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Zealandia

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ABSTRACT

Zealandia is a submerged continent in the southwest Pacific Ocean that can be regarded as a rifted part of eastern Australia and West Antarctica. Described simply, the pre-Gondwana-breakup Zealandia geological record is one of a Cambrian to Early Cretaceous Gondwana convergent margin, followed by Late Cretaceous continental rifting.

NEW ZEALAND AND ZEALANDIA

Submerged continent

Satellite-derived bathymetry (Fig. 1) reveals that New Zealand is surrounded by submarine plateaus, ridges and trenches. Some narrow features (e.g. Kermadec Ridge and Trench, Macquarie Ridge) are obviously related to the Neogene-Recent Pacific-Australian plate boundary. Hotspot tracks (e.g. Louisville and Tasmantid Seamount chains) indicate Cenozoic movement of the Pacific and Australian plates relative to the mantle.

Around the broader plateaus, such as the Campbell Plateau, Lord Howe Rise, and Norfolk Ridge, the 2500 m isobath defines the limits of continental crust. Zealandia (a term first used by Luyendyk, 1995) is the collective name given to the mainly thinned and submerged continental fragments that were formerly contiguous with Australia and Antarctica, and which became stranded on the eastern and northern sides of the Tasman Sea and Southern Ocean spreading centres (Figs. 1, 2). In contrast to the small islands of New Zealand, Zealandia is approximately 40% of the area of onland Australia, but more than 90% submerged. The emergent parts of Zealandia are above sea level either because of Cenozoic crustal thickening due to local obduction and/or collision events (e.g. New Caledonia, New Zealand) or because of isolated intraplate volcanism (e.g. Chatham Islands).

Granites, greywackes, schists, and lavas occur on scattered islands, and they have been sampled at the bottom of oil exploration wells, and in dredges around Zealandia, thus proving its continental nature (Fig. 1). In almost all cases these rocks have been successfully matched with onland New Zealand terranes and igneous suites (e.g. Beggs et al., 1990; Tulloch et al., 1991; McDougall et al., 1994; Mortimer et al., 1998, 2006, 2008).

Surrounding oceanic crust

All continent-ocean boundaries around Zealandia are passive/rift margins except for the Neogene-Recent convergent Pacific-Australia Plate boundary between North and South Zealandia and for the north side of the Chatham Rise which represents a fossil Cretaceous subduction zone (Fig. 1). The age of the oldest oceanic crust on the Australian and Antarctic sides of Zealandia is c. 85 Ma (Gaina et al., 1998; Davy, 2006).

The Hikurangi Plateau (Davy, 1992; Wood and Davy, 1994) is a large igneous province whose main subalkaline plateau-forming basement has been dated at 120-100 Ma and post-plateau alkaline seamounts at 99-86 Ma (Hoernle et al., 2005). About 150 km of the plateau appears to have been subducted beneath the North Island in the Neogene (Reyners et al., 2006). The plateau now abuts the Chatham Rise and there has been considerable speculation as to its involvement in Cretaceous tectonic events at the Zealandia margin by jamming the subduction zone (e.g. Davy, 1992; Vry et al., 2004). The oldest undeformed reflectors that drape both the plateau and Chatham Rise are probably a condensed sequence of latest Cretaceous to Paleogene age (Davy and Uruski, 2002). The actual time of collision remains speculative (Mortimer et al., 2006) but must predate 70 Ma and postdate Hikurangi Plateau formation from about 120 Ma. Downey et al. (2007) infer the crust between the formerly conjoined Hikurangi and Manihiki Plateaus and the Osbourn Trough to be of 85-121 Ma age (Fig. 1).

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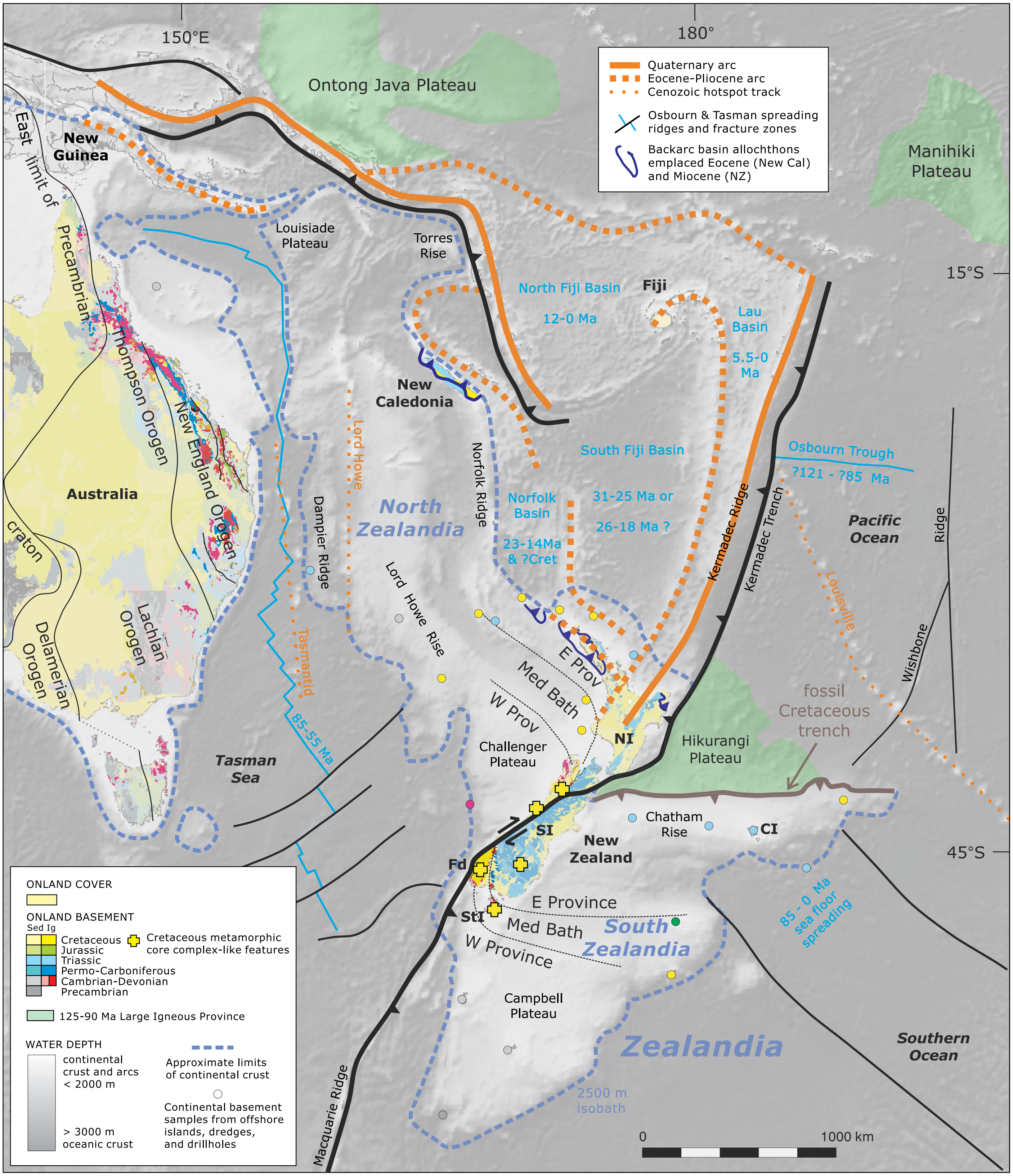

Figure 1. Map of the Australia-New Zealand-New Caledonia area showing major continental and oceanic geological features. Bathymetry is from the dataset of Sandwell and Smith (1997). CI=Chatham Islands, Fd=Fiordland, NI=North Island, SI=South Island, StI=Stewart Island, Med Bath. = Median Batholith.

CAMBRIAN-CRETACEOUS GONDWANA MARGIN RECORD

At the regional scale, the New Zealand crystalline basement can be divided into at least nine tectonostratigraphic terranes, three composite regional batholiths and three regional metamorphic-tectonic belts that overprint the terranes and batholiths (Mortimer, 2004). This short paper gives a summary only of higher level groupings. For summary descriptions of individual basement units, the reader is referred to Coombs et al. (1976), Bradshaw (1989), Mortimer (2004) and Wandres and Bradshaw (2005). Descriptions of regional geology at 1:250 000 scale are given in a recent series of maps (e.g., Turnbull and Allibone, 2003) and national archived rock data can be found at http://pet.gns.cri.nz.

In contrast to Australia and Antarctica, no Precambrian crust is exposed onland in New Zealand. The oldest dated material is a 3.4 Ga zircon in Victoria Paragneiss of the Buller Terrane (Ireland, 1992). The oldest rocks dated by fossils in New Zealand are the Heath Creek beds in the Haupiri Group of the Takaka Terrane which contains Middle Cambrian (c. 505 Ma) trilobites (Cooper 1989).

Terranes

The Cambrian-Devonian Buller and Takaka terranes are the westernmost terranes in New Zealand and are grouped together into the Western Province. The Brook Street, Murihiku, Maitai, Caples, Waipapa Composite and Torlesse Composite terranes range in age from Permian to Early Cretaceous and are grouped together into the Eastern Province. The terranes represent progressive Pacific-ward growth of Gondwanaland through tectonic offscraping at an episodically convergent Cambrian-Cretaceous margin. The Eastern and Western provinces and their offshore continuation are shown in Figure 1.

All New Zealand terranes are dominated by greywacke sandstones. Igneous rocks form important parts only of the Permian Brook Street Terrane (an intraoceanic island arc), and the Permian Dun Mountain Ophiolite Belt (Coombs et al., 1976) which is part of the Maitai Terrane.

Small outliers of Devonian, Permian, Triassic and Jurassic Gondwana sequences are present in the Western Province (Mortimer et al., 1995; Mortimer and Smale, 1996; Campbell et al., 1998). Thus the Western Province terranes are inferred to have been part of autochthonous Gondwana at the time that many of the Eastern Province Terranes were being deposited and/or accreted.

The position of the allochthonous Permian-Cretaceous Eastern Province terranes at the time of their deposition remains a source of debate. Defining characteristics of the terranes include mutually distinct greywacke petrofacies and detrital zircon age populations (e.g. MacKinnon, 1983; Roser and Korsch, 1986, Adams et al., 2002). Adams and Kelley (1998) and Adams et al. (2002), showed a local (Western Province and Median Batholith) source for the Permian-Triassic greywackes of the Eastern Province was unlikely, and proposed a hypothesis for their derivation from northeastern Australia. An alternative, Antarctic, source was proposed by Wandres et al. (2004a).

In contrast to the allochthonous nature of the Permian-Triassic units, sandstones and conglomerate clasts from the youngest (Early Cretaceous) part of the Eastern Province (Pahau Terrane) can be matched with sources in the local Median Batholith (Wandres et al. 2004b). Thus by the Early Cretaceous, the presently observed Median Batholith arc (see below) and Eastern Province forearc-wedge components had probably been assembled.

Batholiths

The Western Province terranes and edge of the Eastern Province are intruded by three composite batholith (>100 km^2) sized belts of plutons: Karamea-Paparoa, Hohonu (not shown in Figure 1) and Median, as well as numerous smaller plutons.

Median Batholith (formerly Median Tectonic Line or Zone) is a recently-recognised Cordilleran batholith between the Eastern and Western Province terranes that represents the site of subduction-related magmatism from c. 360-105 Ma (Mortimer et al., 1999; Tulloch and Kimbrough, 2003). The other batholiths lie entirely within the Western Province; the Karamea Batholith mainly contains Devonian-Carboniferous I- and S-type suites and the Hohonu Batholith Late Cretaceous (110-82 Ma) I- and A-type suites.

Tectonic-metamorphic overprints

The Western Province terranes and the batholiths are locally metamorphosed and deformed into Devonian-Carboniferous and Cretaceous amphibolite-granulite facies gneisses, some of which have been described as metamorphic core complexes (see below). Jurassic-Cretaceous subgreenschist- to amphibolite-facies schist fabrics (Haast Schist) and Cretaceous subgreenschist facies melange fabrics are imprinted on parts of some Eastern Province terranes and represent penetrative and brittle deformation in the Mesozoic accretionary wedge. These overprints are not shown at the scale of Figure 1, but more information is given in Bradshaw (1989), Gray and Foster (2004) and Mortimer (2004).

Cessation of subduction

The exact time in the Cretaceous at which there ceased to be a subducting slab beneath the Zealandia margin remains debatable. There is a reasonably well-established plutonic record of "normal" subduction-related, I-type, low Sr/Y magmatism in the Median Batholith from 170-130 Ma. At 130 Ma, the flux rate of the Median Batholith increased, and it became dominated by plutons of high Sr/Y ("adakitic") character until

105 Ma when Median Batholith magmatism ceased (Muir et al., 1998; Tulloch and Kimbrough, 2003). Models of tectonic thickening of arc crust have been invoked to explain the change in composition but if the high Sr/Y magmas are not slab melts, then they do not necessarily require an actively subducting slab after 130 Ma.

The youngest greywacke depositional ages in the imbricated accretionary wedge of the Eastern Province are c. 100 Ma (Cawood et al., 1999). Ar-Ar ages from schists that can be related to deep accretionary wedge development are in the range 140-160 Ma (Gray and Foster, 2004). Ductile shear zones in the schists, of possible extensional origin, are 106-122 Ma (Forster and Lister, 2003). However, as pointed out by Deckert et al. (2002), extensional exhumation may occur within an accretionary wedge during plate convergence, so this does not mean that subduction had stopped. A structural and petrological "cap" on the duration of Eastern Province accretionary tectonics is provided by a number of c. 97 Ma alkaline igneous centres across Zealandia (e.g. Challis, 1960; Weaver and Pankhurst, 1991; Reay, 1993; Mortimer et al. 2006). While minor A-type granites do occur in association with older I-type plutons in the Median Batholith, these 97 Ma alkaline rocks are well east of the batholith and intrude and/or erupt onto deformed Eastern Province accretionary prism.

The aforementioned observations support a widely held view (e.g. Bradshaw, 1989; Mortimer, 2004) that the Zealandia tectonic regime changed from subduction to extension at or about 100-105 Ma. Models for subduction cessation include ridge subduction (Bradshaw, 1989), Hikurangi Plateau collision (Davy, 1992), and ridge stall (Luyendyk, 1995).

Mazengarb and Harris (1994) documented thrusting (or at least block faulting) as young as c. 82 Ma in the toe of the Eastern Province accretionary prism in eastern North Island. Subalkaline subduction-influenced volcanism of 90-105 Ma produced igneous complexes in allochthons in the North Island (Fig. 1; Nicholson et al. (2000) and references therein). One possible scenario is that at c. 105 Ma, the Hikurangi plateau did, indeed, jam the subduction zone off what is now South Zealandia but between 90-105 Ma, subduction either continued, or became re-established on the Pacific margin, off North Zealandia (Fig. 2; e.g. Schellart et al., 2006). Continued rollback of the trench led to the development of backarc basins that were subsequently emplaced as the allochthons and/or remained as the festoon of intraoceanic arcs between New Zealand and New Guinea (Fig. 1).

LATE CRETACEOUS CONTINENTAL RIFTING

The post-105 Ma and pre-Gondwana-breakup record of continental thinning and rifting is manifest in three main ways, thinned crust, metamorphic core complexes and extensional rift basins.

Outside the Neogene crustal root of the South Island, the crustal thickness of Zealandia averages 28 km (Wood and Stagpoole, 2007), compared with 30-35 km in formerly adjacent Australia. The submerged nature of Zealandia is also clearly consistent with isostatically compensated continental crust of less than normal thickness.

At least four Cretaceous metamorphic core complexes have been recognised in the Median Batholith and/or Western Province (Figs. 1, 2). All include penetratively deformed late Early Cretaceous plutons in their lower plates. The Paparoa Core Complex of northern South Island (Fig. 1) was described by Tulloch and Kimbrough (1989). Other gneiss culminations SW of the Paparoa Core Complex may also represent one or more core complexes (Tulloch, 1995). In Fiordland, Gibson et al. (1988) recognised a deep-level core complex that juxtaposed granulite against amphibolite facies rocks; extensional exhumation on a related shear zone in Fiordland has been dated as 108-111 Ma (Scott and Cooper, 2006). On Stewart Island (Fig. 1), Kula et al. (2007) identified a younger, 89-82 Ma period of extensional shearing and, on that basis, proposed a two stage model for Zealandia rifting.

The Otago Schist of the Eastern Province contains features that resemble a metamorphic core complex. These include regionally flat lying greenschist facies foliation, 106-122 Ma ductile shear zones, and low angle brittle faults dipping off the metamorphic core (Deckert et al., 2002; Forster and Lister 2003; Gray and Foster, 2004).

The distribution of Albian nonmarine rift basins is discussed by Laird and Bradshaw (2004). Most of the terrestrial rift basins are spatially associated with the aforementioned metamorphic cores. Late Coniacian to Santonian (87-85 Ma) marine unconformities cut the deformed basement rocks over much of New Zealand (Laird and Bradshaw, 2004). This time period represents the end of the intracontinental rift phase and a switch to the drift phase. From c. 85 Ma, Zealandia was separated from Australia and Antarctica by oceanic crust.

CRETACEOUS RECONSTRUCTION

Gondwana continental reconstructions were previously made by bathymetric matching of continent-ocean margins (e.g. Griffiths, 1971). The satellite gravity datasets that have emerged in the past 10 years (Sandwell and Smith, 1997) provide a clear view of oceanic fracture zones and thus a geometrically unambiguous means by which to restore Zealandia to its position in Gondwanaland (e.g. Fig. 2). With the Tasman Sea closed, New Zealand restores to a position close to Tasmania but New Zealand's terranes and batholiths are still 1500 km distant along strike from their Australian counterparts.

The reconstruction in Figure 2 predates actual seafloor spreading between Australia, Zealandia and Antarctica but probably postdates much of the aforementioned intracontinental rifting. On a pre-rift (pre-100 Ma) reconstruction, the width of the Zealandia ribbon might have to be halved in order to produce typical arc-trench distances of 150-300 km.

Comparisons between Australian and New Zealand geology include those by Griffiths (1971), Grindley and Davey (1982), Cawood (1984), Cooper and Tulloch (1992), Muir

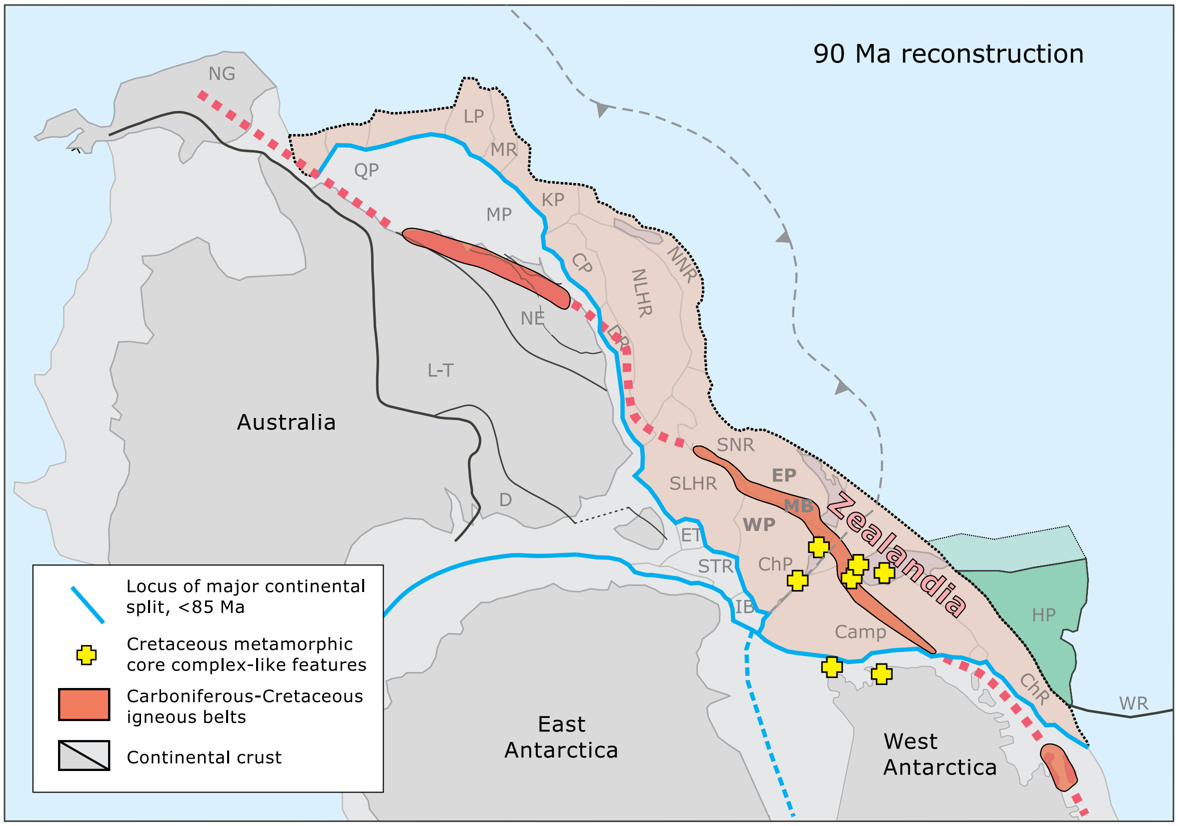

Figure 2. An "untightened" reconstruction of the continental blocks of Australia, Zealandia and Antarctica showing along-strike continuation between Median Batholith of New Zealand and Carboniferous to Cretaceous plutons in Australia and Antarctica (Murray, 1990; Pankhurst et al. 1993). Reconstruction is based on Gaina et al. (1998), Sutherland (1999) and Eagles et al. (2004). The Tasman Sea and Southern Ocean basins have been closed but no attempt has been made to unstretch continental crust. Locations of core complex-like features are from sources mentioned in the text and from Richard et al. (1994) and Siddoway et al. (2004). Thick blue lines show the places where rifting eventually led to formation of the Tasman Sea and Southern Ocean. Position of subduction zone and width of backarc basins east of Australia are speculative and are based on presence of obducted back arc basin basalts (Nicholson et al., 2000). Geographic/bathymetric features: NG=New Guinea, QP=Queensland Plateau, MP=Marion Plateau, LP=Louisiade Plateau, MR=Mellish Rise, KP=Kenn Plateau, CP=Chesterfield Plateau, DR=Dampier Ridge, NLHR, SLHR=Northern and Southern Lord Howe Rise, NNR, SNR=Northern and Southern Norfolk Ridge, ET=East Tasman Rise, STR=South Tasman Rise, ChP=Challenger Plateau, Camp=Campbell Plateau, ChR=Chatham Rise, HP=Hikurangi Plateau (pale green part now subducted beneath Kermadec Trench), WR=Wishbone Ridge, IB=Iselin Bank. Geological features: D=Delamerian Orogen, L-T=Lachlan-Thomson Orogen, NE=New England Orogen, EP=Eastern Province, WP=Western Province, MB=Median Batholith.

et al. (1996), Sutherland (1999), and Mortimer et al. (2008). Figure 2 shows a possible continuation of the Carboniferous-Cretaceous Median Batholith into its along-strike Antarctic and Australian equivalents.

CONCLUSIONS

Zealandia is a mainly submerged continent in the southwest Pacific Ocean. The islands of New Zealand and New Caledonia are the only parts now above sea level. New Zealand basement rocks consist of terranes, batholiths, and rock assemblages with tectonic-metamorphic overprints that all formed or were accreted at an episodically convergent Cambrian-Early Cretaceous plate margin along the east side of Gondwanaland. In the Late Cretaceous, Zealandia and West Antarctica underwent significant crustal thinning. Sea floor spreading fully isolated Zealandia from Australia and Antarctica at c. 85 Ma.

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