The Organising Committee extends a warm welcome to all symposium delegates and visitors to Christchurch.

Please note that information in this publication was correct at the time of going to print.
However, due to unexpected late changes in plans, some abstracts
included here may subsequently have been withdrawn.

Bibliographic References:

Abstracts & Fieldtrip Volume

A.N. Author (2013) What I did in my holidays. In: Wandres, A.M., Storey, B. & Bradshaw, M. (eds.) Programme, Abstracts & Fieldtrip Guide, Bradshaw & Weaver Symposium 2013, Christchurch, New Zealand. Geosciences Society of New Zealand Misc. Publ. 135.

Bradshaw & Weaver Symposium

14–19 October 2013
University of Canterbury
Christchurch

Programme

Organising Committee

Anekant Wandres, Bryan Storey, & Margaret Bradshaw

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General Information

The 2013 Bradshaw & Weaver Symposium is being held in Christchurch, to honour the contributions John Bradshaw and Steve Weaver have made to the field of geology. This symposium is being organised by the Department of Geological Sciences and Gateway Antarctica, University of Canterbury, and will be held from Monday 14 October to Tuesday 15 October 2013.

The conference will be followed by a four-day field trip starting on Tuesday evening 15th October and returning to Christchurch on Saturday 19th October 2013.

Venue

Conference Registration will commence at 400pm at the Staff Club of the University of Canterbury on 13th October, in conjunction with the Icebreaker function. Registration will continue at 8.30am on the morning of Monday 14th October in the South Arts Lecture Theatres on campus. The formal welcome and opening ceremony will commence at 9:00 am in Lecture Theatre A5. For the remainder of the conference programme oral presentations take place in the same Lecture Theatre A5. A Symposium Information Desk will be staffed during coffee and tea breaks in the Foyer of the South Arts Lecture block where the poster presentation will also be displayed.

Registration

Most participants will have registered and paid for conference attendance, and will therefore only need to report to the Registration Desk in the Foyer of the South Arts Lecture Theatres to collect their conference packs. We ask that all talk presenters deposit their electronic files at this time.

The registration/information desk will be open as follows:

South Arts Lecture Theatres Foyer:	Monday 14 October from 8.00 am to 4.00 pm
	Tuesday 15 October 8.00 am to 1 pm

Assistance for Delegates

Delegates requiring assistance should contact the conference information desk (morning and afternoon coffee/tea breaks).

Talks

Oral presentations are scheduled in 30 minute time slots. Please plan for a **maximum 25 minutes presentation**, leaving time for questions and change-over.

Lecture rooms contain two data projectors for PowerPoint presentations. If you requested an overhead projector it will be available in the room at the time of your presentation. Speakers are asked to ensure that their presentations are compatible with a PC platform, and those using Mac computers will need to ensure their presentations will run on a PC.

- All speakers are asked to submit their talks electronically (PC readable) to the registration desk at the time of first arrival at the conference.
- Please carefully label the presentation with the presenter name, initials, title of presentation, and also the day, session, and time of presentation. The digital file (ppt) should also contain author, day and time slot.
- Personal laptops cannot be used for presentations. Mac users please note!

Facilities will be available for speakers to review or work on presentations. Information on a speaker-ready/ preparation area will be advised on site.

If you require an overhead projector that should have been requested at the time of abstract submission, we remind presenters that only one screen will be available in the lecture theatre.

Plenary speakers have been allocated additional time for presentations, further details are included in the conference programme.

Poster Displays

A listing of poster displays is included in the following pages. Posters will be available for viewing in the Foyer of the South Arts Lecture Theatres throughout the conference, in order to facilitate viewing. Provision has been made in the programme for an extended viewing time on Monday, after lunch, when poster presenters will be asked to be available at their poster to answer questions and for discussion. We also recommend that presenters indicate additional times during the symposium when they will be available at their poster for discussion.

Poster presenters are asked to have their posters up for viewing first thing Monday morning, and prior to the conference opening session at 9.00am. All posters should be taken down on Tuesday after the lunchtime break.

Velcro and/or drawing pins can be used to hang posters, materials for this will be available from the registration/information desk.

Refreshments

Morning and afternoon coffee/tea will be provided in the Foyer of the South Arts Lecture Theatres. Lunches will also be provided in the Foyer, and the cost of this has been included in the conference registration. There are also a number of cafés and restaurants available on campus.

Social Events

- An informal "Ice-breaker" at the Staff Club of the University of Canterbury from 4-6 pm on Sunday 13 October (venue and time to be confirmed). Cost is included in the registration fee.
- The Conference Dinner will be held on Monday 14 October at the Hotel Copthorne Commodore on Memorial Avenue near the airport. Transport will be provided, and details will be announced at the conference.

Name Badges

Name badges must be worn at all times at the venue.

Communication

For emergency purposes only messages may be left with our departmental administrator Pat Roberts (phone 03 364 2700; Fax 03 364 2769). Messages for participants will be pinned to the noticeboard at the Registration/Information Desk in the South Arts Lecture Theatres Foyer. No email internet connections or photocopying facilities are available at the conference venue.

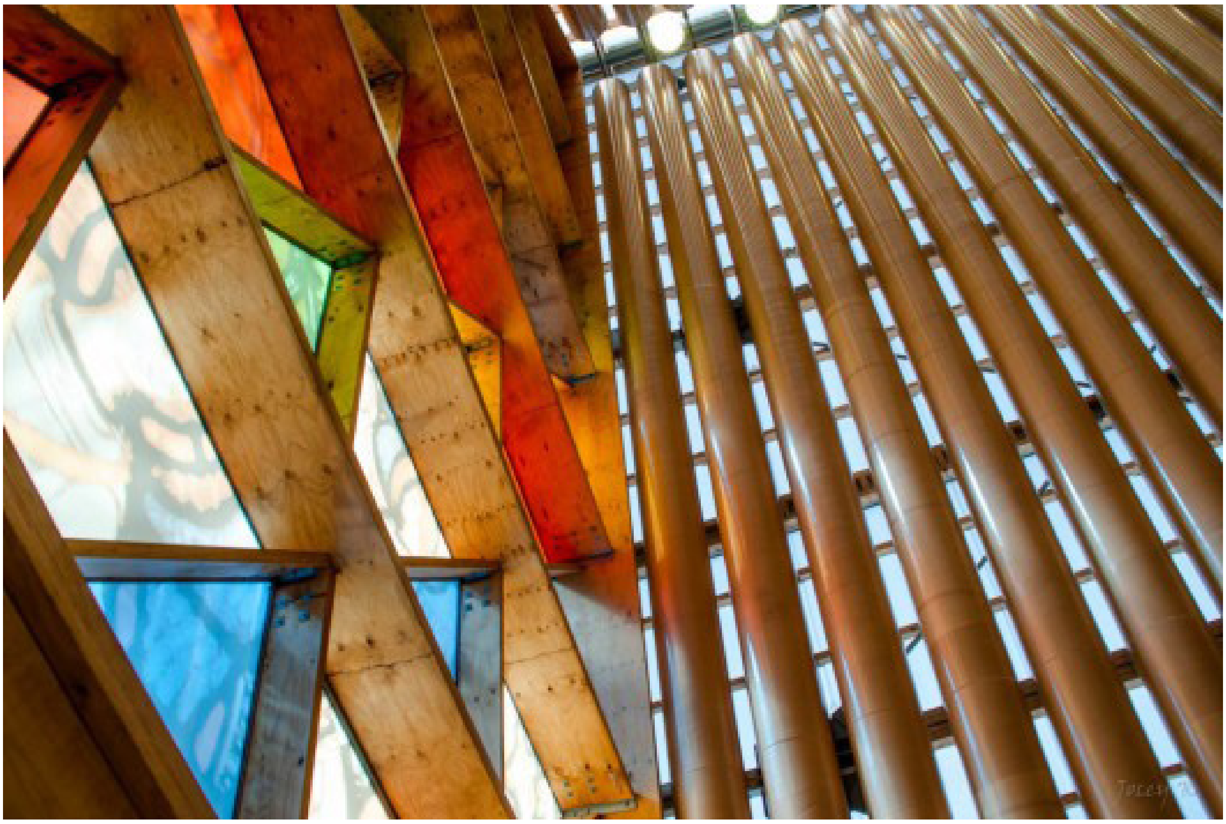
Mobile Phones

Please, cellphones should be turned off or silenced in the lecture theatre at all times.

Field trips

Trip 1: ***The Geological Impacts of the Canterbury Earthquake sequence on Christchurch City***
This afternoon excursion will include a traverse through the central city business district to view the ongoing recovery work post February 2011. More than 1000 commercial buildings have now been demolished, including many heritage buildings. A new city centre redevelopment plan is currently being implemented, and reconstruction is underway. We will view the impacts of the severe ground shaking and widespread liquefaction and lateral spreading damage on the built environment in the heart of the city.

Trip 2: ***NW Nelson and West Coast***. Our field trip to NW Nelson will depart Christchurch on Tuesday 15 October 2013. This is a change from the advertised dates on our website. To have more time for the geology in NW Nelson we will fly to Nelson on Tuesday evening instead of driving to Nelson on Wednesday early morning. The flight leaves Christchurch at 6:45 PM and arrives in Nelson at 7:35 PM. In Nelson we will be met by our students Nick and Jan to spend our first night in Motueka. The accommodation at Motueka Motor Camp has been organized but is not included in the registration fee. The next two nights will be spend at "The Rocks" Hotel in Takaka and on Friday we move to Westport where we will stay at University field station. We will return to Christchurch on Saturday via Arthurs Pass. The expected time of arrival is around 5pm.



Christchurch has officially opened a transitional cathedral made from cardboard in Latimer Square, replacing the neo-Gothic structure destroyed in a 2011 earthquake that killed 185 people in New Zealand's second largest city.

Symposium Programme for Monday 14 October

Time	Lecture Theatre A5
0800-1700	Registration in the Foyer of the South Arts Lecture Theatres
0900–0915	Welcome by Department of Geological Science HOD **Prof Jarg Pettinga**
0915–1000	**Pettinga J** – The 2010-2012 Canterbury Earthquake Sequence: *What's happening beneath our feet?*
1000-1030	Morning Tea in the Foyer of the South Arts Lecture Theatres
	Chair: John Bradshaw
1030-1100	**Mortimer N** – Zealandia and Its Environs
1100–1130	**Elliot D** – Zircons from Permian and Triassic strata on the Ross Embayment Flank of the Central Transantarctic Mountains and from West Antarctica
1130–1200	**Pankhurst R** – The Gondwana connections of Northern Patagonia
1200–1300	Lunch in the Foyer of the South Arts Lecture Theatres
	Chair: Margaret Bradshaw
1300–1330	**Tulloch A** – The Mesozoic Southeast Gondwana Arc
1330–1400	**Duffey B** – Subduction and extrusion of Australian Crust at the Banda Arc
1400–1430	**Bradshaw J** – The structure and tectonic setting of the dike zone of the Dun Mountain Ophiolite in the Bryneira Range, western Otago
1430–1500	**Poster Session**

1500–1530	*Afternoon* Tea in the Foyer of the South Arts Lecture Theatres
	Chair: Bryan Storey
1530–1600	**Davey F** – Extensional tectonics in Western Ross Sea
1600–1630	**Ghisetti F** – Deformation of the top basement unconformity west of the Alpine Fault (South Island, New Zealand): Implications for seismic hazard from inherited fault structure
1630–1700	**Riordan N** – A 'New' Core Complex along the West Coast, South Island
	Symposium Dinner at the Hotel Copthorne Commodore starting at 1830

Symposium Programme for Tuesday 15 October

Time	Lecture Theatre A5
	Chair: Rose Turnbull
0900-0930	**Storey B** – A burst football theory for Gondwana breakup
0930–1000	**Soto F** – Evolution of the Limon Verde Metamorphic Complex, Chile during the Late Paleozoic
1000–1030	**Jongens R** – Ross-Delamerian orogen granitoids in Fiordland, New Zealand
1030-1100	Morning Tea in the Foyer of the South Arts Lecture Theatres
	Chair: Steve Weaver
1100-1130	**Adams C** – Zealandia in Rodinia: Speculations on Precambrian provenances of detrital zircons in New Zealand sedimentary rocks
1130–1200	**Turnbull R** – A recently recognized Western Province magmatic event at 387±3 Ma: a response to Buller-Takaka terrane amalgamation?
1200–1230	**Hiess J** – Zircon and Monazite U-Th-Pb, REE, O And Hf signatures In Western Province gneisses
1230–1330	Lunch in the Foyer of the South Arts Lecture Theatres
1330–1700	**Field Trip 1**: The Geological Impacts of the Canterbury Earthquake sequence on Christchurch City (J**arg Pettinga**)
1845	**Field Trip 2**: Flying to Nelson for the NW Nelson/West Coast field trip

Posters

Margaret Bradshaw	Sequence Stratigraphy: a new approach to the Taylor Group, Beacon Supergroup, in southern Victoria Land, Antarctica
Morag Hunter	Palaeoenvironmental changes during the transition from an Icehouse World to a Greenhouse World: end Permo-Carboniferous glaciation in the Falkland Islands
Jan Sintenie	The tectonic evolution of the Grey Valley Trough
Rudolph Trouw	The role of the Trinity Peninsula Group In West Gondwana: New data from Coronation Island, South Orkney Islands

Abstracts

In alphabetical order by presenting author

Kea –46 cm, male, 1000 g, female, 800 g, olive green with red underwings and rump, upper mandible longer in the male; juvenile has pale crown, yellow cere, eye-ring.

ZEALANDIA IN RODINIA: SPECULATIONS ON PRECAMBRIAN PROVENANCES OF DETRITAL ZIRCONS IN NEW ZEALAND SEDIMENTARY ROCKS

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Oral

Keywords: *Rodinia, Zealandia, Precambrian, detrital zircon, provenance*

ABSTRACT

No Precambrian rocks outcrop in New Zealand, a possible exception being a seafloor sample of granodiorite-gneiss, ca.1100 Ma, dredged at the southernmost edge of the Campbell Plateau (Challis et al. 1982). It is thus significant that Precambrian zircons, as detrital grains, are commonly found in all New Zealand sedimentary rocks. Early Paleozoic rocks in particular, have up to 60% Precambrian zircons. Of these, about 70-90% has a Rodinian supercontinental heritage (700-1600 Ma). The remainder are either Paleoproterozoic or Archean ('Nuna' heritage). The latter occasionally reach a surprising total of 20% total and as old as 3560 Ma. The Rodina zircon age group (RA) is consistently associated with an early Paleozoic Gondwana' age group (GA), 440-700 Ma, such that the RA/GA ratio is always in the range 0.5-2.0.

Within early Paleozoic rocks in Zealandia, the Gondwana (GA) age group is, in total, skewed (about 60-70%) towards its Precambrian segment (542-700 Ma) and with significant age components at ca. 510, 560 and 650 Ma. The Rodinia (RA) age group is concentrated (about 60%) in a central, late Mesoproterozoic segment (1000-1200 Ma) with age components commonly at ca. 1010 and 1065 Ma. These patterns are similar for rocks from both Buller and Takaka terranes. They thus endure over a 150 million year (550 to 400 Ma) depositional interval, across a very large area of southern Zealandia (at least 2000 km N-S, 300 km E-W. This suggests a consistent geographic association of RA and GA rock/zircon sources of voluminous character, such as regional plutonic igneous province emplaced into an older metamorphic basement. Although an Australian or Antarctic setting for these sources is commonly assumed, there are no satisfactory examples adjacent to Zealandia of appropriate age, volume or composition. Very long sediment pathways or multiple episodes of zircon recycling have to be invoked to reach adequate sources in western-central Australia or interior Antarctica. Anomalously high RA/GA zircon age ratios (>2) in Late Cretaceous sandstones, deposited in southern Zealandia after separation from Gondwana, cannot be adequately matched with any known Zealandia source, implying a zircon contribution from a hidden Precambrian basement, at least of Rodinian (ca. 1000-1200 Ma) age under southern Zealandia (Adams & Griffin 2012)

The RA and GA groups in Zealandia rocks are well matched with counterparts in West Antarctica (Marie Byrd Land), but only moderately so with those in southeastern Australia (Victoria, Tasmania). In particular, the ca. 650 Ma component is only poorly represented in the latter, suggesting that this is also from part of a Zealandia basement.

Another striking difference in the Zealandia age datasets is the occasional exceptionally high proportion of "Nuna' (NA) zircons, >2000 Ma. The proportion increases in the northeastern sector of the Zealandia Paleozoic basement (Takaka Terrane) such that late Ordovician quartzites near Takaka have >20% Archean zircons. This pattern suggests that a source, now detached or subsequently hidden, was formerly located the east rather than west of Zealandia. Adams and Griffin (2012) suggested that the Precambrian basement of South China might be an appropriate candidate.

A model is suggested that Precambrian basement underlies much of southern Zealandia (South Island and Campbell Plateau) and possibly including the Challenger Plateau. In its southern part a late Mesoproterozoic plutonic and/or metamorphic basement (1000-1200 Ma) predominates but within this there is a widespread magmatic province of late Neoproterozoic age (542-700 Ma). This may merge westward into the early Paleozoic, Delamerian Orogen (540-470 Ma).of East Antarctica and South Australia. In the northern part, the Mesoproterozoic basement was either close to, or underlain by, an older Paleoproterozoic/Archean basement.

REFERENCES

Adams , C.J., Griffin, W.L. 2012: Rodinian zircons in Late Cretaceous sandstones indicate a possible Precambrian basement under southern Zealandia Precambrian Research 212-213: 13-20.

Challis, G.A., Gabites, J., Davey, F.J. 1982. Precambrian granite and manganese nodules dredged from the southwestern Campbell Plateau, New Zealand. New Zealand Journal of Geology and Geophysics 25: 493-497.

DIKE ORIENTATION AND STRUCTURAL HISTORY OF THE DUN MOUNTAIN OPHIOLITE IN THE BRYNEIRA RANGE, WESTERN OTAGO

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Keywords: *Bryneira Range, Maitai Terrane, Caples Terrane, Livingstone Fault*

Oral

ABSTRACT

The Bryneira Range exposes a sub-vertical cross section of the Permian Dun Mountain Ophiolite that forms the basement to the Permian and Triassic rocks of the Maitai Terrane. To the east, and separated by the Livingstone Fault, lies the poly-deformed Caples Terrane. The lower (eastern) mantle section of the ophiolite is made up of ultra-mafic rocks, separated from the crustal section by the sub-vertical Peanut fault. The crustal section comprises gabbros, dike rocks, pillow lavas, and sedimentary breccias overlain by the Permian Wooded Peak Limestone. The basic 'dikes', best termed intrusive sheets because of their diverse orientation, are of two main petrological types easily distinguished in the field by their weathered colour. The older Grey Intrusive Sheets (GIS) are consistently cut by the younger Orange Intrusive Sheets (OIS). In well exposed areas, the latter can be subdivided into four successive phases on the basis of cross-cutting relationships.

Poles to sheets, that should reveal the predominant extension direction, were found to be of very diverse orientation. Rotation about the paleo-horizontal, represented by the bedding of the Permian Wooded Peak Limestone, produced no improvement. Rather, the pattern suggests that either, the sheets were intruded in a frequently changing stress field, or the rock mass was rotating within a consistently oriented stress field, or some combination of the two. We attempted to resolve this question by unfolding the successively older sets of OIS sheets about two older paleo-horizontals; the bedding of the Upukerora Breccia and the primary flattening of the pillow basalts. These produced better concentrations of poles to the younger sheets and supports fairly uniform stress direction and rotation of the host rock mass. The rotation is thought to represent extensional faulting and rotation within a system of listric faults. The extension direction is very oblique to the strike of the ophiolite.

A potential analogue is seen in the Bransfield Strait (Antarctic Peninsula) incipient back-arc basin. Here extension is marked by numerous normal faults, listric detachment surfaces, a neo-volcanic zone and a number of 'off axis' central volcanoes; a combination of features that could explain the observed diversity in intrusive sheet pattern and the Peanut Fault. An important difference, however, is that the Bransfield Strait extension is acting on pre-existing volcanic crustal rocks. In the Bryneira example we see the extension of pre-existing back-arc basin crust, possibly in an 'off axis' setting.

Though most of the faults in the area show signs of Cenozoic re-activation, we suggest that the Peanut Fault originated as a detachment surface between the mantle and crustal sections of the ophiolite. When rotated back to their original position, many of the observed apparent reverse faults in the area also become extension faults. The major changes in thickness of the Wooded Peak Limestone may indicate that sedimentation was influenced by further normal faulting that continued after the magmatic phase ceased. The oblique extension indicated by the younger sheets might also explain the changes in character of the ophiolite belt along strike. Additionally, they may be a late response to the phase of tectonic erosion proposed by Tulloch et al. (2009).

SEQUENCE STRATIGRAPHY: A NEW APPROACH TO THE TAYLOR GROUP, BEACON SUPERGROUP, IN SOUTHERN VICTORIA LAND, ANTARCTICA

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Keywords: Devonian, Taylor Group, McMurdo sedimentary Basin, Transantarctic Mountains, sedimentary cycles

Poster

ABSTRACT

The Taylor Group forms the lower half of the Beacon Supergroup (Devonian to Triassic) and has a maximum thickness of 1200 m in southern Victoria Land. The sediments were deposited in the McMurdo sedimentary Basin that extended from the Fry Glacier (N) to the Shackleton Glacier (S) along the line of the Transantarctic Mountains. The basin developed early in the Devonian over deeply eroded Ross Orogen rocks. Study is hampered by the narrow and sometimes discontinuous outcrop. The succession has been divided into seven formations with a Devonian age for the Group based on sparse fossil material. Interpretations of depositional environments have varied from marine or marginal marine to fully fluvial and possibly aeolian. The principles of sequence stratigraphy allow the recognition of at least five cycles, each with an erosion surface at their base followed by coarse deposits. The basal unconformity (Kukri Erosion Surface) in the McMurdo Dry Valleys region has a rugged topography, and the succession shows a northward inundation of the Taylor Group basin, with maximum extent during deposition of the Beacon Heights Orthoquartzite. On New Mountain the base of the Taylor Group (Windy Gully Sandstone) progressively buries a block-mantled ridge of Granite Harbour Intrusives at least 30 m high. The Windy Gully Sandstone grades up into the Terra Cotta Siltstone, which thickens south (max. 80 m). The top of the siltstone is marked by deep, sand-filled cracks, and the suggestion of a poorly developed vein network indicates sub-aerial exposure. This is regarded as the end of the first sedimentary cycle. The succeeding New Mountain Sandstone, which is regionally more extensive than the Windy Gully Sandstone, is coarse and feldspathic at its base with layers of granules to small pebbles. It becomes more quartzose higher in the section, with densely bioturbated beds (Heimdallia). Desiccated horizons appear towards the top of the formation. The Heimdall Erosion surface cuts across the New Mountain Sandstone. This surface is remarkably flat and extensive, mantled by the coarse Odin Arkose Member at the base of the Altar Mountain Formation. Biscuit-like slabs of sandstone suggest that lithification of the New Mountain Sandstone had occurred during the period of exposure before the Heimdall Surface was cut, consistent with a fall in sea level. The lower part of the third cycle, Altar Mountain Formation, contains abundant Skolithos, and these are still present where the surface dies out southwards. Ripple-laminated siltstones (Handsley Beds) mark the end of the third sedimentary cycle. Parallel-bedded sandstones of the Arena Sandstone, in which a clay cement may indicate original feldspar, is characterised by the burrow Beaconites. It forms the fourth cycle. A locally developed conglomerate at the base of the Beacon Heights Orthoquartzite marks the beginning of the fifth cycle. This is the time of maximum extent of the Taylor Group, and the end of the cycle is placed at the top of the Aztec Siltstone. The latter formation contains root horizons in sandstone and in overbank silts, while interbedded coarse sandstones contain bioclasts of disarticulated fossils fish. Studies of the fish fossils indicate that the formation youngs from north to south.

EXTENSIONAL TECTONICS IN WESTERN ROSS SEA

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Oral

Keywords: *Western Ross Sea, Cenozoic, geophysics, rifting, basin evolution*

ABSTRACT

Our knowledge of the geological structure and evolution of the Ross Sea and its past environment is based on limited direct geological information supplemented by a broad coverage of geophysical data. The combined data sets have defined the major geological structures in the Ross Sea – the four major basins (Victoria Land (VLB), Northern (NB), and Eastern Basins and the Central Trough) and major faulting through the Ross Sea, although there is some uncertainty over the style and presence of the faulting. The western basins (VLB and NB) lie along the Transantarctic Mountains and appear to continue north into the oceanic Adare Basin (AB). Three major phases of rifting occurred: i) Mesozoic – Gondwana break-up and associated major extension and regional thinning with the initiation of Eastern Basin and Central Trough, but not the western Ross Sea basins; ii) Early to Mid-Cenozoic – the major focused rifting event that developed AB to VLB, the Central Trough, and western Eastern Basin; iii) Late Cenozoic to present – localised rifting, mostly vertical with little extension in Terror rift, Adare Basin reactivation, western Ross Sea volcanics, and prograding sedimentation to shelf edge. A total extension about 500 km occurred across Ross Sea. For the western basins, major rifting (extension) occurred from 45 Ma to 20 Ma for the Adare Basin (magnetic anomalies), 48 to 20 Ma for the offset of the VLB from NB based on the age of intrusives spatially associated with the Polar 3 anomaly, and > 39Ma to about 17 Ma for the VLB (oldest sediments). Post 20 Ma deformation is characterised by i) active high angle normal faulting in Adare Basin and Victoria Land Basin, ii) thick sediment infill in Victoria Land Basin, iii) subsidence in southwestern Adare Basin, and iv) volcanics erupted in western Ross Sea from Cape Adare to Cape Washington, in McMurdo Sound and in central Victoria Land Basin from Ross Island to Cape Washington (Terror Rift). Only minor extension occurred in AB and VLB since the Early Miocene, accompanied by mainly thermal subsidence.

SUBDUCTION AND EXTRUSION OF AUSTRALIAN CRUST AT THE BANDA ARC

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Oral

Keywords: *Banda Arc; Timor; extrusion*

ABSTRACT

The island of Timor in the outer Banda Arc lies within the converging plate boundary zone between the Australian Plate and the Banda Arc. The passive margin north of Australia presently impinges on the Banda Arc. Our structural studies of synorogenic basins in Timor using field and remote sensing techniques, together with published geochronological data, provide new structural and geomorphic evidence for syn-collisional extension that began before pronounced rapid uplift of Timor (Figure 1).

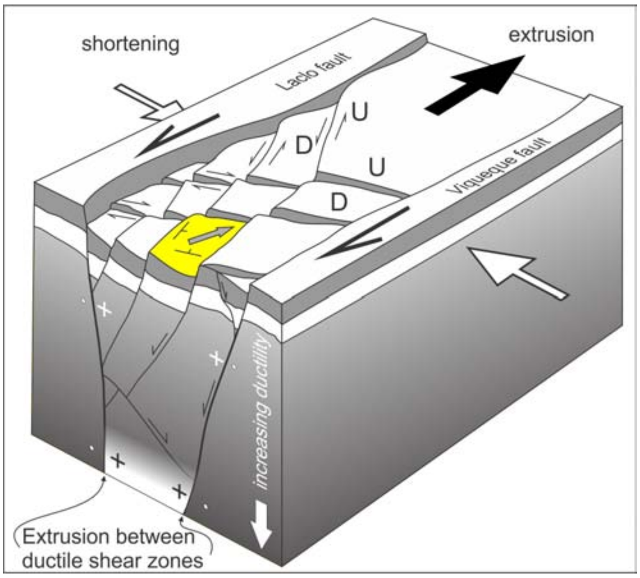

Figure 1: (Duffy et al., 2013) Block diagram showing cross-cutting Riedel shears dipping toward the parent faults, creating a series of fault-bounded blocks that are tilted in the extrusion direction. Brittle faulting at the surface is seated in ductile extrusion at depth.

Fault mapping and kinematic analysis identify a predominance of NW-SE oriented dextral-normal faults and NE-SW oriented sinistral-normal faults that collectively bound large (5–20 km2) bedrock massifs throughout the island. These fault systems intersect at non-Andersonian conjugate angles of approximately 120° and accommodate an estimated 20 km of NE-directed extension across the Timor orogen based on reconstructions of fault-dismembered massifs. Major orogen-parallel ENE-oriented faults on the northern and southern sides of Timor exhibit normal-sinistral and normal-dextral kinematics, respectively.

The overall pattern of deformation is one of lateral crustal extrusion sub-parallel to the Banda Arc (Figure 1). Stratigraphic relationships suggest that extrusion began prior to 5.5 Ma, prior to rapid uplift at ~3Ma. Our observations suggest that the extrusion resulted from collision of an outlying plateau that arrived south of the volcanic arc island of Wetar and was bounded by ocean crust to both west and east. The onset of extension was rapid and involved both the upper and lower plates. Doming of the fore arc above the thickened, buoyant, underplated continental plateau locally increased the coupling of the forearc and pulled it away from adjoining forearc crust, leading to arc-parallel extension in the upper plate. This resulted in supra-subduction zone volcanism due to spreading of the forearc. During continued shortening of the plateau, the middle and lower crust of the lower plate extruded toward the plateau margins, which were less constrained due to subduction of adjoining oceanic crust.

The deformation structures that we document suggest that both upper and lower plate deformation during incipient island arc-continent collision was largely controlled by the geometry and topography of a continental terrace on the Australian plate.

REFERENCES

Duffy, B., Quigley, M.C., Ring, U., 2013. Arc-parallel extrusion of the Timor sector of the Banda arc-continent collision. Tectonics 32, 641-660.

ZIRCONS FROM PERMIAN AND TRIASSIC STRATA ON THE ROSS EMBAYMENT FLANK OF THE CENTRAL TRANSANTARCTIC MOUNTAINS AND FROM WEST ANTARCTICA

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Oral

Keywords: *Antarctica, Permian, Triassic, zircon. geochronology*

ABSTRACT

Gondwana sequence rocks of Permian and Triassic age crop out principally in the Ross Sea sector of the Transantarctic Mountains, but also in scattered localities that include the Amery Ice Shelf region, the Weddell Sea sector, the Ellsworth Mountains, and eastern Ellsworth Land (Erewhon Nunatak). In contrast to the Permian strata, Triassic strata are confined to the Ross Sea sector and the Amery Ice shelf region. Detrital zircons from sandstones cropping out in the central Transantarctic Mountains (CTM) and Erewhon Nunatak, and from tuffs in the Ellsworth Mountains, have been analyzed by SHRIMP for U/Pb geochronology. In CTM the Permian-Triassic Victoria Group forms the most complete Antarctic Gondwana sequence. The depositional setting evolved in early to mid-Permian time from a rift basin to a foreland basin in which the sediment fill was derived from the craton beneath the East Antarctic Ice Sheet on one flank and West Antarctica on the other flank. CTM samples analyzed come from the West Antarctic flank of the basin. Paleocurrent data for lower Permian beds (Mackellar and Fairchild formations) indicate predominant longitudinal flow to the SE. The Buckley Formation marks the inception of the foreland basin, and in the Shackleton Glacier region paleoflow was directly off West Antarctica.

Quartzose sandstones from the Fairchild and lower Buckley formations (CTM), which pre-date the major change in provenance, have detrital zircon age distributions indicating a principal input of grains in the age range of the Ross Orogen (600-500 Ma), a trace component of Grenville-age (ca. 1.0 Ga), and a scattering of older Proterozoic ages. Zircons from the lowest volcaniclastic beds in the upper Buckley Formation and the Mt. Glossopteris Formation (Ohio Range) are dominated by Permian grains with a significant age group in the range 270-260 Ma. These sandstones collectively include Carboniferous, Devonian, and Ross-age grains as well. The influx of volcaniclastic debris and Permian zircon grains marks the first stratigraphic record of the magmatic arc along the Panthalassan margin. This event is also recorded at Erewhon Nunatak where zircons from a sandstone are principally Carboniferous and late Permian in age, but with a scattering of older ages. The Permian arc is more directly recorded by two tuff beds from the Polarstar Formation, Ellsworth Mountains, which have dominant age groupings around 260 Ma.

A quartzose sandstone in the lower Fremouw Formation (CTM) is dominated by Ross-age zircons, although with a trace of Permian, Carboniferous, and Archean grains. In the middle and upper Fremouw Formation the sandstones have a significant component of Triassic-age zircons together with Carboniferous and Devonian grains, and a scattering of older grains which include Silurian and Ross Orogen ages. A sandstone from the upper Falla Formation (CTM) has zircons mainly of Triassic age, but with a minor Ross-age component and a trace of Grenville-age grains.

The magmatic arc, recognized in igneous and metamorphic rocks in West Antarctica, was probably initiated in the late Carboniferous and was active through much of the Permian and Triassic. The influx of detrital zircons, with ages spanning the Permian, into upper Buckley and equivalent strata suggests that earlier in time detrital zircons were trapped in a more proximal basin but were recycled later as a result of tectonism that initiated the flood of volcaniclastic detritus. Paleocurrent data from the Shackleton Glacier region (CTM) show clear derivation of detrital sediment from West Antarctica in the upper Buckley Formation and the overlying Fremouw Formation. This is not the case for the Falla Formation but nevertheless there remained a major magmatic arc input.

Carboniferous and Devonian zircon grains were derived from the Gondwana active margin but the occurrence of Ross- and Grenville-age grains in sediment derived from West Antarctica suggests that sources of those ages existed during Permian and Triassic time. These zircons might have been derived by recycling out of the Swanson Formation in Marie Byrd Land or its extension subglacially into West Antarctica, or by recycling out of Devonian beds that were uplifted and eroded along an inferred fold and thrust belt in the hinterland of the arc, or by erosion of no longer exposed Ross Orogen and Grenville-age basement rocks in West Antarctica.

DEFORMATION OF THE TOP BASEMENT UNCONFORMITY WEST OF THE ALPINE FAULT (SOUTH ISLAND, NEW ZEALAND): IMPLICATIONS FOR SEISMIC HAZARD FROM INHERITED FAULT STRUCTURE

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Keywords: *basement, faults, compressional inversion, seismic hazard, West Coast, South Island, New Zealand*

Oral

ABSTRACT

Geometry and kinematics of inherited and newly-forming faults in relation to regional stress fields govern energy release from intracontinental earthquakes. Larger earthquakes nucleate towards the base of the seismogenic crust (depths of 10-20 km in continental crust) and require large, through-going fault systems rupturing across crystalline basement units which have a long history of superposed deformation giving rise to strong compositional and mechanical heterogeneities. Fault complexity within basement rocks, and the impossibility of direct structural observations, account for many undetected seismic sources that only become apparent after rupture (e.g. 2010-2011 Canterbury earthquake sequence). Hazard maps of active faulting generally rely on deformation of Holocene and Late Pleistocene markers, but may fail to illuminate the fault fabric at earthquake focal depths, especially in regions where the structural continuity of fault systems is obscured by cover sequences, and large seismic events recur over time periods of 103 to 104 years.

We analyse the Top Basement Unconformity (TBU) in the West Coast region of the South Island of New Zealand to highlight fault architecture within the seismogenic domain, and define the extent, geometry and mechanisms of basement-penetrating discontinuities that can potentially be reactivated in the present stress field.

Construction of a closely-spaced set of regional cross sections incorporating surface geology, seismic reflection profiles offshore, data from stratigraphic sections and exploration wells allow the 3D reconstruction of the Top Basement Unconformity (TBU) within the Australian plate crust, west of the Alpine Fault. In a large part of the region the TBU was formed as a low relief and low elevation composite and diachronous surface providing a regional marker for finite deformation. Intense shortening of the TBU onshore (with tectonic relief of several km between antiformal basement pop-ups > 4 km a.s.l. and synformal depressions 5-7 km b.s.l.) is in sharp contrast with a flatter topography and low elevation offshore (-2000 m b.s.l. on average). This geometry arises from the compressional inversion (since the mid Miocene) of sets of N-S to NNE-SSW conjugate normal faults developed during Late Cretaceous to Eocene extension (Bishop and Buchanan, 1995; Ghisetti and Sibson, 2006), with an outer deformation front currently located along the Cape Foulwind-Kahurangi Fault. Some faults already breached the TBU during the extensional phases, whereas others propagated from deeper levels of the basement, through splays that control folding of the TBU and overlying sedimentary cover. Most faults in the uppermost 5 km dip 50º-60º, have caused large vertical separations of the TBU, and contain segments of historically active seismic faults, though their moderate to steep dips do not make them particularly well oriented for reactivation as pure reverse faults in the present tectonic regime. Currently active faults likely comprise sets of low-angle, blind thrust faults at the base of the seismogenic crust, that propagate upsection by exploiting the pre-existing extensional fabric in the basement, thereby imparting a complex short wavelength undulation of the TBU in the upper crust (Fig. 1).

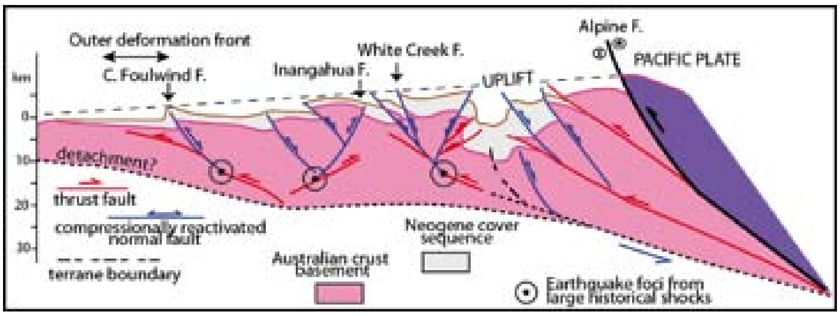

Figure 1: Schematic cross section that illustrates the relationship between moderately to steeply-dipping sets of conjugate inverted normal faults and low-angle thrust faults that remain blind within the basement.

Our analysis favours a scenario where a regional set of inherited, basement faults has been persistently reactivated since the mid Miocene, imparting a strong northerly trending fault fabric in the Australian plate crust west of the Alpine Fault. Deformation of the TBU should be incorporated into hazard models, given the large number of potentially active faults that penetrate to the depth of earthquake nucleation and the localised shortening that appears to mark the coastal transition belt between the emergent compressional orogen and the western areas offshore.

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ZIRCON AND MONAZITE U-Th-Pb, REE, O AND Hf SIGNATURES IN WESTERN PROVINCE GNEISSES

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Keywords: *Zircon, monazite, U-Th-Pb, REE, oxygen, hafnium, paragneiss, orthogneiss, Western Province, Zealandia*

Oral

ABSTRACT

Zircon and monazite from Western Province paragneiss and orthogneiss units, mostly located within the Fraser and Granite Hill Complexes of Westland, were analysed for U-Th-Pb geochronology to constrain the ages of protolith rocks and metamorphic overprints (Hiess et al. 2010). This was followed by the determination of zircon rare earth element (REE) concentrations, oxygen and hafnium isotopic compositions. Experiments performed in situ using a sensitive high-resolution ion microprobe (SHRIMP) and laser ablation multi-collector inductively coupled plasma mass spectrometer (LA-MC-ICPMS) allow better understanding of crustal growth on the Zealandia margin of Gondwana from the micron scale.

Paragneiss zircons were likely sourced from widespread regional Greenland Group meta-sedimentary rocks of the Buller Terrane based on their typical 'Gondwana' age spectra. Detrital grains record variable REE patterns relating to magmatic and metamorphic crystallisation processes operating prior to and following Ordovician deposition. δ18O and δHf(T) values trace major phases of juvenile crust formation and subsequent reworking in provenance sources, signifying an increase in the recycling of compositionally diverse, evolved crustal materials through time.

Orthogneiss zircons relate to two intense episodes of magmatism that record similar REE concentrations. Devonian samples have elevated δ18O and un-radiogenic δHf(T), Cretaceous samples record more primitive δ18O and radiogenic δHf(T). Both orthogneiss suites can be explained by thorough mixing of mantle-derived magmas with Greenland Group rocks. The relative proportion of crustal contamination being ~20-50 % for the Devonian and ~10-40 % for the Cretaceous. Orthogneiss protolith materials were largely hybridised prior to and during zircon crystallisation, suggesting plutonic assembly over limited structural levels.

Both paragneiss and orthogneiss monazite are dominated by Devonian and Cretaceous ages, reflecting thermal pulses related to regional and localised granitoid intrusions. These results demonstrate the ability of zircon to retain detailed petrogenetic information through amphibolite-facies metamorphism with excellent fidelity.

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PALAEOENVIRONMENTAL CHANGES DURING THE TRANSITION FROM AN ICEHOUSE WORLD TO A GREENHOUSE WORLD: END PERMO-CARBONIFEROUS GLACIATION IN THE FALKLAND ISLANDS

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Keywords: *Hell's Kitchen Member, sedimentology, orbital forcing*

Poster

ABSTRACT

The medium term glacial and interglacial cycles that we observe in ice core records and marine sedimentary cores are in fact superimposed on longer term climate fluctuations. Conditions on the Earth alternate between an Icehouse World where we have persistent polar ice and a Greenhouse World without. With the current focus on climate change and many questions about the long term future of our climate one of the questions is how such major changes in climate occur.

This project looked at the last Icehouse Greenhouse transition at the end of the Permo-Carboniferous glaciation. The glaciation lasted nearly 100 million years and affected the whole of the Southern Hemisphere. It ended during the early Permian and was followed by the Greenhouse World of the early Mesozoic.

In order to investigate this Icehouse/Greenhouse transition, core material was collected from the Permo-Carboniferous Fitzroy Tillite and Port Sussex formations of the Falkland Islands. These islands would have been at relatively high latitudes within the Gondwanan supercontinent at this time and the cores preserve glacial diamictite passing into black mudstone up-section via a finely laminated transition unit called the Hell's Kitchen Member.

Detailed sedimentary logging of two core sections, DD090 and DD029, suggest a switch from deposition under a grounded ice sheet to glacio-lacustrine/marine deposition. The transitional Hell's Kitchen Member represents minor episodes of ice advance and retreat during a period of net ice retreat. Deposition was preserved in a depression formed by the weight of the ice-sheet, later filled by glacial meltwater to create a large inland lake bounded by the mountains of the Gondwanian orogeny. The floor of the lake would have rebounded post-glacially during the mid Permian giving rise to the terrestrial environment of the Late Permian.

XRF and reflectance data were collected from both cores using an in situ XRF core scanner. Cyclicity found within this data, combined with broad scale variation in clast size and density, suggest that the transition from Icehouse to Greenhouse took place over a series of climatic oscillations possibly related to orbital forcing. Wavelet and spectral analyses were run to identify prominent periodicities and then compared to possible Milankovitch eccentricity and obliquity rhythms during the glacial retreat. The clast data, in particular, shows two major cycles and when combined with dominant peaks in the wavelet analysis at 100kyr and 400kyr gives an estimate of 1.2 Ma for the transition from Icehouse to Greenhouse in the Falklands. This is the first time anyone has looked at the potential for orbital forcing in these deposits and the results are really exciting.

ROSS-DELAMERIAN OROGEN GRANITOIDS IN FIORDLAND, NEW ZEALAND

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Keywords: *Ross-Delamerian Orogen, Jaquiery Granitoid Gneiss, Pandora Orthogneiss, Fiordland*

Oral

ABSTRACT

Recent mapping and U-Pb zircon dating for QMAP Fiordland has discovered the presence of two Cambro-Ordovician granitoid plutons: the Jaquiery Granitoid Gneiss and the Pandora Orthogneiss (Allibone 2009a,b; Turnbull et al. 2010). These plutons strengthen the previous suggestion that an intrusive element of the Ross-Delamerian Orogeny is present in the New Zealand basement (Gibson & Ireland 1996). The discovery of these plutons has previously been presented at the 2009 New Zealand Geological Society conference but is re-presented at this symposium because of its relevance to Gondwana geology.

The Jaquiery Granitoid Gneiss crops out in the headwaters of Jaquiery and Florence streams and in the Townley Mountains of central Fiordland. First recognised by N. Powell's PhD mapping, this unit is a strongly foliated, fine to medium grained granodiorite or tonalite gneiss. In some parts, evidence of igneous textures is preserved, but much of the gneiss is completely recrystallised to a polygonal mosaic of grains. U-Pb TIMS zircon geochronology indicates an emplacement age of c. 493 Ma (Ramezani & Tulloch 2009). Transposed dikes of the Jaquiery Granitoid Gneiss intrude mafic metavolcanic rocks adjacent to pluton margins. These metavolcanic rocks form part of a conformable metasedimentary sequence from which a psammitic sample in the Jaquiery Stream catchment has yielded a youngest detrital zircon population age of 501 ± 10 Ma (Scott et al. 2009). This age, and the intrusive relationship with the Jaquiery Granitoid Gneiss, implies the metasedimentary sequence was deposited in the Middle to Late Cambrian.

The Pandora Orthogneiss is a body of variably foliated heterogeneous tonalite, granodiorite, and monzogranite orthogneiss outcropping between Thompson and Nancy sounds of western Fiordland. The orthogneiss is generally well foliated, but retains obvious relict igneous textures in some outcrops. U-Pb TIMS zircon geochronology indicates an emplacement age of >454 Ma, possibly at ~504 Ma (Ramezani & Tulloch 2009). Transposed dikelets of the orthogneiss intrude the adjacent metasediments, confirming an intrusive relationship, and implying these metasedimentary rocks are no younger than Ordovician in age.

These Cambro-Ordovician intrusions imply a general correlation with granitoid intrusions in the Ross-Delamerian Orogen of the Transantarctic Mountains and South Australia. Granitoid intrusions of this age are not observed in the Takaka terrane of northwest Nelson, nor in its probable nearest correlative, the Bowers terrane of Northern Victoria Land. They do, however, intrude west of the Bowers terrane, within the Wilson terrane, where metasedimentary rocks in the eastern portion appear similar in character to those seen in central and western Fiordland.

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ZEALANDIA AND ITS ENVIRONS

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Keywords: *New Zealand, Zealandia, Gondwana, continental crust, oceanic crust, tectonic history*

Oral

ABSTRACT

Zealandia is a submerged continent in the southwest Pacific Ocean. It has an area of some 4.9 million km2 or about one third that of the Australian continent. Only 6% of the continental crust is presently emergent.

The Cambrian to Early Cretaceous basement of Zealandia comprises batholiths and terranes that are the products of episodic subduction. At about 105 Ma long-lived subduction ceased and was replaced by a period of widespread extension (Bradshaw, 1989; Luyendyk, 1995). Explanations of why convergence stopped include subduction or stalling of a spreading ridge, or collision of the Hikurangi Plateau. Prior to the 85-105 Ma rifting that thinned and widened the Gondwana margin crust, what eventually became Zealandia was a narrow strip along the edge of southern Gondwana (Figure 1). Orogenic belts can be traced from Antarctica through Zealandia to Australia (e.g. Pankhurst et al. 1998).

Since the late 1990s, the availability of satellite-derived gravity and bathymetric maps, along with marine expeditions east of Zealandia, have shed useful light on the offshore Cretaceous geology (e.g. Mortimer et al. 2006). Although the timing of Hikurangi Plateau collision remains frustratingly imprecise, a c. 105 Ma collision is more plausible than earlier or later options. The Hikurangi Plateau seems to have controlled the configuration of local Late Cretaceous oceanic microplates and of Zealandia-West Antarctic breakup.

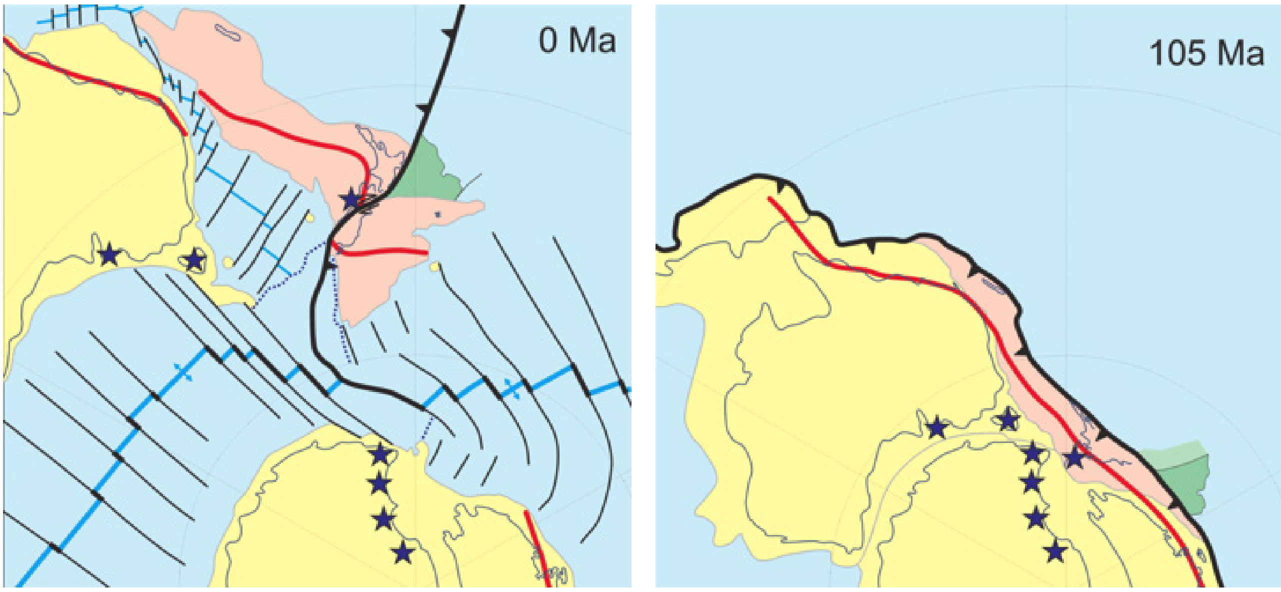

Figure 1: Zealandia (pink) and Hikurangi Plateau (green) in their present configuration and at the end of the main Mesozoic subduction (East Antarctica fixed). Australian and Antarctic continental crust is yellow, Median Batholith shown by red line, Ferrar Dolerite by stars.

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THE GONDWANA CONNECTIONS OF NORTHERN PATAGONIA

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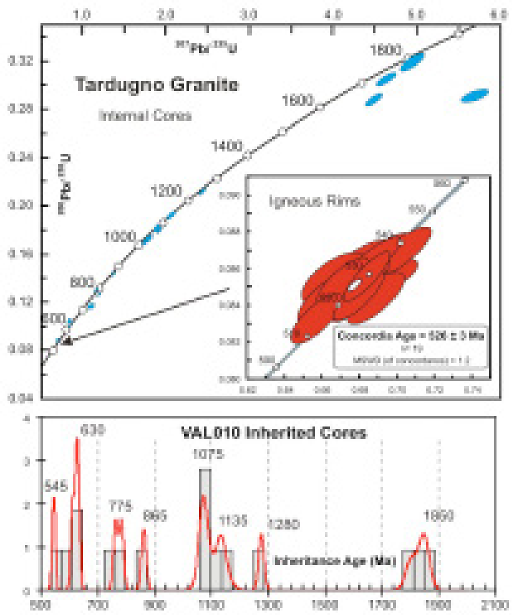
Oral

Keywords: *Patagonia, Gondwana, terranes, U-Pb dating, subduction-related magmatism, Paleozoic*

ABSTRACT

A multidisciplinary study (U-Pb SHRIMP geochronology, Hf and O isotopes in zircon, Sr and Nd isotopes in whole-rocks, as well as major and trace element geochemistry) has been carried out on granitoid samples from the area west of Valcheta, North Patagonian Massif, Argentina. These confirm the Cambrian age of the Tardugno Granodiorite (528 ± 4 Ma) and the Late Permian age of granites in the central part of the Yaminué complex (250 Ma). There is no evidence for a Carboniferous or early Permian pre-collisional magmatic arc in northern Patagonia. Together with petrological and structural information for the area, we consider the possibility that the Cambrian and Ordovician granites of northeastern Patagonia represent continuation of the Pampean and Famatinian orogenic belts of the Sierras Pampeanas, respectively. The arguments for and against the hypothesis that Patagonia was accreted in Late Palaeozoic times as a far-travelled terrane, originating in the Central Transantarctic Mountains, are reviewed. A para-autochthonous origin is preferred with no major ocean closure between the North Patagonian Massif and the Sierra de la Ventana fold belt.



THE 2010-2012 CANTERBURY EARTHQUAKE SEQUENCE: *WHAT'S HAPPENING BENEATH OUR FEET?*

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ABSTRACT

The 2010-2012 Canterbury Earthquake Sequence commenced with the Magnitude 7.1 Darfield Earthquake of 4 September 2010, with epicentral location some 40km west of Christchurch city. The complex fault rupture formed a mesh included at least eight separate fault segments. The main E-W trending dextral strike-slip Greendale fault formed a complex surface rupture trace, with a maximum recorded surface offset in excess of 5 metres, and extending for approximately 30 kilometres. Overall the 2010-2012 earthquake sequence includes six main earthquakes (4 September 2010 (Mw 7.1), 22 February 2011 (Mw 6.2), 13 June 2011 (Mw 5.8 and 6.0) and 23 December 2011 (Mw 5.8 and 5.9), and more than 12,000 aftershocks, 55 of which have been greater than Mw 5.0. Each main shock event triggered a re-energized period of aftershock activity. The sequence commenced west of Christchurch, while subsequent main shock and aftershock activity progressively migrated eastward beneath and immediately adjacent to the city over an extended period of time, finally reaching into the offshore region of Pegasus Bay.

Limited geomorphic and geological evidence in and around Christchurch city indicates this earthquake sequence is a very rare occurrence, with return times ranging from at least several thousands of years to perhaps tens of thousands of years. We acquired approximately 41 line-km of high-fold reflection seismic data in and around Christchurch following the devastating 22nd February 2011 event. The recording system used was the 600-channel Aram Aries system and EnviroVibe belonging to the Department of Geoscience at the University of Calgary. The goal of the seismic survey was to map previously unknown faults in and around the city for hazard assessment and to assist in the post-earthquake recovery effort. Seismic reflection data were collected along six 2D lines, two of which were within the Christchurch metropolitan area and four were in rural areas west of the city. Recording conditions were challenging within the city, but good quality reflection data were obtained along all of the seismic lines, with events interpretable to a depth of approximately 1.5 km. Numerous previously unknown faults were imaged along the lines and these were interpreted in two groups – older faults that show clear offsets in deep (> 1 km) reflections and younger faults that show displacement in shallow reflections. Some faults in the latter group were interpreted to be directly associated with hypocentres of shallow aftershocks in the region.

Impacts in Christchurch city include tectonic subsidence that has affected suburbs within the Avon River catchment, especially in eastern Christchurch, and co-seismic tectonic uplift that has occurred in suburbs within the Heathcote River catchment and the Port Hills suburbs located to the south side of the city.

The four main earthquakes triggered widespread and repeated sediment liquefaction and lateral spreading throughout the region, but the severity varied greatly both spatially and temporally. More than 7,500 properties in the eastern suburbs of Christchurch located adjacent to the Avon River have subsequently been red zoned because of the severe damage to dwellings and infrastructure, and the land is to be cleared and turned into a greenbelt extending from the CBD to Brighton along the coast. Extensive rockfall, boulder roll and landsliding occurred around the Port Hills area, with hillslope suburbs, including Lyttelton, significantly impacted. More than 500 properties were red zoned.

In terms of the tectonic and structural setting of the 2010-12 Canterbury earthquake sequence, the region is situated on the eastern "feather edge" of the active obliquely convergent plate boundary zone. Structural deformation across the Canterbury region is characterized by a south-easterly advancing, repetitive structural pattern dominated by the propagation of northeast-striking thrust assemblages. This pattern is in turn regularly segmented by east-west striking faults inherited from reactivated Cretaceous normal faults. The more evolved and deeply exposed structures in the foothills of north Canterbury provide insights into the tectonic processes of the blind structures now emerging from under the northern and eastern Canterbury Plains, where thrust and strike-slip fault activity are closely linked. The east-west striking faults separate relative motion between thrust segments and accommodate oblique transpressive shear. Early stages of thrust emergence are dominated by anticlinal growth and blind, or partially buried, thrusts and backthrusts. The east-west striking transecting faults therefore record timing of coseismic episodes of uplift and shortening with variable horizontal to vertical ratios and displacement rates on the hidden adjacent thrusts. The Greendale and blind Port Hills faults that ruptured as part of the 2010-2012 earthquake sequence, with their associated aftershock patterns over the extended period of seismicity, are compatible with this style.

A 'NEW' CORE COMPLEX ALONG THE WEST COAST, SOUTH ISLAND

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Oral

Keywords: *Metamorphic Core Complex, Paparoa Core Complex, Pororari Group, Tectonics, West Coast Region, New Zealand*

ABSTRACT

Recent mapping of coastal outcrop north of the Mokihinui River has revealed a sequence of lithologies reminiscent of a metamorphic core complex. From south to north, coastal exposures proceed from protomylonite (foliation dips ~10° to the north), fault breccia, sedimentary breccia (all three unnamed), and undeformed granites (Karamea Suite). To explain the juxtaposition of these metamorphic, sedimentary and igneous lithologies, I invoke a northward-dipping detachment fault intersecting the modern coast just north of Gentle Annie Point. Tulloch and Kimbrough (1989) suggested that a south-dipping detachment fault may be located south of the Mokihinui River based on the juxtaposition of the undeformed Brittania Granite and Constant Gneiss. Situated between these deformed and undeformed basement rocks lies the Torea Rocks, reinterpreted by Bradshaw (1988) as a fault breccia. This sequence of plastic, brittle and undeformed lithologies is consistent with that observed to the north and a detachment fault-related origin. The framework of a core complex not only encompasses the coastal features discussed above, but may also explain the position of the Beeby's Conglomerate located near Lake Rotoiti. The Beebys Conglomerate is an isolated sliver of the Pororari Group (c.f. Laird, 1995), a succession typically associated with a similar style of late Cretaceous faulting within the Paparoa Core Complex. Albeit much thicker and more lithologically varied, Beebys Conglomerate contains units similar in appearance to the sedimentary breccia presented in this study, however, further investigation is necessary to establish whether it would be correct to include the sedimentary breccia north of the Mokihinui River within the Pororari Group. The small size of this core complex relative to the Paparoa Core Complex may reflect diminishing accommodation along more northerly detachment faults during New Zealand's early extensional history.

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THE TECTONIC EVOLUTION OF THE GREY VALLEY TROUGH

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Poster

Keywords: *Grey Valley Trough, Alpine Fault, Tectonics*

ABSTRACT

Towards the end of the 19th century, Oil was found to be seeping out of the ground near Kotuku, North of lake Brunner. Since this discovery, petroleum companies have taken great interest in revealing the subsurface structure of the basin in order to discover economic oil reservoirs. Thanks to the large volume of pre-existing seismic and borehole data collected, we gain a detailed view of how a section of the Australian crust has responded to the transpressional plate boundary evolving directly adjacent to it. This study integrates surface mapping, borehole, seismic, and newly released aerial geophysics data using the 3D kinematic structural geology modelling software MOVE. The result provides insights into the full temporal record of the plate boundary since its inception, something that is poorly understood for the greater West Coast region. Specific findings suggest that early in the Alpine Fault's evolution, a much broader scale of serial partitioning (thrust/strike-slip segments 5-10 km long) developed, with deformation becoming localised to its present fault trace in the time since.

EVOLUTION OF THE LIMON VERDE METAMORPHIC COMPLEX, CHILE DURING THE LATE PALEOZOIC

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Oral

Keywords: *Metamorphism, western Gondwana, PTt path, pseudosection, PerpleX*

ABSTRACT

The building of the Andes Cordillera is based upon collision and collapse of terranes, plus the contribution of magmatic arcs. Particularly, the study of metamorphic complexes and their associated igneous rocks helps to understand the tectonic evolution of the area. The current research thoroughly studies the Limon Verde Metamorphic Complex (LVMC), in the Antofagasta Region, Chile. The LVMC comprises garnet-mica schists, amphibolites, and subordinated quartzites. Whole rock geochemistry analyses of the metamorphic rocks show a protolith with within-plate basalt affinity for the amphibolites, and a psamopelitic protolith for the mica schists; the latter, supported also by the appearance of detrital zircon with different provenance. Zircon U-Pb detrital ages indicate a maximum depositional age of ca. 300 Ma coeval to late stage magmatism of the Limón Verde Igneous Complex (LVIC).

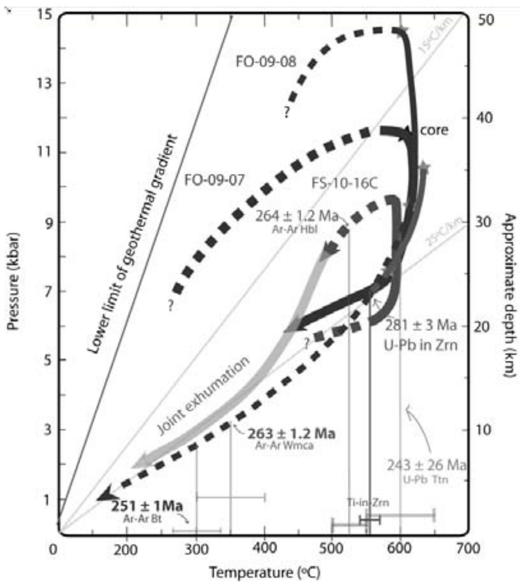

Figure 1: Multi-method approach and forward modeling of pressure-temperature-time paths of the Limon Verde Metamorphic Complex, Chile.

Core-to-rim analyses in garnet from the mica-schist unit indicate a clockwise path of metamorphism reaching a peak at 14.5 kbar, ca. 600 ºC (Figure 1): interpreted to be a depth of formation of 50 km in a cool geothermal gradient regime, consistent with that of a subduction zone. Similarly, the amphibolites show clockwise and anticlockwise paths of metamorphism, with a comparable temperature than the mica-schist, but maximum pressure of formation to be lower (11.5 kbar). The age of peak metamorphism was determined at ca. 280 Ma based upon U-Pb zircon rim ages, whereas the time of metamorphism of the amphibolites was determined at ca. 260 Ma based on hornblende Ar-Ar ages.

Step heating Ar-Ar dates of white mica (ca. 263 Ma) and biotite (ca. 251 Ma) from the mica schist were used to determine cooling rates, where two steps were determined: 11.4 ± 3.47 ºC/My for the first step (U-Pb in zircon to Ar-Ar in white mica) and 4.16 ± 5.03 ºC/My for a second (Ar-Ar in white mica to Ar-Ar in biotite).

A cool geothermal gradient was found during the beginning of metamorphism and reaching to the maximum pressure found. Then, later stages of metamorphism consider a higher geothermal gradient up to 25 ºC/km (normal crust setting); gradient which is also considered during the time of exhumation. Thus the estimated exhumation rates are 0.45 mm/yr and 0.16 mm/yr for the first and second step respectively. When taking into account the blocking temperatures of the above mentioned systems and a normal crust geothermal gradient, then a fast exhumation mechanism, such as the collision of a continental block is proposed.

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A BURST FOOTBALL THEORY FOR GONDWANA BREAKUP

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Oral

Keywords: *Football, Large Igneous Provinces, continental flood basalts, oceanic plateaus*

ABSTRACT

Earth history is punctuated by events during which large volumes of predominantly mafic magmas were generated and emplaced by processes that appear to be and are generally accepted as being unrelated to "normal" sea-floor spreading and subduction processes. These Large Igneous Provinces (LIPs) are best preserved in the Mesozoic and Cenozoic where they occur as continental flood basalts, giant dyke swarms, volcanic rifted margins, oceanic plateaus, ocean basin flood basalts, submarine ridges, and seamount chains. The Mesozoic history of Antarctica is no exception, in that a number of different igneous provinces were emplaced during the initial breakup and continued disintegration of Gondwana leading to the isolation of Antarctica in a polar position. The link between the emplacement of the igneous rocks and continental breakup processes remains controversial. This presentation explores the linkages between the emplacement of large igneous provinces in Antarctica, the isolation of Antarctica from other Gondwana continents, and different break up mechanisms.

THE ROLE OF THE TRINITY PENINSULA GROUP IN WEST GONDWANA: NEW DATA FROM CORONATION ISLAND, SOUTH ORKNEY ISLANDS

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Poster

Keywords: *Trinity Peninsula Group, South Orkney Islands, U-Pb dating of zircon, Geothermobarometry*

ABSTRACT

The Trinity Peninsula Group (TPG) and correlatives is essentially composed of metaturbidites of Late Paleozoic to Early Jurassic age that crop out on the Antarctic Peninsula, and on the South Shetland and South Orkney islands. The tectonic setting and evolution of the TPG were studied by several scientists, among which John Bradshaw played a prominent role (e.g. Bradshaw et al., 2012). We present data that refer to the tectonic setting of the Greywacke-Shale Formation from the South Orkney Islands, considered to be a correlative of the TPG. Trouw et al. (1997a) mapped on Powell Island a gradual transition between the Greywacke Shale Formation and metamorphic rocks, formerly described as the Scotia Metamorphic Complex. This means that the metamorphic rocks of Powell Island and by extrapolation also the ones on Coronation and Signy islands, can be understood as Greywacke-Shale Formation transformed by progressive metamorphism. Apart from the difference in metamorphic grade there is also a difference in protolith composition; on Coronation Island mafic intercalations (amphibolites) are abundant, whereas these are practically absent in the Greywacke-Shale Formation.
In order to test the hypothesis that Coronation Island is underlain by rocks correlative to the TPG, the source rocks for sedimentation were studied by dating (U-Pb) of detrital zircon grains. The result of the obtained ages (Valadares, 2012) shows two groups, one in the interval 550-350 Ma (Cambrian to Lower Carboniferous) and the other one 290-200 Ma (Permo-Triassic). The same pattern is observed in ages of detrital grains of a sample of metasandstone of the Greywacke Shale Formation from Laurie Island (Harabari, in preparation). This reveals that the period of sedimentation of these rocks is confined between 200 Ma (the youngest detrital zircon grain) and ca. 170 Ma, the age of the Spence Harbour Conglomerate, deposited unconformably on top of the metamorphic rocks. Deformation and metamorphism are also confined to this time span. The result shows also a remarkable similarity between the ages of the first group and detrital zircon ages reported from the TPG at View Point, in the interval 487-373 Ma (Bradshaw et al., 2012), demonstrating at least in part a common source area. The metamorphism was studied by mineral chemistry combined with geothermobarometry. The best calculated P-T conditions are: pressure of 4-8 kbar and temperature of 621°±18°C in mafic rocks and 564°±18°C in metasedimentary rocks (Valadares, 2012). P-T calculations using core compositions of grains result in similar temperatures, but with pressures in the range 13 to 16 kbar, although involving large uncertainties. These results show that the metamorphism was subduction related, probably in an accretionary prism tectonic setting. Similar results were reported for the metamorphism on Powell Island (Trouw et al., 1997a) and for the lower grade metamorphism of the TPG at Cape Legoupil (Trouw et al., 1997b). It may be concluded that the TPG started to be deposited in late Paleozoic times on a continental slope (Bradshaw et al., 2012), probably in a passive margin tectonic setting. At the end of the Triassic and/or in the Lower Jurassic subduction started. It deformed and locally metamorphosed the more distal parts that were localized in or close to the trench containing more oceanic components (Coronation and Powell islands). At the end of the Lower Jurassic deformation ceased, the TPG was uplifted and eroded and the Botany Bay Group, Spence Harbour and Powell Island conglomerates were deposited unconformably on top. At Livingston Island, South Shetland Islands, this sequence of events may have occurred diachronically until the Middle to Late Jurassic when the magmatic arc resulting from subduction was in full development on the Antarctic Peninsula.

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THE MESOZOIC SOUTHEAST GONDWANA ARC

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ORAL

Keywords: *Mesozoic, Gondwana, arc, geochronology, Median Batholith, Whitsunday Volcanics, Campbell Plateau*

ABSTRACT

The New Zealand segment of the Mesozoic convergent margin, extending 7000 km from Papua New Guinea via Queensland and New Zealand to West Antarctica, is the only location where arc (Median Batholith), forearc basin and accretionary prism are all preserved and exposed. The Median Batholith also contains one of the deepest exposed arc roots anywhere (65 km in Fiordland; De Paoli, 2009).

The Median Batholith ranges in age from 230 to 105 Ma and is largely comprised of two margin parallel belts. The outboard (Pacificward) belt of 230-135 Ma plutons consists of typical low Sr/Y (LoSY) plutonic and volcanic suites. The inboard belt consists of 131-105 Ma, high Sr/Y (HiSY), TTG-like sodic plutons that dominate the deepest exposed levels (Muir et al. 1998). There is a prominent age gap at c. 135 Ma. Zircon U-Pb and garnet Sm-Nd geochronology indicate that thickening and granulite facies metamorphism closely followed HiSY magmatism in Fiordland (Stowell et al. 2010). Minor but widespread A-type and peralkaline granites may indicate discrete intra-arc extensional episodes. Compositional proportions are HiSY = LoSY >> A-type.

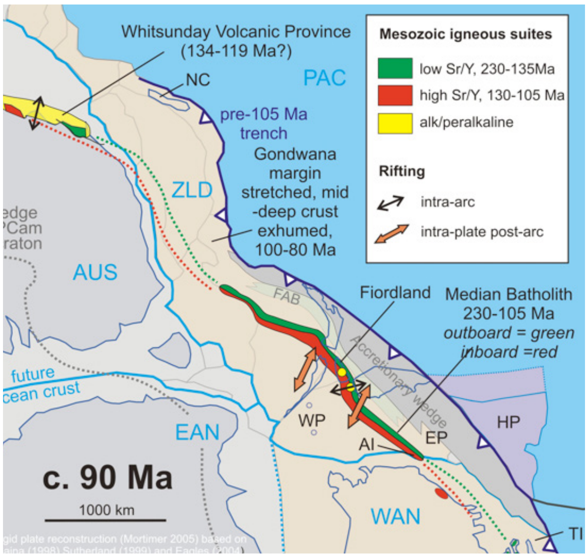

Figure 1: Reconstruction of the Southeast Gondwana margin and Mesozoic subduction-related magmatism. NC New Caledonia, WP, EP Western and Eastern Provinces, AI Antipodes Island, TI, Thurston Island, HP Hikurangi Plateau.

The Whitsunday Volcanic Province of Queensland has previously been interpreted as intra-plate magmatism associated with formation of the Tasman Sea (Bryan et al 1997). However, age and geochemical similarities (Tulloch et al. 2010) indicate that these rocks more likely represent a NW extension of the Median Batholith along the Lord Howe Rise, as suggested by Wandres and Bradshaw (2005). Significant differences include an older minimum age of magmatism (c.120 Ma), a predominance of extrusive rocks, and A-type >> LoSY = HiSY in Australia versus New Zealand. We suggest that the geochemical rift signature observed in the Whitsunday Volcanic Province is due more to to intra-arc rifting. Because the shallow structural level exposed in Queensland contrasts with the deeper levels in tectonically extended and exhumed NZ, the potential for each area to inform on the other, as shallow and deep levels of the same subduction system, is significant. To the SE, the Median Batholith extends across the Campbell Plateau, where arc and rift magnetic anomalies overlap, and into Marie Byrd Land (Pankhurst etal. 1998).

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A RECENTLY RECOGNIZED WESTERN PROVINCE MAGMATIC EVENT AT 387±3 MA: A RESPONSE TO BULLER-TAKAKA TERRANE AMALGAMATION?

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ORAL

Keywords: *Takaka Terrane, Buller Terrane, terrane amalgamation, granite, U-Pb geochronology, Karamea Suite*

ABSTRACT

Recent LA-ICPMS U-Pb zircon analyses on S- and A-type Karamea Suite aged plutons (368-370 Ma; Tulloch et al., 2009) have detected a distinct inherited age component at c. 387±3 Ma, a period where magmatism has until recently been unrecognized in the Western Province of New Zealand. Recent geochronological studies by Hiess et al., (2010) and our work have revealed the presence of c. 387±3 S-I-type granitoids in the Western Province. These mostly gneissic granites represent the only known dated exposures of a Devonian plutonic event that immediately preceded the voluminous Karamea Suite, and which is interpreted to be the most likely source of the 387±3 Ma inheritance.

Similarities in whole-rock compositions and zircon inheritance patterns for both plutonic episodes suggest derivation from a similar source, however, the contrast in magma volumes produced indicate the same tectonic setting and crustal melting conditions were probably not responsible for the generation of both magmatic events.

Newly dated A-type granites contemporaneous with S-type Karamea Suite emplacement offer some clues to the possible tectonic setting(s) responsible for both episodes of Devonian magmatism. Karamea A-type granites are classified as high-K calc-alkaline aluminous A2-subtype granites; characteristics associated with extensional post-orogenic tectonic settings, and voluminous magmatism of mixed crust-mantle origin (Eby, 1992). Our tectonic interpretation of the new U-Pb zircon ages, in combination with whole-rock and zircon O-Hf isotope geochemistry, is that the earlier, smaller volume S-I-type granites emplaced at c. 387±3 Ma reflect an initial orogenic crustal thickening event, and that the subsequent emplacement of the S-I-A-type magmas of the Karamea and Paringa suites from c. 370 Ma represents a change in tectonics from orogenic thickening, to an episode of post-orogenic extension.

We propose that crustal thickening at 387±3 Ma may have occurred in response to convergence and amalgamation of the Buller and Takaka terranes, and may also account for the synchronous regional folding event that occurred in both terranes prior to Karamea Suite emplacement (Jongens, 2006). A crustal thickening event at 387±3 Ma may correlate to the c. 389 Ma Tabberabberan Orogeny that is widely recognized through eastern Australia. A change in tectonism from orogenic compression to post-orogenic extension appears to be contemporaneous along most of the east Gondwana margin in the late Devonian, and has been invoked by several authors to account for voluminous production of c. 360-380 Ma S-I-A-type granites and rhyolites in Marie Byrd Land, the Melbourne Zone of the LFB, and eastern Tasmania (Siddoway & Fanning, 2009; Vandenberg et al., 2000; Black et al., 2010). The remarkable brevity over which voluminous crustal melting and Karamea Suite emplacement occurred (c. 2 Ma) may indicate that extension, and, therefore, heat flow was greatest along the NZ sector of the Gondwana margin during the late Devonian.

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Fieldtrips

Kereru, the New Zealand pigeon – 51 cm, 650 g, (NZ), 800 g, (Chatham Islands): head, throat and upper breast and back a metallic green flecked with gold and with a purple sheen, its belly white and its eye, beak and feet crimson.

FIELD TRIP 1

THE GEOLOGICAL IMPACTS OF THE CANTERBURY EARTHQUAKE SEQUENCE ON CHRISTCHURCH CITY

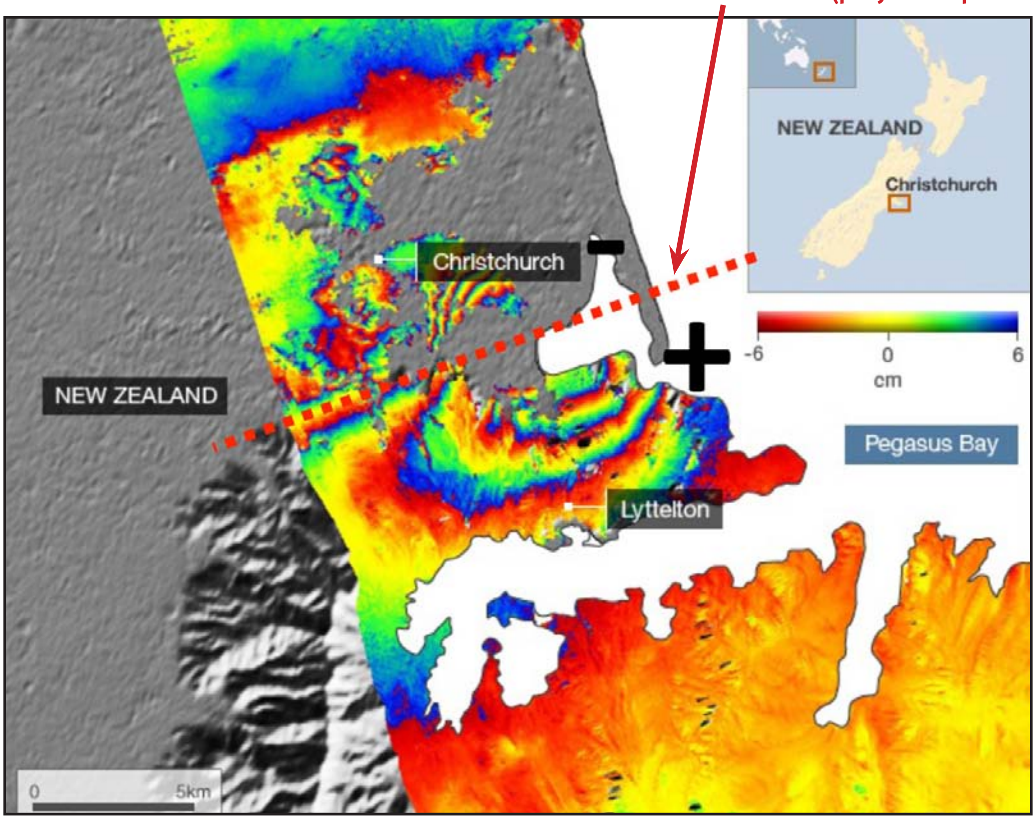
Jarg Pettinga and Thomas Wilson

1.30PM TO 5.00 PM - 15 OCTOBER 2013

This afternoon excursion will include a traverse through the central city business district to view the ongoing recovery work post February 2011. More than 1000 commercial buildings have now been demolished, including many heritage buildings. A new city centre redevelopment plan is currently being implemented, and reconstruction is underway. We will view the impacts of the severe ground shaking and widespread liquefaction and lateral spreading damage on the built environment in the heart of the city.

From the CBD we will travel on into the eastern suburbs where the impacts of liquefaction and lateral spreading have dramatically impacted suburban communities. Large areas have been red zoned, including more than 7,500 properties which have had to be abandoned. Demolition work is underway, while the impact of the repeated liquefaction and lateral spreading damage is still very evident.

Time permitting we will continue out to the Port Hills suburbs between the city and Lyttelton port. Here, close to the epicentre of the devastating 22 February 2011 Mw6.3 Christchurch Earthquake, the geological impacts include widespread and extensive rockfall with associated debris avalanches and boulder roll run-out zones, large-scale cliff top instability and deep-seated landsliding, as well as lateral spreading and ground fissuring. Some of the strongest ground accelerations ever recorded were captured by strong motion instruments here, in excess of 2g vertical. The associated effects of topographic focusing and amplification of the seismic energy have also impacted severely on many high cost properties in ridge crests and in valley floors. More than 500 properties were red zoned because of the life risk posed by ongoing aftershocks in areas in the Port Hills suburbs.



Superb new datasets from satellite radar interferogram data. (Source: Alos/Comet+; Courtesy John Beavan, GNS Science)

12:51pm 22 Febuary 2011 Christchurch earthquake. (Photo: Gillian Needham)

Liquefaction. (Photo: Brendon Bradley -UoC)

Lateral Spreading. (Cubrinovski et al. 2012)

Large subsidence in some suburbs. (Cubrinovski et al. 2012)

Large areas covered by thick sand ejecta. (Cubrinovski et al. 2012)

Cliff collapse at Redcliffs (Photo: J Pettinga 2011 – UoC)

Lateral spreading. (Photo: M. Cubrinovski - UoC)

M. Quigley, P. Villamor, K. Furlong, J. Beavan, R. Van Dissen, N. Litchfield, T. Stahl, B. Duff y, E. Bilderback, D. Noble, D. Barrell, R. Jongens, and S. Cox

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PAGES 469–488

Previously Unknown Fault Shakes New Zealand's South Island

PAGES 469–470

At 4:35 A.M. local time on 4 September (1635 UTC, 3 September), a previously unrecognized fault system ruptured in the Canterbury region of New Zealand's South Island, producing a moment magnitude (M_w) 7.1 earthquake that caused widespread damage throughout the area. In stark contrast to the 2010 M_w 7.0 Haiti earthquake, no deaths occurred and only two injuries were reported despite the epicenter's location about 40 kilometers west of Christchurch (population ~386,000). The Canterbury region now faces a rebuilding estimated to cost more than NZ$4 billion (US$2.95 billion).

On the positive side, this earthquake has provided an opportunity to document the dynamics and effects of a major strike-slip fault rupture in the absence of death or serious injury. The low-relief and well-maintained agricultural landscape of the Canterbury Plains helped scientists characterize very subtle earthquake-related ground deformation at high resolution, helping to classify the earthquake's basic geological features [*Quigley et al.*, 2010]. The prompt mobilization of collaborating scientific teams allowed for rapid data capture immediately after the earthquake, and new scientific programs directed at developing a greater understanding of this event are under way.

The September 2010 Darfield (Canterbury) Earthquake

The epicenter of the earthquake was approximately 10 kilometers southeast of the town of Darfield (Figure 1a) with a focal depth of 10.8 kilometers [*Gledhill et al.*, 2010] within the Canterbury Plains, an area of moderately low historical seismicity just east of the Southern Alps foothills. The previous largest earthquake to affect Christchurch was the 1888 *M* 7–7.3 North Canterbury earthquake, which ruptured the Hope Fault about 100 kilometers north of the city. Moment tensor solutions indicate that the Darfield earthquake main shock is associated with almost purely dextral strike-slip displacement on a subvertical, nearly east-west striking fault plane. The event produced a dextral strike-slip surface rupture trace greater than 29 kilometers long (Figure 1a). Using data from New Zealand national and strong-motion seismic networks, New Zealand seismologists have identified a reverse faulting component in the overall rupture sequence [*Gledhill et al.*, 2010]. As of mid-November, the region has experienced thousands of aftershocks of local magnitude (M_L) greater than 2, including 12 aftershocks of M_L greater than 5.0, with decreasing frequency in approximate accordance with current theories of aftershock decay.

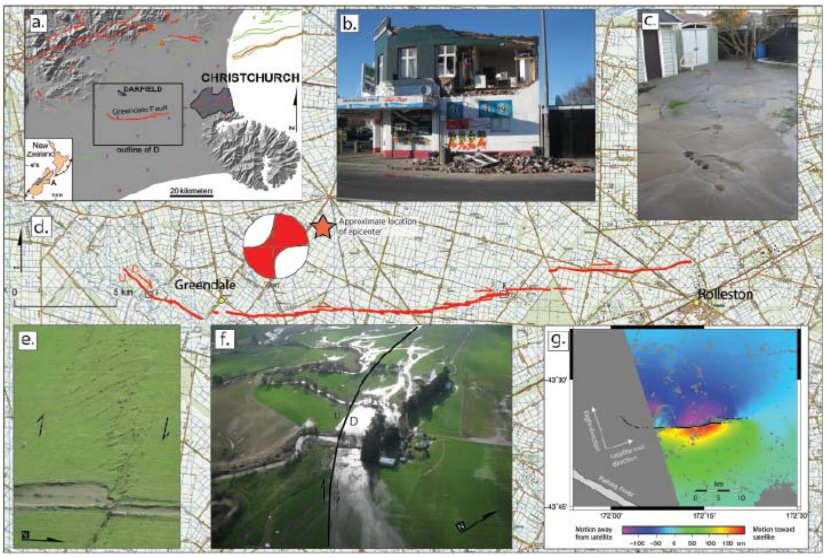

Fig. 1. (a) Digital elevation map of Canterbury region showing location of Greendale Fault and other tectonically active structures relative to selected urban centers. Red lines are active faults, and green lines are active folds (data from Forsyth et al. *[2008] (see www.gns.cri.nz, search word "QMAP Christchurch") and GNS Science Active Faults Database). Blue squares are GeoNet national strong-motion network sites, and purple squares are Canterbury regional strong-motion network sites. Locations of sites in Figures 1e and 1f are shown on map. A PDF of the fault map is available at http://www.drquigs.com and http://www.geonet.org.nz. (b) Failure of an unsupported wall in Christchurch. (c) Linear trend of sand boils in a liquefaction-affected part of Christchurch. (d) Mapped location of Greendale Fault, showing a pattern of similarly oriented faults and relative fault movement (arrows denote relative motion of area north of fault, with U representing up (the hanging wall of the secondary thrust component) and D representing down (the footwall of the secondary thrust component), although the centroid moment tensor "beachball" diagram for this earthquake (http://www.globalcmt.org) shows that the majority of motion on the fault is strike-slip). (e) Greendale Fault surface rupture patterns and dextral offset of irrigation channels. (f) Partial diversion of the Hororata River because the northeast side of the Greendale Fault has moved down at this location. (g) Unwrapped differential interferometric synthetic aperture radar (InSAR) image of coseismic ground deformation from Advanced Land Observing Satellite phased array type L-band synthetic aperture radar (ALOS/PALSAR) ascending track 336 between 11 March 2010 and 11 September 2010, with the mapped surface rupture overlaid. ALOS processing by Sergey Samsonov, University of Western Ontario, London, Canada. ALOS data used with permission.*

By M. Quigley, P. Villamor, K. Furlong, J. Beavan, R. Van Dissen, N. Litchfield, T. Stahl, B. Duffy, E. Bilderback, D. Noble, D. Barrell, R. Jongens, and S. Cox

The shallow depth and proximity of the earthquake to Christchurch resulted in felt intensities of as much as IX on the Modified Mercalli (MM) Intensity Scale, although most were MM VIII or less. Extensive damage occurred to unreinforced masonry buildings throughout the region (Figure 1b), but no buildings totally collapsed. The earthquake struck early in the morning, minimizing human exposure to hazards such as exterior wall and parapet collapses onto normally busy sidewalks. Nonetheless, many thousands of brick chimneys collapsed throughout the region. Extensive liquefaction, differential subsidence, and lateral spreading occurred in areas close to major streams and rivers throughout Christchurch, Kaiapoi, and Tai Tapu (Figure 1c). In these areas, as well as near the fault trace, some homes were rendered uninhabitable by the earthquake and resulting liquefaction. Parts of the city were without water and power for several days following. Slow ground settlement has continued to affect liquefaction-prone areas.

An M_L 5.1 aftershock on 8 September located about 7 kilometers southeast of the city center at a depth of approximately 6 kilometers caused further damage to previously compromised structures.

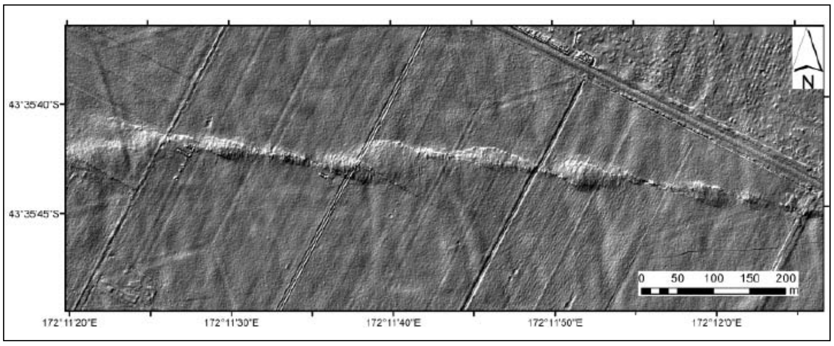

Fig. 2. Lidar (light detection and ranging) hillshade (illuminated from the northwest) digital elevation map of a short section of the central Greendale Fault, showing characteristic left stepping rupture pattern and right-lateral offsets of farm roads and fences. Lidar from NZ Aerial Mapping Limited.

A Rapid and Coordinated Scientific Response

Immediately following the earthquake, Earth scientists from the University of Canterbury (UC) in Christchurch rushed to inspect earthquake damage in the city and provide immediate information to the public via media. Within 3 hours of the earthquake a reconnaissance and response team led by scientists from the UC Active Tectonics team and GNS Science (GNS) had been deployed. By 9:30 A.M. the UC reconnaissance team located the first evidence for ground surface fault rupture and began to assess local hazards and conduct detailed measurements of fault offsets across roads and fences. GNS scientists undertook a helicopter reconnaissance flight to define the limits of obvious surface deformation and photograph key features. Another team of UC staff and students, aided later by colleagues from other organizations, began mapping liquefaction features in and around Christchurch. By the end of the day, a first approximation of the surface rupture length and general damage patterns had been established throughout the region, which formed the basis for planning the scientific documentation of the event.

The rapid collaborative scientific response ensured that fault deformation features were accurately documented before they were removed by land remediation. The fault was mapped in detail over the following 2 weeks using a variety of methods, ranging from tape and compass to Global Positioning System (GPS) surveys and terrestrial laser scanning. The fault rupture occurred entirely in a region with numerous linear features such as roads, fences, hedgerows, and irrigation channels, which provided an invaluable wealth of fault displacement markers. Progressive iterations of maps of the surface rupture features were made available to the public online and presented to local and regional councils and landowners. Airborne lidar (light detection and ranging) was flown over a roughly 20-kilometer-long section of the fault rupture (Figure 2) 6 days after the event. As a consequence, a spectacular data set of fault displacement, buckling, and detailed fracture patterns was captured over the full length of the surface rupture. Fault data continue to be analyzed by GNS and UC personnel.

Scientists working on GeoNet, a New Zealand–based geological hazard monitoring system operated by GNS for New Zealand's Earthquake Commission (EQC), deployed portable earthquake recorders the day after the main shock and have been continuously processing seismological data since the event. A GNS-led team used GPS to resurvey more than 80 existing survey marks within 80 kilometers of the rupture starting 3 days after the event; the 45 marks closest to the main shock were resurveyed 2 weeks later. GNS is working with overseas colleagues to collect and process interferometric synthetic aperture radar (InSAR) data from both Japanese and European satellites; some of the early images have produced very high quality maps of surface displacements (Figure 1f) [*Beavan et al.*, 2010]. The InSAR data are being combined with GPS, geological, and seismological data to develop rupture models.

Characteristics of the Surface Fault Rupture

The zone of identified surface rupture extends from about 4 kilometers west-northwest (WNW) of the hamlet of Greendale for about 29 kilometers to an eastern tip roughly 2 kilometers NW of the town of Rolleston (Figures 1a and 1d). The fault, not previously recognized, has been named the Greendale Fault. High-quality observations and measures of offsets and fracture patterns reveal more than 4 meters of right-lateral displacement (Figures 1e and 2). Vertical offsets of up to approximately 1 meter occur at constraining or releasing bends. Oblique northeast-side down slip on the NW striking western portion of the fault resulted in partial diversion of the Hororata River (Figure 1f). The gross morphology of the fault is that of a series of EW striking, NE stepping surface traces (Figure 1d) that in detail consist of ESE trending fractures with right-lateral displacements, SE trending extensional fractures, SSE to south trending fractures with left-lateral displacements, and NE striking thrusts and folds (Figure 1e). Offsets as small as 1–5 centimeters were mapped due to the numerous straight features (e.g., roads, fences) crossing the fault. Ongoing research and mapping of deformation will provide additional constraints on the spatial pattern of surface rupture.

The Greendale Fault ruptured primarily across gravelly alluvial plains abandoned by rivers at the end of the last glaciation, about 16,000 years ago [*Forsyth et al.*, 2008]. No evidence of previous faulting had been recognized, either prior to the earthquake or in retrospective examination of pre-earthquake aerial photographs. However, thorough cultivation of the Canterbury Plains following the arrival of Europeans in the mid-1800s has subdued some detail of the original river channel form. Coupled with the possibility that previous earthquakes may not have produced significant surface rupture, the long-term earthquake history of the Greendale Fault is difficult to assess.

What Are Earth Scientists Doing Now?

Together with research partners in New Zealand and abroad, several UC- and GNS-led research programs have been initiated following the earthquake. High-precision GPS surveying and measurement of fault offsets continues, with an emphasis on refining the characteristics of the surface rupture. Structural analysis of fault fracture arrays is providing insights into fault behavior and kinematics. Repeat surveying of markers across the Greendale Fault, conducted at weekly intervals, helps document postrupture relaxation and/or ongoing fault growth. Reoccupation of pre-earthquake survey points, combined with GPS and InSAR studies, will provide high-resolution data sets relevant to characterizing the earthquake source.

The earthquake has provided seismologists with an exceptional set of near-source strong-motion data from the GeoNet national strong-motion network and the Canterbury regional strong-motion network (Figure 1a). The station nearest the rupture recorded peak ground accelerations greater than those of gravity [*Cousins and McVerry*, 2010], and understanding why accelerations diminished over small distances is important for understanding the future seismic hazard throughout this region.

Seismologists are currently working on better defining the rupture's evolution using inversion methods and recently developed source-tracking methods. Landslide mapping and monitoring programs are in place. Geophysical surveys (seismic and ground-penetrating radar), fault trenching, and excavations of areas that experienced liquefaction during this earthquake are being conducted to investigate the subsurface geometry and earthquake history of the newly discovered Greendale Fault. Mapping of tree damage is providing insights into the extent to which coseismic shaking, changes in water table, and damage by faulting of root systems played a role in generating observed patterns of forest destruction. Mapping of displaced boulders is providing data relevant to understanding the factors influencing peak ground acceleration variability. Collaborative efforts to link remote sensing, seismological, and geological data to fault rupture propagation models are providing intriguing insights into the rupture dynamics of this earthquake and continental strike-slip earthquakes in general.

Acknowledgments

Field mapping in the weeks following the earthquake would not have been possible without the dedicated efforts of many GNS Science staff and students and staff at the University of Canterbury's Department of Geological Sciences. GeoNet provided an invaluable resource of rapid information on earthquake for researchers and the public. We would also like to thank the landowners for gracious access to the fault trace and other field sites during this stressful period. Personnel from GNS Science, Land Information New Zealand, University of Otago, and Victoria University participated in postearthquake GPS surveys. We thank Duncan Agnew for reviewing this article.

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Mark Quigley (right) and Timothy Stahl standing in a graben along the Greendale Fault Canterbury Earthquake 2010

FIELD TRIP 2

Post-Symposium Field Excursion to NW Nelson and the West Coast

John & Margaret Bradshaw

Background

A terrane approach has proved to be the only practical way to describe and discuss the pre-Late Cretaceous geology of New Zealand (Fig. 1). The terranes present a record of 450 million years on the Gondwana margin and fall into two groups, a western group of Cambrian to Devonian age and an eastern group of Permian to Early Cretaceous age. They are separated physically by a belt of magmatic rocks of Devonian to Cretaceous age, the Median Zone or Median Batholith (Fig. 2), and geodynamically by a period of tectonic erosion in the Carboniferous (Tulloch et al.2009).

Locations in the guide relate to New Zealand Transverse Mercator grid used in the latest 1:50,000 topographic maps. It does not correspond to the grid on earlier editions of 1:50,000 maps. The bold numerals correspond to a conventional six figure grid reference.

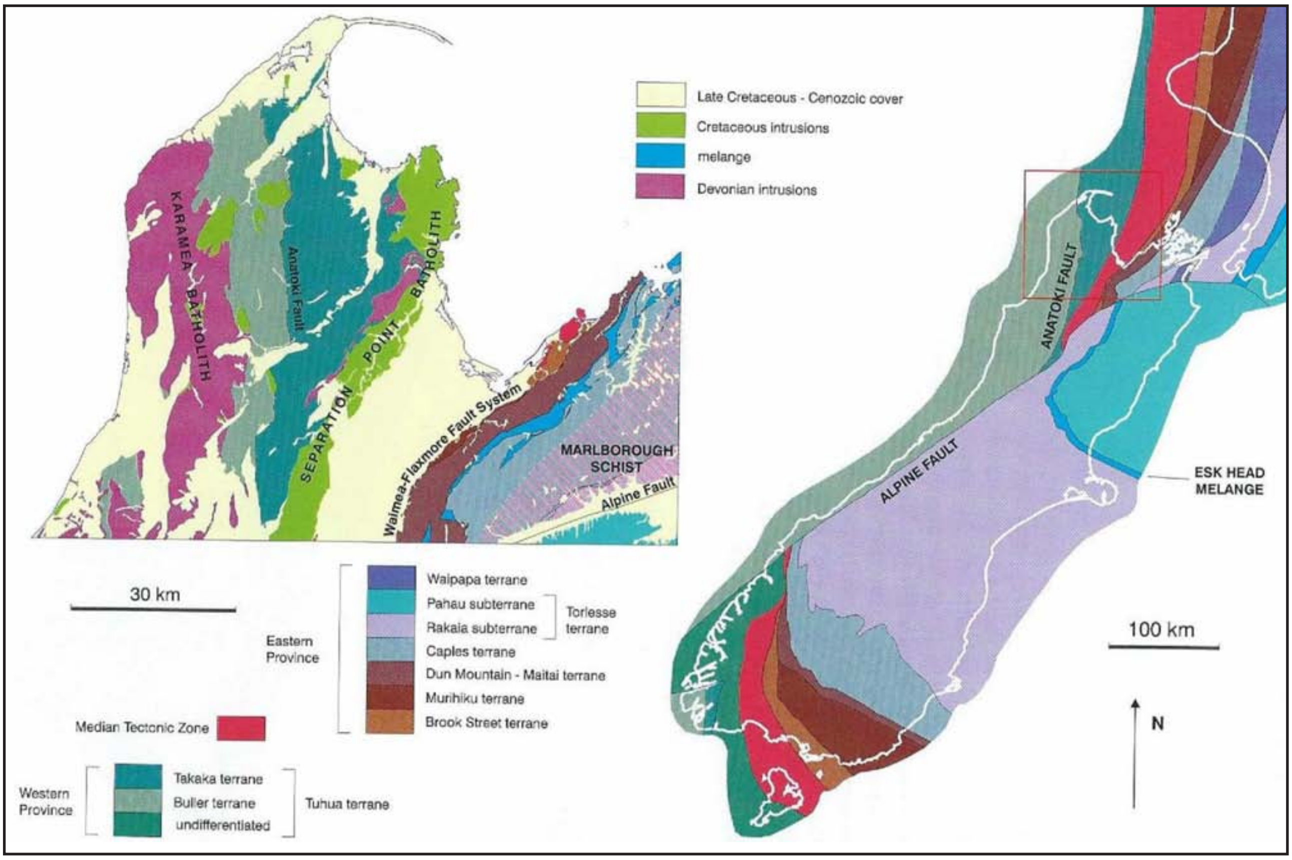

Figure 1: Terrane map of New Zealand (from Rattenbury et al. 1989).

Introduction

Slices of NW Nelson Geology

The magmatic rocks of the Median Batholith (or Median Zone) form an eastern limit to the Cambrian to Devonian rocks of New Zealand. The Eastern Province, is made up of Permian and Mesozoic volcanic-arc related rocks and accretionary complexes, the older parts of which form the hills across Tasman Bay to the east. The low-lying ground in between is underlain by magmatic rocks. The Cretaceous Separation Point Batholith is a younger component of this zone. Some Late Devonian and Carboniferous magmatic rocks (Fig. 2) compare well with those of the Lachlan Orogen and New England Orogen of Australia, but the volume of Carboniferous rocks of any type in New Zealand is very small and the bulk of the New England Orogen does not continue into New Zealand. Tulloch et al. (2009) suggest that it has been displaced dextrally, leaving The Takaka Terrane on the outer margin of Gondwana in the Permian (Fig. 2)

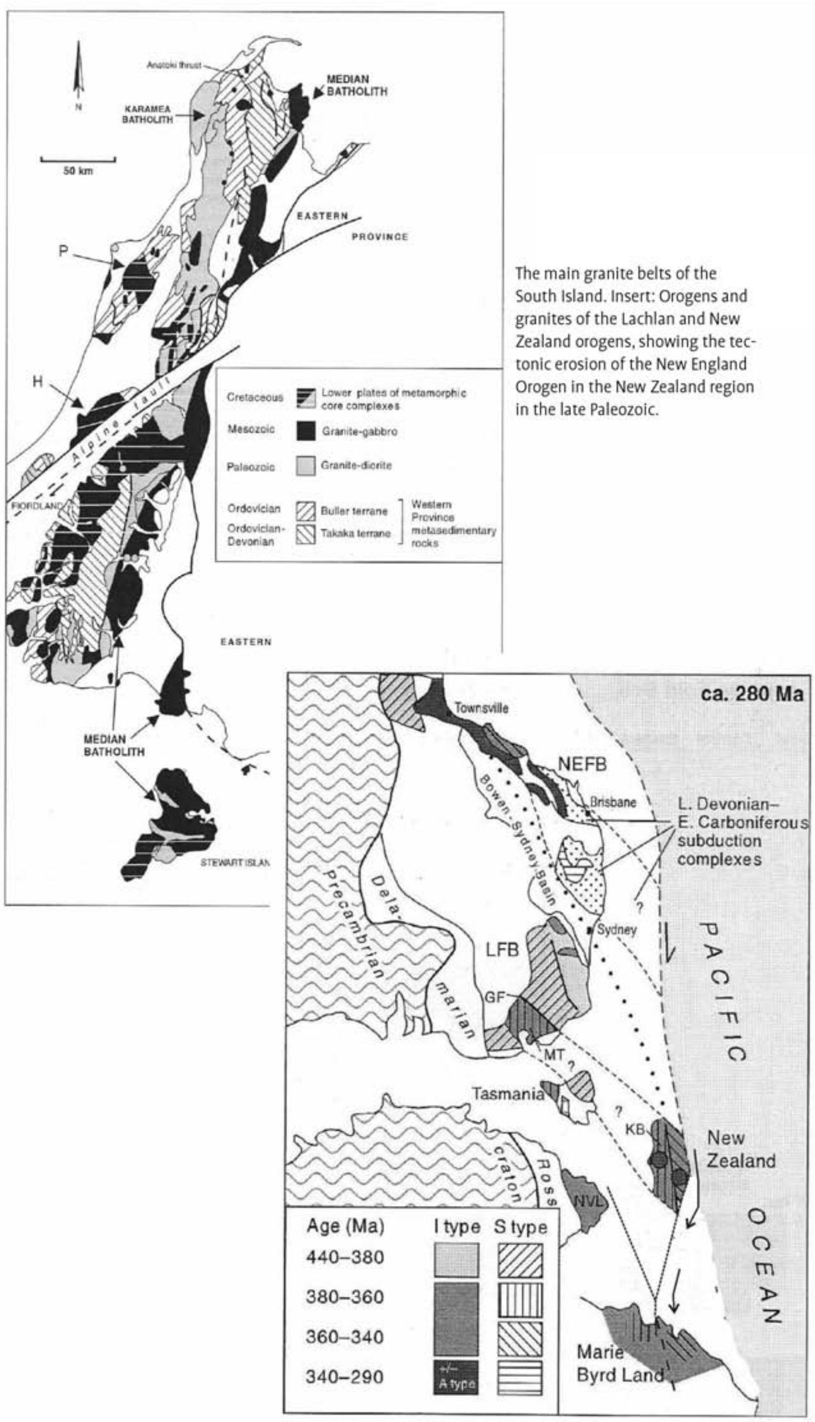

Figure 2: New Zealand granite batholiths, and inset with suggested Late Paleozoic tectonic erosion. (after Tulloch et al. 2009)

In the west, the Paleozoic rocks lie in two terranes, the Buller Terrane to the west and the Takaka Terrane to the east, separated by the north-south Anatoki Fault (Fig.3). Very similar folds and cleavage are developed on either side of the terrane boundary and are thought to have developed in the later stages of terrane amalgamation in the late Early Devonian (Jongens, 2006; Turnbull et al. 2013), and this conference). The nature of the folds suggests that the last stage, at least, was a simple convergence.

The rocks of the Buller Terrane will be seen later near Westport, where they show clearly the Late Ordovician to early Silurian deformation of the Benambran Orogeny of Australia. The Takaka Terrane is divided into two by the north-south Devil River Fault. To the west lies the mainly Cambrian 'Central Belt' and to the east the Ordovician–Devonian 'Eastern Belt'. Ten tectonic slices (Figs. 4 & 5) are identified in the 'Central Belt' (Grindley, 1980; Rattenbury et al. 1998). Three slices have been identified in the 'Eastern belt', though more may be present.

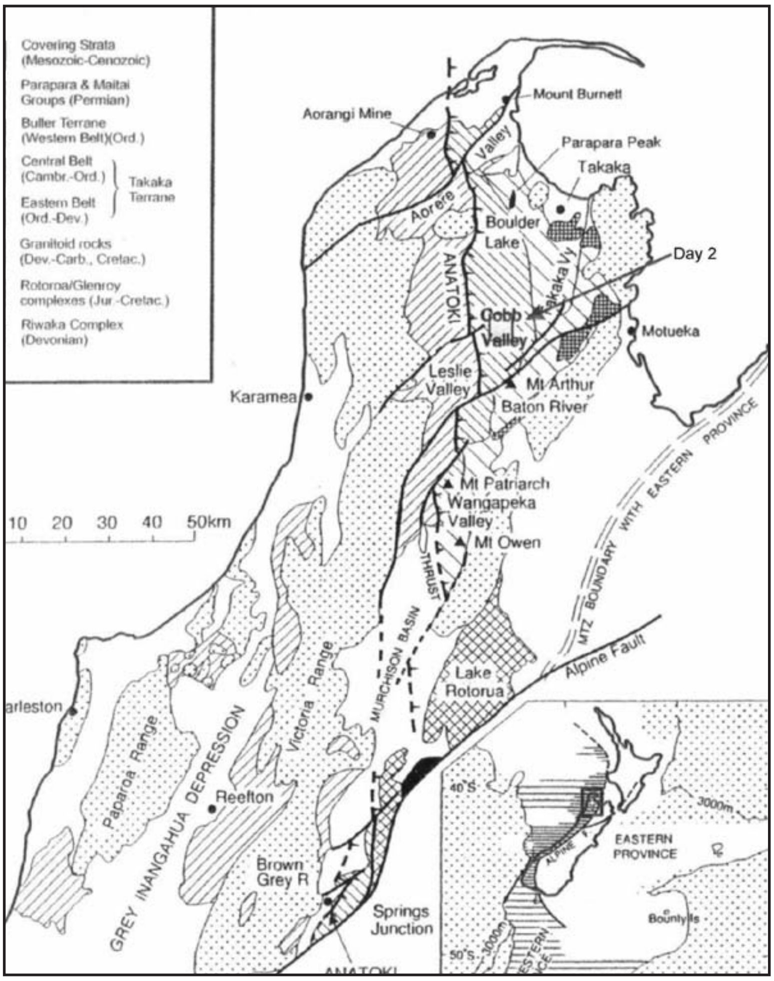

Figure 3: Simplified map of NW Nelson.

It has been conventional for many years to refer to these faults as thrusts, though many are sub-vertical.

The 'Central Belt' is made up of rocks that are considered to represent parts of a Cambrian arc and back-arc basin assemblage (Munker & Cooper,1999). Magmatic rocks include arc- volcanic types that inter-finger with arc-derived sediments and continent derived sediments Fig. 5b). Detrital zircon geochronology and isotope geochemistry strongly support a Gondwana margin provenance for the continent-derived sediment. A discrete fault bounded slice has a thick development of basalts with back-arc affinities and ultra mafic rocks (Fig. 5b).

The recognition of thrusts usually implies that older rocks are emplaced over younger rocks, or that higher grade rocks or plutonic rocks are emplaced over superficial rocks. The geological mapping in this region was founded on a stratigraphic succession that comprised the Balloon Formation at or near the base, the Devil River Volcanics, the Tasman Formation, the Lockett Conglomerate, and the Anatoki Formation at the top (e.g. Grindley 1980). Since then the situation has proved to be more complex. The Balloon 'Formation' is now regarded as a mélange that appears to include blocks of most other formations and is at least

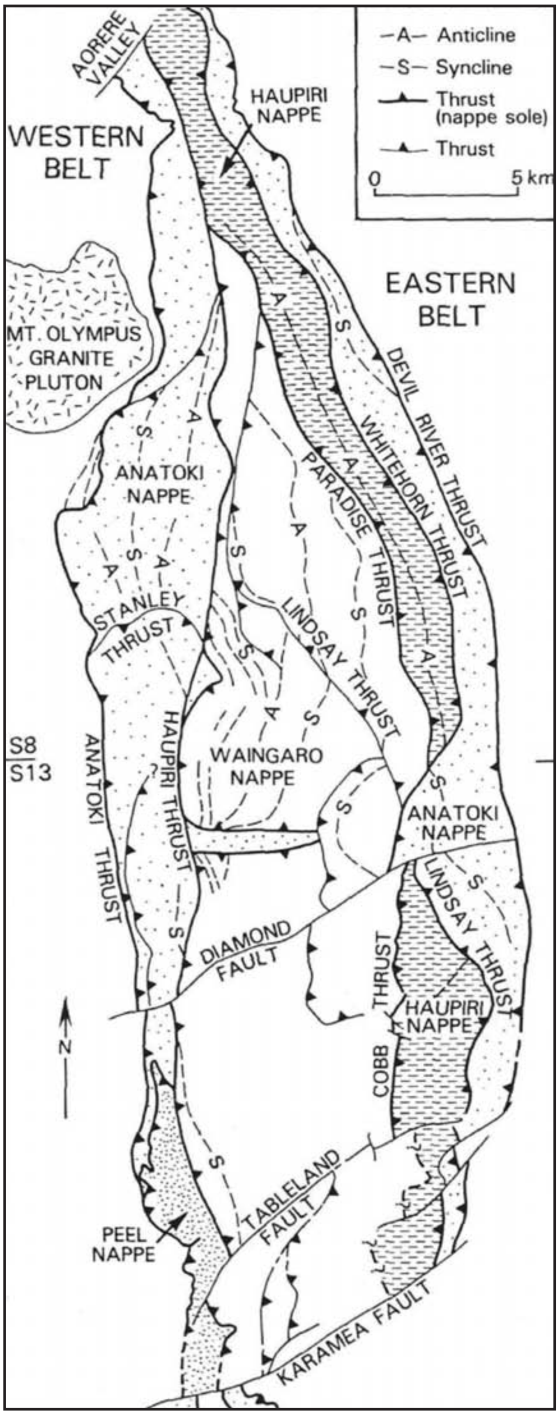

Figure 4: Thrust slices identified by Grindley, 1980. (Redrawn by Bradshaw).

in part intrusive (Fig. 7, see Jongens et al. 2003). The Devil River Volcanics is now considered a 'Group' of varied magmatic rocks of different ages and tectonic settings (Munker & Cooper 1999). There are a number of distinct conglomerates at different stratigraphic levels and the Anatoki Formation may be composite. Though there are undoubtedly well marked shear zones, care is needed to establish whether every fault is necessary and which faults are (or were) truly thrusts. The most recent 1:250,000 geological map (Rattenbury et al. 1998) identifies fewer faults as thrusts.

A further complicating factor is the problem of distinguishing the of effects of the Late Cambrian Ross-Delamerian Orogeny, indicated by the emplacement of the Balloon Mélange in NW Nelson and Cambrian granitoids in Fiordland, from later deformations. The subsequent tectonic history includes two more phases of folding, two generations or more of Paleozoic faults, plus late Mesozoic and late Cenozoic faulting. During this excursion we would like to review the evidence and the problems posed by the rocks of NW Nelson and your input would be welcome.

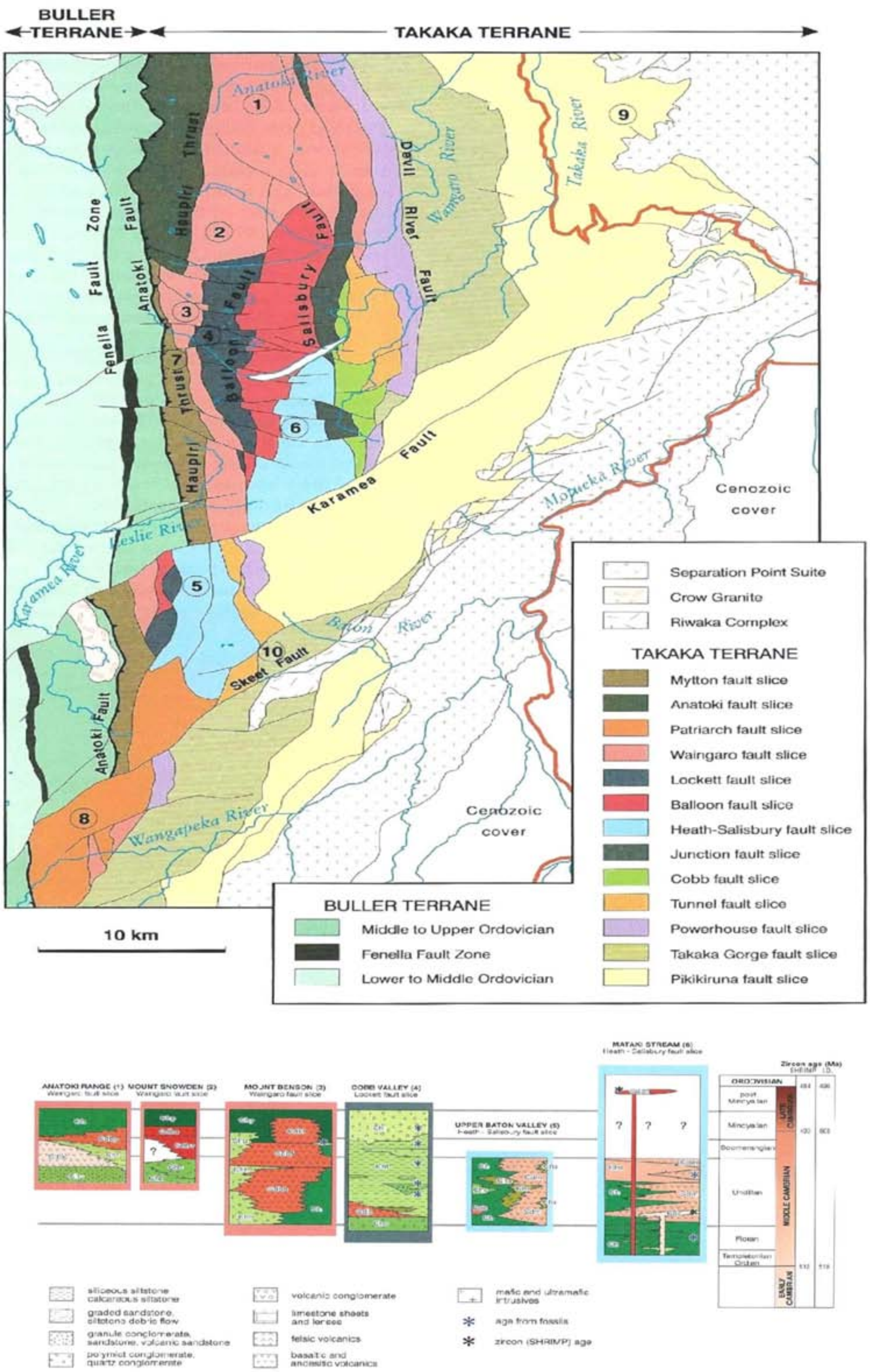

Figure 5: Tectonic slices after Rattenbury, 1998, with a more recent view of the stratigraphic relationships. Note the distinctive character of the Salisbury Slice.

Day 1 Motueka to Takaka

The beautiful coastline of the Abel Tasman National Park is the best place to see the Cretaceous Separation Point Granite. The granite intrudes older magmatic rocks of the Median Batholith and sediments of the Takaka Terrane. Other Cretaceous granites occur to the west in the Buller Terrane (Figs.1 & 2).

Stop 1 – Breaker Bay just north of Kaiteriteri (1601805, 5457507).

Road section between the main road and the village (possibly also major road works) show deeply weathered granite, but at the coast reasonable fresh rock is exposed. Though tempting, it is probably too early in the year for swimming. Rose Turnbull may wish to add further insights into the granites.

Return to the main road and continue up Takaka Hill. The road is cut though deeply weathered Separation Point Granite and older mid-Paleozoic plutonic rocks of the Riwaka Complex. After climbing to approximately 700 m the road crosses onto the sediments of the 'Eastern Belt' (marked the marble quarry on the right). The marble is part of a thick pile of Ordovician to Devonian rocks of 'passive margin' aspect. The Ordovician comprises quartzose sandstone and mudstone (Wangapeka Formation) with large bodies of carbonates now forming the Arthur Marble. The Silurian and Devonian rocks are mainly quartzose sandstone and mudstone with much smaller limestone bodies. The Cambrian arc to back-arc assemblage forms the basement to the Ordovician to Devonian succession. Exactly what " passive margin" means in this context is an interesting question, particularly as the Gondwana-derived deeper water Buller Terrane rocks lie to the west (Bradshaw 2007, Bradshaw et al.2009).

Stop 2 – Opposite the side-road to Ngarua Caves (1591612, 54559075).

(Please take care crossing the road and stay inside the left hand white line and on the rocks). The exposure shows typical Arthur Marble with well developed karstic topography. In detail, the layering is not bedding and small scale folding is shown by thin dark layers. The fabric aligns with the axial plane of these folds. Is the fabric mylonitic. Continue southwest for approx 2 Km through karst to near Bob's Lookout.

Stop 3 (1589815, 5458322)

Beyond, roadside outcrops show small separated hinge zones in a deformed chert band in the Marble. These illustrate the highly deformed nature of the marble. Other exposures in this vicinity may be visited if time permits. Continue 2.5 Km to summit of the road at ~900 m, descend to first hairpin bend.

Stop 4 View point (1587778, 5457366)

The view to the west is of a broad dome of accordant summit heights in the Tasman Mountains. The surface is locally overlain by mid Cenozoic deposits, notably the Takaka Limestone of Oligocene age. This and younger rocks indicate that the doming is post-Middle Miocene. The range front is the fault-line scarp of the Pikikiruna Fault, and we will cross it a little above the 3rd Hairpin known as Eureka Bend (drivers may shout 'Eureka!'). Outcrops in this vicinity are of Cenozoic sandy limestone. A low area of Arthur Marble to the south of the road originally mapped as a nappe has been shown to be a major rock fall.

Continue down the hill to Upper Takaka and turn left on to the road to Cobb Dam.

Stop 5 – To view Hailes Knob

A syncline of mainly Silurian sandstone resting on Arthur Marble. The lower part of the section has Ordovician fossils and is less deformed and the contact with the Silurian has been interpreted as sedimentary. Our own observations suggest that near the contact the limestone is highly deformed and the contact may be tectonic. (Margaret Bradshaw may be persuaded to add some comments on fossils).

Stop 6 Bridge – Over the Takaka River (1582198, 5456773)

Access to the outcrops in the river bed is now difficult due to road widening, but the main features of the accompanying sketch can be seen from the bridge. Alternating sandstone and mudstone beds show half-folds that plunge towards the south and are cut by shear planes with apparent dextral displacement (Fig. 6 upper.) The rocks are Hailes Quartzite of Silurian age.

Continue along the road through the gorge for about 6 km to the southwest. Outcrops have largely become overgrown since the last road widening/natural disaster and are entirely of sandstone, mudstone and shale. In the northeastern part they are interpreted as Silurian Hailes Quartzite, although there is no fossil control. A transition into muddier Ordovician Wangapeka Formation occurs around Sam Creek, although at Sam Creek itself there are thick beds of quartzite. Sparse Ordovician fossils have been found east and west of the Sam Creek. (Stop made on demand).

Ordovician rocks continue to Drummond Flat where they are cut by the Drummond Fault and juxtaposed against strongly sheared Wangapeka Formation rocks forming the margin of the Waingaro Schist. To the west schist and mylonites are related to the Devil River Fault that marks the edge of the 'Central belt'. These rocks are poorly exposed in the roadside shortly before the power station (stop on demand) but are better exposed a little further to the west).

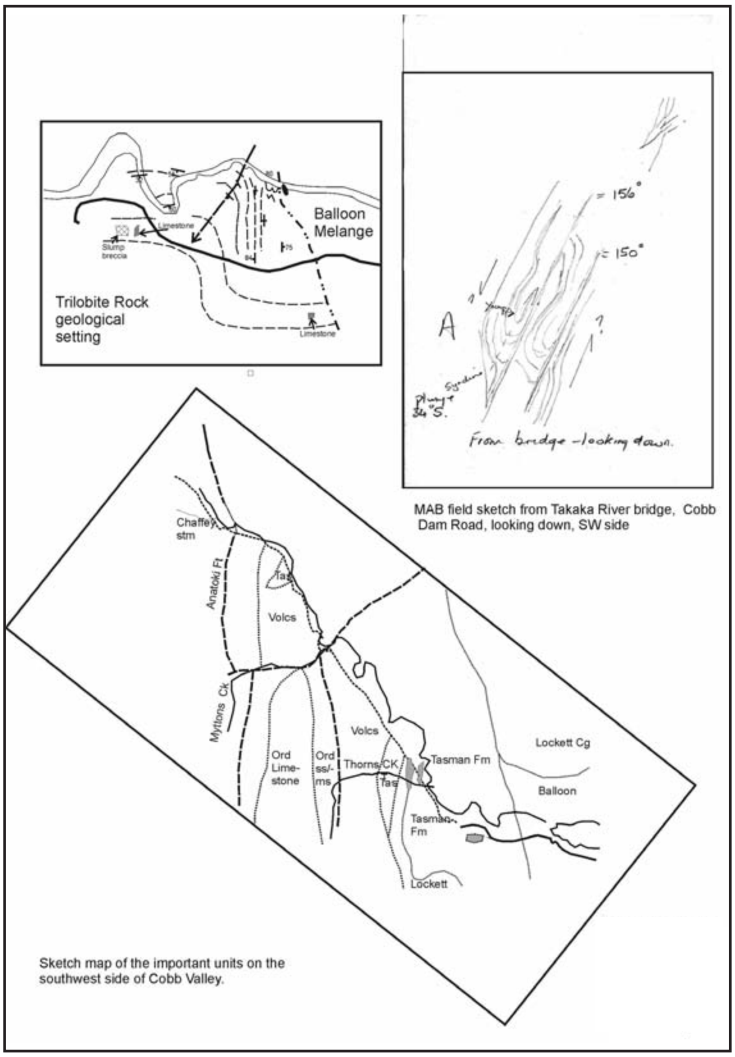

Figure 6: Top right, details of the structures at the Takaka River bridge, Cobb Valley road (M.A.B sketch). **Top left** , geological setting of Trilobite Rock. **Centre**, sketch of aspects of the geology northwest of Trilobite Hut.

Stop 7 – Behind the power house (1577510, 5451630)

Here, and in the Takaka River, there are clean exposures of the Waingaro Schist. The Schist occurs widely along the eastern edge of the 'Central Belt', though its origin is enigmatic. The belt is 5 km wide in places, but is usually narrower. The fabric overprints Cambrian volcanic rocks (Devil River Volcanics Group) and sedimentary rocks including the Balloon Mélange and the Lockett Conglomerate with both matrix and clasts showing strong ductile deformation. These fabrics appear to be truncated in places by later "thrusts" and still younger sub-vertical faults.

The only detailed study of the structure and metamorphism of the zone is an M.Sc thesis (University of Auckland) by N. G. Powell (1984) that, unfortunately, has never been published. The foliation is everywhere steeply dipping, the lineation is steeply plunging and probably developed at the same time as the foliation. The grain-size of the material is usually finer than the parent lithologies and grades into mylonites (including calc-mylonites) eastwards. Powell infers a large component of simple shear. He also considered that the zone was originally sub-horizontal with thrusting towards the east. The formation of the schist post-dates the deposition of the "passive margin" succession but probably pre-dates the mid-Paleozoic magmatism. Shelley (1984) also considered that the evidence from the 'passive margin' rocks of the Takaka Gorge and Takaka Hill suggested tectonic transport towards the northeast. A possible alternative explanation is that the Devil River Fault is a detachment surface between a deformed Cambrian assemblage and Ordovician-Devonian cover rocks.

Return to Takaka

Piwakawaka, the fantail – Known for its friendly 'cheet cheet' call and energetic flying antics, the aptly named fantail is one of the most common and widely distributed native birds on the New Zealand mainland. It is easily recognized by its long tail which opens to a fan. It has a small head and bill and has two colour forms, pied and melanistic or black. The pied birds are grey-brown with white and black bands.

Day 2 Takaka to Takaka

Today were return to the Takaka River Gorge and continue west across Cobb Ridge to Cobb Reservoir. Cobb Ridge is at ~1000 m and it would be wise to bring clothing for cooler, windy and/or wet weather.

Stop 1 (1574117, 5449518 to 1573330, 5448758)

The ridge provides a good view of the central belt. During the climb from the power station we have crossed the Waingaro Schist and are here in Balloon rocks. They comprise cleaved to scaly weathering micaceous sandy mudstone that hosts large blocks of white weathering dark grey to black metachert ranging from a few metres to tens of metres in size. Metachert was quarried for aggregate during the construction of the dam and is used as road metal. Metachert, volcanic rocks, limestone and conglomerate have been mapped as bands or beds within the Balloon Formation. Stewart (1988) provided the first detailed map of these included masses. It is now generally accepted that these are blocks within a mélange and that the mélange is intrusive (Jongens et al, 2003 and Fig. 7).

Further down the hill there are basic igneous rocks above sheared serpentinite (Fig 8) of the Cobb igneous Complex occur. These rocks were originally mapped as a thrust slice but are now mapped as a body enclosed in the mélange (Rattenbury et al. 1998). Continue to culvert 138 where the vans should be waiting.

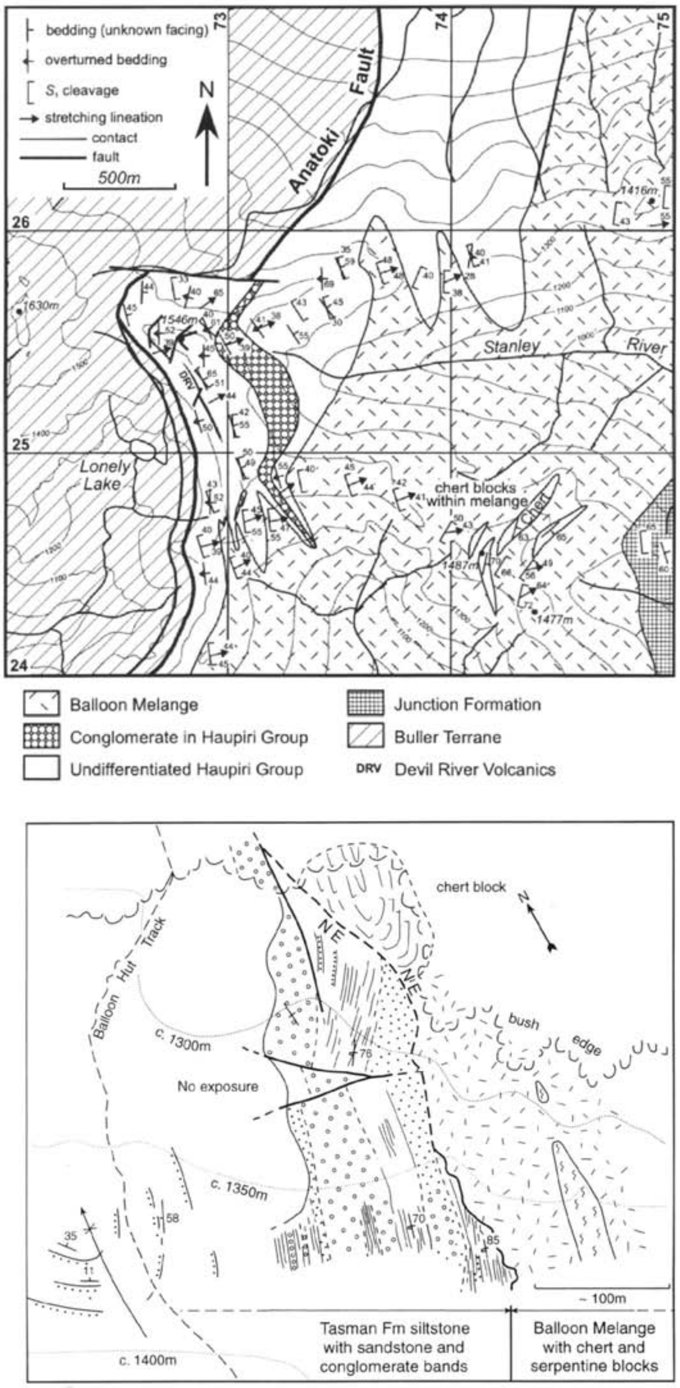

Fig. 7: Some of the evidence for the intrusive nature of the Balloon Mélange from Jongens et al. 2003.

Stops 2 and 3 – situated near the head of the lake (1568243 and 54446644)

(These stops will be accessed from the same parking area) Below and upstream in the Cobb River are exposures of Balloon mélange in which block and matrix relationships between sandstone and mudstone can be seen (Fig. 8). Bedded sandstone and mudstone occurs to the east before a rocky gully and are thought to be an included mass. Beyond the gully and beech trees (stop 3), coarse conglomerate of well rounded igneous cobbles and boulders in a volcanic sandstone matrix occurs (Fig. 9). The composition of the clasts and matrix is so similar that the texture is very difficult to see in weathered outcrops across the road. The clasts are of Devil River arc rocks and the whole appears to be a large block within the mélange and can be traced for a short distance on both sides of the river.

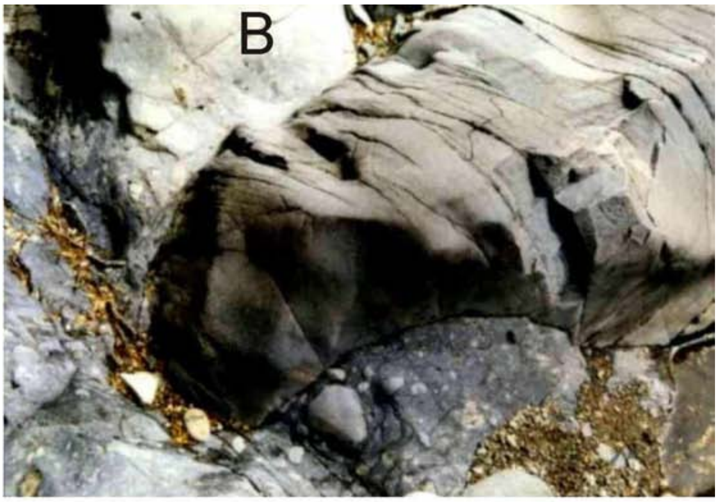

Fig. 8 A & B: block and matrix textures developed in Balloon Melange, Cobb River near lake head.

C: shear planes cutting platy fabric in Serpentinite, road section, Cobb Ridge.

Fig. 9 Above left and right. Conglomerate igneous clasts in a sandstone matrix with the same mineral composition that weathers at the same rate as the clasts. Cobb Valley head of the lake.

Below left. Slump breccia of laminated Tasman Formation type sandstone blocks with a matrix of similar composition. This lithology may be the host of the fossiliferous limestone exposed a few metres to the west of Trilobite Rock.

Stop 3, 4A – Trilobite Rock (1567370, 5446631)

Walk a short distance to Trilobite Rock. This is a geological reserve, so no collecting. The rock is a limestone island in scrubby bushes and was the first site where Cambrian rocks were identified in New Zealand. The fauna of this and several other limestone blocks in the valley includes agnostid and other trilobites, conodonts, inarticulate brachiopods and bivalves. Algal material is also present and the limestones are thought to have originated as a shallow water carbonate shell banks or shoals adjacent to a volcano. This is the largest block on the valley floor and its size is exactly what you see. This and the other blocks are olistoliths within the Tasman Formation. Similar trilobites have been found in the clastic rocks of the Tasman Formation confirming that the blocks and the enclosing sediments are of the same age. A few metres to the west a slump breccia of Tasman Formation lithologies probably represents the host layer of Trilobite Rock (Fig. 9).

A very similar assemblage of rocks and relationships is seen in northern Victoria Land and supports a close proximity in the Cambrian of the Bowers Terrane and the Takaka Terrane (Bradshaw et al. 2009)

Stop 4B (1567797, 5446851)

On the south bank of Cobb River (Fig. 6), well bedded Tasman formation (with typical laminated appearance) pass downstream to a zone of small folds. Fossils have been found here. The Tasman Formation is in contact with Balloon Mélange and a large sepentinite block occurs adjacent to the contact. This was originally interpreted as the "Balloon Fault" but is now though to be an intrusive contact.

4X. From this area good views can be had of the rocks on either side of the terrane boundary. A bold limestone hill to the west is Mount Mytton, showing Early Ordovician limestone within the Takaka Terrane, 400 m from the Anatoki Fault. Immediately beyond are mudstone, graptolitic black shale and quartzite of the Douglas Formation (Buller Terrane). The latter are part of an Ordovician succession that is entirely made up of sand and mud but is equivalent in age the Carbonate rocks of the Takaka Terrane. Well before the concept of terranes was advocated, the contrast was recognized and the two successions were thought to have been brought together by thrusting.

Time, weather and inclination determine the rest of the day.

Options

1. Climb approximately 400 m to clear exposures above the bush-line showing folded Tasman Formation, including igneous conglomerate, intruded by Balloon Mélange with serpentinite and chert blocks (see Fig. 7).
2. Continue along the valley floor towards the terrane boundary (We have not checked the quality of the outcrops for many years. Outcome uncertain (see Fig 6).
3. Relax and maybe feed the sandflies.
4. Get out of this dreadful weather and return to the bar.

Return to Takaka

Day 3 Takaka to Westport

Leave as early as possible (pack before 7.00 am breakfast). Today involves a long road trip. Stops will be made, but we will be constrained by time.

Return to Motueka and travel south up the Motueka Valley (coffee at Kohatu ?). Join the main road to the West Coast and continue to Hope Saddle (1576610, 5391564). Here there is a good view point that extends from the mountains of Arthur Marble in the west to the Spencer Mountains and the peaks of the Torlesse accretionary complex to the east (on the other plate).

Continue to the southwest, mainly across weathered Separation Point Granite, following the Hope River that joins the Buller River at Kawatiri Junction. From here we follow the Buller River to the sea (eventually). After about 15 or 16 km the valley widens with flats on the left bank, then suddenly narrows where the Owen River enters from the north (1554384, 5384977). At this point we cross on to Cenozoic rocks and narrowing reflects thick Miocene sandstones on the east limb of a major syncline that stretches south towards the Alpine Fault. The syncline contains more than 8 km of sediments, mainly of Miocene-Pliocene age. The Miocene rocks contain numerous conglomerate bands and studies of composition show that conglomerate clast composition change up-section as the terranes of the Eastern Province rocks pass the end of the basin on the southwest moving Pacific plate (Fig.10). Clasts representative of the Alpine schist that currently forms the western zone of the Southern Alps only occur in the youngest conglomerates reflecting strong Pliocene-Pleistocene uplift. Upwards coarsening sediment packets containing a high proportion of volcanic arc clasts (of types now seen in Southland and Otago) can be see south of the main road near Murchison (1547229, 5372857). These rocks can be regarded as the ‘molasse’ of the ongoing phase of uplift in a strongly developed proximal part of a foreland basin. Folding of the syncline is of late Pliocene-Pleistocene age

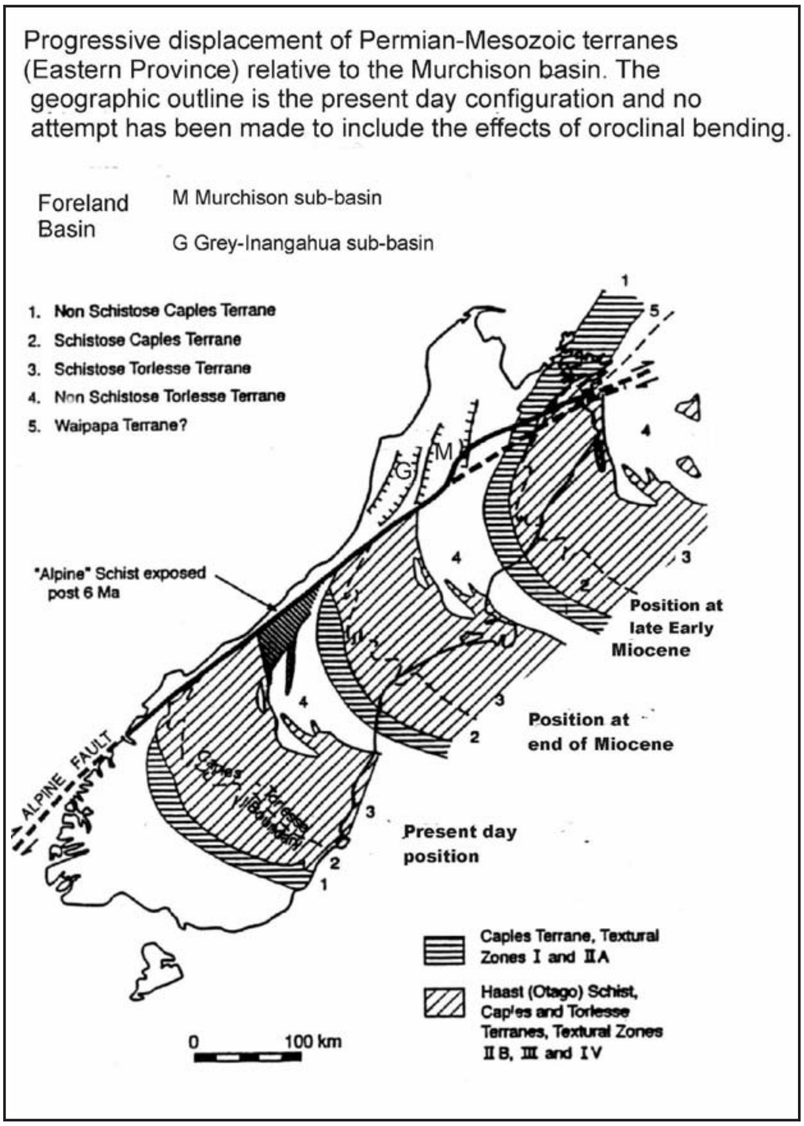

Fig. 10: Provenance map of the Murchison basin.

The town of Murchison lies in the centre of the syncline and further outcrops of Cenozoic rocks occur along the road to the west. On the west limb the Eocene-Oligocene section is thicker than on the east limb and includes important Oligocene limestone forming the Sphinx.

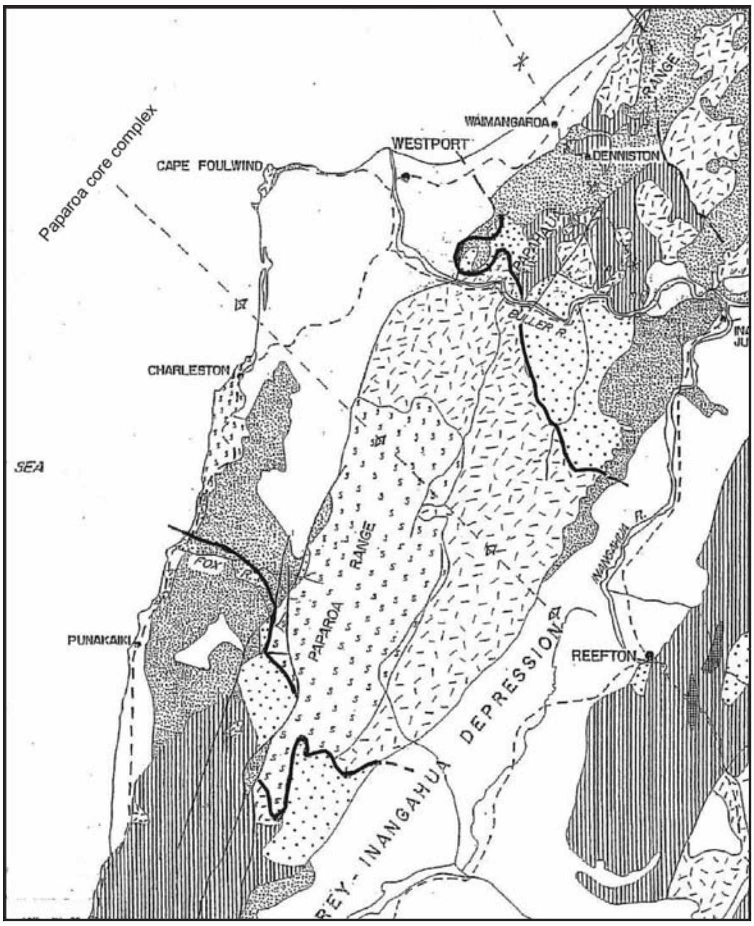

Fig. 11: General map of the Westport area. Pliestocene-Holocene rocks blank. Late Cretaceous to Pliocene stippled, Paleozoic sediments vertical ruling.

About 10 km west of Murchison we turn right and cross the Buller River by Sullivans Bridge and descend the upper Buller Gorge. The gorge is cut through the northern end of the Victoria Range. The range is young and probably still growing. It is largely made of granites of the Devonian Karamea Batholith with several in-faulted relics of Early Cenozoic cover. The fault line of the White Creek Fault that was responsible for the Murchison Earthquake of 1929 cross the road near White Creek (15333420, 5376380). The earthquake had an estimated magnitude of 7.8 and caused serious damage in Nelson, Westport and Greymouth. Murchison was destroyed. Most of the 21 people who died were is houses destroyed by landslides. Landslides also created 38 lakes, 21 one of which still exist. Lake Stanley, north of Cobb Valley is one of these. The maximum vertical displacement was 4.5 m with 2.5 m of sinistral displacement. The epicenter was about 65 km north of White Creek. An impression of the displacement can be seen in an offset water race on the northwest side of the road (with some difficulty due to forest regrowth).

We continue down the gorge past the old gold mining town of Lyell and cross the Buller River at a steel bridge with abutments in vertical Oligocene limestone. Further downstream, village of Inangahua was the locus of the 1968 Inangahua Earthquake of magnitude 7.1. Again landslips were the main cause of damage. One landslip temporarily dammed the Buller River but was washed away in a few days. The earthquake was marked by strong vertical acceleration and steel reinforcing in the rail bridge of over Inangahua River failed by vertical extension (a foretaste of the Christchurch experience). The activity was related to the Glasgow Fault, which, further to the north, thrusts Paleozoic basement rocks over Cenozoic sediments.

Inangahua lies in the Grey-Inangahua Depression (Fig.11), a late Cenozoic sedimentary basin that is a more distal portion of the foreland basin. Cenozoic rocks occur on the west flank of the basin for the next 12 km before we enter the Lower Buller Gorge near Berlins. The Lower Gorge cuts through the Paparoa Range. The eastern part of the range is in sediments of a Cretaceous extensional basin that is the surface expression of crustal extension that led to the development of the Cretaceous Paparoa metamorphic core complex (Fig. 12, 13). The sediments include the spectacular breccia seen at Hawks Crag (1498838, 5364522). The Crag itself is formed of breccia made almost exclusively of thermally metamorphosed Paleozoic Greenland Group rocks, but upstream (opposite the car park) they inter-finger with quartzo-feldspathic sandstones and granite bearing fluvial conglomerate. The two contrasted sediment types indicate a position near the active western margin of an asymmetric faulted basin (Fig 13). The sediments rest on Greenland Group to the northeast with the Stitts Tuff near the base. This has a U-Pb zircon age of 101 Ma.

The breccia, with a range of compositions, continue downstream for about 4 km until close ot the Ohikaiti River bridge a sliver of moderately deformed and thermally metamorphosed Greenland Group rock occurs between the breccia and the Cretaceous Buckland Granite (109 Ma) that shows ductile deformation. Tulloch and Kimbrough (1989) place the main detachment fault between the core complex and the cover just east of the Ohikaiti River (Fig 10).

If time permits, we will continue to Cape Foulwind (1472418, 5377135 to 1471925, 5376568). The Cape Foulwind Granite Suite has SHRIMP zircon ages of ~327 (Muir et al 1994) and trace element composition (high Ga, Zr, Zn) reminiscent of 'A' type granites. At Cape Foulwind there are three intrusive phases, Cape Foulwind, Siberia Bay, and Tauranga Bay granites forming a zone pluton. Preliminary isotopic data indicates Sr/Sr initial ratios in the range 0.7106 – 0.7189 and Nd values of +3.2-+ 0.4i. The fine-grained phase shows few phenocrysts and little sign of deformation. The coarse-grain phases have abundant k-feldspar phenocrysts that often show a preferred orientation. The fabric may, in part, be of Carboniferous 'magmatic origin, but in some areas it is clearly tectonic with well developed augen and bookshelf feldspars (Fig.14). Despite well developed planar fabric, a clear lineation is difficult to detect. Elongate biotite-rich metsedimentary enclaves have Greenland Group whole rock compositions.These rocks are considered to be part of the core complex. Return to Westport.

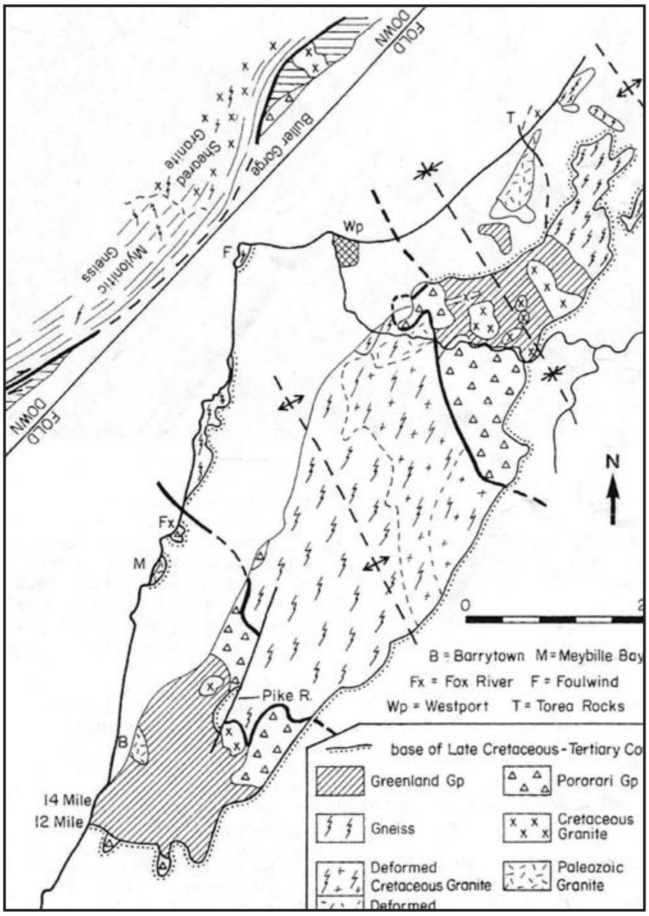

Fig. 12: Simplified map of the Paparoa core complex with a cross section viewed from the northwest (Based on Tulloch and Kimbroug, 1998)

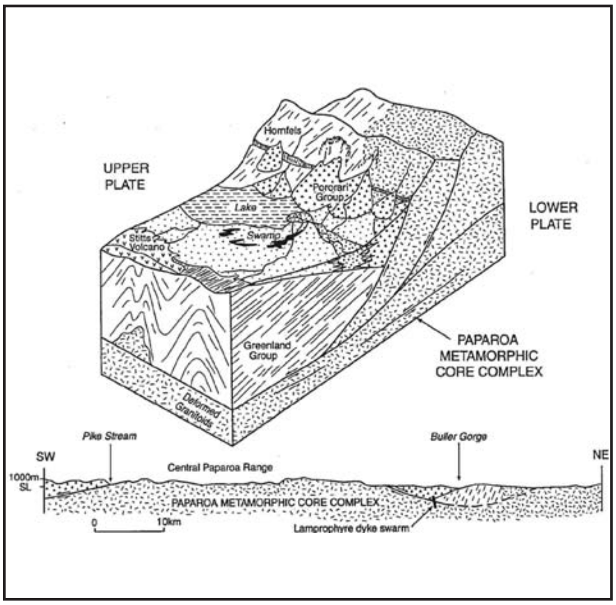

Fig. 13: Model for the origin of the Pororari Group.

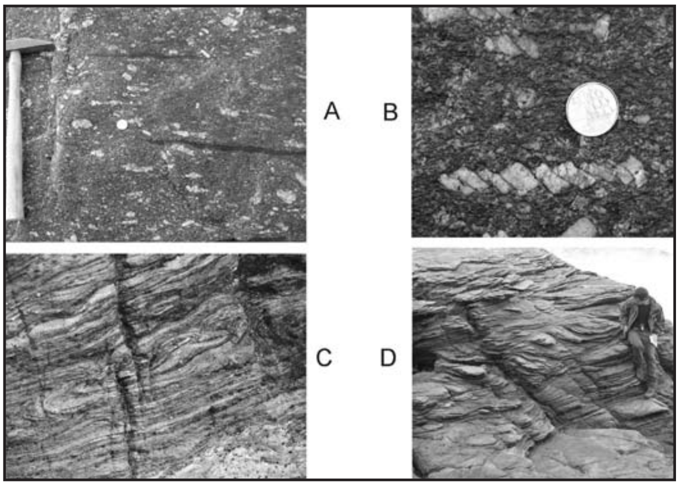

Fig. 14: Fabrics and structures in the Paparoa Core Complex. **A & B** at Cape Foulwind. **C & D** at Parsons Hill.

Day 4 Westport to Christchurch

The main objective today is to look at aspects of the Paparoa metamorphic core complex, the syn-tectonic sediments and the cover rocks. The outcrops are coastal and the tides are not ideal. We will attempt to look at Parsons Hill (coastal; 1471098, 5361122 Fig.14), Whitehorse Creek (road section; 1468058, 5350442, Fig.15), Morrisey Creek (coastal; 1467718, 5351302), Fox River caves (coastal; 1466044, 5345528), Meybille Bay (coastal; 1464376, 5341288) and Fourteen Mile Bluff (coastal; 1458578, 5315475). Some are more tide restricted than others and we will need to take on-the-spot decisions.

Background

Because of the uncertainty about the day's itinerary, the main rock groups are outlined below (in italics). These notes form a background to a selection of stops from those listed above.

Cenozoic rocks

Eocene and Oligocene rocks form a transgressive non-marine to marine succession unconformable on the basement. In general the deeper basins with thicker fill correspond to the present topographic highs and thinner successions occur closer to sea-level. Coal occurs widely in the basal sediments, but is thicker and of higher rank in uplifted basins. Taken together they provide a nice example of basin inversion. The reverse faults that define the ranges are re-activations of normal faults of Eocene and Oligocene age. As we drive south an escarpment of Oligocene limestone is commonly visible to the left (east) and for many miles the road follows close to the unconformity between granitic and metamorphic rocks and the cover.

Fig. 15: Low angle normal faulting in a pegmatite cutting core complex rock, south of Whitehorse Creek, Paparoa Core Complex.

Paparoa (Cretaceous) metamorphic core complex

The metamorphic rocks to the north were originally considered to be Precambrian and their relationship to the Cambro-Ordovician Greenland Group was much debated, particularly as they appeared to contain relics of metasediment that closely resemble Greenland Group and bodies similar to Paleozoic granites. A demonstration of a Cretaceous age for some deformed granitoids led Tulloch & Kimbrough (1989) to propose a core complex model with gently inclined detachment zones between the highly deformed core and the less deformed cover. The core, and genetically related mid-Cretaceous sedimentary basins (Pororari Group, see below) are overlain unconformably by Eocene sediments. Tulloch & Kimbough (1989) suggest that the northern Paparoa Range is underlain by an antiform in the detachment surface with a corresponding synform north of the Buller River (Note the present topography is controlled by late Cenozoic folding and faulting with trends almost *perpendicular to the structure of the core complex. However research by Nick Riordan suggests that NW-SE structures affected sedimentation too).*

The core complex pre-dates the oldest ocean crust in the Tasman Sea (~85 Ma) and it is thought to represent the initiation of the crustal extension that led to break-up. The challenger Plateau, northwest of the South Island is a large area of thinned continental crust that is linked to the Lord Howe Rise. The initiation of Cretaceous extensional basin formation is very close in age to the end of active subduction on the eastern margin of New Zealand, with the death of a spreading ridge and the annexation of the New Zealand crust by the northeast moving Pacific plate.

The core contains rocks as young as the 109 Ma Buckland Granite and the Pororari Group in the Buller Gorge has the 101 Ma Stitts Tuff near its base. Spell et al (2000) have made a comprehensive Ar-Ar study of the cooling history of the core complex that is consistent with these U/Pb SHRIMP ages.

Pororari Group

On the West Coast of the South Island outcrops of mid-Cretaceous sediments are grouped into the Pororari Group. The most extensive occurrences are two WNW-ESE trending basins on either flank of the Cretaceous core complex. Palynological studies indicate that the bulk of the Pororari Group is of mid to late Albian age: and tuffaceous sediment from near the base of the Group yield U-Pb zircon SHRIMP ages consistent with that date.

The fault controlled basins developed above low-angle detachment faults associated with a mid Cretaceous metamorphic core complex (Tulloch & Kimbrough, 1989) and the trend of the basins is approximately perpendicular to the NNE trend of stretching lineations in the underlying metamorphic rocks.

The most diverse range of sedimentary facies occurs in the southern half-graben system, where over 2000 m of strata have been divided into three facies assemblages (Laird, 1995). Coarse basin margin breccia facies representing debris flows and sheet flood deposits of alluvial fans laterally into sandstone debrites and turbidites that interfinger with lacustrine carbonaceous mudstone. Conglomerate compositions, in detail, strongly reflects local catchments and in general shows an upward change from Greenland group dominated conglomerate and breccias to deposits with abundant granitoids including the 109 Ma Buckland Granite.

Paleozoic cover rocks

A short distance south of the Fox River, undeformed Devonian granite is well exposed at Meybille Bay. Although the contact is not exposed here, the Paleozoic granites cut folded sediments of the Buller Terrane. The latter can seen at Fourteen Mile Bluff, where they lie in the core of a WNW trending anticline. The Greenland Group is a thick succession of grey sandstone with good 'turbidite' internal structures. They are very similar in composition and character to rocks of same age in western Victoria (Australia), northern Victoria Land and Marie Byrd Land (Antarctica). All these areas show similar style of folding and a similar range of cleavage ages around the Ordovician-Silurian boundary, ages typical of the Benambran Orogeny of Victoria. The trend of the folding here is anomalous and the folds normally trend NNE-SSW, sub-parallel to the Anatoki Fault. Very similar rocks form the lower part of the succession east of the Karamea Batholith (e.g. in upper Cobb Valley), but east of the batholith the Benambran folding has not been identified. In a rather similar way, the Melbourne Zone of central Victoria shows no Benambran deformation although is it developed in the Bendigo Zone immediately to the west. These differences may relate to the differing character of the basement.

Beyond Greymouth we need to move more quickly. If possible we will go east via Moana and Lake Brunner, and drive along the line of the plate boundary and cross it at Inchbonnie, (1474651, 5269088) near the Taramakau River where there is a well mark fault trace (Fig 16). This locality is important. South of the Taramakau much of the oblique convergence between the Pacific and Australia plates is expressed at the Alpine Fault involving both thrust and strike slip sectors. North of this point the Alpine Fault is less active and a large proportion of the dextral relative motion takes place on the strike slip of the Hope Fault that runs eastwards to the sea north of Kaikoura. The last movement on the Hope fault was a dextral offset of 2.4 m in 1888. The Hope Fault is almost tangential to the small circles about the present rotation pole.

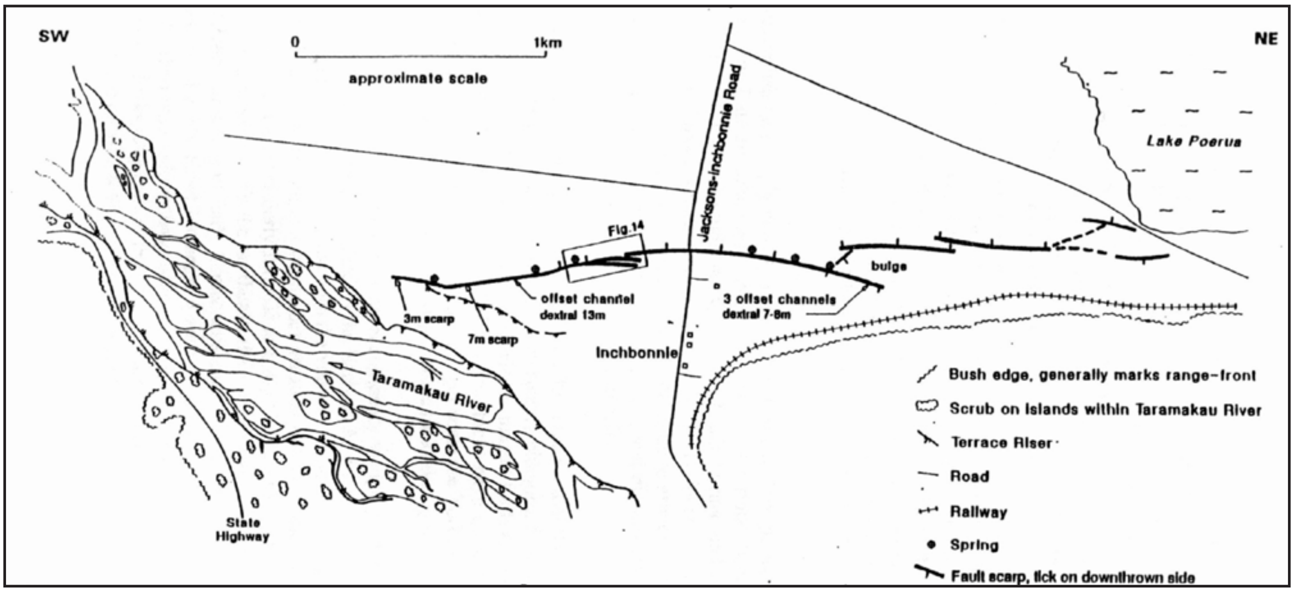

Fig. 16: Fault trace of the Alpine Fault at Inchbonnie, near Jacksons.

From the crossing of the Alpine fault eastwards to Christchurch and beyond the basement is the Permian to Cretaceous composite accretionary complex, the Torlesse assemblage. The section we traverse is almost entirely of Triassic rocks, with possible Jurassic rocks east of Porters Pass. As far as can be determined, these rocks form the full thickness of the continental crust in eastern New Zealand and represent a massive addition to the margin of Gondwana prior to break-up. The sandstones are predominantly quartzo-feldspathic with a lesser and variable volcanic component. Composition and grain size vary little over the period Permian to mid-Cretaceous. Detrital composition and U-Pb zircon ages from sandstone and particularly conglomerate clasts indicate provenance from a succession of active continental-margin arcs (Wandres & Bradshaw, 2005). The youngest detrital components are typically only a little older than the depositional age indicated by fossils (Adams et al. 2009).

Slices of rocks, considered to be the original oceanic basement, pillow lavas, red chert and limestone, have fossil ages older that the enclosing sediments. They include Late Carboniferous, Permian and Triassic limestone with conodonts, fusulinid foraminifera, and shelly macro-fossils. They represent the age of the ocean floor on which the detritus was deposited.The broad Esk Head Mélange (Fig. 1) separates the older Permo-Triassic portion in the south west(with carboniferous and Permian oceanic basement) from the younger Late Jurassic-Lower Cretaceous portion to the northeast outboard side (with Triassic and ?younger basement).The structure of the Torlesse rocks, due to their uniformity and lack of marker horizons, is difficult to work out. Evidence of early recumbent folding and tectonic imbrications is indicated in rocks that were still weak and hydrated. Bedding parallel extension is commonly developed). This deformation was followed by low temperature moderate to high pressure metamorphism. Further deformation occurred in the Cretaceous and Late Cenozoic and is ongoing.

The main road continues east along the line of the Hope Fault until it turns south up the Otira River. Gradient increase towards Arthurs Pass and culminates in a steep climb through the Otira Gorge that ends in a high viaduct built to avoid a major rock fall on the north side. Beyond the Main Divide the rainfall decreases rapidly and the road continues at a high level through the Canterbury High Country to a second pass (Porters Pass) where a steep descent leads to the Canterbury Plains. If time permits, we will stop to view the curiously folded Cenozoic rocks in the Castle Hill structural basin (Fig. 17). These rock were part of the Canterbury sedimentary basin before the uplift of the Torlesse and Craigieburn Ranges in post Middle Miocene times. The bounding faults of these ranges are still active. The succession comprises a transgressive Late Cretaceous to Oligocene succession that culminated in the development of widespread limestone. The Miocene is regressive and concludes with conglomerate of Torlesse cobbles derived from uplifted ridges further to the west.

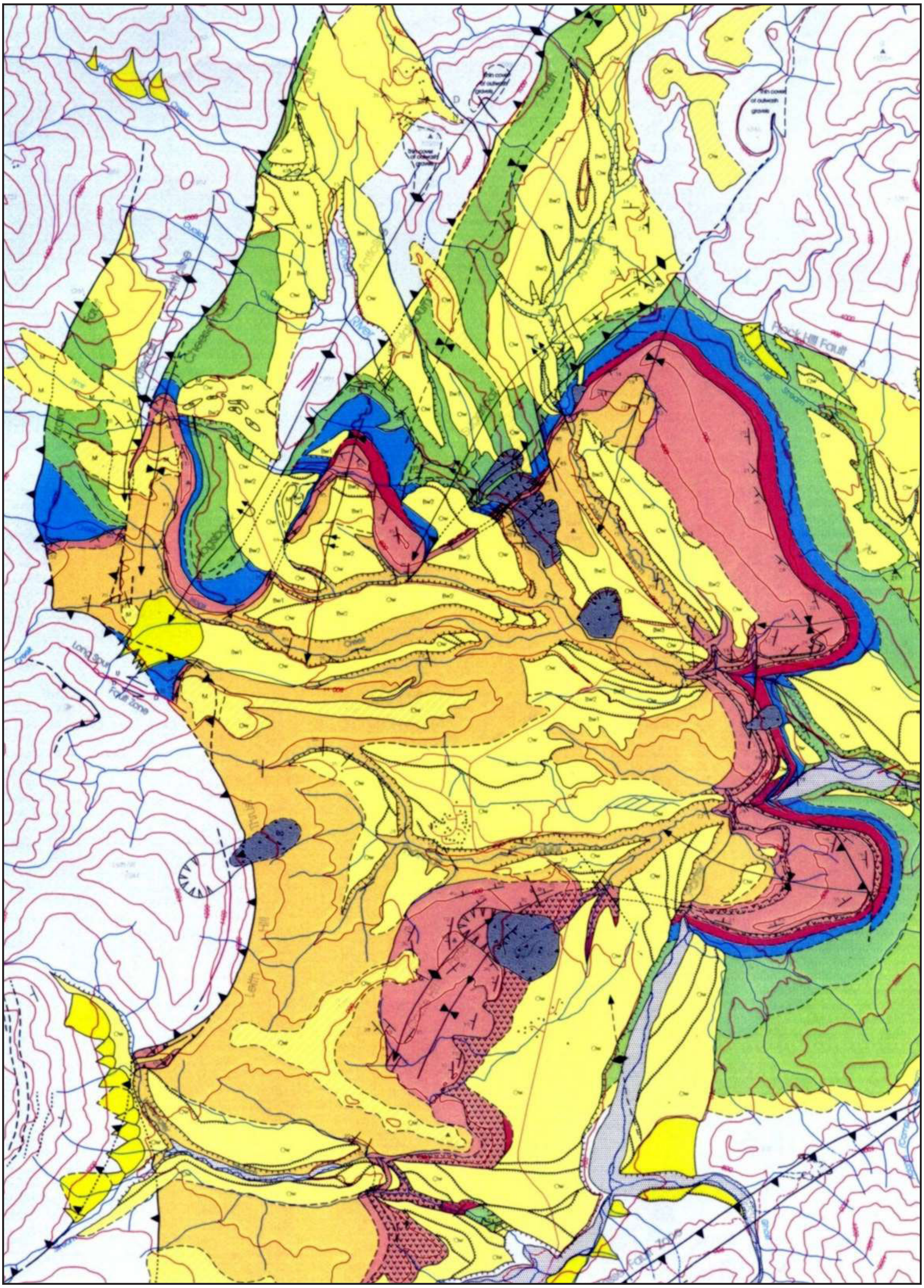

Fig. 17: Geology of the Castle Hill structural basin.

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A full reference list for all the data and ideas about the geology and development of this region would be very long. I hope that this shortened list of papers (and the references therein) will provide a pathway into the literature for those who wish to follow-up in more detail.

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