occurred within the Staircase target. The high-CSAMT-resistor targeted in hopes of being a silicified zone containing gold precipitation is an unaltered andesitic intrusion, found from geological sampling of the exploration drill-hole. However, the Ohui tenement overall has the ability to contain high grade ore deposits. The conundrum presented for the tenement is the abundance of gold precipitation may be confined to small veins that could render the tenement a non-economical resource. Continuing research and exploration in the form of drill-holes is underway.

The broad use of geochemical, geophysical, and geological techniques throughout this project will be used for further research into active geothermal systems, specifically the generation and deposition of hydrothermal eruptions. Utilizing a combination of these sub-disciplines allows a development of understanding into the initiation mechanisms and progression of these destructive events leading to better forecasting of future eruptions.



## **CONSTRUCTING AN HIGH-RESOLUTION STRATIGRAPHIC FRAMEWORK OF A BURIED VOLCANO: A CASE-STUDY FROM THE KORA VOLCANO, TARANAKI BASIN, NEW ZEALAND**

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Establishment of High Resolution Volcano-stratigraphic Frameworks (HRVF) of buried volcanoes is important to understand the evolution of the volcanic system and its potential to form volcanic reservoirs. However, the perceived complex contact relationships and internal architectures can complicate the reconstruct of HRVF. In this paper, we present the HRVF of Kora Volcano, an andesitic submarine composite volcano active during the Miocene and now buried by ca 1000 m of sedimentary strata offshore the Taranaki Basin, New Zealand. We use a large dataset of 2D and 3D seismic lines, and data from five boreholes, to analyse the eruptive evolution of Kora Volcano and the unconformities that limit genetically related volcanic and sedimentary units. We mapped 22 units that include predominately deposits from pyroclastic and lava eruptions, together with reworked debris flow deposits. The Kora Volcano can be divided into five parts according to major unconformities that are related with active and quiescent eruptive periods and with the formation and migration of distinctive eruptive centres. The HRVF can be built by using the wells and normally 3D seismic data. The findings presented in this work can provide insights of the evolution of volcanic systems elsewhere, and contribute to the likelihood to find natural resources such as hydrocarbons and geothermal energy.

## THE DYNAMICS AND SEDIMENTATION OF VOLCANIC PLUMES IN SUPERVOLCANO ERUPTIONS

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Large Plinian eruptions constitute one of the most powerful natural disasters on Earth. Eruptions of this type can eject tephra volumes of  $> 10\text{km}^3$  into the atmosphere. The typically strong and long sustained volcanic plumes produced often become unsteady and can generate violent pyroclastic density currents that extend radially outwards from the source. Therefore, further understanding of the dynamics of these extreme volcanic events is essential for hazard planning and decision making at many volcanoes globally.

This PhD research aims to better understand the gas-particle transport and sedimentation dynamics of large Plinian eruption plumes through a combination of fieldwork and numerical modelling techniques. Unit 5 (Y5) of the AD 232 Taupo eruption is an unusually well-preserved example of a large Plinian fall deposit, providing an ideal focal point for this research. Previous estimates of the plume height of the Y5 eruption phase, following different sampling strategies, yielded strongly contrasting results. These highlight the need for unambiguous methods to delineate sedimentation isochrones in Plinian fall deposits. Such methods would allow for investigation of the contrasting effects of steadiness and magnitude of source mass discharge, turbulent transport and sedimentation and wind drift of large Plinian plumes on the evolution of Plinian fall deposits.

Here we present a preliminary dataset of stratigraphic logs of Y5 along transects aligned with and perpendicular to the main plume dispersal axis. These aim to illustrate vertical and lateral deposit facies variation over a range of length scales, including the outcrop scale, characteristic length-scales of instabilities and large eddies of the umbrella cloud, and the width of the umbrella cloud. We examine vertical profiles of grain-size distribution and componentry at a key section to identify potential parameters that allow for characterisation of the temporally evolving tephra deposition and time-variant deposition of variably gas-coupled pyroclast species.

## SPATIOTEMPORAL CHANGE OF SOURCE PARAMETERS OF REPEATERS DUE TO THE AFTERSLIP OF THE 2011 TOHOKU-OKI EARTHQUAKE, NE JAPAN

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Afterslip which follows great earthquake causes an increment in loading rate. Source parameters including magnitude and stress drop are expected to vary associated with the increment in loading rate. The change of source parameters of repeating earthquake (repeater) is expected to appear clearly since repeaters rupture the same isolated area repeatedly. In this study, we investigated the spatiotemporal change of source parameters of repeaters occurred on the Pacific interplate boundary before and after the 2011 Tohoku-oki earthquake. We analyzed seismic waveforms from 3,595 repeater sequences and 10,569 repeaters in total. In this study, we show the spatiotemporal change of afterslip estimated by the method of Nadeau and Johnson, 1998 and stress drop and its relation to afterslip.

We found two types of repeater sequences. The first, hereinafter called type A, has sequences which show increment in magnitude ( $M_w$ ) with increasing in recurrence interval ( $T_r$ ). The second, hereinafter called type B, has sequences which show increment in  $M_w$  with decreasing in  $T_r$ . In addition to  $M_w$ - $T_r$  relationship, stress drop ( $\Delta\sigma$ ) increases with decreasing in slip rate ( $V_s$ ) for type A, and with increasing in  $V_s$  for type B, respectively.  $M_w$ - $T_r$  and  $\Delta\sigma$ - $V_s$  relations found in this study are consistent with the numerical simulated results using rate- and state- frictional law (Chen et al., 2010). They showed that the variations of source parameters depend on the ratio of velocity-weakening patch size to the nucleation size: if the ratio is larger than 1, source parameters change as type A; if the ratio is comparable to 1, source parameters change as type B. Hence it is suggested that the change of stress drop estimated in this study is controlled by the loading rate, velocity-weakening patch size, and nucleation size as shown by the simulation.

## **THE IMPORTANCE OF GEOLOGICAL MODEL DEVELOPMENT FOR BRIDGE DESIGN: A NORTHLAND CASE STUDY**

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Sea level transgression and several stages of tectonic activity, including the overthrusting of the Northland Allochthon, have led to a complex arrangement of sedimentary and volcanic rocks in Northland, New Zealand, which present a challenge for bridge design and construction. The Kaeo Bridge, 2.6 km north of the Kaeo Township in Northland, is currently one lane and as part of a key tourism route an upgrade is imminent. In July 2019, a ground investigation comprising of boreholes, hand augers and seismic cone penetrometer tests were undertaken adjacent to the Kaeo Bridge to obtain an updated geological model of the proposed development site.

The area is characterised by a north-south oriented valley, constrained by hills on either side and shaped by several localised faults. These hills are comprised of Te Kuiti Group Eocene-age sedimentary rocks which overlie Waipapa Basement rocks (argillite and greywacke). The Kaeo Bridge is located within this valley on a graben-like structure, infilled with a thick covering of Quaternary Tauranga Group alluvial and estuarine deposits.

Our investigation uncovers a different story to those previously undertaken. The updated geological model identifies several geotechnical hazards for bridge design and construction such as, artesian groundwater, layers prone to settlement, liquefaction susceptibility, low bearing strength surficial soils and varying bedrock depth and quality. From the geological model an appropriate design and construction methodology can be developed that manages ground risk. Embankments on soft soils can be reinforced with geosynthetics to manage bearing instability and preloaded with wick drains to reduce long term settlements. Design of piles and abutments can also be developed using casing and piling fluid (polymer) that can maintain pile hole stability within the fractured Te Kuiti Group and Waipapa group basement rock. A well-developed geological model is essential for a suitable and resilient bridge design.

## **NGĀ KŌRERO MAI I NGĀ WĀ O MUA - STORIES FROM A DISTANT PAST REVEALED BY THE NATIONAL PALEONTOLOGICAL COLLECTION**

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The National Paleontological Collection (NPC) is New Zealand's largest and most comprehensive collection of fossils, accumulated over more than 150 years by GNS Science and its predecessors (including the New Zealand Geological Survey).

The collection, featuring type, figured, reference and bulk macrofossil and microfossil material, represents all of Zealandia's geographic span, including New Zealand's offshore territories, surrounding Pacific islands and Antarctica. Specimen ages range from Cambrian to Recent (about 500 million years ago to the present day).

The NPC is a fundamental resource with applications to a wide range of scientific research. The material has helped unlock the stories of New Zealand's natural whakapapa, paleoenvironment, paleoclimate and natural resources. The collection is a paleontological archive of national and international significance, with many more stories yet to tell.

## USING TRACE ELEMENT MODELLING TO CONSTRAIN THE FORMATION OF RARE EARTH ELEMENT RICH CARBONATITES IN THE ALPINE DYKE SWARM

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Liquid immiscibility, or magma unmixing, is a widely accepted yet poorly constrained mode of formation of carbonatite magma. An outcrop of closely associated dikes of alkaline tinguaitite-trachyte and carbonatite in the lamprophyric Alpine Dyke Swarm within the Burke River valley of Mt Aspiring National Park has been studied to investigate the mechanism of magma unmixing. Dyke textures appear to indicate, both in the field and petrographically, contemporaneous intrusion into the host Alpine Schist. The tinguaitite is chemically equivalent to a phonolite, and is enriched in incompatible elements and light REE enriched relative to heavy REE. The carbonatite dyke is a calciocarbonatite that is rich in Sr, Ba and REE but depleted in large ion lithophiles relative to the tinguaitite, due to mobilisation into carbothermal fluids during fenitization of the host schist. Major and trace element trends, combined with fractional crystallisation models and whole rock isotopic compositions, suggest 70-80% fractionation of clinopyroxene+olivine+amphibole+titanbiotite+apatite±feldspar to produce a tinguaitic magma from a lamprophyric parent melt, a low degree partial melt generated in a depleted (and later metasomatised) mantle. Theoretical immiscible carbonatite compositions calculated using experimental liquid-liquid partition coefficients show that the tinguaites can yield carbonatite magmas with trace element compositions comparable to the Burke River dykes. The partitioning behaviour of trace elements between the dykes is also consistent with unmixing from an evolved (tinguaitic) parent. Liquid-liquid partitioning has shown REEs preferentially partition into carbonatites upon unmixing. Further fractionation of 30-50% apatite+calcite+clinopyroxene+dolomite+albite concentrates the residual liquid in REE, facilitating crystallisation of REE-carbonates. This process has proven to be fundamental in the formation of REE-rich carbonatites, and could be considered as an important driver in the enrichment of REE in global carbonatite complexes.

## WATER CHEMISTRY AND ICE MECHANICS

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Laboratory experiments have been used to quantify the creep behaviour of polycrystalline ice. These are the basis of flow laws, such as the Glen flow law, which describe the strength of ice for given applied stresses and temperatures. Flow laws are crucial in modelling the flow of bodies of ice, such as the West Antarctic Ice Sheet, and their response in a warming climate. All existing flow laws are based on experiments that use ice free of soluble (chemical) and insoluble (particulate) impurities. This is unrealistic in natural Antarctic ice. Past work has shown ice with impurities tends to be weaker than pure ice, as intracrystalline impurities should encourage the formation of dislocations and deformation of grains. As ice flows, the impurities are swept to grain boundaries and influence mechanical behaviour by inhibiting grain growth through grain boundary pinning. This is seen in natural ice cores, with higher concentrations of ionic species found in finer grained bands of ice. The effects of chemistry have proven difficult to quantify, as different chemical species appear to behave differently; Recent work has shown  $\text{Ca}^{2+}$  ions have a hardening effect, while  $\text{H}_2\text{SO}_4$  enhances creep rates in ice. In this study, ice with major ion chemical compositions comparable to coastal and central Antarctic ice has been synthesised, and deformed in a series of uniaxial compression experiments at varying strain rates ( $10^{-4}$ ,  $10^{-5}$ ,  $5 \times 10^{-6} \text{ s}^{-1}$ ) and temperatures ( $-10$  and  $-30^\circ\text{C}$ ) at the University of Pennsylvania. Mechanical data suggest chemistry has no significant effect on the strength of ice. This suggests insoluble impurities or higher ionic concentrations than those studied contribute to the softening of natural ice. Microstructural and detailed chemical analysis in the coming months will be vital in determining this.

## **DISTINGUISHING TURBIDITE TAILS FROM BACKGROUND SEDIMENTATION ON THE HIKURANGI MARGIN AND ITS IMPLICATIONS FOR DATING TURBIDITES**

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Turbidite paleoseismology can increase the spatial density and temporal extent of paleoearthquake records. Here, we look at the paleoseismicity records from a suite of cores along the Hikurangi Margin. Producing earthquake records using turbidites relies on temporal correlation of deposits to provide evidence of synchronous triggering over a wide area, underpinned by precise dating of deposition. Turbidites are typically dated using radiocarbon dating of pelagic foraminifera obtained from the 'background' sediment deposited between turbidites. However, accurately distinguishing between background sedimentation and the fine-grained tails (tops) of turbidites has proven difficult. Here, we develop criteria for distinguishing background sedimentation from turbidite tails along the Hikurangi margin. A suite of cores retrieved within months of the 2016 M<sub>w</sub>7.8 Kaikōura earthquake contain co-seismic turbidites, including turbidite tails. <sup>210</sup>Pb<sub>ex</sub> profiles from cores that do not contain the Kaikōura turbidite deposits will be used to independently identify background sediment. All sediment will be analysed using non-destructive (CT tomography, magnetic susceptibility, micro-XRF derived geochemistry) and destructive (grain size, organic content, carbonate content, foraminiferal test-size distribution) analyses. A multi-variate statistical model will be developed to provide a quantitative basis for distinguishing background sedimentation from turbidite tails. The reliability of the criteria will be tested by radiocarbon dating background sediments identified by the criteria that surround the primary tephra horizons from the 1718 cal yr BP Taupō eruption in other cores along the Hikurangi margin. Once validated the approach will be applied to date turbidite records along the margin and to develop paleoseismic records that span the Holocene.



## TRIGGERING OF A LARGE AND DAMAGING EARTHQUAKE ( $M_w$ 5.5) BY HYDRAULIC STIMULATION DURING THE DEVELOPMENT OF AN ENHANCED GEOTHERMAL SYSTEM IN POHANG, SOUTH KOREA

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The  $M_w$  5.5 Pohang earthquake occurred on 15 November 2017 close to two 4 km-deep boreholes drilled as part of South Korea's first enhanced geothermal system (EGS) project and within 5 km of the city of Pohang. The experimental EGS project was intended to demonstrate the feasibility of geothermal energy production in southeastern South Korea as the country works to reduce its reliance on hydrocarbons and nuclear energy. The earthquake caused dozens of hospitalizations, one fatality, the displacement of 1700 people into emergency housing, and total economic impact of ~US\$300M. Its location close to the EGS site led to immediate concern that EGS activities had played some role in the earthquake's nucleation. The key finding of the government inquiry into the earthquake's causes was that high-pressure injection of water into one of the two boreholes ("stimulation") had unequivocally induced seismicity and triggered the damaging  $M_w$  5.5 earthquake. In this talk, we review the geological and geophysical observations that underpinned the findings of the Overseas Research Advisory Committee convened by the Geological Society of Korea as part of the official inquiry. We focus on the sequence of events that occurred during each phase of stimulation, the geomechanical significance of those events, and the lessons this earthquake provides for managing risks associated with induced seismicity in other cases.

## **DISTRIBUTED OPTICAL FIBRE TEMPERATURE AND STRAIN SENSING TO 893 M DEPTH IN THE ALPINE FAULT HANGING-WALL**

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The Alpine Fault produces large (M8) earthquakes that pose substantial seismic risk to New Zealand. More than 300 years have elapsed since the most recent large Alpine Fault earthquake in 1717 CE, and the likelihood of a M8 earthquake in the next 50 years is estimated to exceed 30%. In 2014, during the second stage of the Deep Fault Drilling Project (DFDP-2), an 893-m borehole was drilled in the hanging-wall of the Alpine Fault. An optical fibre was installed while the borehole was being cased. Distributed temperature measurements made along the full length of the borehole reveal an average geothermal gradient of approximately 120°C/km. Monitoring and understanding this temperature gradient is of high scientific interest. The fibre optic cable has also been used successfully as a high-frequency acoustic sensor during an active-source seismic survey. In order to enable ongoing optical measurements of temperature and strain, we are developing a low-power distributed optical fibre sensor based on spontaneous Raman and Brillouin scattering. Spontaneous Raman scattering is an inelastic process caused by molecular vibrations, whereby incident light of a particular wavelength is back-scattered at longer (Stokes) and shorter (anti-Stokes) wavelengths. The ratio of the back-scattered signals provides a direct measurement of temperature. In contrast, changes in wavelength associated with spontaneous Brillouin scattering are produced by changes in fibre density and hence a change in refractive index. If the temperature profile along the fibre is known, the strain can be determined. In this presentation, we discuss the sensor designs, bench-top temperature and strain measurements made to date, and plans for field-testing in early 2020.

## THE GEOCHEMICAL FINGERPRINTS OF HUMAN IMPACT ON URBAN DUNEDIN SOILS

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The first urban geochemical baseline survey in New Zealand has recently been completed for the city of Dunedin. The major, minor, trace and isotopic composition of soils from different depths across the city are shown to vary spatially due to the influence of natural (geogenic) sources, overprinted in many places by human-related activities. Principal component (PC) analysis for soils from the shallowest 2 cm indicate that at least 40% (PC1 and PC3) of soil chemistry variability can be attributed to a geogenic influence. Elements associated with PC1 (e.g. Cr, Fe and Ni) are linked to underlying mapped units of the basaltic Dunedin Volcanic Group. At least 23% of soil chemistry variability (PC2 and PC5) are attributed to anthropogenic influences. Specifically, the heavy metals As, Bi, Cd, Cu, Pb, Sb, Sn and Zn are strongly associated with soils sampled from high-density urban residential, commercial and industrial locations, and elevation in these elements is therefore interpreted to reflect heavy metal contamination from human activities. Heavy metal concentrations in urban Dunedin soils are elevated well above median values established in the Southland-Otago regional survey but are comparable to median values of urban soils in many cities worldwide. Elevated concentrations of Pb in soils from residential properties (some above Ministry for the Environment guidelines) is linked to a legacy of decades of accumulation from leaded-paint sourced from old (pre-1970s) buildings, leaded petrol and coal burning. Stable isotopes (C, N and S) are also shown to have significantly different values in urban Dunedin soils when compared to baseline values from the regional survey.

## **ANALYSIS OF DEEP MARINE ACTIVE SEDIMENTARY PROCESSES WITHIN SEDIMENT STARVED MINI-BASINS ON THE HIKURANGI MARGIN, NEW ZEALAND.**

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The imbricated frontal wedge of the Hikurangi Subduction Margin (HSM) is host to a complex basin and ridge slope morphology. Thrust faulting controls the formation of mini-basins, characterised as small enclosed basins, ~4 km in diameter from east to west on the outer and lower continental slopes. Three mini-basins on the outer slope of Ritchie Ridge, offshore Mahia Peninsula, were sampled during the TAN1613 voyage of the R/V *Tangaroa*. Ritchie Ridge is the southern point of the thin, non-accretionary zone of the northern Hikurangi Margin, making it an ideal setting to address what active sedimentary processes deposit material in HSM mini-basin settings. Core analysis of TAN1613\_38, TAN1613\_40 and TAN 1613\_41 was carried out at NIWA, Wellington, where grain size, carbonate, total organic matter and XRF data were collected and processed. Analysis of the submarine environment was carried out in ArcGIS ArcMap at the University of Auckland. A cross section down the eastern slope of Ritchie Ridge shows stepped seafloor morphology from 2242-2663 m water depth between the three mini-basins. Watershed analysis indicates that flows dominantly originate from the west. Bioturbated and non-bioturbated beds of silt were observed across the cores, along with beds of non-graded and normally graded sandy silt. Each core contains a primary tephra deposit at the base, with TAN1613\_38 in the deepest Ritchie Ridge mini-basin also containing a 60 mm deposit of reworked tephra. Tephra deposits at the base of the core have been dated and correlated to the Taupo eruption, 1718 cal. yr BP, suggesting sedimentation rates of ~0.6 mm per year in HSM mini-basins. Understanding the active sedimentary processes in these mini-basin settings can provide insight into the potential extent of earthquake-triggered flows that deposit reworked and sandy sediments in a silt dominated setting.

## A NEURAL NETWORK APPROACH TO REAL-TIME VOLCANO MONITORING USING DOPPLER RADAR DATA

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Volcanic ash being emitted during large volcanic eruptions strongly affects the surrounding population, infrastructure, as well as the aviation industry. Contrary to most modern volcanological monitoring techniques Doppler radar systems are mostly weather and visibility independent. They are roughly sensitive to particles greater than a tenth of the wavelength of the transmitted signal (e.g. volcanic clasts, and rain). Human interpretation is needed to differentiate between rain and ash emission in Doppler radar data. The differentiation is very time consuming, and not always possible in real-time. Automation is therefore highly desirable for fast risk and hazard assessment.

Here we present a neural network approach to automatically analyse Doppler radar data for discrimination between ash emission, rain, and noise. We use single Doppler spectra assigned to the three classes to train a neural network for this task. Those Doppler spectra yield distance and velocity information of particles inside the radar beam. Here the spatial information is separated into discrete distance intervals, so called range gates (RGT). We prove such a network can reliably differentiate between the three classes with accuracies up to 99%.

When monitoring remote volcanoes, data has to be transmitted from the instrument to an observatory or processed on site with limited computational resources. We therefore explored how reducing the input data into the neural network affects the ability to detect eruptions. Our sensitivity study shows a reduction of input data to be possible while still getting reliable classifications. A single RGT (input reduction by 85%) is sufficient, while two RGTs (input reduction of over 70%) increased the accuracy of the neural network significantly (from 90% to 97%). In conclusion, neural networks can automatically detect ash emission in Doppler radar data, independent of weather and visibility.

## HOW OLD ARE THE OLDEST SEDIMENTARY ROCKS IN DEEPWATER TARANAKI?

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The Deepwater Taranaki Basin lies beyond the shelf edge of Taranaki Basin, New Zealand and occupies the head of the New Caledonia Trough, a bathymetric depression that extends for some 2,300 km in a generally north-northwest direction as far as the Coral Sea. The basin is unquestionably a rift basin that contains up to 10 km of sedimentary fill. The oldest sedimentary rocks drilled by Romney-1, the only well in the basin, are of Teratan age, based on palynology (Schioler et al, 2014). Romney-1 did not drill the syn-rift succession. So far, no direct method of dating the older succession is available and a wide range of ages is possible. Nevertheless, a dominant view has evolved that the sedimentary succession in Deepwater Taranaki can be no older than Korangan (Late Aptian to Early Albian ~108 to 117 Ma). This paper examines the evidence for the age of the oldest sedimentary rocks in the Deepwater Taranaki Basin.

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## PALEOSEISMOLOGY OF THE NW CARDRONA FAULT, CENTRAL OTAGO

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The northeast-striking Northwest Cardrona Fault is a major range-bounding fault with as much as ~1 km of Late Cenozoic throw. It forms the northeastern component of a major geological structure; the Nevis-Cardrona Fault System, and defines the northwestern margin of the Otago range and basin province. Pre-existing knowledge of the NW Cardrona Fault was based largely on mapping, trenching, and dating led by the late Sarah Beanland in the 1980s, as part of seismic hazard investigations for hydroelectric development (Beanland and Barrow-Hurlbert 1988 – NZJGG 31:337–352). Current efforts involve re-assessing the paleoseismicity of the NW Cardrona Fault, focusing on obtaining fault rupture chronologies via OSL dating, a method that post-dates the 1980s work, as well as determining the location of the fault (van den Berg in prep). A trench excavated in 1984 by Sarah Beanland across a subsidiary scarp of the NW Cardrona Fault was re-opened, interpretations reviewed, and OSL samples collected. Eight OSL dates have been obtained, with two of them appearing to be too young in the context of other dates. The remaining dates imply that between 3 and 4 m of dip-slip surface-rupture displacement has occurred since ~40,000 years ago, in at least one and possibly as many as three rupture events. There is indication that the most recent rupture is younger than ~14,000 years ago, although assessment of the results is continuing. Additionally, a recent review (Barrell 2019 – GNS Science Consultancy Report 2018/207, prepared for Otago Regional Council) has refined mapping of the fault location, and via the aid of LiDAR, found that post-glacial activity on the fault has probably extended north through the Wānaka township rather than continuing northeast towards Lake Hāwea as previously thought.

## MILLENNIAL-SCALE SLIP RATE VARIATIONS ON MAJOR STRIKE-SLIP FAULTS IN CENTRAL NEW ZEALAND AND EXAMPLES OF POTENTIAL RESULTING IMPACTS ON HAZARD ESTIMATION

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Geological investigations over the last decade have demonstrated that major strike-slip faults in central New Zealand (e.g., Awatere, Clarence, Wellington faults) have experienced significant millennial-scale variations in slip rate over the last 10-12 kyr (1 kyr = 1000 years). For example, the central Clarence Fault has had a dextral slip rate of ~2 mm/yr over the last ~8 kyr, whereas, over the preceding ~4 kyr it had a significantly faster rate of ~9 mm/yr. The southern Wellington Fault provides an even more extreme example. Between ~5-8 kyr ago, it had a relatively slow slip rate of 1-2 mm/yr, whereas, between ~8-10 kyr ago its slip rate, at nearly 20 mm/yr, was approximately an order of magnitude faster.

In probabilistic seismic hazard assessment, the hazard contribution of an active fault (i.e., an active fault earthquake source) is typically a function of its slip rate, and that slip rate is often assumed to be constant. Here we investigate – in a first-order manner – potential impacts of the above slip rate variations on probabilistic ground shaking hazard estimation. Specifically, we utilise the New Zealand National Seismic Hazard Model and track changes in calculated peak ground acceleration and spectral acceleration that result from slip rate variations on the above faults equivalent in magnitude to those experienced in the past, and plausibly anticipated in the future. We report these changes for a representative suite of urban centres in central New Zealand (Wellington, Blenheim, Kaikoura). For example, we find that slip rate variation on the central Clarence Fault has little impact on hazard estimation at these centres, due to large source to site distances. However, there is a 30-50% difference in probabilistic estimates of peak ground accelerations for Wellington City between those derived utilising a fast Wellington Fault slip rate and those using a slow rate.



## **SLOW SLIP THROUGH A MACHINE LEARNING LENS**

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Investigating Slow Slip Event (SSE) activity in subduction zones provides insight into the slip behavior of megathrusts, which gives important clues about the rupture extent of future great earthquakes. In the last few years, these SSEs have been detected and studied at the Hikurangi margin through manual detection and modeling. Having an automated system to detect and confirm ongoing SSE will improve National Geohazard Monitoring Center (NGMC) situational awareness. This is also important from a hazards forecasting perspective, as such a system is needed to incorporate slow slip events into National seismic hazard models.

We apply different types of supervised Machine Learning methods, to effectively detect and classify Slow Slip Events in near-real time. Once trained we dramatically expand our capability to identify and build a complete catalogue of SSEs, likely detecting more events compared to the manual process. We present a project update showing some Machine Learning approaches tested and results on the detection of Slow Slip events.

Machine learning algorithms have been applied successfully to similar problems in other disciplines, such as Human-Activity Recognition, Earthquake phases detection, estimation of GPS displacement from microseismicity in the Cascadia subduction zone. However, such algorithms have not yet been used to detect and classify SSEs.

## THE DYNAMICS AND STABILITY OF LARGE PLINIAN PLUMES – INVESTIGATING VERTICAL AND LATERAL VARIATIONS IN THE 232CE HATEPE PLINIAN DEPOSIT

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The Taupo Volcanic Zone is one of the most frequent producers of Plinian eruptions globally. Eruptions of this magnitude involve up to ten cubic kilometres of ejected magma that lead to strong atmospheric disturbances during plume dispersal and extensive, coarse-grained fall deposits on the ground. The dispersal and sedimentation of pyroclasts in Plinian eruptions pose significant environmental and societal threats with immediate and short-term effects on aviation and general public safety, infrastructure stability and water resources, while longer term effects include increased flood risk and impacts to agriculture. Moreover, Plinian eruptions are notorious for producing violent pyroclastic currents. The Hatepe pumice of the CE232 Taupo eruption (eruption phase Y2) is a well-exposed example of a 'well-behaved' Plinian fall deposit. Previous studies have highlighted the remarkably uniform vertical deposit structure and the lack of indicators of source discharge unsteadiness, e.g. the absence of collapse-derived pyroclastic density currents. This MSc research is characterising vertical variations in grain-size, componentry and pumice densities along transects of Y2 in line of and perpendicular to the main plume dispersal direction. This approach is used to establish quantitative markers of synchronous deposition across fall deposits to investigate lateral variation in plume sedimentation. Here we present preliminary results of our field and laboratory results from key sections in medial deposit reaches. These show characteristic changes componentry and density of juvenile pyroclast components. Systematic variations in these data for small- and large Stokes-number particles are used to examine turbulent gas-particle transport and sedimentation in the spreading umbrella cloud. We also present evidence for the occurrence of minor column-collapse derived pyroclastic density currents. These occurred towards the end of the Y2 eruption phase show almost immediate transition into the phreatoplinian eruption phase Y3. These results indicate that the Y2 eruption phase may not have been as steady as hitherto thought.

## STUDIES OF SEISMIC VELOCITIES IN SUBDUCTION ZONES FROM CONTINUOUS OBS DATA

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In recent years, Ocean Bottom Seismometers (OBSs) have become widely used to record seismic data, to expand the coverage of seismic networks onto the ocean. This study takes advantage of offshore observations at the northern end of the Hikurangi margin and southwestern Okinawa Trough to study the tectonics in both regions.

In the Hikurangi subduction zone, slow slip events (SSEs) have been observed, which are caused by the subduction of the Pacific Plate under New Zealand. The behaviour of SSEs and how they influence the physical properties of Earth materials are open to question. From 2014 to 2015, 15 OBSs were deployed offshore Gisborne, New Zealand on the Hikurangi margin. Ambient noise data from the OBSs are used to study velocity changes related to SSEs. Single station cross component cross-correlations and auto-correlations are computed, from which coda waves are used to monitor the velocity changes before, during and after the SSEs in 2014 and 2015 to analyse the slow earthquake behaviour and its relation to stress changes. Preliminary result from one station shows a velocity decrease about 0.03% before the SSE in October 2014 and a velocity increase about 0.05% after the SSE starts.

The southwestern Okinawa Trough tapers towards Taiwan. How the back-arc crust accommodates the narrowing process remains to be understood. At various times between 2010 and 2017, 22 OBSs on a small scale ( $\sim 0.2^\circ \times 0.3^\circ$ ) were deployed in Southwestern Okinawa Trough offshore northeast Taiwan. Ambient noise recorded on vertical velocity and pressure sensors is used to retrieve Rayleigh waves or Scholte waves for studying shear wave velocity structure. Phase velocity dispersion curves are measured from cross-correlations and 1D shear velocity is inverted, revealing a very low shear velocity structure about 0.5 km/s at 5 km depth. Earthquake data will be added to test the results from ambient noise.

## SEICHE EFFECTS IN LAKE TEKAPO NEW ZEALAND IN AN MW8.2 ALPINE FAULT EARTHQUAKE

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This study investigates the potential for seismic seiches in Lake Tekapo of New Zealand, triggered by ground shaking from an Mw8.2 Alpine Fault earthquake. Synthetic ground motions are used as a forcing boundary to drive water motions by further developing the tsunami modelling code COMCOT (Cornell Multi-grid Coupled Tsunami). Our modelling results reveal that lake water oscillations will be mobilised immediately by the ground movement and further amplified by cross-lake seiching motions with peak-to-trough amplitudes reaching up to 6.5 m occurring in the lake's narrow southern arm and over 1.0m along the shore of Lake Tekapo township, posing potential threat to tourists, residents, boats and infrastructure in lake water and near waterfronts. These large amplitude oscillations will quickly attenuate in the first 5 to 10 minutes after the earthquake due to their relatively short periods while long period oscillations will continue, albeit with much smaller amplitudes. Both fundamental and higher seiche modes are identified in the lake through spectral analysis, with fundamental longitudinal oscillation periods at about 27 minutes for the whole lake, and about 10 minutes in the southern arm. Spectral analysis clearly shows the presence of higher order seiche modes, e.g. mode 2 & 3, across the lake and longitudinally along the lake. We find that large amplitude lake oscillations are better correlated with low-frequency, less energetic ground motion content than with high-frequency, strong ground shakings.

## COMPARING AND CONTRASTING THE 9<sup>TH</sup> JUNE AND 12<sup>TH</sup> AUGUST 2019 M5.5 FIORDLAND EARTHQUAKES: PRELIMINARY INSIGHTS FROM DWARFS

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Two moderate-magnitude M5.5 earthquakes occurred within 2 months and 40 km of each other in northern Fiordland in mid-2019. The events occurred in the complex transition zone between dextral strike-slip on the southern Alpine Fault, in the northeast, and compressional Fiordland subduction to the southwest. Both earthquakes exhibited reverse moment tensor solutions, but had epicentral locations coincident with the surface trace of the dextral southern Alpine Fault. Given their initial proximity to the Alpine Fault they generated notable public and media interest. However, their remote location between sparsely distributed permanent seismic stations meant it was difficult to accurately attribute them to a particular fault and to thereby assess their implications, if any, for hazard associated with the Alpine Fault.

In this study we use recently collected data from two temporary broadband seismometer networks that were operating nearby at the times of the two M5.5 events and associated aftershock sequences. Data from the DWARFS (Dense Westland Arrays Researching Fault Segmentation) and COSA (Central Otago Seismic Array) networks provide much improved azimuthal coverage of the sequences and location accuracy than the permanent seismic network alone. We present preliminary matched-filter detection and double-difference relative relocation results for the two aftershock sequences, focal mechanisms for the largest events and preliminary modelling of static stress changes on the Alpine Fault.

These preliminary results will allow us to examine the structures responsible for the earthquakes, their relationship to one another and to hazard on the Alpine Fault. We will also examine whether the aftershock sequences were unusual and comment on the difference in felt reports despite their similar size and location.

## **TECTONIC AND GEOMORPHIC CONTROLS ON THE DISTRIBUTION OF SUBMARINE LANDSLIDES ACROSS ACTIVE AND PASSIVE MARGINS, EASTERN NEW ZEALAND**

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Submarine landslides occur on continental margins globally and can have devastating consequences for marine habitats, offshore infrastructure and coastal communities due to potential tsunamigenic consequences. Evaluation of the magnitude and distribution of submarine landslides is central to marine and coastal hazard planning. Despite this, there are few studies that comprehensively quantify the occurrence of submarine landslides on a margin-wide scale.

We present the first margin-wide submarine landslide database along the eastern margin of New Zealand comprising >2200 landslide scars and associated mass-transport deposits. Analysis of submarine landslide distribution reveals 1) locations prone to mass-failure, 2) spatial patterns of landslide scale and occurrence, and 3) the potential preconditioning factors and triggers of mass wasting across different geologic settings.

Submarine landslides are widespread on the eastern margin of New Zealand, occurring in water depths from ~300 m to ~4,000 m. Landslide scars and mass transport deposits are more prevalent, and on average larger, on the active margin, compared the passive margin. We attribute higher concentrations of landslides on the active margin to the prevalence of deforming thrust ridges, related to active margin processes including oversteepening, faulting and seamount subduction. Higher sediment supply on the northernmost active margin is also likely to be a key preconditioning factor resulting in the concentration of large landslides in this region.

In general, submarine landslide scars are concentrated around canyon systems and close to canyon thalwegs. This suggests that not only does mass wasting play a major role in canyon evolution, but also that slope undercutting in canyons may be a fundamental preconditioning factor for slope failure.

Results of this study offer unique insights into the spatial distribution, magnitude and morphology of submarine landslides across different geologic settings, providing a better understanding of the causative factors for mass wasting in New Zealand and around the world.

## MANAGING HIGH SULPHATE WATER FROM OROGENIC GOLD MINE WASTE ROCK

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Highly elevated sulphate is a common issue in waterways around mines with sulphide mineralization due to the oxidation of exposed sulphides, which produces sulphuric acid. At many orogenic gold mines such as Macraes in Otago, the sulphuric acid is neutralised by calcite in the host rock, leaving high concentrations of sulphate in a circum-neutral solution. This research characterises the water-rock interactions and investigates management techniques for reducing sulphate concentration in waters on site. Of key focus is initiating precipitation of sulphate minerals such as gypsum to remove sulphate from solution.

In some waterways on the mine site, large amounts of precipitate have been observed. These precipitates were analysed with handheld XRF, XRD and SEM to determine their composition. It was found that most of the precipitate was not sulphate minerals as expected, but aragonite ( $\text{CaCO}_3$ ). However, in an evaporative environment around a schist outcrop, significant amounts of epsomite ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ) was observed. Long term data records of water quality analysis' have been used to assess temporal and special trends in the chemistry of the water associated with waste rock stacks. Geochemical modelling has shown that approximately 95% of typical high-sulphate water needs to be evaporated to begin precipitating sulphate minerals such as gypsum and epsomite.

One of the management strategies that has been proposed is to use the high sulphate water for irrigation. Spraying the water over a large area of land will increase evaporation, allowing for precipitation of gypsum and epsomite, removing the sulphate from solution. If high sulphate water can be used for irrigation without degradation in pasture and waterway quality, there are positive implications for the surrounding environment and farmlands which need water over dry summers. A laboratory scale trial shows promising decreases in sulphate concentrations of mine water irrigated over columns of grassed soil.

## DETECTING CONDENSATION CORROSION IN THE WAITOMO GLOWWORM CAVE THROUGH $\Delta^{13}\text{C}$ AND $\Delta^{18}\text{O}$ CHANGES.

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Condensation corrosion is the process of cave walls enlarging by dissolution. Dissolution takes place when naturally acidic waters, form films on the cave walls and their decorations (e.g. stalactites and stalagmites). Therefore, condensation corrosion is particularly important in touristic caves such as those like Aranui, Ruakuri and Glowworm caves in Waitomo, New Zealand. In this study, we placed 2 cm square speleothem and limestone tiles on the cave walls of different chambers in the Glowworm Cave. These tiles were exposed for three- and six-months periods to the cave atmosphere and were analysed for stable isotopes of carbon and oxygen; in addition to SEM imaging of calcite precipitates. Changes in  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  suggest that isotopic exchange occurred between  $\text{CaCO}_3(\text{calcite})$ ,  $\text{H}_2\text{O}$  and  $\text{CO}_2(\text{g})$ , reflecting water evaporation and  $\text{CO}_2(\text{g})$  degassing events in the Glowworm Cave. Understanding condensation corrosion process is relevant to the conservation of touristic caves.



## **GEOPHYSICAL AND GEOCHEMICAL CONSTRAINTS ON THE REGIONAL HYDROGEOLOGY OF THE BANFF HOT SPRINGS, CANADA**

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In Banff National Park, located within the Front Ranges of the Canadian Rockies, nine thermal springs occur along a 4 km interval of the Sulphur Mountain Thrust (SMT) fault. In recent years the highest elevation hot springs have experienced seasonal flow stoppages over the late winter to spring months, threatening critical habitat zones and causing operational interruption to a commercial spring-fed swimming pool. We use geophysical and geochemical investigations to provide spatial and temporal constraints for regional-scale hydrological models of the hot spring system. These models will be used to forecast future hot spring flow aiding in understanding the ecological and economic risk associated with flow stoppages.

Previous studies showed that spring flow is driven by precipitation infiltrating to the flanks of Mount Rundle to the East, and Sulphur Mountain to the West of the SMT. The infiltrating water flows down through a unit of carbonate rock and is heated by the Earth's natural geothermal gradient along its flow path. At a maximum depth of 3.2 km the groundwater intercepts the permeable SMT fault zone, is quickly returned to the surface, mixes with cold fresh water from Sulphur Mountain and discharges from the hot springs.

Reduced freshwater contributions are considered the main cause of spring flow stoppages. Seasonal changes in spring water chemistry and groundwater residence times provide temporal constraints on the mixing ratio of shallow to deep thermal groundwater. Electrical resistivity and seismic refraction surveys transecting the SMT show the springs are restricted to the lower elevation boundary of the 100 m wide SMT fault block, which is interpreted as a low resistivity zone (10 – 100's  $\Omega\text{m}$ ) associated with water bearing fractured rock. The fault zone strikes NNW-SSE and dips 60 degrees to the west, in agreement with regional structural geological maps.

## NEW PERSPECTIVES FROM MAPPING AND HIGH-RESOLUTION $^{40}\text{Ar}/^{39}\text{Ar}$ DATING OF TONGARIRO VOLCANO, NEW ZEALAND: IMPLICATIONS FOR STRATOVOLCANO LIFECYCLES AND GLACIO-VOLCANIC INTERACTIONS

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We present new results from an extensive mapping campaign of Tongariro volcano, a  $\sim 90 \text{ km}^3$  andesitic composite stratovolcano in the southern Taupo Volcanic Zone, New Zealand. New  $^{40}\text{Ar}/^{39}\text{Ar}$  age data from samples from previously under-examined ( $\sim 40\%$ ) parts of the edifice are integrated with existing data to establish a comprehensive eruptive stratigraphy for the mountain. Our dataset consists of new field observations, 30 high-precision lava age determinations (added to 40 existing K/Ar ages) and geochemical analyses of 250 whole-rock samples (that sum to 700 analyses with pre-existing data), which describe the evolution of Tongariro's edifice and magmatic system. The oldest rock dated is an inlier of basaltic-andesite from the NW flank of Tongariro, possibly erupted from a separate volcano, which yields an age of  $512 \pm 59 \text{ ka}$ . The oldest edifice-forming materials confidently attributed to Tongariro in the Lower Tama Lake area yield an  $^{40}\text{Ar}/^{39}\text{Ar}$  lava age determination of  $304 \pm 11 \text{ ka}$ . Other  $^{40}\text{Ar}/^{39}\text{Ar}$  lava age determinations demonstrate effectively continuous edifice-building activity since  $\sim 300 \text{ ka}$ . Volume estimates for 37 distinct units show that edifice growth is more rapid in warm climatic periods, which reflects a preservation bias due to the lack of ice cover on the edifice. During periods of elevated ice coverage (MIS 6, 4-2), the preservation rate of effusively-erupted materials is only  $\sim 15\text{-}20\%$  of the preservation rate during ice-free periods. No available evidence supports deglaciation as a trigger of increased eruptive rates which has been suggested to arise when edifices are unloaded. Whole-rock MgO concentrations in 37 eruptive units record abrupt increases at  $\sim 230 \text{ ka}$ ,  $\sim 160 \text{ ka}$ ,  $\sim 117 \text{ ka}$  and  $\sim 60 \text{ ka}$  that are followed by periods of gradual decline until the next increase. MgO increases do not correlate with climate indicators but are associated with the emergence of new flank vents.

## CONTRASTING EVOLUTIONARY HISTORIES OF THE TAUPŌ-REPOROA BASIN AND WESTERN TAUPŌ RIFT

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The evolution of the central Taupō Volcanic Zone (TVZ) reflects a delicate *pas de deux* between extensional tectonics and intense magmatism. Between the frequently active Taupō and Okataina volcanoes lie the Taupō-Reporoa Basin (TRB) to the east, and the western side of the modern Taupō Rift (wTR). Both areas saw caldera-related volcanism between 350 and 250 ka. However, the modern TRB forms a topographic low with rare surface faulting, and has been largely volcanically inactive since ~100 ka while the wTR is topographically elevated (particularly across the Maroa-north Taupō area), has several young vents and is traversed by numerous fault traces. The TRB has numerous high-temperature geothermal systems; the wTR has only limited geothermal manifestations. Both the TRB and wTR in their present forms post-date the 350-340 ka Whakamaru Group eruptions and cut across the caldera structure formed at that time. Between the TRB and wTR is a long-lived horst feature, expressed at the surface at Waiotapu (Ngapouri ridge), as a subsurface structure at Wairakei, and at the surface in the Tukairangi block just west of Taupō. <sup>40</sup>Ar/<sup>39</sup>Ar dating of surficial eruptives and U-Pb dating of zircons from subsurface units confirm that the TRB and wTR have contrasting subsidence histories. The wTR has surface rocks that postdate the Whakamaru age by <50 kyr (e.g. Goldies dome, 305 ka), indicating rapid infill of the Whakamaru caldera, and little subsequent subsidence. In contrast, the TRB remains an area of net subsidence: the oldest surficial lava near Reporoa has an age of 264 ka (following the 298 ka collapse of Reporoa caldera) and equivalent age rocks to the SSW are buried by a kilometre or more beneath Rotokawa and Wairakei-Tauhara geothermal fields. These contrasts between the TRB and wTR reflect complexities in magmatic supply and stress states that remain a challenge to explain.

## **AUTOMATICALLY IDENTIFYING SUBMARINE LANDSLIDE SCARS ON MULTIBEAM DATA – AN ATTEMPT**

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Over the last 50 years, advances in multibeam echosounder (MBES) mapping technology have enabled vast regions of ocean floor to be mapped more accurately, faster and at greater resolution than ever before. These data divulge a great number of seafloor features that have led to a better understanding of submarine processes including tectonic plate motions, volcanism, mass wasting, and sediment erosion and deposition. However, the wide availability of MBES data has resulted in information overload due to the time-consuming and subjective nature of manual feature identification. The vast volume of MBES data available necessitates automated feature detection to effectively process and interpret these data.

Automated feature detection and classification algorithms have been successfully developed and used in a range of contexts including, the measurement of coastline changes in LIDAR imagery, mine detection in side-scan sonar imagery and pockmark classification in MBES data.

In this study we use MBES data on the eastern margin of New Zealand and machine learning algorithms to develop methods of automating submarine landslide detection. Submarine landslides are ubiquitous across all continental margins, with potentially hazardous consequences for natural and human-made seafloor structures and coastal communities due to the potential for generating tsunamis. Thus, there is a need to quickly, accurately and reliably map submarine landslides to identify locations that may be prone to failure.

Developing automated submarine landslide detection techniques for MBES data will enable faster, more consistent, reproducible results, and facilitate feature comparison across different scales and settings.

## A TIME-DEPENDENT INVERSION OF ONSHORE GNSS TIME SERIES DATA FOR THE MARCH - MAY 2019 SLOW SLIP EVENT AT THE HIKURANGI SUBDUCTION ZONE

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Slow slip events (SSEs) have been documented at several regions of the Hikurangi subduction margin, over the last fifteen years. Short, shallow (< 15 km depth) SSEs recurring every one to two years have occurred off the east coast of North Island near Gisborne and Hawkes Bay. Longer duration SSEs with a recurrence period of approximately five years have been observed in central and southern North Island (the Manawatu and Kapiti regions), where the Hikurangi interface is at a depth of 30-70 km. We are currently undertaking seafloor geodetic deployments to better resolve the distribution of shallow SSEs and seismicity at the offshore Hikurangi subduction zone. Over the last year, we have deployed 21 Absolute Pressure Gauges, 8 Ocean Bottom Seismometers, and two GPS-Acoustic arrays. The GeoNet continuous GNSS network detected a large SSE off the east coast of the North Island between mid-March and mid-May 2019, directly beneath our seafloor geodetic and ocean bottom seismic array. Using the absolute pressure gauge data, we hope to resolve cm-level vertical movement of the seafloor above the region of slow slip. To resolve the along-strike extent of the offshore slip and its temporal evolution, we use the time-dependent inversion software TDefnode to invert onshore GeoNet GNSS time series data. After the seafloor geodetic data are recovered in November 2019 using the R/V Tangaroa, we will incorporate these data into our inversions. Seismic swarms were observed during the SSE (with magnitudes up to 5.1), and our inversions reveal intriguing relationships between the seismicity and the slow slip evolution. We also hope that the improved resolution of offshore slip from the seafloor geodetic data will reveal insights into the relationship between slow slip offshore Hawkes Bay and the inferred location of past earthquake ruptures offshore Hawkes Bay determined from paleoseismic investigations.

## **BIOMONITORING OF NEW ZEALAND'S MARINE ENVIRONMENT USING TRACE ELEMENT ANALYSIS OF CRUSTACEA**

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The effective management of New Zealand's marine resources is paramount to our societal and economic wellbeing. Key to preserving our unique marine estate is understanding its chemistry and monitoring any change brought about by human-induced activity, such as mining, trawling, pollution or ocean acidification. Biomonitoring – the measurement of potentially ecotoxic elements in an organism's body burden – is an essential tool in this process as it allows the levels of toxic elements in the marine environment, including their uptake into the food web, to be monitored.

A new biomonitoring tool using the trace element profile of crustacea has been investigated over the past three years as part of an MBIE Smart Ideas project, 'Crustacea As Indicators for the Marine Environment' (CAIME). Several species of Amphipoda and Decapoda from coastal and deep marine localities around New Zealand have been analysed for > 30 trace elements. The results show that for each species, trace element contents vary depending on location, reflecting the influence of regional environment on body burden chemistry. Furthermore, localised areas of contamination (e.g. higher Cd levels) may be identified at small (< km) scales. Measured abundances of trace elements from different species from the same location do differ due to differences in organism's trophic level, metabolism, diet and ability to bioregulate elements. Direct comparisons between regions, or of single regions over time, can therefore only be made using the same species. However, in environments with anomalously high trace element levels, the excess concentrations appear to be reflected in crustacean body burden regardless of species. This tool therefore provides a means of monitoring changes in ecotoxicity in wide ranging marine (and even freshwater) environments.

## TOPOGRAPHIC CONTROLS AND HAZARDS ASSOCIATED WITH A LARGE VOLUME PYROCLASTIC FLOW DEPOSIT, THE 1.2 MA ONGATITI IGNIMBRITE

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The 1.2-Ma Ongatiti Ignimbrite (ONIG) was emplaced by a super-eruption at Mangakino Volcanic Centre (MVC), central TVZ. We determine how the vertical and lateral distribution of ONIG is controlled by the paleotopography to understand more about the transportation of the pyroclastic flow and the potential hazard such a flow poses. Proximally, ONIG occurs mostly as a welded to non-welded, columnar-jointed cliff-forming deposit. It comprises six different facies based on variations in pumice and lithic-clast abundance, and welding rank. ONIG's minimum volume is revised to  $\sim 720 \text{ km}^3$  ( $\sim 512 \text{ km}^3$  DRE); its VEI is 7. Combining the field observations with GIS data and a DEM of the covered area by ONIG shows it covered up to  $\sim 3$  m thickness on hills and 36 m in valleys. The ignimbrite reached elevations of approximately 900 m asl in proximal regions and in medial areas it filled valleys and attained elevations of  $\sim 150$ – $300$  m asl. However, the distal equivalent tephras (Oparau Tephra; bed K12, Kauroa Ash), were emplaced at elevations of  $< 50$  m asl.

The ONIG eruption was a landscape-modifying event impacting at least the western North Island as well as inundating locations as far away as Auckland and Wellington. Comparing the DEM and the ONIG distribution reveals that up to  $\sim 40$  km from MVC, the ignimbrite blankets hills and valleys, but beyond that, the pyroclastic flow travelled only through the antecedent valleys. The modern TVZ landscape is mostly dominated by relatively low-lying land with only moderate relief. This spatial association means that there are few large natural barriers (i.e. high hills, ranges) to control voluminous or powerful pyroclastic flows and so they could travel and bury a vast area of the North Island catastrophically. Hence, our findings show the extent of hazardous area that would be significantly affected by a similar-sized eruption from TVZ.

## RESEARCH ON MARS ENVIRONMENTAL EVOLUTION BASED ON THE COMPARATIVE ANALYSIS OF ROCK SEDIMENTARY ENVIRONMENT

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In this study, we tried to prove that there were some necessary environmental conditions for life on Mars from the point of view of rock-sedimentary environment. Based on our research on the characteristics and sedimentary conditions of the red beds on earth, we have carried out large-scale data statistics and comparative analysis on the characteristics of the red beds on earth and the existing reddish continental sedimentary rocks on Mars. Based on this, the sedimentary conditions of reddish continental sedimentary rocks on Mars are presumed, and the diagenetic mutation period test is designed to simulate and verify the presumption obtained in this paper. The results show that the continental sedimentary rocks on Mars and the red beds on earth have similarity in color, geomorphology, stratigraphic structure, mineral composition and chemical composition. Based on this similarity, we assume that the sedimentary environments of the two types of rocks will be similar to some extent. Therefore, we speculate that Mars also had suitable oxygen content and temperature conditions for life to exist before large-scale volcanic eruptions. Furthermore, we proposed an environmental evolution model of Mars. We believe that, similar to the red beds on the earth, there used to be a large number of carbonate rocks on Mars. But under the action of sulfuric acid gas produced by large-scale volcanic eruptions, in the long process, surface carbonate was replaced by sulfate. Mars is gradually losing vital conditions for life to survive. To verify our model, we designed a diagenetic mutation period test. Through experiments, we have realized the simulation of the evolution process from carbonate rock to sulfate rock, which makes the environmental evolution model proposed in this paper well verified.