### A brief introduction to the geology of the South Island (New Zealand)

By Francesca Ghisetti (2007) with significant modifications by Dave Prior (2012)

#### References

There is a vast literature on the geology of the South Island. The following text focuses on a few aspects and gives a summary overview. It has been compiled from the following publications:


**NB:** Exercises and field classes will provide insights and progressive understanding of the complex geological history of New Zealand. You will find useful to read and re-read the following section as you acquire more information on field geology from maps and from your personal experience. In the following you might encounter some terms you are not familiar with. You are welcome to ask for more explanation when needed!
The New Zealand continent (Zealandia) extends over a large area in the South Pacific (Figure 1). The continental crust in this region is about one third the area of Australia, but most of the continental shelf edge is submerged to depths of ≤ 2000 m. Though continental, the crust is submerged because average crustal thickness is ≤ 25 km. The New Zealand Islands (Figure 2) are emergent because of high-rate, compressive deformation, associated crustal thickening and uplift that have given rise to the Southern Alps in the last 5 Ma.

New Zealand as we see it today has been shaped by recent tectonic events, but the geological record preserved onshore and offshore makes possible to reconstruct a complex history of:

- Terrane accretion and amalgamation (Tuhua orogeny, mid Paleozoic and Rangitata orogeny, early Cretaceous) (Figure 3)
- Rifting (Cretaceous) consequent on break-up of Gondwana (Figure 4);
- Drifting as a passive margin (Cenozoic)
- Oblique collision-subduction (Kaikoura orogeny, Late Cenozoic-Present, Figure 5).

The tempo of geological activity in New Zealand is very high compared with much of the rest of the world. A great deal happens over comparatively short period of geological time. Because of this, New Zealand stratigraphy and tectonics are very dynamic.

When describing the geology of New Zealand, it is useful to distinguish basement from cover sequence.

The basement comprises mostly metamorphic and igneous assemblages and slightly metamorphosed sedimentary sequences, that have undergone a complex series of tectonic events, associated with the Tuha and Rangitata orogenies. These assemblages have been rotated, translated and internally deformed and are largely allochthonous, i.e. far (both in horizontal and vertical distance) from their original place of formation and/or emplacement.

The cover sequence comprises the terrestrial, transitional and marine sediments that were deposited on New Zealand crust since the spreading in the Tasman Sea and in the southwest Pacific, consequent on the break-up of Gondwana. These sediments span the later Cretaceous and the Cenozoic and are described in paragraph 2.2.

The basement geology of New Zealand can be described in terms of a number of tectono-stratigraphic Terranes (Figure 2), which were accreted to the margin of the supercontinent Gondwana during late Paleozoic and Mesozoic time.

The term terrane indicates a rock assemblage characterised by internal homogeneity in stratigraphy, tectonic style, and geologic history. Terranes are separated from one another by major faults, across which it is not possible to recognise the same stratigraphic units and/or geologic evolution. Terranes that are now found close to each other might have originated at different places. Terrane juxtaposition results from translations and rotations associated with subduction and oblique collision. Reconstruction of terrane movements is sometimes difficult, and therefore some of the terranes are named "suspect terranes".
These terrane assemblages are now offset along the Alpine Fault (Figure 2). We can distinguish a Western Province and an Eastern Province, separated by the Median Batholith (or Median Tectonic Zone) (Figure 2).

The present shape of the New Zealand continent is mainly the result of Cretaceous and Cenozoic tectonics (Figures 3, 4, 5 and 6).

Figure 1. From Sutherland (1999b). Note how the 2000 isobath effectively defines the limits of sub-continental crust (>20 km thick).
Figure 2. From King (2000)
During the Cretaceous (between 130-80 Ma) there was a change from subduction on the Gondwana margin to extension and rifting. The break-up of Gondwana in the mid-Cretaceous and the ocean floor spreading in the Tasman sea and southwest Pacific during Late Cretaceous-Paleocene led to formation of a number of extensional basins, filled with several km of syn-rift terrestrial to shallow marine sediments (Figure 4). Subsidence induced by rifting was accompanied by progressive regional marine transgression (late Cretaceous, about 80 Ma), with submersion of large areas by 60 Ma (Paleocene).

Tasman Sea spreading stopped in the late Paleocene (c. 56 Ma) and the New Zealand subcontinent became remote from any plate boundary (Figure 5a). Basin development was characterised by regional subsidence, with deposition of clastic and carbonate sediments.

A new extensional plate boundary propagated through New Zealand at c. 45 Ma (late Eocene) along the line of the Emerald fracture zone (Figures 5b, 5c and 6). The southeast Tasman and Emerald Basins (Figure 6) formed as mirror basins on the two sides of a spreading ridge that separated the Pacific from the Australia Plate during Eocene-Oligocene time. The Resolution Rift margin formed as a conjugate feature of the Campbell Rift margin at this time (Figure 6). The rifting propagated into continental crust at its northern tip, through systems of transtensive faults (e.g. Moonlight Fault) that controlled continental to transitional marine basins (Solander, Waiau and Te Anau basins, mid-late Eocene). In the late Eocene-Oligocene an alignment of extensional basins extended as far north as southern Taranaki (Figure 5c).
Mid-Cretaceous (90 Ma) reconstruction showing major basement provinces prior to the onset of seafloor spreading in the Tasman and Pacific oceans. Present-day coastline is included for reference, and 2000 m bathymetry as a proxy for the continental margin. The continental margins for the Lord Howe Rise, Norfolk Ridge and Chatham Rise were estimated after allowance was made for distributed extensional deformation in the Bounty Trough, New Caledonia Basin and Bellona Trough. The Australia-Antarctica finite rotation was interpolated from Royer and Sandwell (1989). Faults interpreted from gravity anomaly maps and major geological boundaries are shown as black lines.

Figure 3. From Sutherland (1999b).
Figure 4. From Sutherland (1999b)
Figure 5. Figures from 5a to 5e illustrate a snapshot of paleogeographic reconstructions at different time intervals. Redrawn from King et al. (1999).
Figures 5b. Redrawn from King et al. (1999).

Figures 5c. Redrawn from King et al. (1999).
See Figure 5a for legend.
Figures 5d. Redrawn from King et al. (1999).

Figures 5e. Redrawn from King et al. (1999).
See Figure 5a for legend and Figures 1 and 2 for present configuration.
Progressive change in the orientation of the Pacific-Australia plate motion vector after 12-10 Ma changed the plate interaction from extensional to compressional, leading to the present oblique collision-subduction margin across the South Island and to the south (Figure 5d and 5e). The collisional margin consists of:

1. the intra-continental right-lateral Alpine Fault (c. 600 km long) that cuts obliquely across the basement terranes (Figure 2) and the Eocene-Oligocene extensional basins

2. the Fiordland-Puysegur oblique subduction zone (ca. 600 km long)

3. the intraoceanic Macquarie Ridge Complex (ca. 1600 km long; see Figure 6). The Ridge is 80-100 km wide and rises to 6500 m above the surrounding seafloor.

The change from extension to compression is well recorded in the sedimentary wedge of the Te Anau, Waiau and Solander Basins, and in the compressional inversion of former extensional structures. (This aspect will be highlighted during the Borland field trip).

In the vicinity of the South Island, Cenozoic strike-slip faulting overprints earlier deformation, and is most clearly manifested by a 460 km dextral separation of the Maitai Terrane along the Alpine Fault (Figure 2).

Note that the terranes and their boundaries curve in towards the Alpine Fault in a manner consistent with dextral shearing.

The Alpine Fault is a remarkably linear, continuous feature that can be traced the length of the South Island, from Milford Sound to the coast near Blenheim.

Displacement rates for central and southern parts of the Alpine Fault (measured using offset Pliocene-Quaternary markers) are of the order of 25-30 mm/year (i.e. 60-80% of the Quaternary plate displacement rate, which is 38-40 mm/yr in the South Island).

The Alpine Fault has an apparent total dextral offset of c. 480 km (Figure 2), and total shortening across the structure is about 90 km in the last 6 M years.

Although the Alpine Fault in the central and southern South Island is currently accommodating a large proportion of plate boundary deformation, the timing of its inception and history of movement are poorly known. Early workers suggested a significant component of Cretaceous displacement, but there is growing evidence that all or most of the displacement has taken place since the late Oligocene-early Miocene (c. 25 Ma).
Global gravity anomalies (FAA) [Sandwell and Smith, 1997] and basin structures south of New Zealand. Numbers along fracture zones help to recognize conjugate fracture zone on either side of the plate boundary. Solander Trough corresponds to the basin limited southward by the Te Awa fracture zone and northward by the Tauru Fault. Very thick black line represents the Pacific-Australia plate boundary. Black lines represent other active structures. Thick continuous and dashed gray lines represent the Dun Mountain ophiolite belt and the offshore-associated magnetic anomaly, respectively. Thin lines represent inactive or secondary structures. Thin dot-dash line indicates the position of RRS prior to rifing of SETEB, as can be seen on gravity data [Sutherland, 1995]. Frame indicates location of Figure 2. DMOB, Dun Mountain ophiolite belt; MFS, Moonlight Fault System; RR, Resolution Ridge; SB, Solander Basin; Sol. V. Solander Volcano (Island size not at scale for better legibility); TF, Tauru Fault. Mercator projection. Insert: Location map. Large dot labeled “Aus/Pac” represents Nuvol 1A Australia relative to Pacific fixed pole of rotation [DeMets et al., 1994]. Rotation occurs clockwise at 1.1°/Myr. Undense landmasses are gray shaded. Thick lines represent plate boundaries, thin lines represent major fracture zones, the 2000-m bathymetric contour is indicated. ANT, Antarctic Plate; AUS, Australian plate; CR, Chatham Rise; H-K, Hikurangi-Kermadec Trench; NI, North Island; PAC, Pacific Plate; TJ, Aus-Pac-Antarctic Triple Junction; SEIR, Southeast Indian Ridge; SI South Island; SWPR, Southwest Pacific Ridge.

Figure 6. From Lebrun et al. (2003).
1 **Basement Terranes in the South Island**

At a regional scale (Figure 2) the volcanic, sedimentary, plutonic and metamorphic basement of New Zealand can be described in terms of:

1. Volcano-sedimentary tectono-stratigraphic terranes
2. Composite regional batholiths that intrude the terranes
3. Metamorphic and deformation overprints (schists, gneiss and mélanges) on the terranes and batholiths.

The ages of basement rocks vary from Middle Cambrian (c. 500 Ma) to late Early Cretaceous (c. 100 Ma). The youngest New Zealand granite in the western South Island has been dated at 82 Ma.

### 2.1.1 Volcano-Sedimentary Terranes

In the South Island these are subdivided into a Western and an Eastern Province, separated by the plutons of the Median Batholith.

#### WESTERN PROVINCE

**Buller Terrane**

This is the westernmost terrane in New Zealand, and it was the closest to the interior of Gondwana. It consists of variably metamorphosed Ordovician siliciclastic sandstones and mudstones, originally deposited on a continental margin. These units are deformed by upright folds with associated steep slaty cleavage.

**Takaka Terrane**

This comprises silicic-clastic, carbonate and volcanic rocks of Cambrian to Early Devonian age, with mélanges. The original tectonic environment was probably a primitive intra-oceanic island arc in the Cambrian that evolved into a continental passive margin in the Ordovician to Devonian. The boundary between the Takaka (Western Province) and Brook Street (Eastern Province) terrane has been intruded by the plutons of the Median Batholith.

#### EASTERN PROVINCE

**Brook Street Terrane**

This consists mainly of a Permian, subduction-related, basaltic volcanic pile and volcanic-clastic apron in a primitive intra-oceanic island arc assemblage. Up to 14 km of homogeneously E-dipping strata are preserved in parts of the South Island.

**Murihiku Terrane**

This comprises the Murihuku Supergroup, a 9-13 km thick Late Permian to Late Jurassic volcanic-clastic - sandstone-dominated - marine succession (plus subordinate conglomerates, mudstones and tuffs). Deposition is thought to have occurred in a long-lived basin, probably at the rear of a subduction zone. Murihiku rocks are metamorphosed to zeolite facies assemblages and deformed in a broad syncline that can be traced for a distance of c. 450 km through the South and North Islands.
Maitai Terrane
Maitai or Dun Mountain-Maitai Terrane, consists of the eastern, Early Permian Dun Mountain Ophiolite Belt, unconformably overlain by a late Permian to middle Triassic volcanic-clastic sedimentary sequence, which is up to 6 km thick (Maitai Group). The ophiolite and cover sediments are currently interpreted as having originated in a near-arc setting. HP-LT (high pressure-low temperature) metamorphism gave rise to Lawsonite-Albite-Chlorite assemblages.

Caples Terrane
This comprises a tectonically imbricated, weakly metamorphosed sequence of marine volcanic-clastic Permian-Triassic lithic quartzofeldspathic sandstones and mudstones (greywackes and argillites), with andesitic sandstones. The sequence is up to 5-7 km thick. Deposition occurred in a submarine fan deposit in lower trench-slope basins and on a trench floor adjacent to an island arc, before juxtaposition with the Rakaia Terrane. The contact with the Rakaia Terrane has been overprinted by metamorphism and deformation in the Haast Schist (Otago Schist Belt).

Rakaia Terrane
The Rakaia Terrane (Torlesse, in part, of traditional terminology) is dominated by turbiditic sandstones and mudstones of Permian to late Triassic age. Minor cherts, limestones and basalts of Carboniferous and Permian age represent an oceanic crust substrate on which the clastic rocks were deposited. It is very monotonous lithologically, but occupies a significant portion of New Zealand. Sandstones are inferred to be derived from an active continental volcano-plutonic arc. Metamorphic grade increases west into the Haast Schist.

2.1.2 Plutonic Rocks
Median Batholith
This is a long-lived, composite batholith, made up of dozens of 1-10 km size, gabbroic-granitic sub-alkaline Devonian to early Cretaceous plutons that have been variably deformed and metamorphosed. Plutons become younger to the west. These intrusions are thought to be remnants of magmatic arcs related to subduction at the Gondwana margin in the interval 375-110 Ma. The youngest pluton is the Separation Point Suite (c. 110 Ma). The eastern half of the Median Batholith has also been called the Median Tectonic Zone.

Karamea-Paparoa Batholith
This lies entirely within the Buller Terrane. Constituent plutons are dominated by Devonian-Carboniferous granites. Cretaceous plutons (110-115) Ma are also present in both the upper and lower plate of the extensional Paparoa Metamorphic Core Complex.

Metamorphic Core Complexes are geological structures consisting of a dome-like metamorphic basement and an unmetamorphosed cover. These are separated by a discontinuity (detachment) generally marked by ductile fault rocks (mylonites). These complexes show evidence of tectonic denudation and exhumation, with associated syn-extensional magmatism along low-angle normal faults.
Hohonu Batholith
Hohonu Batholith represents an episode of plutonism that was the closest to the Gondwana interior prior to Late Cretaceous-Cenozoic seafloor spreading. Plutons are granite-dominated, generally younger (82-110 Ma) than suites in the other batholiths. They record the transition from subduction to extension on the Gondwana margin.

2.1.3 Tectono-Metamorphic Overprints

Gneisses
These are common in western New Zealand, where they overprint the Buller and Takaka Terranes and some of the batholiths. They result from amphibolite-granulite facies conditions events during the Devonian and Cretaceous polyphase deformations. Some are restricted to the lower plates of the Cretaceous Paparoa and Fiordland Metamorphic Core Complexes.

Haast Schist
This belt (also named Otago Schist Belt) underwent polyphase deformation under pumpellyte-actinolite to amphibolite facies metamorphic conditions, overprinting the Caples and Rakaia Terranes. Most of this low-grade belt was at the Earth’s surface by 110 Ma (early Cretaceous). However, deeper amphibolite facies schists and gneisses have been exhumed along the Alpine Fault over the past 5 M years. The schists represent the deeply exhumed parts of the Caples-Rakaia accretionary prism.

An accretionary prism consists of faulted and folded material scraped off subducting oceanic crust and added to an island arc or continental margin at a subduction zone. The mass of deformed trench sediments and ocean floor sediments accumulate in wedge like slices on the underside of the overlying plate above a plate undergoing subduction. Thus, you may also find the term accretionary wedge.

In synthesis: The basement terranes of New Zealand are interpreted in terms of progressive Pacific-ward growth of the Gondwana-Pangea supercontinent by Terrane accretion and batholith intrusion at an obliquely convergent margin.

The Early Paleozoic Buller and Takaka Terranes were accreted to Gondwana in the Devonian (Tuhua orogeny). A regime of oblique transpression may have persisted along the New Zealand Gondwana margin from the Carboniferous to the Cretaceous, with pulses of magmatism (Median Batholith) and progressive development of the Caples-Haast Schist-Rakaia accretionary wedge.

The end of subduction and the passage to an extensional tectonic regime is traced by the rapid exhumation of mid-to-deep crustal gneisses in the 110-90 Ma Fiordland and Paparoa Core Complexes, by alkaline volcanism (c. 100 Ma), and by the development of fault-controlled extensional sedimentary basins (see next paragraph). This continental extension led to the onset of the Tasman Sea and Southern Ocean seafloor spreading from c. 85 Ma.

The entire New Zealand basement was subjected to renewed deformation in the Neogene with inception of the modern Australia-Pacific plate margin.
2 Sedimentary Sequences in the South Island

Apologies- a lot of this is written in the terminology of sequence stratigraphy. I have tried to add notes to explain things and will revise this more fully for next year.

The complete Cretaceous-Cenozoic succession that overlies different basement terranes in New Zealand can be considered a complete transgressive (relative sea level rise) –regressive (relative sea level fall) Megasequence , (known as the "Kaikoura Sequence"), ca. 100 M years long, interrupted by a number of regional unconformities (Figure 10) that can be recognised in the field, in seismic reflection profiles or from biostratigraphic determinations of missing sections.

Within the first order Kaikoura cycle, seven second-order depositional cycles are distinguished in New Zealand (Figure 10).

The sedimentary sequence of the first order depositional cycle is separated from the underlying basement rocks by a marked unconformity that formed over a considerable period of erosion and peneplanation following the Rangitata Orogeny.

Transgressive (during relative sea level rise) cycles (Cycles 1 to 4)

Second order cycle 1
In most cases, the oldest strata overlying the basement have a mid Cretaceous age (NZ Motuan Stage, Cm; these include synrift terrestrial deposits (e.g. northern Otago, West Coast), with depocentres controlled by active normal faults. The fault-controlled grabens evolved during a period of crustal extension prior to opening of the Tasman Sea. This succession comprises coarse-grained clastic rocks deposited in alluvial fans, meandering rivers and braided rivers, with local lacustrine environments (e.g. Puysegur Formation in western Southland, Pororari Group in Westland, Kyeburn Formation in Otago).

Second order cycle 2
The first major marine transgression occurred in eastern New Zealand at about 80 Ma, but in western New Zealand significant marine flooding only began in the latest Cretaceous (ca. 67-65 Ma). This transgression was related to Tasman Sea spreading, with synrift sediments in western basins, and passive margin sediments in eastern basins. The western basins are thought to have belonged to a transform zone linked to the Tasman Ridge (Figure 1). In the western basins the succession comprises terrestrial to shallow-marine facies. Stratigraphic units include the Ohai Group (Western Southland) and Paparoa Formation (West Coast). In eastern basins sequences were deposited in coastal plains and transgressive (sea level rising) shallow-marine to bathyal sedimentary environments. Significant units in Otago include the Taratu and Wangaloa Formations. The Tasman Sea extension continued across the Cretaceous-Tertiary boundary, with the end of rifting defined in the sedimentary succession by a widespread (but not universally present) regional unconformity related to protracted subaerial peneplanation, doming, and erosion, followed by accelerated subsidence at the end of the extensional regime.
**Second order cycle 3**

The period of post-rift subsidence (controlled by crustal thinning and cooling) is represented by terrestrial and marginal marine deposits followed by fully marine units. Examples are in the West Coast region (Brunner Coal Measure and Kaiata Formation), in western Southland (Nightcaps, Annick and Lower Balleny Groups) and in Otago (Abbotsford, Moeraki, Burnside, Katiki and Hampden Formations, Green Island Sandstone).
Figure 10. Redrawn and modified from King et al. (1999).
Second order cycle 4
A significant facies shift occurred about the Eocene-Oligocene boundary in many parts of New Zealand. This is testified by the generally highly calcareous nature of Oligocene rock, reflecting widespread submergence of former land areas and consequent reduction of available clastic detritus. This event is commonly considered to represent the culmination of passive margin development and encompasses the full age span of the Landon series (Oligocene to earliest Miocene).

However, during this interval local deformation was associated with the initial development of the Australia-Pacific plate boundary. In western Southland and in the West Coast region local basins subsided within a zone of extensional down-faulting (Moonlight rift), linked to the northward propagation of Emerald Basin spreading (Figure 6).

The base of the carbonate succession of this second order cycle 4 is considered a regional marine flooding surface, and is often marked by a depositional hiatus (a gap or interruption in space, time, or continuity). Prominent greensands are often present at this stratigraphic level, indicating a considerable reduction or starvation of clastic supply caused by the relatively sudden regional marine transgression. Carbonate-dominated successions include the Nile Group in the West Coast. Marine transgression was generally earlier in the east and became progressively younger westward. In many areas the carbonate-dominated interval is very thin compared with the clastic successions below and above and contains a number of unconformities, disconformities or depositional hiatuses (including the Marshall unconformity). Thus, this entire carbonate interval can be considered a condensed sequence within the first order megasequence (Figures 9 and 10).

*Higstand (highest relative sea level) and regressive (during relative sea level fall) cycles (Cycles 5 to 7).* The Neogene (Miocene-Holocene) succession in most New Zealand basins is thick, clastic-dominated and regressive. This interval reflects the progressive infilling of previously formed marine basins during stages of compressive deformation.

Second order cycle 5
The base of this cycle is marked by the first influx of primarily terrigenous sediments above the carbonates of the second order cycle 4. This event marks the onset of uplift and erosion of clastic source areas, coincident with the inception of the convergent plate boundary through New Zealand. The basal portion of second order cycle 5 is given by sandstones in western Southland (Takaro Formation), by flysch-like sequences in the Murchison Basin (lower Mangles Formation), and by mudstones and sandstones in the Canterbury Basin (Mt Harris Formation).

The top of this cycle is a major transition in tectono-sedimentary patterns (especially in western New Zealand), which occurs at the Lilliburnian-Waiauan (Sl-Sw) boundary (mid Miocene). This transition probably relates to a change in plate boundary configuration and to the initiation of subduction along the Puysegur Trench. This event is marked by local compressional inversion of earlier faults and by erosion in the West Coast.

Second order cycle 6
This cycle occurs between the Lilliburnian-Waiauan (Sl-Sw) unconformity described above and a major unconformity at the Miocene-Pliocene boundary. This event marks a significant
tectonic pulse, manifested by uplift and erosion in many basins. This cycle comprises coarse-grained deposits, mostly marine.

**Second order cycle 7**

From Pliocene to Recent, sedimentation is characterised by a considerable volume of coarse clastic sediments, and is overall strongly regressive. This sedimentation reflects the high rates of convergent margin uplift, erosion and outpouring of clastic sediments in most New Zealand basins during the Plio-Pleistocene. Adjacent to the rising Southern Alps thick coarse grained fluvial sediments are developed.