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Regional geological framework of New Zealand's mineral deposits

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ABSTRACT

New Zealand is the emergent part of a 4.9 Mkm^2, mainly submerged continent in the SW Pacific Ocean that was formerly part of the Gondwana supercontinent. The geology can be described in terms of two main Cambrian-Early Cretaceous basement units (Western and Eastern provinces) and a Late Cretaceous-Holocene sedimentary and volcanic cover (Zealandia Megasequence and Rūaumoko Volcanics).

The Early Paleozoic greywacke terranes and Cambrian-Early Cretaceous Tuhua Intrusives in the Western Province formed along strike from similar rocks in the Lachlan and New England orogens of Australia. The main mineral deposits in the Western Province are orogenic Au-quartz lodes in the Buller Terrane. Tuhua Intrusives host a variety of metalliferous deposits including granite-related Au and Mo, Ag±W porphyry Mo, vein and greisen W and Sn, magmatic Ni-Cu sulfide, Pt group element (PGE), and titanomagnetite-ilmenite.

Mesozoic greywacke and schist terranes in the Eastern Province were assembled at a convergent accretionary margin in the Jurassic and Early Cretaceous. The Haast Schist represents the deeply exhumed part of the Torlesse-Caples-Waipapa terrane accretionary wedge. Greenschist facies schist in Otago and Marlborough contains widespread Au ± W ± Sb mineralisation in shear zones and quartz lodes, including the large Macraes deposit in east Otago. Volcanogenic massive sulfide Cu deposits and volcanogenic Mn-chert deposits occur in flanking schist and greywacke, and talc-magnesite lenses and nephrite jade (greenstone/pounamu) occur in ultramafic schists of the Southern Alps. A Permian ophiolite in the Eastern Province (Dun Mountain-Maitai Terrane) has associated Cu, chromite, PGE and chrysotile asbestos mineralisation.

The older part of Zealandia Megasequence comprises Late Cretaceous (ca 105-85 Ma) syn-rift deposits (Momotu Supergroup), overlying transgressive non-marine and marine successions of the Haerenga Supergroup and Oligocene (ca 35-25 Ma) maximum marine inundation limestones of the Waka Supergroup. These Late Cretaceous to Oligocene sedimentary rocks contain most of New Zealand's economic petroleum, coal and limestone deposits.

From latest Oligocene time (ca 25 Ma) another major tectonic and paleogeographic change took place in Zealandia related to re-initiation of subduction. In the North Island, allochthons were emplaced and the Northland-Coromandel volcanic arc erupted. All over New Zealand thick flysch- and molasse-like deposits of the Miocene Maui Supergroup overlie the Waka Supergroup limestones and are, in turn, succeeded by clastic dominated Pliocene-Holocene Pakihi Supergroup. Igneous rocks within Zealandia Megasequence have three separate origins. Whakaari Supersuite are subduction-related andesitic to rhyolitic lavas, Te Raupua Supersuite are the oceanic basin ophiolitic rocks in the Northland and East Coast allochthons and Horomaka Supersuite rocks are intraplate basaltic rocks.

Economically important volcanic-hosted epithermal Au-Ag deposits occur in Miocene Whakaari Supersuite rocks in the Coromandel region. Porphyry Cu mineralisation is associated with subvolcanic intrusive rocks in northern Coromandel and in eastern Northland, where Pb-Zn skarn mineralisation has also been found. Zeolite, microsilica, perlite, pumice and native sulfur occur in the Taupo Volcanic Zone Whakaari Supersuite rocks. Massive base metal sulfide ± Au mineralisation occurs at several submarine volcanoes in the southern Kermadec volcanic arc. Mineralisation associated with the allochthonous Te Raupua Supersuite includes small Cu ± Au volcanic massive sulfide deposits in Northland and an occurrence of massive sulfides containing barite + pyrite + sphalerite ± Au ± Ag near Lottin Point, East Cape. Subtropical weathering of alkaline rhyolite domes belonging to the Horomaka Supersuite has produced high quality halloysite clay deposits in the Matauri Bay area of Northland.

Gold bearing quartz gravels associated with Maui Supergroup coal measures are widespread in Otago and Southland. Extensive non-marine, and in part fluvioglacial, Pakihi Supergroup fanglomerates and gravels in Nelson, Westland and Otago have resulted from progressive uplift and erosion of the Southern Alps. Fluvial reworking has formed large Au placers in riverbed and terrace (glacial outwash) gravels in Westland and Otago and ilmenite-garnet-gold placer deposits in Westland. Significant coastal placer deposits of ironsand along the west coast of the North Island formed by erosion of the Taranaki andesite volcanoes (titanomagnetite) and rhyolitic rocks of the Taupo Volcanic Zone (ilmenite).

INTRODUCTION

New Zealand contains a large number of different kinds of mineral deposits and occurrences. The metallogenic map of New Zealand (Brathwaite and Pirajno, 1993) lists more than 600 metallic mineral deposits classified into 25 different types. This mineral diversity for a land area of only 270 500 km^2 is a function of a varied and complex geology resulting from New Zealand's location at or near active plate boundaries for the past half billion years.

Since the last overview of New Zealand's mineral deposits in the AUSIMM Monograph series (Brathwaite and Christie, 2006), several advances have been made in our understanding of the country's regional geological framework and development. These include completion of the 1:250 000 QMAP geological map series (Rattenbury and Isaac, 2012), production of a revised 1:1 000 000 geological map (Edbrooke *et al*, 2015), greatly increased geochemistry and geochronological data on plutonic rocks (eg Tulloch *et al*, 2009 a, 2009b), a new high-level stratigraphic nomenclature framework for the country (Mortimer *et al*, 2014), and aeromagnetic maps of Northland and Westland (Stagpoole *et al*, 2012; Rattenbury, 2014). Additionally an authoritative summary of New Zealand geoscience, including a chapter on Mineral Wealth, has been updated (Graham, 2015), and there is increasing acceptance and adoption of the concept of the continent of Zealandia to describe the context of New Zealand and New Caledonia in the SW Pacific (eg Timm *et al*, 2010; Mortimer and Campbell, 2014). A revised timescale calibration for New Zealand rocks was published in 2015 (Raine *et al*, 2015). All of this recent work is relevant to New Zealand mineral exploration.

This paper provides a brief overview of New Zealand's mineral deposits and occurrences in the context of the currently understood geological and tectonic framework, especially the Litho2014 scheme of Mortimer *et al* (2014). Geological information is drawn mainly from the references listed above, and a deliberate attempt has been made to use literature from the last 10 years. Background mineral occurrence information is drawn mainly from Williams (1974), Brathwaite (1989), MacFarlan and Barry (1991), Brathwaite and Pirajno (1993), Thompson, Brathwaite and Christie (1995), Christie and Brathwaite (2006) and Christie *et al* (2000).

The overview presented here is largely confined to mainland New Zealand. The more distant offshore islands such as the Chatham Islands, Subantarctic Islands etc. are not specifically referred to herein even though their geology has been embraced in terms of the revised stratigraphic framework of Mortimer *et al*, (2014).

ZEALANDIA

The bathymetric limits of the broad plateaus of the Lord Howe Rise, Challenger Plateau, Chatham Rise and Campbell Plateau define the extent of the continental crust of Zealandia (Figure 1; Luyendyk, 1995; Mortimer, 2004; Mortimer and Campbell, 2014). The Kermadec-Tonga, Lau-Colville and Macquarie ridges are volcanic and tectonic expressions of the Oligocene-Holocene Pacific-Australian plate boundary. They are not presently proven or considered to be underlain by continental crust.

Zealandia has all the features of continents: large area (4.9 Mkm^2, c 40% of onland Australia), well-defined bathymetric and/or tectonic limits, substantially higher average elevation compared with surrounding oceanic crust, and a crustal thickness of 15-40 km. Rock types such as granitoids, siliceous lavas, greywackes and schists make up the geological basement of New Zealand and New Caledonia. Samples have been obtained from remote islands, submarine exploration (wells, dredges) and xenoliths in Neogene volcanoes from around Zealandia.

The extreme (94%) submergence of Zealandia mainly results from thin crust and lithosphere that is isostatically compensated. Substantial crustal thinning took place in the Late Cretaceous just prior to breakup of Zealandia from the Australian and Antarctic segments of Gondwana. Formerly adjacent West Antarctica shares the thinned crust and low elevation of Zealandia. Only after this part of Gondwana started to break up at ca 85 Ma did Zealandia become isolated on the eastern and northern sides of the Tasman Sea and Southern Ocean spreading centres. The emergent parts of Zealandia are above sea level because of Cenozoic crustal thickening due to local continent-continent collision (South Island), uplift associated with continent-ocean subduction (east coast North Island and top South Island), obduction events (New Caledonia, New Zealand) or because of volcanism (eg Taupo Volcanic Zone, Chatham Islands).

Lying adjacent to Zealandia, but not forming part of it, is the Hikurangi Plateau (Figure 1), an oceanic large igneous province (LIP). The main sub-alkaline plateau-forming basement on the Hikurangi Plateau has been dated at 120-100 Ma and the post-plateau alkaline seamounts at 99-86 Ma (Davy, Hoernle and Werner, 2008; Hoernle *et al*, 2010). The plateau now abuts the Chatham Rise and is thought to have collided with Zealandia at about 105 Ma, jamming the long-lived subduction zone and forcing a change in the local tectonic regime to one of continental rifting (Reyners, 2013).

NEW ZEALAND'S GEOLOGICAL FRAMEWORK

A revised stratigraphic scheme for New Zealand's Cambrian to Holocene igneous, sedimentary and metamorphic rocks and unconsolidated deposits was proposed by Mortimer *et al* (2014). The impetus for a revised scheme was the need for a standardised terminology for interactive publically available national digital earth science databases (such as Petlab http://pet.gns.cri.nz).The province, terrane, batholith, and group-level units in the scheme are unchanged from previous usage, but several new high-level names were introduced (Figure 2). In New Zealand a major regional unconformity separates basement (generally hard, deformed and metamorphosed, crystalline rocks of Cambrian to Early Cretaceous age) from cover (generally, softer, less deformed, sedimentary and volcanic rocks and unconsolidated deposits of Late Cretaceous to Holocene age). To date, no Precambrian rocks analogous to those generally considered basement in many other continents have been discovered in Zealandia, although parts of the sub-continental lithospheric mantle under the South Island have yielded Precambrian Re-Os ages (eg Liu *et al*, 2015). All New Zealand basement rocks were given the formal stratigraphic name Austral Superprovince, to denote that it consists of rocks of the longstanding and still currently used Western and Eastern provinces (Landis and Coombs, 1967). The term Tuhua Intrusives was re-introduced as a collective name for all plutonic rocks that intrude the Western Province terranes and were reaffirmed as a defined part of the Western Province. Apart from these new names the familiar terrane, batholith and igneous suite names remained unchanged. All New Zealand cover rocks were given the formal name Zealandia Megasequence by Mortimer *et al* (2014) as, in all New Zealand sedimentary basins, they comprise a c 100 my long rift-transgressive-regressive megasequence (King et al, 1999). The Zealandia Megasequence was divided into five diachronous lithostratigraphic supergroups (Momotu, Haerenga, Waka, Māui and Pākihi) which correspond to different phases in Zealandia's tectonic development, and this terminology is used below.

For summary descriptions of individual basement units, the reader is referred to Coombs *et al* (1976), Bradshaw (1989), Mortimer (2004),Wandres and Bradshaw (2005) or the relevant 1:250 000 scale geological maps (Rattenbury and Isaac, 2012).

Western Province Basement

Terranes

The Cambrian-Devonian Buller and Takaka terranes make up the volcano-sedimentary part of the Western Province. They are the westernmost terranes in New Zealand and have been offset c 460 km along the Alpine Fault between Fiordland and NW Nelson (Figure 2). They have broad correlatives in the Lachlan Orogen of Tasmania, Victoria and New South Wales.

The Buller Terrane consists of a thick sequence of monotonous greywacke and argillite (Greenland Group) that is metamorphosed to lower greenschist facies and, structurally, is characterised by upright folds and associated axial plane cleavage (Mortimer *et al*, 2013). Age controls are scarce but Ordovician ages on rare graptolites are confirmed by detrital zircon ages (Adams *et al*, 2015). Buller Terrane records a geological history of a formerly extensive turbidite apron of Ordovician age. Orogenic (mesothermal) Au quartz lodes are hosted in Greenland Group turbidites (at Lyell and Reefton) and in black slates in west Nelson (Golden Blocks) and southwest Fiordland (Preservation Inlet) (Figure 3). The Reefton Goldfield (Barry, 1993; Christie *et al*, 2006a) is by far the largest of these fields, with an historic production of 67 t Au mainly from the Blackwater (Waiuta) and Globe Progress mines. Extensive exploration of the Globe-Progress deposit has led to its redevelopment as an open pit mine (Whetter, 2006). The Reefton lodes are lensoid quartz bodies, and wider zones of disseminated arsenopyrite localised along shear zones and minor faults, many of which developed after region-wide folding and sub-greenschist facies metamorphism. The Au-quartz lodes mainly contain arsenopyrite and stibnite whereas pyrite is less common.

The Takaka Terrane has a more varied lithostratigraphy than the Buller Terrane and is made up of thrust slices of Cambrian to Ordovician island arc-related igneous and volcaniclastic rocks, and Ordovician to Early Devonian continental passive margin, basin and shelf quartzites and limestones (Cooper, 1989). The Takaka Terrane has been variably metamorphosed and multiply deformed, including deformation during accretion to the Buller Terrane in the Middle Devonian and again in the Cretaceous (Jongens, 2006). The layered mafic Cobb Igneous Complex of Cambrian age in NW Nelson contains chrysotile asbestos, talc and magnesite deposits (Williams, 1974). Some of the Takaka Terrane volcanic rocks (eg Devil River Volcanics) have potential for volcanogenic massive sulphide deposits. The Ordovician-Silurian passive margin sedimentary rocks contain carbonate rocks which have been worked for marble on Takaka Hill and dolomite at Mt Burnett (Figure 4).

Note that Gondwana cover sequences of Permian (Parapara Group; Campbell *et al*, 1998), Triassic (Topfer Formation; Mortimer *et al*, 1995) and Jurassic (Kirwans Intrusives; Mortimer *et al*, 1995) age are known from restricted outliers within Western Province.

Tuhua Intrusives

Plutons of the Tuhua Intrusives are currently grouped into 12 petrogenetic suites based on age and geochemistry (Jacquiery, Karamea, Paringa, Tobin, Ridge, Foulwind, Longwood, Tarpaulin, Ferrar, Darran, Rahu and Separation Point; Mortimer *et al*, 2014). They comprise I, A and S-type granitoids variously related to subduction and anorogenic tectonic settings. Most of the plutons occur in two major (>100 km^2) batholiths, Karamea Batholith and Median Batholith (Figure 2; Mortimer *et al*, 2014). Two major pulses of plutonism occurred in the Late Devonian-Early Carboniferous (375-335 Ma) and in the Late Jurassic-Early Cretaceous (170-110 Ma), but Cambrian, Late Carboniferous, Late Permian and Late Triassic plutonic rocks are also known (Mortimer *et al*, 1999; Tulloch and Kimbrough, 2003; Tulloch *et al*, 2009a; McCoy-West, Mortimer and Ireland, 2014)

In Fiordland, plutons as young as Early Cretaceous (as well as their host rocks) are metamorphosed to granulite facies orthogneisses. Devonian-Carboniferous and Cretaceous plutons form the amphibolite facies gneissic lower plate of the Paparoa Metamorphic Core Complexes (Tulloch and Kimbrough, 1989; Ritchie *et al*, 2015).

S-type Paleozoic granites have related vein W and Sn deposits: vein and greisen scheelite (with occasional cassiterite) in Westland (Maxwell, 1989), and wolframite-cassiterite greisen on Stewart Island (Williams, 1974) (Figure 5). A hydrothermally altered peralkaline granite dike of possible Late Cretaceous age (ca 109 Ma) at Sams Creek, NW Nelson, hosts Au + arsenopyrite + pyrite + quartz + siderite vein mineralisation (Windle and Craw, 1991; Brathwaite and Faure, 2004; Brathwaite, Reynolds and Faure, 2006a; Angus *et al*, this volume). The age of the Sams Creek dike and its relationship to the mineralization remain debated.

The Late Devonian mafic-ultramafic Riwaka Complex (Turnbull, Tulloch and Ramezani, 2013) has associated Cu-Ni-platinum group mineralisation (Bates, 1989; Challis, 1989). A number of porphyry style Mo occurrences in NW Nelson (eg Karamea Bend) are associated with small granodiorite stocks of high Na and Sr/Y chemistry belonging to the 126-105 Ma Separation Point Suite (Eggers and Adams, 1979; Tulloch and Rabone, 1993; Tulloch and Kimbrough, 2003). A molybdenite-mineralised granodiorite porphyry associated with a Cu skarn (Wodzicki, 1972; Seccombe *et al*, 2005) at Copperstain Creek is older (133.5 Ma) and compositionally different from the Separation Point Suite (Brathwaite, Kamo and Faure, 2004).

A Late Permian layered mafic-ultramafic intrusion on the south coast of the South Island (Longwood Range) marks the eastern edge of the Median Batholith. It intrudes Early to Late Permian Brook Street Terrane basaltic and andesitic volcanic rocks, and is regarded as the source for alluvial Pt group minerals and Au in Southland. It has been explored for hard rock Pt-Pd deposits in recent years (Challis, 1989; Hay, 1989; Spandler *et al*, 2005; Craw, MacKenzie and Ashley, this volume; Mortimer, Caratori-Tontini, and Martin, this volume).

Eastern Province Basement

Terranes

Seven Early Permian to Early Cretaceous terranes and composite terranes make up the Eastern Province. From west to east these are Drumduan, Brook Street, Murihiku, Dun Mountain-Maitai, Caples, Waipapa Composite and Torlesse Composite terranes (Coombs *et al*, 1976; Bradshaw, 1989; Mortimer *et al*, 2014). The Drumduan, Brook Street, Murihiku, and Dun Mountain-Maitai terranes are relatively well-stratified (divisible into groups and formations), for the most part structurally simple and, except where intruded by the Median Batholith, are mostly of relatively low metamorphic grade. In contrast the Caples, Waipapa Composite and Torlesse Composite terranes comprise monotonous greywacke-argillite sequences, are structurally complex and grade into the polyphase Haast Schist which ranges up to amphibolite facies. The Eastern Province terranes formed as products of plate convergence and subduction in a series of Permian-Early Cretaceous forearc basins, trench-slope basins, and accretionary complexes along the Gondwana margin (Mortimer, 2004).

The Drumduan and Brook Street Terranes both comprise volcanic and volcaniclastic rocks and were once mapped together as the same unit (Grindley, 1958). However, the Drumduan Terrane is Jurassic in age and contains intermediate-silicic volcanic rocks and plant fossils whereas the Brook Street Terrane is Permian to Jurassic and mainly basaltic, andesitic and submarine. Faults are now known to separate the two terranes. Note that the Jurassic age attribution of the Brook Street Terrane is based on the presence of Barretts Formation which is in primary depositional contact on Middle to Late Permian Productus Creek Group rocks exposed below the terrane boundary with Murihiku Terrane (Letham Ridge Thrust Fault) in the Wairaki River valley, Southland (Landis *et al*, 1999).

The Late Permian to Late Jurassic Murihiku Terrane contains fossiliferous, mostly marine, volcaniclastic sandstone, siltstone and conglomerate, shellbeds and tuff that were deposited in a forearc or backarc basin. Metamorphic grade is zeolite facies and occurrences of bedded zeolites are common, particularly in Southland (Coombs, 1959; Boles and Coombs, 1977).

The Dun Mountain-Maitai Terrane consists of an Early to Middle Permian igneous ophiolite assemblage of serpentinised peridotite, tectonic melange, gabbro, dolerite and basalt (Dun Mountain Ophiolite Belt, DMOB). This is depositionally overlain by a Late Permian to Middle Triassic sedimentary assemblage of bedded volcanic breccia, volcanic sandstone, mudstone and limestone. The DMOB contains Cu, chromite and PGE deposits, and chrysotile asbestos and serpentine deposits (Brathwaite and Pirajno, 1993; Brathwaite, Jongens and Christie, 2012).

The more deformed and metamorphosed Eastern Province terranes, the Caples, Waipapa and Torlesse terranes, consist dominantly (>95%) of quartzofeldspathic and volcaniclastic greywacke and argillite protoliths with minor (<5%) basaltic volcanic rocks, chert and limestone. The basalt-chert-limestone lithologic association represents the uppermost parts of the oceanic crust or seamounts tectonically emplaced into the clastic-dominated sedimentary sequences during subduction (Spörli and Ballance, 1989). Sandstones of the Torlesse Composite Terrane have a granitic-metamorphic provenance, whereas sandstones of the adjacent Caples, Maitai and Murihiku terranes have a volcaniclastic provenance (Mackinnon, 1983). This compositional juxtaposition is attributed to an allochthonous origin for the Torlesse, possibly from a source area in northeastern Australia (Adams and Kelley, 1998).

Small volcanogenic massive sulfide Cu deposits and volcanogenic Mn chert deposits occur in Waipapa Terrane (Stanaway, Kobe and Sekula, 1978).

Haast Schist

The Caples, Waipapa and Rakaia terranes are partially overprinted by the Haast Schist belt. Locally, Haast Schist is geographically subdivided into Chatham Schist, Otago Schist, Alpine Schist, Marlborough Schist and Kaimanawa Schist. Regional metamorphism occurred in the Middle Jurassic to Early Cretaceous and the metamorphic grade is mainly sub-greenschist and greenschist facies, rising to amphibolite facies with greater Neogene exhumation along the Alpine Fault (Mortimer, 2000).

Chlorite zone schist in Otago and Marlborough contains widespread Au ± W ± Sb mineralised shear zones and quartz lodes (eg Paterson, 1986; McKeag, Craw and Norris, 1989; Teagle, Norris and Craw, 1990; MacKenzie and Craw, 1993; Christie, 2002; Begbie and Craw, 2006; Begbie and Sibson, 2006; MacKenzie, Corner and Craw, 2006; Mackenzie, Youngson and Craw, 2006; Skinner and Brathwaite, 2006) (Figure 3). Some of the mineralised shear zones are laterally very extensive: 25 km along strike in the case of the Hyde-Macraes Shear Zone, 20 km for the Bucklands Fault at Barewood, and more than 10 km at Carrick. The quartz lodes are lensoidal and contain minor pyrite + arsenopyrite + gold ± scheelite ± stibnite. The Macraes deposit in east Otago has been mined since 1990. There are minor manganese (pyrolusite, rhodonite and rhodochrosite) occurrences in low grade Otago Schist.

The Haast Schist of the Southern Alps hosts lenses of serpentinite (Pounamu Ultramafics) with talc magnesite and nephrite jade deposits. The nephrite jade is the source of greenstone boulders that have been recovered and worked by the Maori from Pleistocene to Holocene glacial and fluvial deposits in several rivers on the West Coast (Beck, Mason and Apse, 2015; Cox and Nibourel, 2015).

Zealandia Megasequence Cover

The initial separation of Zealandia from Gondwana by the opening of the Tasman Sea and Southern Ocean is dated at c 85 Ma. However, extension accompanied by rifting began in the region at about 105 Ma, supplanting a long period of convergent margin tectonics (Laird and Bradshaw, 2004). This change in tectonic pattern from convergent margin to extension (Austral Superprovince rocks to Zealandia Megasequence rock record) is attributed to the collision of the Hikurangi Plateau with the Chatham Rise part of Gondwana, and subsequent transfer of Zealandia to the Pacific Plate (Bradshaw, 1989; Luyendyk, 1995; Laird and Bradshaw, 2004; Reyners, 2013).

Syn-rift: Momotu Supergroup

The base of the Zealandia Megasequence is marked by a major regional angular unconformity, and deposition of the Late Cretaceous Momotu Supergroup (Mortimer *et al*, 2014). In southern and western New Zealand preserved Momotu Supergroup sedimentary rocks comprise non-marine conglomerates, sandstones, and siliceous igneous rocks including tuffs (eg Hawks Crag Breccia of the Pororari Group in

Buller, Kyeburn Formation in Otago, Mount Somers Volcanic Group in Canterbury). Bedded uranium mineralisation occurs in the Hawks Crag Breccia in the Buller area (Figure 5), and Cretaceous fanglomerates in Otago contain placer gold.

At the same time, marine strata were deposited in what is now the East Coast of the North Island, Marlborough and North Canterbury regions, close to the position of the formerly active trench.

Extension was also marked by the development of metamorphic core complexes in Westland, Fiordland and Stewart Island (Tulloch and Kimbrough, 1989; Kula *et al*, 2007). Minor rare-earth element mineralisation may be associated with the low angle detachment faults (Tulloch, 1995; Tulloch and Christie, 2000).

Marine transgression: Haerenga Supergroup

Zealandia underwent a prolonged period of subsidence and a dramatic reduction in land area as it moved away from Gondwana. This is recorded in a Late Cretaceous to Eocene (ca 85-35 Ma) transgressive sequence, typically beginning with coal measures and passing into shallow marine sediments consisting of quartzose and glauconitic sandstones, mudstones, marls and limestones. These rocks are found in a number of sedimentary basins onshore and offshore of the North and South Islands and contain most of New Zealand's economic petroleum, coal and limestone deposits.

Many of the South Island basins contain basal quartzose gravel and sand, which are important as sources of Au in Otago and silica sand for industry in Canterbury, Otago and Southland (Christie *et al*, 2000) (Figure 4). Some of the coal measures contain kaolinite clay deposits (eg Waikato). On the east coast of the North and South Islands, Late Cretaceous to Eocene marine sediments contain siliceous mudstone (Whangai Formation), limestone and smectite mudstone, locally with bentonite deposits and some organic-rich mudstones (Waipawa Formation) (Lee and Begg, 2002; Rattenbury, Townsend and Johnston, 2006).

Maximum flooding: Waka Supergroup

By the Oligocene the regional marine trangression had led to the widespread deposition of mudstones, marls, limestones and glauconitic sandstones. These rocks belong to Waka Supergroup of Mortimer *et al* (2014). Waka Supergroup Oligocene to earliest Miocene crystalline limestones are economically very important and occur mainly in eastern Northland, Waikato (eg Te Kuiti), Nelson, Westland, Canterbury and Otago (Figure 4; Christie, Thompson and Brathwaite, 2001; Mortimer and Strong, 2014). The mid Cenozoic limestone sequences are locally phosphatic, but only one previously mined deposit of phosphate (Clarendon, Otago) is known.

Convergent margin and marine regression: Māui Supergroup

The Waitakian stage in New Zealand (25.2-21.7 Ma; Raine *et al*, 2015) was a time of three profound events in New Zealand geology, all related to the re-establishment of a convergent plate boundary along the northeastern edge of Zealandia:

(1) allochthons were emplaced from a northeasterly direction across Northland and East Cape (Ballance and Spörli, 1979; Figure 2), followed immediately by

(2) establishment of a subduction related volcanic chain in Northland, and

(3) all New Zealand sedimentary basins experienced a flood of marine and non-marine clastic detritus that started a phase of marine regression that continues today.

Māui Supergroup comprises volcanic arc rocks and flysch- and molasse-like clastic groups and formations (Mortimer *et al*, 2014). Momotu, Haerenga and Waka supergroup rocks are all present in the Northland and East Coast Allochthons as well as oceanic igneous rocks (described below under Te Raupua Supersuite). The Miocene to Pleistocene shelly limestones of Gisborne, Hawkes Bay, Wairarapa, Taranaki and Southland (Māui and Pākihi Supergroups, see below) are also important local sources of agricultural lime.

Maui Supergroup quartz gravels with a Central Otago schist provenance form an extremely pure quartz gravel deposit at Pebbly Hills in Southland, potentially economic as a source for photovoltaic grade silicon and ferrosilicon.

Ice Ages to Present: Pākihi Supergroup

From the Pliocene to the present day, accelerated regional uplift along the Alpine and related fault systems has produced the axial mountain ranges of the North and South Islands. Erosion of the up-faulted mountain ranges, enhanced by Quaternary glaciation, has deposited extensive piedmont and fluvial gravels and fanglomerates in Nelson, Westland and Otago, including those of modern day rivers. These constitute the Pākihi Supergroup of Mortimer *et al* (2014). Holocene fluvial reworking of the older deposits has formed extensive Au placers in riverbed and terrace (glacial outwash) gravels in Westland and Otago (Henley and Adams, 1979; Youngson, 1996; Manhire, Loudon and Ryan, 2006) (Figure 3). Historic Au production from these giant placers is more than 245 tonnes from Westland and 255 tonnes from Otago.

Erosion of garnet-grade Haast Schist in the Southern Alps has resulted in the formation of ilmenite-garnet-gold placer deposits along, and offshore from, the west coast of the South Island (MacFarlan and Barry, 1991; Brathwaite and Pirajno, 1993; Brathwaite and Christie, 2006). The ilmenite and other heavy minerals (garnet and minor zircon with traces of monazite and gold) are concentrated in beach and dune deposits along 320 km of coastline between Karamea River and Bruce Bay (Figure 5). Deposits at Barrytown and near Westport have been investigated but not yet developed as a source of TiO_2.

Erosion of the Taranaki andesite volcanoes and volcanic rocks erupted from the Taupo Volcanic Zone (see Whakaari Supersuite below) has shed titanomagnetite and ilmenite (respectively) onto the North Island's west coast, forming significant Neogene placer ironsand deposits along 480 km of coastline and offshore on the inner continental shelf from Kaipara Harbour south to near Wanganui (Figure 5) (MacFarlan and Barry, 1991; Brathwaite and Pirajno, 1993; Brathwaite and Christie, 2013, 2014, 2015). The deposits have been mined since 1971, and the Waikato North Head and Taharoa deposits currently produce about 1 Mt of titanomagnetite concentrate (55-56 per cent Fe) per annum (Barakat and Drain, 2006; Barakat and Ruddock, 2006; Mauk, Macorison and Dingley, 2006; Mauk *et al*, this volume).

Rūaumoko Volcanics

The c 100 million years long Zealandia Megasequence contains a variety of plutonic and volcanic rocks termed Rūaumoko Volcanics. Mortimer *et al* (2014) divided them into three broad supersuites (Figure 2).

HOROMAKA SUPERSUITE is the name given to all intraplate igneous rocks within Zealandia Megasequence, ie those not directly related to subduction. The rocks are overwhelmingly volcanic and hypabyssal but exhumation has exposed Late Cretaceous plutons in Westland (Hohonu Range), Marlborough (Tapuaenuku), and Northland (Houhora Complex), and a Miocene pluton in Coromandel Peninsula.

Late Cretaceous igneous rocks in eastern basins of New Zealand typically consist of layered alkali gabbros and basalts (Tapuaenuku and Mandamus Igneous Complexes, Lookout and Gridiron Volcanics). The plutonic rocks contain minor Cu-Ni nickel sulfide and ilmenite-magnetite mineralisation (Figure 5). Further south in inland Canterbury, high K andesite and rhyolite of Late Cretaceous Mount Somers Group have locally weathered to produce economic kaolinite deposits.

Scattered low volume Miocene and Pliocene alkaline and tholeiitic volcanic and hypabyssal rocks are present in Canterbury and Otago, with major volcanic centres on Banks Peninsula, the Otago Peninsula the Chatham Islands and most of New Zealand's Subantarctic Islands. In New Zealand these are major sources of aggregate. Non-swelling calcium bentonite is associated with basaltic ash lake beds near Coalgate, 65 km west of Christchurch (Carlson, Grant-Mackie and Rogers, 1980). A Miocene carbonatite-lamprophyre dike swarm occurs in the Southern Alps.

In Northland, intraplate basalt volcanism commenced at about 10 Ma (later in Auckland), and is distinct from Northland-Coromandel-Taupo Volcanic Zone subduction-related volcanics (Smith *et al*, 1993). Epithermal hot spring Hg deposits in Northland appear to be associated with alkaline rhyolites (Figure 5). Subtropical weathering of the alkaline rhyolite domes has produced several high quality halloysite clay deposits in the Matauri Bay area of Northland (Townsend, 1989; Townsend, Luke and Evans, 2006; Brathwaite *et al*, 2012, 2014; Brathwaite and Christie, this volume). Several small deposits of bauxite have been formed by subtropical weathering of older basalt flows in the Kerikeri district of Northland (Kear, Waterhouse and Swindale, 1961; Williams, 1974).

TE RAUPUA SUPERSUITE is the name given to ophiolitic igneous rocks in the Northland and East Coast allochthons. The Tangihua Complex and Matakaoa Volcanics are dominantly basaltic, submarine and are interpreted as having erupted east of Zealandia in a back-arc basin setting adjacent to a magmatic arc (Ballance and Spörli, 1979; Malpas *et al*, 1992; Nicholson, Picard and Black, 2000; Whattam *et al*, 2004, 2005). The ophiolitic basalts contain small volcanic massive sulfide (pyrite-chalcopyrite) deposits in Northland (eg Pakotai and Parakao; Mason and Kobe, 1989), and an occurrence of massive sulfide containing barite + pyrite + sphalerite ± Au ± Ag assaying 1.5-22.3 g/t Au and 5-75 g/t Ag near Lottin Point, East Cape (Pirajno, 1980; Christie and Brathwaite, 2006; Brathwaite, Sewell and Christie, 2008) (Figure 5).

WHAKAARI SUPERSUITE is the name given to all subduction-related igneous rocks within the Zealandia Megasequence. Apart from the Pleistocene Solander Island volcano, south of Fiordland, subduction-related rocks are known only from the northern and central North Island. The oldest example is the Early Miocene Northland Volcanic Arc which consists of basalt, andesite and dacite (Smith, Ruddock and Day, 1989; Smith Black and Itaya, 1995; Herzer, 1995; Hayward *et al*, 2001; Booden *et al*, 2011). At about 15 Ma, there was a major change in oriantation of the arc, with the cessation of volcanism in Northland and rejuvenated volcanism in the Coromandel Peninsula region, including extension and rhyolite volcanism. Brathwaite and Skinner (1997) suggested that this change was caused by the propagation of the Colville-Lau oceanic island arc into the region. Volcanism continued in the Coromandel Peninsula region until the Late Pliocene, when activity shifted to the Taupo Volcanic Zone and the Kermadec Arc. Volcanism in the Taupo Volcanic Zone is predominantly rhyolitic, with lesser andesites and dacites (Wilson *et al*, 1995). Arc volcanism above the deeper part of the slab is manifested by andesitic volcanoes on the west coast of the central North Island (Mt Taranaki and associated high-K andesites; Price *et al*, 1999).

The Northland and Coromandel volcanic zones have associated epithermal mineralisation, mainly Au and Ag, but also Pb, Zn, Cu, Hg, and Sb, as well as deposits of native sulfur, perlite, pumice and zeolite (Figures 4, 5). Porphyry Cu style mineralisation is associated with subvolcanic intrusive rocks in Northland and Coromandel, and Pb-Zn skarn is hosted by limestone in Northland (Brathwaite *et al*, 1990). The epithermal Au-Ag deposits of the Coromandel region occur mainly as quartz ± carbonate veins with a variety of sulphide minerals (Brathwaite, Christie and Skinner, 1989; Christie *et al*, 2006b). Notable deposits include Martha (Brathwaite, Torckler and Jones, 2006), Favona (Torckler, McKay and Hobbins, 2006; Mauk *et al*, 2006), Golden Cross (Mauk and Purvis, 2006), Karangahake, Thames, Komata, Tokatea-Success, Kapanga and Hauraki. The Taupo Volcanic Zone contains several epithermal Au-Ag prospects (Barker and Christie, this volume) and deposits of ignimbrite building stone, perlite, pumice, microsilica, native sulfur and zeolite (Brathwaite, Hill and Merchant, 2006; Brathwaite and Henderson, this volume).

Recent exploration of the offshore extension of the Taupo Volcanic Zone, the Kermadec Arc (Figure 1), has located massive sulfide (Cu+Zn+Pb+Ba±Au) mineralisation at several submarine volcanoes (de Ronde, 2006) and submarine venting of metals at multiple sites along the southern part of the arc (Massoth and de Ronde, 2006).

CONCLUSIONS

Most of New Zealand's onland metallic mineral deposits and occurrences are found as (1) intrusion-related associations in the Western Province Tuhua Intrusives, (2) mesothermal associations in Paleozoic Western Province metasediments and Mesozoic Eastern Province schists and shear zones, (3) epithermal associations in Miocene (subduction-related) Whakaari Supersuite volcanic rocks, (4) placer associations in Holocene Pakihi Supergroup beach and river deposits.

Industrial minerals such as limestone, silica and clay are obtained principally from Cenozoic Zealandia Megasequence sedimentary rocks and from Whakaari Supersuite lavas

The Litho2014 high-level stratigraphic scheme for New Zealand (Mortimer et al, 2014), developed for national digital database needs, offers a more holistic and complete description and interpretation of New Zealand geology than previous schemes. The high-level stratigraphic units are bounded by intrusive contacts, faults, and/or unconformities. As such the units define discrete depositional, tectonic and magmatic episodes that can be related to mineralisation and crustal fluid flow, and provide fresh insights and understanding of mineralising processes.

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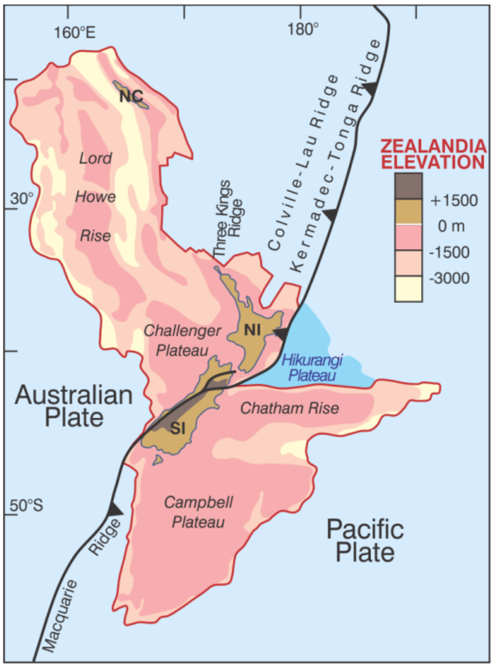

FIG 1 – Extent and bathymetry of Zealandia. NC=New Caledonia, NI=North Island, SI=South Island.

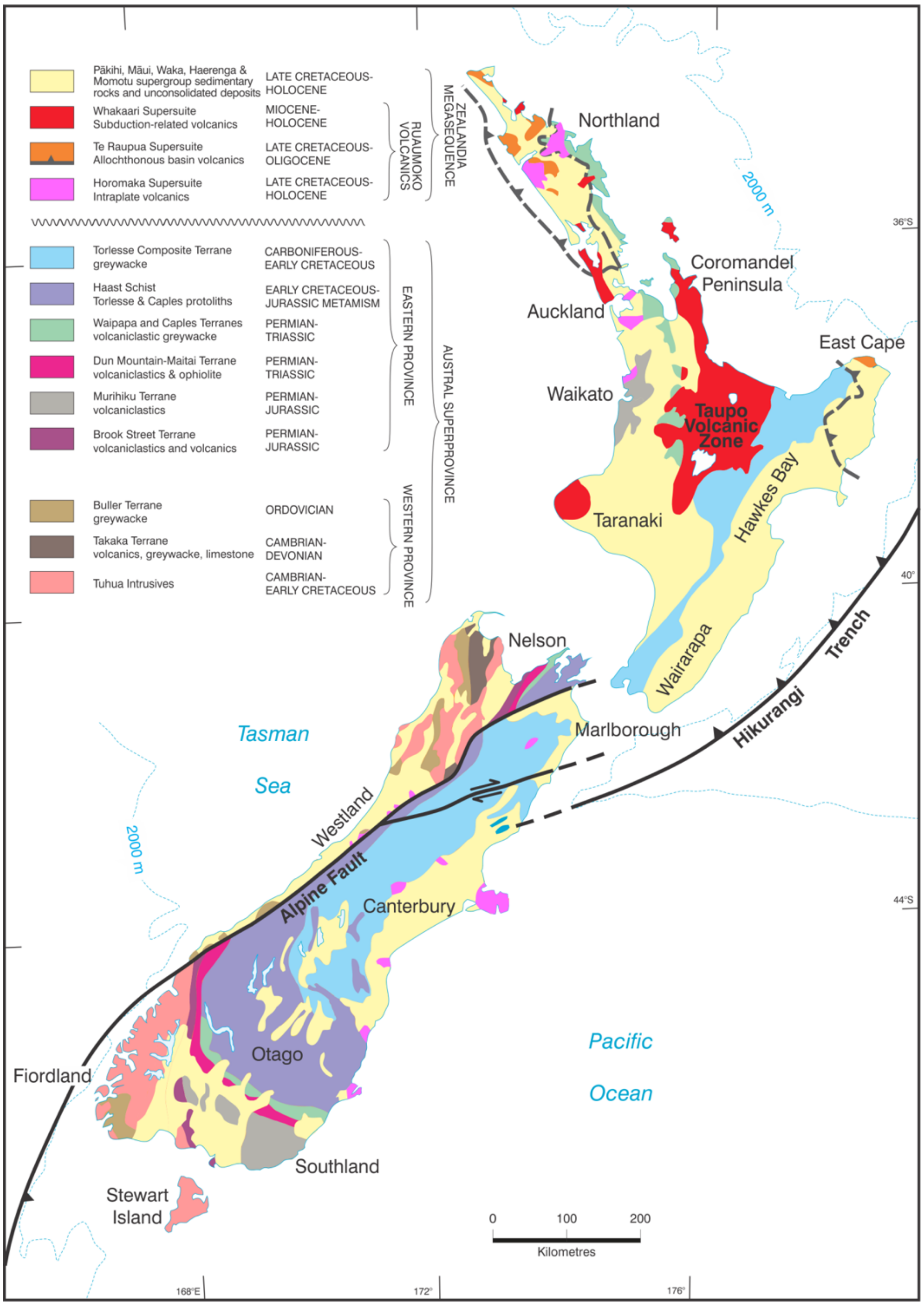

FIG 2 – Simplified geology of New Zealand using new high level stratigraphic names of Mortimer *et al* (2014).

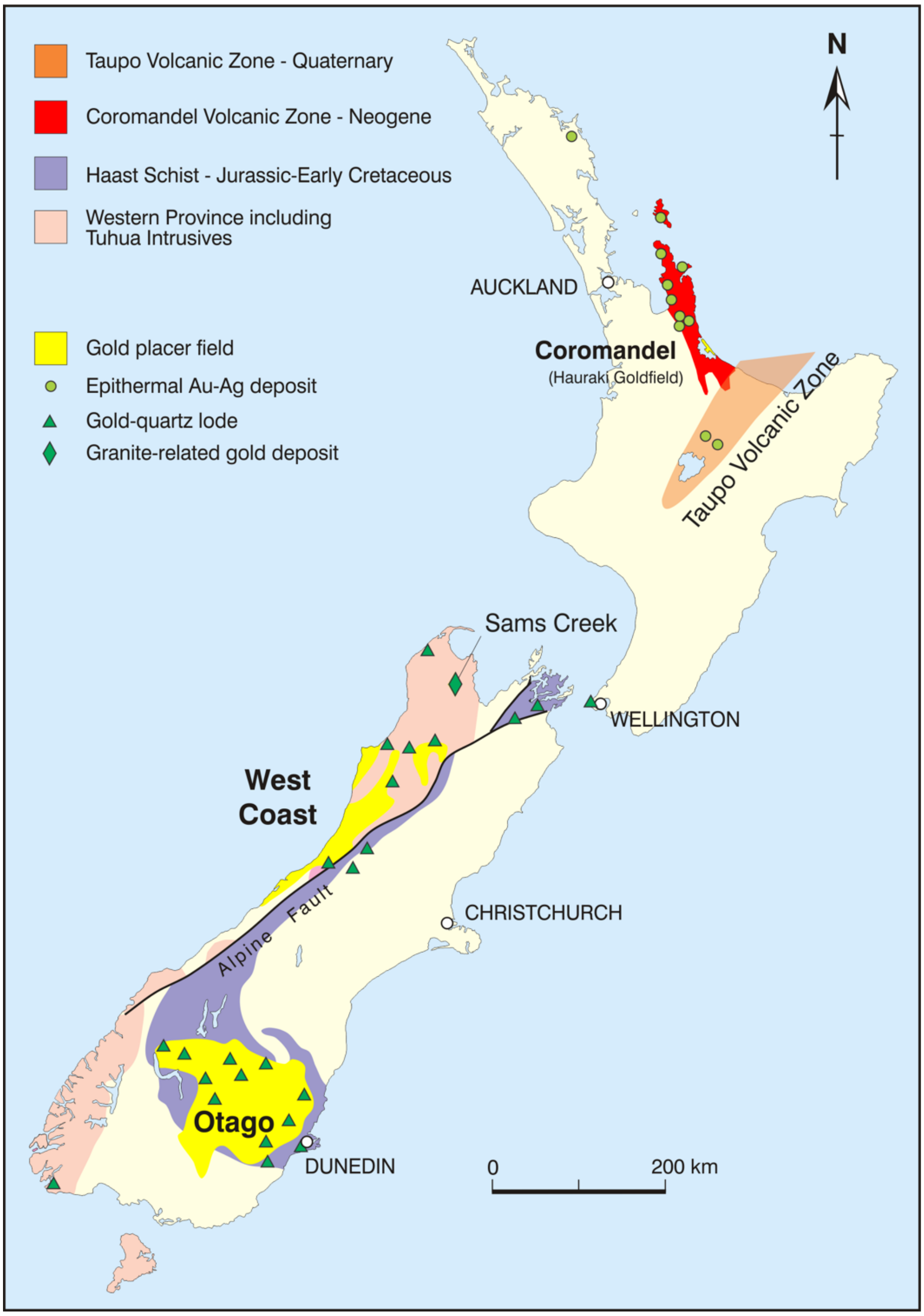

FIG 3 – Distribution of principal Au deposits in New Zealand.

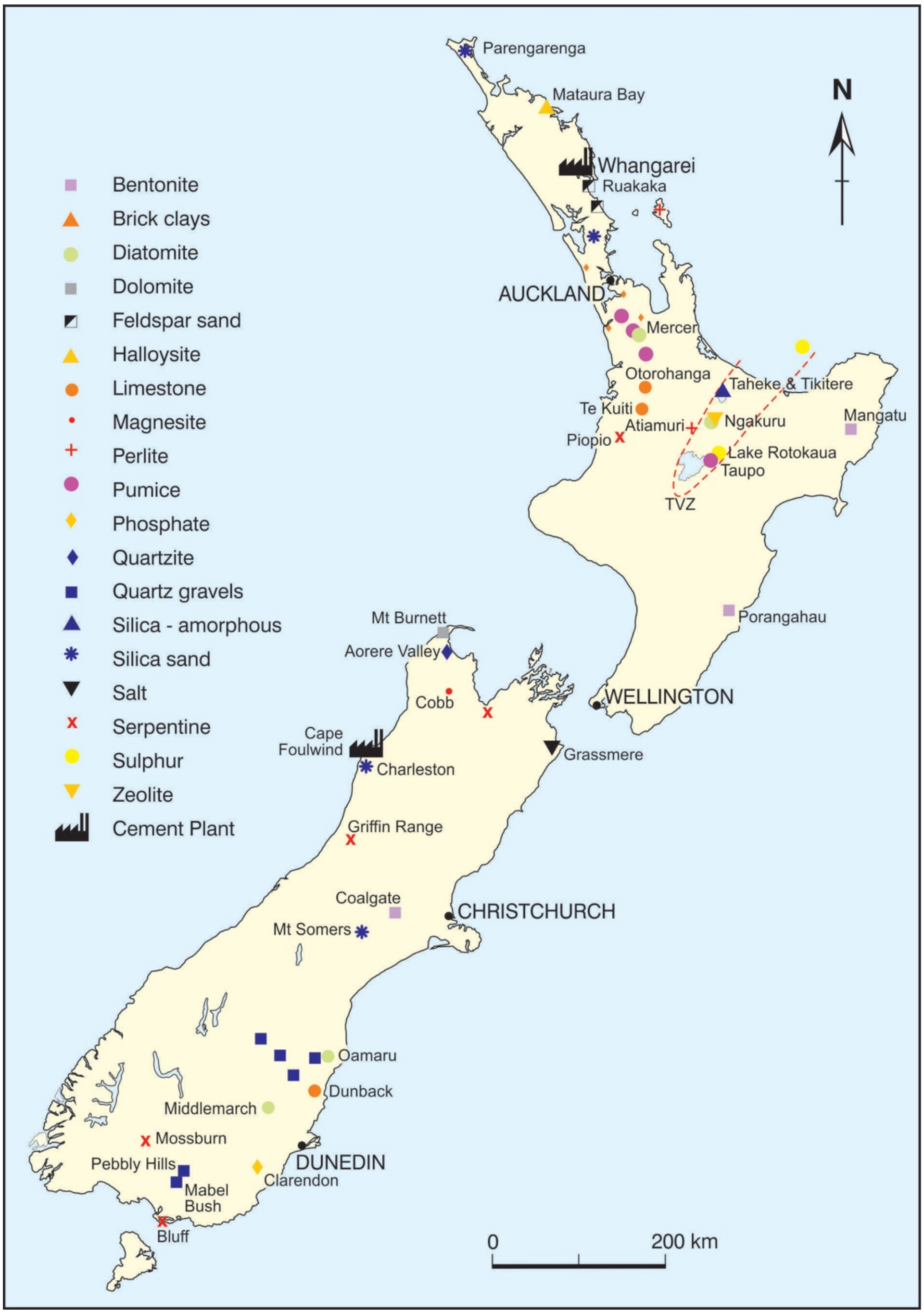

FIG 4 – Distribution of principal non-metallic mineral deposits in New Zealand.

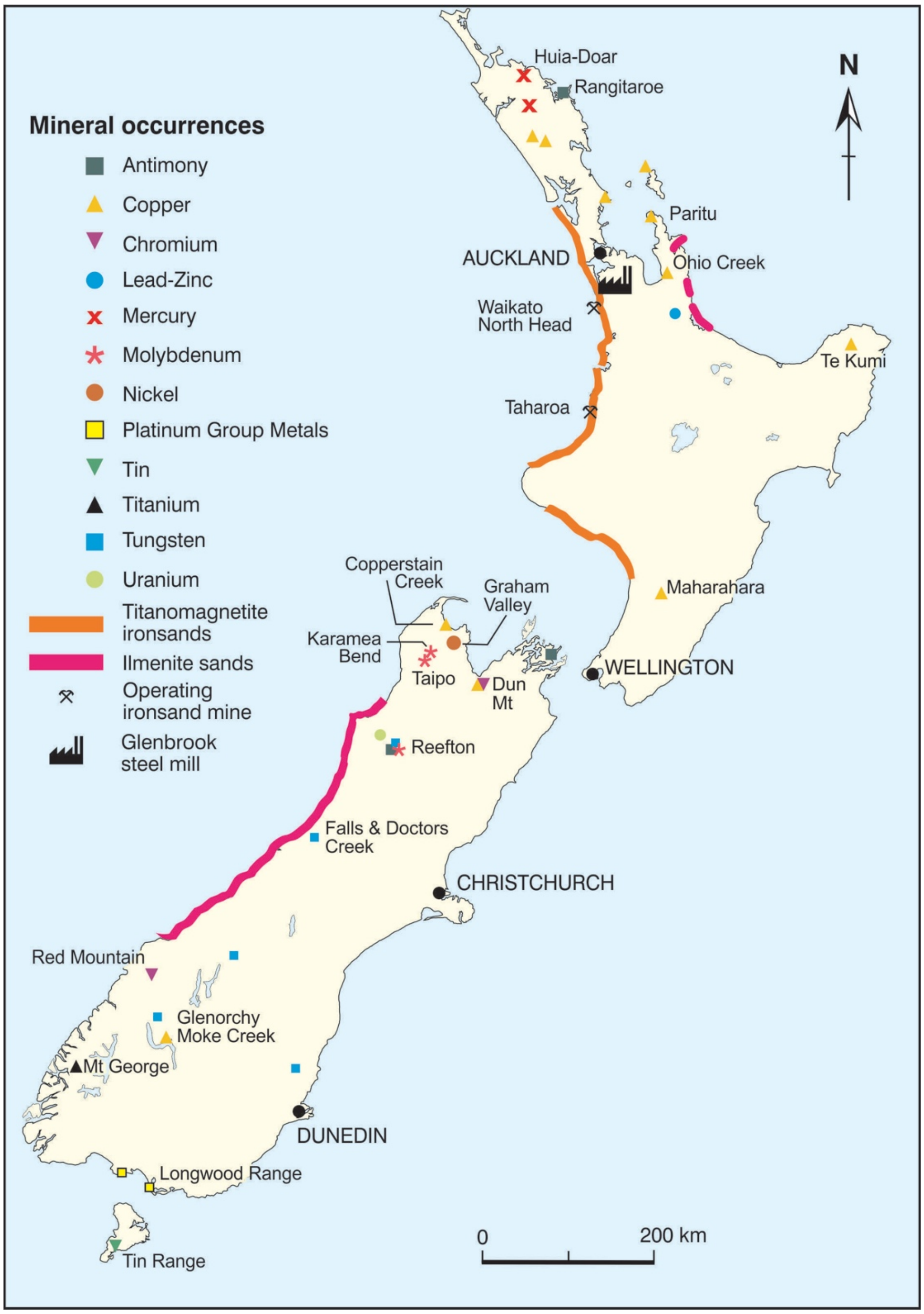

FIG 5 – Distribution of principal metallic mineral deposits, excluding Au, in New Zealand.

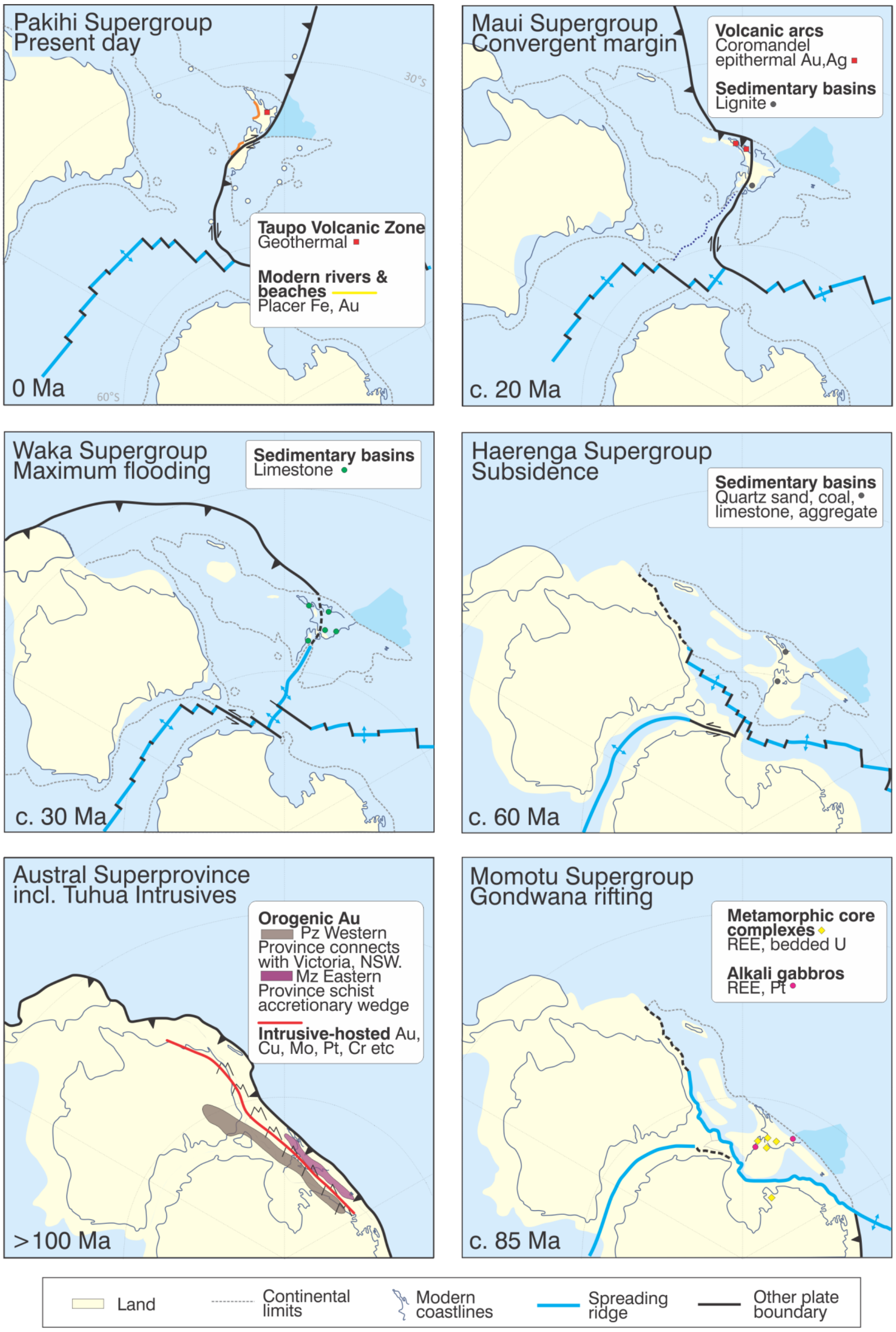

FIG 6 – Paleogeographic reconstructions of New Zealand mineral deposits showing connections with Australia and Zealandia breakup. Lands area prior to 0 Ma speculative.