by Hamish Campbell, Alex Malahoff, Greg Browne, Ian Graham and Rupert Sutherland

New Zealand Geology

GNS Science, 1 Fairway Drive, Avalon, P.O. Box 30368, Lower Hutt, New Zealand. E-mail: h.campbell@gns.cri.nz; a.malahoff@gns.cri.nz; g.browne@gns.cri.nz; i.graham@gns.cri.nz; r.sutherland@gns.cri.nz

New Zealand is renowned for its diverse geology and dynamic tectonic setting astride an active segment of the boundary between the Pacific and Australian plates. New Zealand is an emergent fraction (5%) of the largely submerged 'continent' of Zealandia which is half the size of Australia. Zealandia is comprised mainly of continental crust but because it is less than 30 km thick, it is largely below sea level. Zealandia's origins relate to eastern Gondwanaland from which it rifted during the Late Cretaceous to early Cenozoic, with formation of the Tasman Sea floor. Continental Zealandia may be thought of as part of the Australian/Gondwanaland mineral estate, and it is rich in natural resources. However, it was stretched and thinned for 100 Myr, culminating in the Eocene with development of the modern plate boundary. New Zealand largely owes its emergence to plate collision processes within the past 25 Myr.

Introduction

This general account of New Zealand geology emphasises only a few aspects of broad current research interest: mineral and petroleum prospectivity, the Alpine Fault and current tectonic activity including rifting, subduction and the Christchurch earthquakes.

Many of the concepts, facts and images presented herein are drawn from a much broader, more detailed reference work on New Zealand geology (Graham, 2008). Concerns and issues relating to natural resources (coal, oil, natural gas, water, and minerals), natural hazards (earthquakes, volcanic eruptions, landslides, tsunamis, storms) and natural systems (climate, environment, biosphere, society) dictate direction of research and development in New Zealand earth sciences.

New Zealand is recognised as a small emergent part of a largely submerged 'seventh continent' – Zealandia (Figure 1), that is submergent because of tectonic subsidence caused by Cretaceous–Paleogene rifting, not global rise of sea level. Paleozoic and Mesozoic rocks of New Zealand were forged by inter-plate processes on the margin of Gondwanaland, during the Cambrian to Cretaceous (510–110 Ma).

From Cretaceous–Eocene time (110–50 Ma), extensional tectonics separated Zealandia from Gondwanaland attended by widespread subsidence creating the Tasman Sea and South Pacific oceans. Eocene–Oligocene (50–25 Ma) resumption of subduction and plate collision N of Zealandia developed a new extensional plate boundary configuration through southern Zealandia. During maximum

submergence of Zealandia at c. 23 Ma (earliest Miocene) there may not have been any land in the area now occupied by New Zealand (Campbell and Hutching, 2007; Landis et al., 2008).

Since the Miocene New Zealand has been pushed up and Zealandia divided into northern and southern crustal plates so creating the Alpine Fault and subduction zones beneath Fiordland and eastern North Island.

Extent of New Zealand

The 'Extended Continental Shelf' (ECS) of New Zealand lies within the submarine boundary, recognised by the United Nations, that delineates sovereignty over the seabed spanning from 159°E–166°W, and 23–58°S (Figure 1). The offshore area of New Zealand is c. 24 times its land area.

The land area of 267,707 km², is about the same size as the United Kingdom or Japan. The highest point above sea level is 3,754 m (Mount Cook/Aoraki) and the lowest point (onshore) is 462 m below sea level (bottom of Lake Hauroko).

New Zealand consists of the North and South islands that are separated by the 20 km wide (minimum) Cook Strait, Stewart Island and subantarctic Auckland, Campbell, Snares, Antipodes and Bounty islands to the S, the Chatham Islands to the E, the Kermadec Islands to the N, and a host of tiny islands proximal to the two main islands. New Zealand is more than 1,600 km long and up to 450 km wide, with a coastline of more than 18,000 km. About 75% of the land is over 200 m above sea level. In the South Island 223 named peaks are more than 2,300 m above sea level.

New Zealand on a plate

Most of New Zealand lies NE–SW, reflecting the principal 'grain' of the country, parallel to and straddling the active segment of the Pacific–Australian plate boundary. The plate boundary (Figure 2) runs down the eastern side of the North Island, some tens of kilometres offshore, and is defined by the Tonga–Kermadec Trench and Hikurangi Trough. The North Island is on the Australian Plate.

The boundary swings around the SE end of the North Island and cuts through the northern half of the South Island along the Hope Fault (Rattenbury et al., 2006). The Wairau, Awatere, Clarence faults are active sub-parallel faults in this Marlborough region but the Hope Fault is most active and the best proxy for the boundary. The Hope Fault runs along the southern margin of the Seaward Kaikoura Mountains inland towards Hanmer Springs, to cross the Southern Alps where it joins the Alpine Fault near Inchbonnie on the West Coast of the South Island. The Alpine Fault can be traced on land from the entrance of Milford Sound at its southern end, to Tophouse near Lake Rotoiti. It continues to the Cook Strait coast as the Wairau Fault. South of Milford Sound, it skirts around

Figure 1 Zealandia in relation to Australia, New Zealand, New Caledonia, Fiji and the SW Pacific Ocean. This is a gravity-derived bathymetric map. Shading depicts water depth; the darker the colour, the deeper the water. The 2,500 m isobath, located at c. the boundary between green and blue, is taken as a proxy for delimiting the location and extent of the largely submerged Zealandia continent. It is the assumed boundary between oceanic crust and continental crust.

Fiordland some tens of kilometres offshore, and connects with the Puysegur Trench.

The South Island, S of the Hope Fault and E of the Alpine Fault, is the deforming edge of the Pacific Plate. The Marlborough and Nelson regions and much of the West Coast are on the opposing boundary of the Australian Plate. This plate boundary zone running through New Zealand involves highly-oblique right-lateral collision that varies along the zone causing differences in geology and topography.

In eastern and southern North Island, and NE South Island, continental crust on the Australian Plate is in collision with oceanic crust on the Pacific Plate. The resultant effects relate to normal subduction processes, including 'Pacific Ring of Fire' volcanism in the North Island. The Pacific Plate is descending beneath the Australian Plate from E–W at 4–6 cm/year. Subduction-related seismicity can be recognised as far S as Amberley, c. 30 km N of Christchurch.

In general, things are different in the remainder of the South Island from what is happening further N. The collision involves continental crust on the Australian Plate and continental crust on the Pacific Plate.

Figure 2 New Zealand and the modern day plate boundary showing subduction zones and average rates of plate motion.

The Southern Alps are the result, analogous to the European Alps or the Himalayas.

In the very SW of the South Island, continental crust on the Pacific Plate is in collision with oceanic crust on the Australian Plate. This is the reverse of the situation in the North Island. The Australian Plate is approaching the Pacific Plate from SW to NE at 3–4 cm/year and is obliquely twisted beneath Fiordland. Its motion on this subduction thrust caused the Mw 7.8 Dusky Sound earthquake of July 2009 – the largest event in New Zealand since the Mw 7.8 Napier earthquake of February 1931 (Beavan et al., 2010a). The nearest volcano to southern South Island is Solander Island, 50 km SW of Te Waewae Bay. Solander last erupted more than 200 kya (Mortimer et al., 2008) and would have been as big as Mount Ruapehu in the North Island.

The shape of New Zealand

Northland projects to the NW, Mount Taranaki creates a very pronounced boss to the shape of central western North Island, and Cook Strait breaks the country in two. Mount Taranaki is an active, 2,518 m high, subduction-related, stratovolcano that lies, with its predecessors, well W of the active arc, which is characterised by the active White Island, Tongariro and Ruapehu volcanoes. Mount Taranaki may be an expression of residual or remnant volcanism that best relates to a previous orientation of the modern volcanic arc. Eastward roll-back of the arc has occurred within the past few Myr, producing a double or coupled arc; an older arc to the W, the modern arc to the E (Figures 1 and 2). The most recent significant eruption of Mount Taranaki was in 1755. Based on its interpreted history, it erupts every 100–300 years and has done so for at least 120 kyr.

The orientation of Northland relates to active continental rifting (or back-arc rifting) of the Taupo Volcanic Zone (TVZ). If Ruapehu is the fulcrum, the 'V' described by Northland and East Cape (eastern

North Island) is a gape resulting from rotation (Figure 2). The rate of E-W rifting of the TVZ at Rotorua is 8–10 mm/year. This motion is being accommodated by active normal faults in the zone, such as the Edgecumbe Fault which last ruptured in 1987.

The Cook Strait region includes the Marlborough Sounds in the NE of the South Island and the South Taranaki Bight to the N. It may be thought of as an artifact of plate collision. In crustal terms, it is a low region developed within continental crust on the Australian Plate that is being drawn down tectonically, as a function of the descending Pacific Plate beneath. The Cook Strait region is where the mechanics of plate collision switches from continent–ocean collision to continent–continent collision. In a sense, the tectonic forces in this region are too weak to raise the crust above sea level. This means that the Marlborough Sounds are a drowned landscape, not just because sea level has risen since the Last Glacial Maximum, 24–18 ka, but because the crust is sinking.

With the advent of lasers, satellites, GPS etc., the manner and rate of deformation of New Zealand is readily determined, and it is interesting to speculate on what New Zealand will look like in the future (Figure 4). New Zealand is subject to 16,000–18,000 recorded earthquakes/year. On average there are 3–6 earthquakes/year that are greater than magnitude 6, a magnitude 7 or greater earthquake occurs about every decade, and a magnitude 8 or greater earthquake occurs about every century.

Zealandia (83–23 Ma)

New Zealand has an extensive continental shelf referred to historically as the ‘New Zealand Submarine Platform’ or ‘Tasmantis’. With the advent of bathymetric mapping based on satellite-captured gravity data in the 1990s, and other geophysical data, it was realised that New Zealand is part of an extensive area of continental crust (Figure 1) referred to as ‘Zealandia’ (Luyendyk, 1995) and equal to India or more than half of Australia.

Zealandia rifted away from eastern Gondwanaland with formation and growth of oceanic crust in the Tasman Sea. The oldest basalt on the Tasman Sea floor is c. 83 Ma, and the youngest is c. 53 Ma. These ages, based on paleomagnetic signatures, imply that spreading

Figure 3 Zealandia reassembled: reconstruction of eastern Gondwanaland showing Zealandia, New Zealand and New Caledonia, at 90 Ma. Rifting had commenced at 125 Ma but clean separation was not accomplished until c. 83 Ma. The Tasman Sea spreading ridge formed along the split.

Figure 4 The deformation of New Zealand as it might appear in 4 million years' time.

in the Tasman Sea ceased at least 50 Ma, and that the Tasman Sea floor formed over 30 Myr during Late Cretaceous–Early Eocene.

As Zealandia rifted NE away from Gondwanaland, it was stretched and cooled, slowly losing buoyancy and subsiding below sea level. Much of Zealandia is 1,000–2,000 m below sea level. The 2,500 m isobath is a rough proxy for the boundary between continental crust and oceanic crust. The crust of Zealandia is mostly only 10–25 km thick.

Zealandia includes the Campbell Plateau S of New Zealand, the Challenger Plateau to the W, the Chatham Rise to the E, and the Lord Howe Rise, Norfolk Ridge and Three Kings Ridge to the N. The largest emergent areas are New Zealand and New Caledonia.

Rocks attributed to New Zealand's Zealandian geological history prior to the impact of compressional plate boundary tectonism, are the mainly sedimentary formations, with minor volcanics, of Late Cretaceous–earliest Miocene (83–23 Ma) (Figure 5). They represent a transgressive marine sequence relating to the slow sinking of Zealandia and increasingly oceanic conditions. The older Zealandian rocks include widespread Late Cretaceous–Eocene coal measures, whereas the younger Zealandian rocks are latest Oligocene–earliest Miocene, predominantly limestone and greensand.

New Zealand (23–0 Ma)

A profound tectonic change occurred in the earliest Miocene, although the beginnings may be traced to the Eocene in the far N and S of New Zealand. Movement at the modern-day active plate boundary was very slow during Eocene and Oligocene time in New Zealand, but rapidly accelerated at the beginning of the Miocene (Cande and Stock, 2004).

The Fiordland subduction zone was initially formed in Early Miocene time (Sutherland et al., 2010). However, continental crust of the Australian plate was too buoyant to be subducted, resulting in progressive formation and lengthening of the Alpine Fault along the Eocene continent–ocean transition as oceanic crust was subducted at the Puysegur Trench but continental crust was displaced sideways (Sutherland et al., 2000). An estimated 800+ km of plate motion and 60 km of shortening has taken place since earliest Miocene across the South Island (Sutherland, 1999; Cande and Stock, 2004), resulting

Figure 5 Distribution of exposed rocks relating to Zealandia, 83–23 Ma.

in crustal thickening and dramatic mountain building leading to rapid erosion.

This Miocene–Recent crustal collision is responsible for New Zealand’s oil, gas and water reserves. The flood of clastic sediment derived from uplift has produced a substantive and widespread regressive sequence. Offshore, this sediment has infilled at least 20 sedimentary basins within New Zealand’s EEZ. It buried organic-rich Late Cretaceous–earliest Miocene source rocks so that much of New Zealand’s oil and gas is derived from the Cretaceous–Eocene coal. As yet, only the Taranaki Basin, has been explored in detail, and it is the only one being exploited.

Subduction-related volcanism has provided airborne nutrients to improve the fertility of the land for agriculture and forestry. The New Zealand Earthquake Commission (EQC), and the GeoNet Project, the natural hazard surveillance arm of GNS Science, New Zealand communicate hazard mitigation incentives and GeoNet provides information about processes below the surface. GeoNet monitors all active volcanoes in New Zealand, records all earthquakes in real time, and monitors tsunami (see www.geonet.org.nz).

As subduction rolled back to the E during Miocene–Recent, successive volcanic arcs in northern New Zealand have been subject to epithermal mineralisation creating a source of Au and Ag, especially in the Hauraki Goldfields, Coromandel Peninsula. Erosion of rocks derived from late Pleistocene eruptions of Mount Taranaki has produced extensive ironsand (dominated by titanomagnetite) deposits along the W coast of central North Island.

Subduction-related volcanism in the Taupo Volcanic Zone (TVZ) is superimposed on a continental rift (or backarc basin) which includes a string of at least eight rhyolite dominated Pleistocene super-volcanoes (Leonard et al., 2011). The youngest is the Taupo caldera, which last erupted in 233 AD (Taupo Eruption). However, the most recent significant, but relatively minor eruption, the Tarawera Eruption of 10 June 1886, was from the Okataina caldera, near Rotorua, and involved basaltic magma, not rhyolite.

These eruptions can be voluminous and are responsible for substantial blanketing of the central North Island landscape by pyroclastic flows (ignimbrites), pumice and ash deposits. More distal products can be found thousands of kilometres away. These TVZ rhyolite volcanoes are also the source of New Zealand’s geothermal energy resources. Recent volcanic eruptions in New Zealand relate to subduction-related andesitic volcanism. The most recent, just 7 minutes long, was from the Crater Lake on Mount Ruapehu on 25 September 2007. New Zealand’s most active volcano, White Island, last erupted in July 2000 (Leonard et al., 2011).

Rifting of continental crust in the TVZ (Figure 6) involves stretching of the crust which has made its mark on the edges of the rift zone, including Auckland. The basaltic volcanic field beneath Auckland, may well relate to this process. Some 53 volcanic cones and maars dotting the Auckland landscape are mostly monogenetic, and apparently all erupted within the past 250 kyr, most recently at Rangitoto c. 600 years ago (Edbrooke, 2001).

Figure 6 The Taupo Volcanic Zone (TVZ; defined by the red line) located SW of the Bay of Plenty, central North Island, is an active back-arc rift zone within continental crust (Australian Plate). The TVZ is one of the most geothermally active zones in the world. At least eight rhyolite calderas (named) are recognised. Andesite volcanoes (e.g., Ruapehu, White Island) associated with westward subduction of the Pacific Plate, are superimposed on the rift.

Gondwanaland (510–83 Ma)

Uplift of New Zealand and subsequent erosion has revealed the basement geology, especially in the South Island (Figure 7) where Western and Eastern provinces are separated by a long-lived magmatic complex, the Median Batholith (Figure 8). Granites of the latter relate to the Cretaceous rifting of Zealandia from Gondwanaland.

Figure 7 Distribution of exposed 'basement' rocks inherited from Gondwanaland (red), 510–83 Ma, and all younger rocks and sediments relating to Zealandia and New Zealand (grey).

The two provinces are dominated by weakly to moderately metamorphosed sedimentary (dominantly marine) and Paleozoic–Mesozoic volcanics. Both provinces are dominated by subduction-related volcanic arc suites, ocean floor associations and accretionary sedimentary wedges. These are organised into elongate belts that have been mapped as tectonostratigraphic units (terrane), generally older to the W, younger to the E. This age progression is compatible with ocean ward growth of the eastern Gondwanaland margin with respect to the western margin of the Panthalassa (or Paleo-Pacific) Ocean.

The Western Province comprises early Paleozoic sedimentary and volcanic rocks and is divided into the Buller and Takaka terranes. Buller Terrane sedimentary rocks are intruded by granite whereas the oldest rocks in New Zealand, early Middle Cambrian (c. 510 Ma), are in the Takaka Terrane being found in the Cobb Valley of NW Nelson (Rattenbury et al., 1998). This terrane also contains an

extensive Ordovician record with much poorer Silurian and Devonian records.

The Eastern Province involves the Brook Street, Murihiku, Dun Mountain–Maitai, Caples, Waipapa, Rakaia, Kaweka, Pahau and Waioeka terranes, which range from Carboniferous–Early Cretaceous. The predominant rock type within the Eastern Province is quartzofeldspathic greywacke, largely derived from granitic rocks (Adams et al., 2007, 2011). More than 60% of the New Zealand landmass is greywacke. However, other rock types are present in Eastern Province, including subduction-related volcanogenic sediments (Brook Street, Murihiku, Dun Mountain–Maitai and Caples terranes) and the distinctive Permian Dun Mountain Ophiolite (Rattenbury et al., 1998).

In early 2012, GNS Science completed all 21 geological sheets (1:250,000 scale) within the GIS-based QMap (quarter million) project. This 15-year exercise has generated considerable new geological knowledge and insight, especially in the more remote and mountainous terrains of the Southern Alps, Fiordland, Stewart Island, Northland, central North Island and the Urewera region of eastern North Island (Isaac, 1996; Edbrooke and Brook, 2009; Cox and Barrell, 2007; Turnbull et al., 2010; Leonard et al., 2011; Lee et al., 2011).

Based mainly on detrital zircon age studies the provenance of the greywacke is most probably in the granitic terrains of NE Australia i.e., the E Queensland and NE New South Wales sectors of eastern Gondwanaland.

Much of New Zealand's basement rocks started off as sediment derived from the erosion of mountainous terrain on an active subducting margin of eastern Gondwanaland. This accumulated on the ocean floor and was bulldozed back on to the Gondwanaland margin by accretionary tectonic processes, forming elongate belts (terrane) that built eastwards through time. This lasted from Cambrian–Cretaceous time, and ceased with the onset of continental rifting of Zealandia away from Gondwanaland (Adams et al., 2007).

Investigations of the seafloor around New Zealand have shed light on the submarine depositional environment in which the original greywacke sediments may have accumulated. Mapping of the Cook River and Hokitika River canyons off the Tasman Sea coast of S Westland, suggest that they may be appropriate depositional analogues. Whereas on land these large-volume, rapid-flowing but short, steep-gradient rivers occupy valleys 1–2 km wide, on the sea floor the valleys burgeon outwards and may become 10–20 km wide.

Mineral resources

New Zealand is relatively well-endowed in natural mineral resources such as Au, coal, fresh water, oil, gas, geothermal energy, ironsand, limestone, clay, zeolite, sand and construction aggregate. The land remains under-explored for mineral deposits and known resources are relatively under-developed (Williams, 1974; Kear, 1989; Brathwaite and Pirajno, 1993; Christie and Brathwaite, 2006).

During 1860–1880 there were Au rushes in Otago, Nelson–Marlborough, West Coast and Coromandel, that boosted the country's population and wealth, leading to a demand for coal for steam-powered machinery and heating, and building stone for public and commercial buildings. Demand for fertilisers for agriculture led to the quarrying of limestone, and, in the central North Island, the mining of geothermal sulfur.

Figure 8 The distribution of pre-Cenozoic basement rocks in New Zealand, showing tectonostratigraphic provinces, terranes and batholiths. The extent of the Northland and East Coast Allochthons, emplaced in Early Miocene time, is also shown; all other units were assembled by Late Cretaceous time.

Gold production in New Zealand totalled 900 tonnes (29 M ounces) up to 2005 (Christie and Brathwaite, 2006) and recent increases in the Au price have enabled the mining of low-grade Au deposits such as Macraes. Exploration and research indicate potential for new Au discoveries in Northland, Coromandel, central North Island, Otago and the West Coast.

The black ironsands along the western coast of the North Island were investigated as a source of iron, but the high titanium content defeated traditional blast furnace smelting. This problem has been resolved and ironsand is now being smelted into iron and steel for New Zealand use, and exported (Barakat and Ruddock, 2006; Mauk et al., 2006). Submarine ironsand deposits on the inner continental shelf, mapped in the 1970s, are being re-assessed.

Since the 1940s, exploration for coal has established new coal mines and identified large lignite resources in Southland and Otago (Edbrooke, 1999). Waikato coal is used for electricity generation and is widely used as fuel for the steel, dairy, cement, forestry and meat processing industries, and there are plans to convert the lignite resources into fire briquettes and diesel fuel.

Annual coal production in 2007 exceeded 5 Mt, including high quality coals from the West Coast for export, and lesser quality coals for local power generation.

Geothermal energy has been generated in New Zealand since

1858. A global first, the Wairakei power station near Taupo (central North Island) exploits water-dominated geothermal systems. Geothermal energy from seven power plants now provides 13% (435 megawatts) of New Zealand's electricity needs. There is potential for an additional 1332 megawatts from 11 geothermal systems in central North Island and another 200–400 megawatts from non-traditional sources of geothermal energy such as abandoned deep oil and gas wells in sedimentary basins. Direct usage of geothermal energy for heating and drying in industry, agriculture, horticulture and aquaculture is growing.

Platinum, currently more valuable than Au, has been discovered in plutonic rocks of the Longwood Range in Southland (Christie et al., 2006). Extensive Fe-Mn nodule fields have been mapped along the southern and eastern flanks of the Campbell Plateau in water depths of 4,000–4,500 m (Graham and Wright, 2006). These nodules are a huge potential resource of Fe, Mn, Ni, Cu, Co and rare earth elements.

Extensive phosphate deposits on the Chatham Rise represent a resource of c. 100 Mt of phosphorite (von Rad and Kudrass, 1984).

Recent surveys of the southern part of the Kermadec Arc have located submarine hydrothermal vents with associated massive sulfide deposits containing high concentrations of Ba, Cu, Zn, Pb and Au. These deposits are also associated with unusual microorganisms, which might themselves have value for medicinal or other purposes (Massoth and de Ronde, 2006; de Ronde, 2006).

Petroleum prospectivity

In 2008, the United Nations Law of the Sea (UNCLOS) accepted New Zealand's legal claim for jurisdiction over a greatly enlarged area of sea floor. New Zealand's Exclusive Economic Zone (EEZ) and Extended Continental Shelf (ECS) are now more than 5.7 million km² (Figure 1) including 1.5 million km² of petroleum-prospective sedimentary basins.

Oil was first produced in New Zealand in 1865 from Taranaki, but the first significant discoveries came a century later with two large gas-condensate fields: the onshore Kapuni Field in the late 1950s, and the offshore Maui Field in the late 1960s. They supply natural gas for electricity generation, gas-to-gasoline, methanol, urea fertiliser, and industrial and home heating.

New Zealand's first significant commercial oil field, the McKee Field, was discovered in 1979 in onshore Taranaki. Since 2000, four new fields have been developed in Taranaki: the onshore Pohokura and Kupe gas fields, and offshore Tui and Maari oil fields. By the end of 2007 more than ten oil and gas fields were producing, with two new fields due to come on-stream, but the combined reserves of these new fields are still only c. a quarter of the size of the declining Maui Field.

In 2010, New Zealand's second biggest export commodity in terms of earnings (after dairy produce) was oil. Production is only from Taranaki Basin. A total of c. 2 BBOE (billion barrels of oil equivalent) has been discovered in Taranaki (Uruski et al., 2011), with 19.6 million

Figure 9 The economic mineral resources of New Zealand as distributed on land and across Zealandia. Of prime importance are the onshore occurrences of oil, gas, coal, Au, aggregates, groundwater, and geothermal energy, and the offshore potential for oil and gas, metals and methane gas hydrates. The dotted line denotes the limit of New Zealand's EEZ + ECS.

barrels of oil and 145 BCF (billion cubic feet) gas produced in 2009 (see www.nzpam.govt.nz).

The Ministry for Economic Development has undertaken a number of regional 2D seismic surveys since 2005 in Great South, Pegasus, East Coast, Raukumara, and Reinga basins (Figure 9). Results from these surveys have identified encouraging prospective petroleum plays. Multi-national companies ExxonMobil, Anadarko, OMV, Hyundai Hysco, AWE, Mitsui, PTTEP, and Petrobras are evaluating these data, along with locally based New Zealand exploration companies.

Future prospective areas are the Raukumara Basin and the Canterbury Basin. In 2010, Petrobras was awarded a 12,000 km² exploration block off the East Coast of the North Island in the Raukumara Basin, and is acquiring and interpreting seismic data. Sediments in the basin

are as much as 11 km thick, but little else was known about the geology of the region until 2D seismic data was acquired in 2005 and 2007 (Stagpoole et al., 2008). Four major sedimentary megasequences, range between Cretaceous and Recent, with a number of stratigraphic and structural plays (Figure 10). One of the megasequences recognised is a submarine slope failure tentatively correlated with the East Coast Allochthon. No wells have been drilled in the Raukumara Basin.

In the inner Canterbury Basin, eastern South Island Cretaceous source rocks have been recognised in a NE-trending graben, in close association with reservoir sandstones of comparable age. This is the Carrack-Caravel prospect located 50–80 km offshore from the North Otago coast. This basin has had only sporadic drilling (Mogg et al., 2008). This 390 km² prospect has the potential to contain up to 750 million barrels of recoverable oil or 2.7 trillion cubic feet of recoverable gas and 500 million barrels condensate (Petroleum Review 2010). In 1985, Galleon-1, located 30–50 km from the Carrack-Caravel prospect, produced sub-commercial gas that tested at 10 MMCFGPD and 2300 CFPD of condensate. Another drillhole, Cutter-1, recently completed, is the only offshore exploration well drilled in the Canterbury Basin since the mid-1980s.

Source rocks are typically Cretaceous through to Eocene in age, dominated by terrestrial coal deposits. Reservoir rocks range between fluvial and deep marine, and are as young as Pliocene. Widespread mudstone, marl and limestone of Late Oligocene–Early Miocene age provide regionally extensive seal rocks.

On the western margin of the North Island, progradational successions built out into the rift-related New Caledonia Basin in the Jurassic and Early Cretaceous and are as much as 2,500 m (1.5 sec TWT) thick. This is the so-called “Taranaki Delta” of Uruski (2007), which may include substantial volumes of source rock (Figure 11). Rift basins W of the North Island are common and formed over much of Zealandia in the Early Cretaceous during continental fragmentation of eastern Gondwanaland (e.g., Gippsland, Capel, Faust basins; Uruski et al., 2002; Hashimoto et al., 2010). Mesozoic rocks on mainland New Zealand (e.g. Murihiku Supergroup) have been considered economic basement. However, their source rock potential has long been postulated (Fleming, 1958; Cook et al., 1999); only now are they are being recognised as significant potential source rocks. As

Figure 10 Seismic line through the Raukumara Basin showing postulated migration pathways (green arrows), from Early Eocene source rocks at depth (Waipawa Formation; a potential source rock), around the toe of the submarine slope failure megasequence (grey shading) and up-dip into possible Neogene reservoir formations. Several potential traps (labelled 1 to 4) are indicated. Depth is in two-way-travel time (TWT) and the image is approximately 40 km across (after Stagpoole et al., 2008).

Figure 11 Representative seismic profile (Line DTB01-17) from Kupe South-1 (SE) to the Deep Water Taranaki Basin (NW), western margin of North Island, New Zealand. Broad-scale stratigraphic interpretation of seismic units is shown (lower left; Uruski, 2007).

exploration goes into deep water, these older rocks may become an important component of frontier basin petroleum systems.

With the much broader mandate that the 2008 UNCLOS jurisdiction now provides, substantial offshore exploration efforts are planned, especially for frontier areas such as the Deep Water Taranaki, Northland, Reinga, Pegasus and Great South basins. Planned drilling in Deep Water Taranaki Basin will test geological interpretations of Cretaceous non-marine and shallow marine source and reservoir facies, but also the thick deltaic succession postulated to underlie it. Seaward of these deltaic sediments there is potential for pro-delta turbidites that may contain kerogen carried into deeper waters. The largest structure recognised to date is the Romney prospect, with a closure area of 200 km² in 1600 m water depth, and with the potential to contain up to 1100 to 1650 million barrels of oil-in-place or between 1.7 and 2.7 trillion cubic feet of gas (Uruski et al., 2010).

Some 5,900 line kilometres of 2D seismic (Figure 12) in Northland Basin and the neighbouring Reinga Basin indicate a thick rift succession of likely Jurassic to earliest Cretaceous age and that total sediment thickness in these basins is up to 9 km. Regional mapping indicates several plays ranging from structural to stratigraphic (Uruski et al., 2008; Stagpoole et al., 2009; Uruski et al., 2010). Only one well, Waka Nui-1, has been drilled.

Other basins of note include the Pegasus Basin SE of the North Island, an unusual basin, because it has been largely undeformed by late Cenozoic subduction-related tectonics, despite its location adjacent to the modern day plate boundary and Hikurangi Trench. Also of interest is the Great South Basin SE of the South Island.

The New Zealand region of Zealandia has producing petroleum fields both on land and near to land, but with such a vast and unexplored continental area lying further out to sea, there is the potential to discover continental scale resources.

Alpine Fault

The Alpine Fault was first recognised and mapped by Harold Wellman and Dick Willett in the 1940s, and Wellman postulated 480 km of displacement (Nathan, 2011). It is the main active structure in the oblique continental collision zone of the South Island. It is continuous at the surface for c. 800 km and accommodates c. 70% of current plate motion (Norris and Cooper, 2001). A 480 km offset of basement rocks implies that the Alpine Fault has accommodated >50% of plate displacement since the Eocene (45 Ma) (Sutherland, 1999).

Observed geophysical, geological, and contemporary kinematic data can be successfully explained by a model involving Pleistocene

Figure 12 Physiography of the Reinga Basin and adjacent area showing the Northland Basin and the Deepwater Taranaki Basin. Recent seismic acquisition lines (the REI09 survey) are shown in pink; drillhole locations (mainly DSDP sites) are black dots; the outer limit of the New Zealand EEZ is the bold white line; the outer limit of the New Zealand ECS is the bold red line (after Stagpoole et al., 2009).

slip on a narrow Alpine Fault zone extending into the lower crust (Beavan et al., 2007).

The Alpine Fault represents a major lithospheric discontinuity within Zealandia that previously separated Paleozoic continental lithosphere of the Challenger Plateau from Eocene–Miocene oceanic lithosphere (Sutherland et al., 2000). Subduction of oceanic lithosphere at the Puysegur Trench and strike-slip motion on the Alpine Fault since c. 25 Ma has translated this passive margin into an active continent–continent collision zone. The orientation of the Alpine Fault is inherited from the Eocene geometry of rifting and is not perfectly oriented to accommodate strike-slip motion. The obliquity of plate motion to this inherited structure has resulted in widespread deformation of the Pacific plate and consequent uplift of the Southern Alps.

Erosion of the Southern Alps by strong westerly weather systems is highly efficient and has deposited vast quantities of sediments offshore (Sutherland, 1999). This erosion has an important role in stabilising localised slip on the Alpine Fault and inhibits growth of a broad mountain range within the Australian Plate (Koons, 1987).

Previous studies of the central Alpine Fault (Figure 13) suggested that the adjacent mid-crust is hot (Koons, 1987; Toy et al., 2010) and over-pressured (Stern et al., 2001). Hanging-wall seismicity terminates at a depth of c. 10–12 km (Leitner et al., 2001), and focal mechanism analysis suggests that the Alpine Fault sustains shear stresses lower than expected for idealised faulting models (Townend, 2006). Geodetic

studies have yielded elastic locking depths as shallow as 5–8 km (Beavan et al., 1999) though partial locking may extend to as deep as 18 km (Wallace et al., 2007).

The near-surface fault plane is segmented on a 1–4 km along-strike-scale into reverse segments with strike 030–050°, and strike-slip segments with strike 070–090° (Norris and Cooper, 1995). It is thought that this segmentation has formed in response to topographic stress perturbations caused by erosional processes (Koons and Kirby, 2007).

The 1 km-thick hanging wall Alpine Fault rock sequence (Figure 14) has been exhumed from depths of <35 km at rates more than 4 mm/year regionally, and locally >10 mm/year during the past 5 Myr (Little et al., 2005; Beavan et al., 2010b). Large scale plate motions that are driving the deformation have changed only slightly since 20 Ma, therefore the exposed sequence was probably entirely deformed under conditions presently experienced at depth.

The Alpine Fault (Figure 13) has not produced significant earthquakes or measurable creep during New Zealand's relatively short written history, but is thought to fail in large earthquakes (Mw c. 7.9) every 200–400 years, and to have last ruptured in 1717 (Wells et al., 1999).

At least nine key attributes make the Alpine Fault an attractive target for fundamental research into tectonic deformation,

Figure 13 Map of the Alpine Fault and adjacent structures highlighting the inferred rupture extent of past Alpine Fault earthquakes in 1430, 1620 and 1717 (Sutherland et al., 2009). Light grey shading demarcates topography higher than 800 m.

Figure 14 Sequence of fault rocks, exposed in the hanging wall (Mesozoic basement, Eastern Province; Pacific Plate) of the Alpine Fault that have been exhumed from depths of as much as 35 km and are thrust on top of young (typically <16 kyr) Pleistocene-Recent fluvio-glacial gravels and Paleozoic basement rocks (Western Province; Australian Plate) (Norris and Cooper, 2007).

seismic hazard, and mineral formation. (1) It has well-determined and rapid (25 mm/year) Pleistocene slip rates; (2) precisely known plate motion history with a single fault that has accommodated most plate boundary displacement for >20 Myr; (3) >300 km along-strike exposure of uniform-composition rocks in the hanging wall and fault

Figure 15 Inter-seismic coupling on the Hikurangi margin of the westward subducting Pacific Plate interface. Modelling derived from the 1991-2004 GPS campaign (Wallace et al., 2010). The coupling factor is the fraction of inter-block motion being stored as elastic strain energy: high coupling factor (red); low coupling factor (blue). Green contours are previous slow slip events (SSE); grey contours are newly discovered Wairarapa coast SSE. The red area is locked (stuck) subduction interface that is inferred to be building up for a large subduction thrust earthquake.

rocks derived from them; (4) sequences of fault rocks developed during unidirectional exhumation on well-determined trajectories over relatively short time periods; (5) it has had rapid uplift resulting in advection of crustal isotherms so that brittle-ductile transition processes can be studied at shallower (potentially drillable) depths than normal; (6) it offers the opportunity to monitor a locked fault late in its perceived earthquake cycle with a high (c. 25%) probability of rupture in the lifetime of a fault-zone observatory (c. 30 years); (7) there is an extensive body of existing geological and geophysical knowledge, and a modern nationwide geophysical monitoring network (GeoNet); (8) it has an inclined fault orientation enabling fault penetration with sub-vertical boreholes; and (9) New Zealand has a relatively benign political and physical environment in which to operate, with existing industry and supporting infrastructure.

Understanding what conditions prevail within the interiors of active faults is crucial for elucidating the mechanisms governing long-term fault evolution and, in particular, the earthquake-rupture processes that are of special interest to society (Tullis et al., 2007; Zoback et al., 2007).

This motivation, combined with the factors listed above, led to an ambitious multinational project, the “Deep Fault Drilling Project, Alpine Fault (DFDP)” (Townend et al., 2009). The DFDP project completed Phase 1 by drilling two boreholes (maximum depth 152 m) at Gaunt Creek, c. 20 km NE of Franz Josef Glacier, during January and February 2011.

Phase 2 of the project will determine physical conditions at upper- and mid-crustal depths by drilling to a depth of >1 km, hence seeing through near-surface effects of topographic relief on stress, temperature, and fluid flow and chemistry, and of critical importance for inferring conditions at greater depth (Fulton and Saffer, 2009; Koons and Kirby, 2007; Liu and Zoback, 1992; Norris and Cooper, 1997).

Current tectonic activity

The Pacific Plate is subducting beneath the Hikurangi Trough at 5–6 cm/year offshore of Gisborne, E coast North Island, making this subduction thrust the fastest slipping fault in New Zealand. Farther S, beneath southern North Island, the subduction rate reduces to 3–4 cm/year and GPS data show the subducting plate is locked by friction on the subduction plate interface to a depth of c. 40 km (Wallace et al., 2010). This is in contrast to the Gisborne region, where GPS data show episodic movement in “slow slip events” to shallow depths (<10 km), and is of concern because locked regions may eventually become unstuck with a resultant large earthquake. Data from around Wellington bear striking resemblance to data from Japan near Sendai before the 11 March 2011 M 9.0 Tohoku Earthquake. However, no conclusive geological evidence has yet been found of such subduction thrust earthquakes in southern North Island.

GPS technology has transformed seismology in the past 14 years and, in particular, understanding of subduction zone kinematics. It has led to the discovery of slow slip events (SSE) also known as slow or silent earthquakes. These are hypothesised to occur around the edges of locked zones and may help to identify those areas on the plate interface where subduction earthquakes may occur in the future.

Active volcanoes and associated geothermal fields in the TVZ are all the products of active subduction of the Pacific Plate along the Hikurangi Trough beneath the Australian Plate and/or back-arc rifting of continental crust of the Australian Plate.

Figure 16 The Taupo Volcanic Zone as an active rift within continental crust of the Australian plate, which is closely associated with subduction of the Pacific Plate. This NW-SE depth profile shows the conductivity structure within the upper 70 km that has been constructed from 2-D inverse modelling of magnetotelluric (MT) data (Heise et al., 2007). Earthquake hypocentres mark the slab of the subducting Pacific Plate. The colour code is expressed in terms of resistivity. Note the rapid change that occurs beneath the TVZ at 10 km, some 3 km below the base of the seismogenic zone. This is a reasonable and plausible interpretation of the depth to the melt zone (magma) in the thin crust beneath the TVZ.

Data acquired using magnetotelluric (MT) technology has enabled the TVZ to be mapped in terms of electrical conductivity and has produced a compelling thermal picture of the deep geological structure of the TVZ (Heise et al., 2007). An example of this research is shown along a NW-SE profile across the TVZ (Figure 16). It suggests that the mantle wedge beneath the TVZ is anomalously conductive, compared to the Pacific Plate lithosphere beneath the South Island. This supports the presence of a partially interconnected melt fraction in the mantle wedge above the plate as suggested from seismological data by Reyners et al. (2006). The melt fraction is greater along the SE margin of the TVZ, where the geothermal flux and geothermal activity is greatest.

Subduction along the E coast of New Zealand, recognised on the basis of the pattern of seismicity, effectively ceases S of Wellington and N of Christchurch. Plate motion mechanics are transformed into complicated crustal deformation as the nature of the collision changes from ocean-continent (North Island) to continent-continent (South

Island). A series of faults connect the subduction zone to the Alpine Fault. Right lateral motion on the Alpine Fault has involved relative plate displacement of 480 km since the Early Miocene.

The rate of Pacific Plate motion in the South Island is 38 mm/yr W with respect to the N-moving Australian Plate. This continent-continent collision is responsible for the Southern Alps, and the same tectonism also has the potential to activate faults located beneath the alluvium of the Canterbury Plains.

Relief of this westward Pacific Plate stress through fault motion along buried faults has recently generated a number of disastrous earthquakes in the Christchurch area.

The first of these earthquakes occurred at 04:55 on Saturday 4 September 2010 (local time) with a moment magnitude (M_w) of 7.1. The earthquake epicenter was located 10 km SE of Darfield and 40 km W of Christchurch at a depth of 10.8 km. An E-W oriented surface rupture, some 30 km long with an average horizontal displacement of 2.5 m (Quigley et al., 2010) developed 4 km S of the epicenter.

This strike-slip fault was previously unknown and is now named the Greendale Fault. There was no loss of life. The older brick and masonry buildings of Christchurch were badly damaged. Liquefaction, lateral spreading and

slumping caused major damage with an estimated \$NZ4 billion to repair the damage (Gledhill et al., 2011). The Darfield Earthquake was followed by more than 4,000 aftershocks through January 2011, with 14 aftershocks of local magnitude (ML) 5.0 greater and 155 of ML 4–5 (Figure 17).

A destructive aftershock of local magnitude (ML) 6.3 and shallow depth of 2.8 km (Kaiser et al., 2012) struck c. 6 km SE of downtown Christchurch at 12:51 on Tuesday 22 February 2011 local time causing extensive damage and a loss of 185 lives.

This Christchurch Earthquake was very energetic (M_e 6.7 with a recorded maximum vertical acceleration of 2.2 g near the epicenter (Gledhill et al., 2011), leading to greater destruction and liquefaction than the Darfield Earthquake almost six months earlier. The eastern suburbs of Christchurch were especially hard hit with liquefaction, lateral spreading, flooding and subsidence. More than 900 buildings in the central business district were irreparably damaged as well as 10,000 or more residential homes.

Figure 17 Central Canterbury showing the aftershocks and faults relating to the Christchurch earthquake sequence. The first major event on 4 September 2010 (green) was associated with rupture of the Greendale Fault was followed by major aftershocks on 22 February 2011 (red), and 6 June 2011 (blue). These latter two events were associated with blind faults proximal to central Christchurch. From Kaiser et al. (2012).

This earthquake occurred on a previously unrecognised NE-SW oriented blind fault; it did not rupture the surface. However, resultant permanent ground deformation caused relative uplift of the Port Hills and the mouth of the Heathcote-Avon River system, and down-drop of much of eastern Christchurch, which was already low-lying and close to sea-level. Cathedral Square in central Christchurch was 5.50 m asl; it is now 5.15 m asl. With the additional effects of lateral spreading, liquefaction and compaction, parts of eastern Christchurch have subsided by up to one metre.

The 22nd February Christchurch Earthquake caused an additional \$NZ15–20 billion of damage making the Christchurch earthquake the most expensive in New Zealand's history.

The E-W orientation of the Greendale Fault and other faults in Canterbury suggest that these recent earthquakes may have occurred on re-activated Cretaceous faults (Reyners, 2011). Numerous E-W normal faults relating to extensional tectonism when Zealandia rifted away from Gondwanaland have been mapped on the Chatham Rise to the immediate E of Banks Peninsula (Wood and Herzer, 1989).

The extinct Late Miocene basalt shield volcano of Banks Peninsula (Figure 17) may have contributed to concentrating the stress field following the Darfield Earthquake (Reyners, 2011). The Christchurch Earthquake involved oblique - reverse faulting. The red dots (Figure 17) show that the aftershocks are consistent with a NE-SW striking fault plane dipping to the SE.

These Christchurch earthquakes are considered to be an unusual sequence. Available geological evidence prior to the Darfield Earthquake indicated no disturbance of this nature for at least 10 kyr. On the other hand, the damage sustained by the particularly violent nature of these earthquakes was not unexpected. Detailed geological and hydrological mapping completed in the 1980s correctly interpreted susceptibility of eastern Christchurch to seismic shaking and liquefaction hazard (Brown and Weeber, 1992; Forsyth et al., 2008).

The tectonism that Christchurch has experienced is due to stress

release associated with routine plate boundary deformation. Whereas c. 70% of plate motion is taken up proximal to the plate boundary in the South Island by the Alpine Fault and Southern Alps, the remaining c. 30% is accommodated further afield. For all that the Christchurch experience is topical, it is important to remember that the entire plate boundary zone running through New Zealand is alive.

Conclusion

The geological history of New Zealand makes sense in terms of the large scale tectonic history of the SW Pacific. Our Gondwanaland heritage lasted from 510–83 Ma and was dominated by active subduction margin tectonism and accretionary growth of the eastern margin of Gondwanaland.

Our Zealandian history 83–23 Ma was utterly different and relates to passive margin tectonism. This was a

60 Myr period of relative tectonic quiescence and sustained subsidence. In fact, rifting of Zealandia commenced at least 40 Myr prior to 83 Ma, so extensional tectonism of eastern Gondwanaland lasted for 100 Myr. The exposed geological record of our Zealandian heritage may be relatively meager, but this belies its much more widespread significance subsurface especially within New Zealand's submarine sedimentary basins.

The New Zealand history, relating to the past 23 Myr is just as interesting, reflecting the return to active subduction-related collision tectonics. However, there is a profound difference from our Gondwanaland heritage. The modern plate boundary involves continent-continent collision as well as ocean-continent collision, with all its attendant hazards. New Zealand is the product of continental Zealandia being split to form two sub-continents: northern Zealandia and southern Zealandia.

The geology of New Zealand can be explained in terms of crustal processes operating on a scale of 10s of kilometres, lithospheric processes occurring on a scale of 100s of kilometres, and mantle processes occurring on a scale of 1000s of kilometres. Just about everything in New Zealand is currently governed by oblique plate convergence at a rate of 3–5 cm/year.

Thanks to New Zealand's unique geological history and active tectonic setting, it is a spectacular natural laboratory for the study of both resource- and hazard-related geological processes, past and present. Advances in geophysics in particular are providing significant new insight into how the crust 'works', especially in the context of rifting and subduction.

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Hamish Campbell is a Senior Scientist with GNS Science. He has BSc (Hons) (Otago University, 1975), MSc (Auckland University, 1979) and PhD (Cambridge University, England, 1985) qualifications in geology. He commenced his professional career as a macropalaeontologist (Permian–Triassic) with the New Zealand Geological Survey in 1978. His research interests relate to the origin and history of New Zealand's older sedimentary rocks.

Ian Graham completed a BSc (Hons) in geology and a MMinTech in mineral technology at the University of Otago (1977; 1978), and a PhD in geology at Victoria University (1985). As an isotope geochemist and geochronologist, he has for the past 30 years undertaken research across a diverse range of topics, including volcanology, basement geology, paleoclimates, geothermal energy, mineral resources, and nuclear physics.

Alex Malahoff, PhD (University of Hawaii), BSc, MSc and DSc (Hon) (Victoria University of Wellington), is the Chief Executive of GNS Science. He leads and directs strategy, policy, investment, and science programmes. He is a geophysicist and prior to his present role (2002), he served as Professor of Oceanography and Chair of the Ocean Engineering Department at the University of Hawaii. He was also Director of the Hawaii Undersea Research Laboratory.

Rupert Sutherland is a Principal Scientist with GNS Science. He completed a Natural Sciences degree at Cambridge University, UK, and PhD at Otago University, NZ. He has worked for GNS Science since 1995 and currently leads the “Tectonics and structure of Zealandia” research programme. His personal research interests include active tectonic processes, and the history of tectonic events that created the continent of Zealandia and its surrounding ocean crust.

Greg Browne is a sedimentologist at GNS Science with degrees from Auckland University (BA, BSc and MSc Hons) and a PhD from the University of Western Ontario (Canada). He has worked in many sedimentary basins of New Zealand as well as in several overseas countries, and specialises in deep water and fluvial successions. That work spans over 30 years and is primarily aimed at a better understanding of how depositional systems have evolved over time.