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RESEARCH ARTICLE

Palaeogeographic evolution of Zealandia: mid-Cretaceous to present

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ABSTRACT
We present a suite of 15 palaeogeographic maps illustrating the geological evolution of the entirety of Zealandia, from mid-Cretaceous to present, highlighting major tectonic phases, from initial Gondwana rifting through to development of the Neogene plate boundary. They illustrate palaeobathymetric and palaeofacies interpretations along with supporting geological datasets and a synthesis of regional tectonics. The maps are underpinned by a geologically-constrained and structurally-based rigid retro-deformation block model. This model, tied to the global plate circuit, is relatively simple for the main regions of Northern and Southern Zealandia, but breaks central Zealandia into numerous fault-bounded blocks, reflecting complex Neogene deformation associated with the modern plate boundary. Production of maps using GPlates and GIS allows for simple alteration or refinement of the block model and reconstruction of any geological dataset at any time. Reconstructions are within a palaeomagnetic reference frame, allowing assessment of palaeo-latitude, critical for palaeo-climatic and palaeo-biogeographic studies.

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Palaeogeography; tectonics; Cretaceous; Paleogene; Neogene; palaeobathymetry; palinspastic reconstruction; rifting; subduction

Introduction

Zealandia, Earth's most recently recognised continent (Mortimer and Campbell 2014; Mortimer et al. 2017), forms a roughly 4.9 million km^2 area of continental crust in the southwest Pacific (Figure 1). Although it includes the landmasses of New Zealand, New Caledonia, and numerous smaller islands, 94% of Zealandia is below sea level. The majority of Zealandia is encompassed by the extended continental shelf (ECS) of New Zealand (Figure 1), with parts of Northern Zealandia falling within the ECS of Australia and France (New Caledonia).

The present-day extent, physiography/bathymetry and tectonic setting of Zealandia have been recently summarised (Mortimer 2020; Mortimer et al. 2020b, 2020c). However, the palaeogeographic evolution of Zealandia as a whole has not previously been considered in detail. Zealandia's present-day architecture is known at a broad scale, and formed from a combination of subduction accretion, magmatism, rifting, and passive-margin sedimentation over the last 100 Myr. Palaeogeographic reconstructions are important for resolving the distribution of the elements that comprise Zealandia, such as its sedimentary basins, volcanic arcs, and fault systems. They provide a valuable means of synthesising large amounts of geological data and help to summarise the long and complex geological history of regions such as Zealandia. Palaeobathymetry, restored to its correct palaeolatitude, also provides important input data for palaeo-oceanographic, palaeoclimate and biogeographic studies (e.g. Bunce et al. 2009; Trewick and Bland 2012). Palaeogeographic maps also provide a better understanding of our biological heritage, such as the location and size of landmasses and land bridges, and how extensive terrestrial and marine habitats were through time. They also provide an important framework for sediment provenance and dispersal studies (Bull et al. 2019; Sagar et al. 2022).

This paper presents a new set of palaeogeographic maps covering the entirety of Zealandia retro-deformed through time, and represents the culmination of many years of research and compilation. These maps mark a major advance from the tectonic summary maps of King (2000) and the derived schematic palaeogeographic maps (e.g. King et al. 1999; Sutherland et al. 2009; Mortimer and Campbell 2014). Whilst palaeogeographic maps have been produced for parts of Zealandia (see section 2.2), unified maps covering the whole region or covering the entire mid-Cretaceous to present-day time period have not. Nor have maps been produced in a retro-deformed framework, and placed in an accurate latitude/longitude reference frame. It is beyond the scope of this paper to provide a full detailed geological history for all of Zealandia. Instead, a listing of data sources and methods used to build the maps is provided, as well as brief descriptions of the geological evolution as

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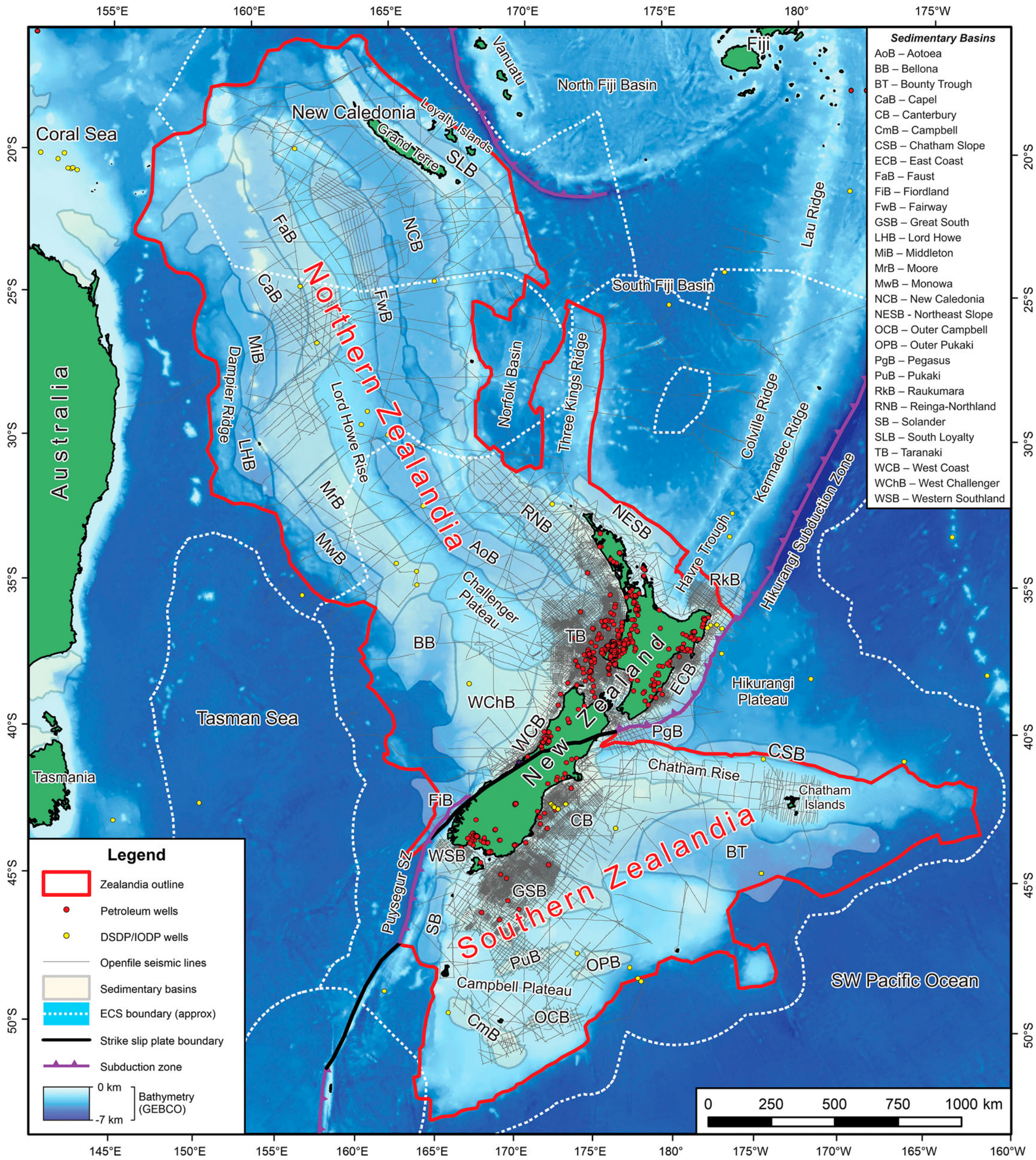

Figure 1. Map of Zealandia showing the distribution of seismic and well datasets upon which palaeogeographic and basin studies are based. This shows the high data density in proximal New Zealand basins, but the very sparse datasets in much of Northern Zealandia and the distal Campbell Plateau. Bathymetry courtesy of GEBCO. 2D seismic dataset from New Zealand Petroleum & Minerals (2015) and Sutherland et al. (2012).

illustrated by each of the palaeogeographic maps, and some discussion of any issues or points of interest.

Regional geological setting

Zealandia and surrounding regions have experienced a dynamic geological history, reflecting the complex tectonics of the southwest Pacific region over the last 100 Myr. The continent is presently bisected by an active convergent boundary between the Australian and Pacific plates (Figure 1). The area north (Australian Plate) and south (Pacific Plate) of the present day plate boundary are hereafter referred to as Northern and Southern Zealandia, respectively, as defined by Mortimer et al. (2017). Beneath eastern North Island, the plate boundary manifests as subduction of oceanic Pacific Plate beneath the continental Australian Plate, along the Hikurangi margin (Walcott 1978; Nicol et al. 2007). This margin transitions southwards from subduction of the Pacific Plate along the Tonga-Kermadec Trench (and associated back-arc extension in the Lau Basin-Havre Trough), to continental collision and strike-slip along the Alpine Fault in South Island, New Zealand. To the southwest of South Island, a reversed subduction polarity sees oceanic Australian Plate crust being subducted obliquely beneath Pacific Plate continental crust (Gurnis et al. 2019).

From the Paleozoic to Early Cretaceous, the region that would later become Zealandia formed part of eastern Gondwana, with long-lived subduction along its palaeo-Pacific eastern margin, and associated terrane accretion and magmatism. Rocks associated with this time period within the New Zealand region form the Austral Supergroup of Mortimer et al. (2014), and are subdivided into a series of basement terranes (Figure 2). Overlying the 'basement' rocks of the Austral Superprovince are mid-Cretaceous to Recent sedimentary and igneous 'cover' rocks of the Zealandia megasequence (Mortimer et al. 2014), which are the focus of this study. As the early part of the cover sequence straddles the Early to Late Cretaceous boundary, we use the informal term mid-Cretaceous.

Deposition and emplacement of the Zealandia megasequence began immediately following the cessation of subduction along the palaeo-Pacific margin at c. 100 Ma (Crampton et al. 2019; Riefstahl et al. 2020a). Some models infer complex subduction continued for some time (e.g. Cooper and Palin 2018), although a model of early subduction cessation is favoured here (see discussion in Crampton et al. 2019). Widespread rifting occurred throughout much of Zealandia (Laird and Bradshaw 2004; Strogen et al. 2017), which continued until initial separation of Zealandia from the remainder of eastern Gondwana at c. 83 Ma (Gaina et al. 1998b). Following this, sea-floor spreading began in both the southwest Pacific and Tasman Sea, and Zealandia drifted away from both Antarctica and Australia. This was a mostly tectonically quiescent time, although some minor rifting did occur in central Zealandia (Strogen et al. 2017). Tasman Sea spreading ceased by c. 52 Ma (Gaina et al. 1998b), with Zealandia then fully separated from Australia. There are several competing tectonic models for the evolution of northeastern Zealandia and surrounds, especially with regards to Late Eocene ophiolite obduction in New Caledonia (Collot et al. 2020). Onset of Pacific-Australia plate-boundary formation may have affected Northern Zealandia from as early as 50 Ma (Sutherland et al. 2020), and deformation migrated south through Northern Zealandia during the Eocene (Bache et al. 2012; Sutherland et al. 2017), concomitant with complex opening of back-arc basins east of Northern Zealandia through the Eocene–Middle Miocene (Mortimer et al. 2007; Herzer et al. 2011). In the Middle Eocene, intra-plate rifting began in Southern Zealandia (Turnbull et al. 1993) related to Emerald Basin opening (King 2000), which continued through to roughly the end of the Oligocene. From the Early Miocene, deformation related to the modern plate boundary affected much of central Zealandia (Nicol et al. 2007) with establishment of subduction along the full length of the Hikurangi margin. Deformation continued and intensified through the Neogene (Sutherland 1995), with the onset of subduction on the Puysegur subduction zone in Southern Zealandia (Gurnis et al. 2019). From the Middle Miocene onwards intra-arc rifting occurred (Giba et al. 2013), with opening of the Havre Trough in the Pliocene (Wysoczanski et al. 2019).

Data sources and methodology

Regional-scale syntheses of many of Zealandia's sedimentary basins were presented in publications resulting from the Cretaceous-Cenozoic petroleum basins programme (CCP) led by the New Zealand Geological Survey and GNS Science between the mid-1970s and late 1990s (Nathan et al. 1986; Field et al. 1989; Wood et al. 1989; Turnbull et al. 1993; Edbrooke et al. 1994; Isaac et al. 1994; King and Thrasher 1996; Field et al. 1997; Cook et al. 1999). In many cases, the study areas were largely onshore (Nathan et al. 1986; Field et al. 1989), and most of the far-offshore regions were not studied. A number of sedimentary basins, such as Raukumara, Pegasus and Reinga basins, were almost unknown at that time (e.g. Sutherland et al. 2009; Uruski 2010; Bland et al. 2015). Significant advances in mapping and understanding the geological history and architecture of Zealandia were subsequently made during the past two decades, primarily driven by New Zealand's United Nations Convention for the Law of the Sea (UNCLOS) programme (Uruski 1997; Davy and Uruski 2002; Wood 2002; Wood and Davy 2002; Wright et al. 2002) and by Government-driven seismic data acquisition programmes to encourage petroleum exploration (e.g. Uruski et al. 2005; Stagpoole et al. 2008; Uruski et al. 2008; Stagpoole et al. 2009; Uruski and Bland 2011; Bland et al. 2012; Bland et al. 2014a; Bland et al. 2014b; Crutchley et al. 2016). Recent data compilations and syntheses for the major offshore sedimentary basins, covering the entirety of New Zealand's extended continental shelf (ECS), have recently been produced by the Atlas of Petroleum Prospectivity (APP) programme (e.g. Arnot et al. 2016). By far the biggest sources of new geological data have come from regional seismic data (2D and 3D), and deep wells acquired for petroleum exploration. We have not carried out new seismic interpretation as part of this study, rather we have synthesised the open-file observations and the interpretations of others. This phase of discovery extended beyond the main sedimentary basins, and has included numerous dredging campaigns, often in more remote parts of Zealandia (e.g. Herzer et al. 1997; Browne et al. 2016; Mortimer et al. 2018; Lawrence et al. 2020; Mortimer et al. 2020a; Mortimer et al. 2020d) as well as scientific drilling by DSDP/ODP/IODP (e.g. Sutherland et al. 2019).

We compile, evaluate and reconcile this wealth of existing, disparate datasets. A full listing of previous palaeogeographic and geological studies used in this study is given for each region or basin in the

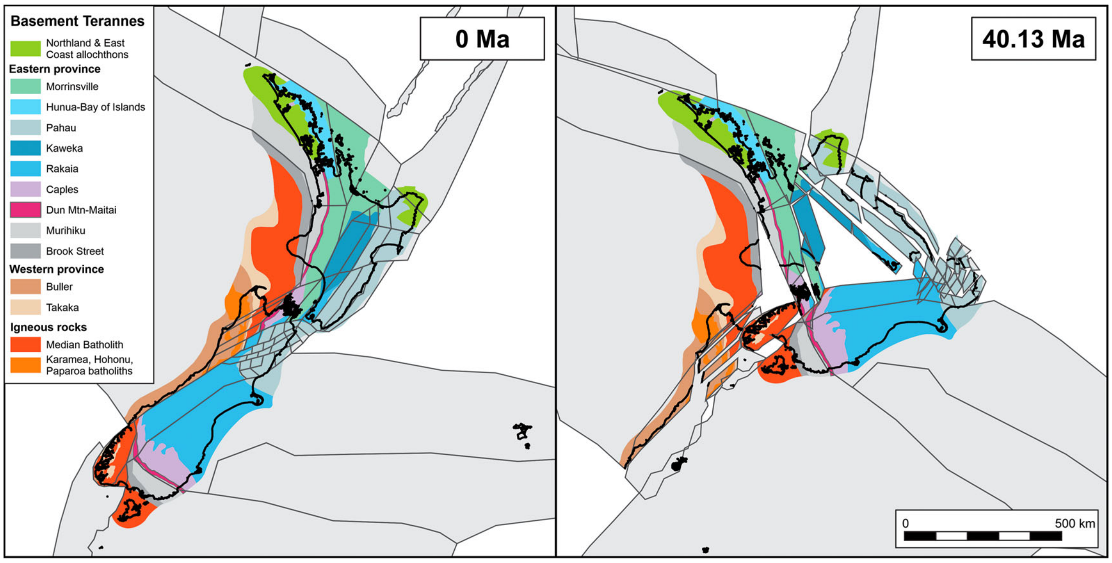

Figure 2. The tectonic block model (Seebeck et al. 2018) used to retro-deform Zealandia, focusing on central Zealandia, shown at the present day and at c. 40 Ma. Overlain in onshore/nearshore New Zealand are simplified basement terranes, after Mortimer (2004).

supplementary material (http://doi.org/10.6084/m9.figshare.20500113). Detailed references to these studies are given where relevant in the detailed description for each map, also in the supplementary material. We have also digitised 'paper copy' (non-digital) datasets.

Where no existing palaeogeographic maps were available for a region of Zealandia, we have constructed them using any available, often sparse, datasets. These palaeogeographic interpretations were then placed into a restored tectonic position and a unified palaeogeography for the whole of Zealandia was produced for each time step. The data and maps were all managed and produced in ArcGIS, with tectonic reconstructions using GPlates. These digital compilations then allowed interrogation of data within a common projection and geographic framework.

Tectonic reconstruction model

Underpinning the palaeogeographic maps is a new rigid block model (58 blocks in total; Figure 2), developed using the open source GPlates plate tectonic reconstruction software (Boyden et al. 2011; Müller et al. 2018b), which we use to sequentially retro-deform Zealandia. An outline of the construction of the block model and methodologies involved in the tectonic reconstructions are given in Seebeck et al. (2018) and Hines (2018). Details on the geological justifications for the choice of blocks and their deformation history is discussed in detail in Hines et al. (2022), including in their supplementary material. A forthcoming paper will further describe the GPlates model in more detail, and release the model itself. An advantage of GPlates is that geospatial data of practically any type can be easily imported into and exported from the associated geographic information system (GIS), and reconstructed for any time step within the model. This leads to a second advantage, that the rigid block model is readily testable, adjustable, and updateable using GPlates. Further iterations of the model will take account of any feedback and new data, and will allow for more complex non-rigid modelling of both extension and compressional deformation (Müller et al. 2018a).

The majority of Northern and Southern Zealandia consists of only a handful of large blocks tied to the global plate circuit. However, the area in central Zealandia associated with the present-day plate boundary, particularly in the East Coast-Marlborough region, is broken into numerous smaller blocks to best approximate the complex deformation that has occurred there. Our model uses more, smaller blocks, particularly in Marlborough, than previous studies (Crampton et al. 2003; Lamb et al. 2016; Lamb and Mortimer 2020; Ghisetti 2021). Block boundaries were chosen to reflect real pre-Miocene structures and basement geology, and block rotations are constrained where possible by palaeomagnetic data (Hines 2018; Hines et al. 2022). Although rigid blocks cannot capture the true ductile deformation that occurred, with gaps between blocks opening up through time (Figure 2), they do allow the relative positions of features to be estimated.

Relative motions between Northern and Southern Zealandia are defined by total reconstruction poles for the Australia-East Antarctica, Australia-Lord Howe Rise, East Antarctica-West Antarctica and Pacific-West Antarctica plate pairs determined from seafloor and magnetic anomaly data along a plate motion chain that links Lord Howe Rise to Australia, East Antarctica, West Antarctica, and hence the Pacific plate (Gaina et al. 1998b; Cande and Stock 2004; Whittaker et al. 2007; Croon et al. 2008; Granot et al. 2013; Whittaker et al. 2013; Wright et al. 2015; Choi et al. 2017). The block model was reconstructed at selected times (2.58, 4.24, 6.04, 10.95, 20.13, 26.55, 40.13 and 83.5 Ma; corresponding to seafloor magnetic anomalies 2Ay, 3y, 3Ay, 5o, 6o, 15o, 18o and 34y) which define well constrained total reconstruction poles for Australia-Pacific relative motion (e.g. Cande and Stock 2004). These ages also generally correspond to significant tectonic events within the New Zealand plate boundary zone (King 2000) where passive strain markers are progressively restored back through time. The GPlates model then interpolates between these time points. As only relatively minor intraplate deformation is documented within Zealandia between 40 and 83 Ma (King 2000) all the model blocks are fixed in their 40.13 Ma positions (Figure 2b) relative to the main Southern Zealandia (Campbell Plateau) block, and carried back to the onset of seafloor spreading and the break-up of Gondwana at c. 83 Ma (Gaina et al. 1998b). In order to restore the reconstructed plate geometries to their correct latitude/longitude, it is necessary to use an absolute reference frame that describes how the plates have moved relative to a fixed reference system (Torsvik et al. 2008; van Hinsbergen et al. 2015). We utilise the palaeomagnetically-derived true polar wander corrected reference frame of Torsvik et al. (2012), which links to the global plate circuit through Africa, which has moved <500 km over the last 100 Ma (Torsvik et al. 2008; Seton et al. 2012).

Between the cessation of palaeo-Pacific subduction c. 100 Ma (Davy 2014; Reyners et al. 2017b; Crampton et al. 2019; Riefstahl et al. 2020a) and the breakup of eastern Gondwana at c. 83 Ma, there are many uncertainties concerning the disposition of Zealandia. Some models suggest significant strike-slip motion between Northern and Southern Zealandia and East and West Antarctica (e.g. Lamb et al. 2016; Lamb and Mortimer 2020) or at least significant internal deformation of Zealandia (Mortimer 2014) and possible continued complex subduction (Cooper and Palin 2018). Other models also break Northern Zealandia up into a number of smaller blocks to allow better closure of the Tasman Sea (Gaina et al. 1998b). Due to these uncertainties, there are significant issues when producing reconstructions for this time. We have however produced maps for both 85 and 98 Ma, in order to display the distribution of early syn-rift strata (Strogen et al. 2017). For simplicity, we keep the same relative block positions as for 40–83 Ma, with the position of Northern Zealandia, and all the smaller blocks in central Zealandia, dictated by the well-constrained positions of Southern Zealandia and West Antarctica. See further comments in the discussion.

Biostratigraphic, palaeoenvironmental and other map data

Geological outcrop data for New Zealand, derived from Heron (2018), have been grouped according to age for each map. Onshore measured section data from various New Zealand CCP studies (summarised in King et al. 1999), have been compiled by Galbraith et al. (2015) and provide litho- and biostratigraphic data, which are especially useful for delineating non- to marginal-marine sections. All palaeontological data for the Zealandia megasequence containing both robust age information and foraminiferal assemblages useful for assessing palaeo water depth (Hayward 1986, 2004; Hayward et al. 2013) have been extracted from the New Zealand fossil record file (FRED database; Clowes et al. 2021). Where possible, both age and palaeoenvironmental data have been extracted from DSDP/ODP/IODP wells, which provide the only control points across large parts of Northern Zealandia. These include legacy DSDP leg 21 (sites 206-208; Burns et al. 1973), leg 90 (sites 588-593; Kennett et al. 1986), ODP leg 181 (sites 1120–1125; Carter et al. 1999) and the recent IODP legs 371 (sites U1506–1511; Sutherland et al. 2019) and 372B/375 (sites U1517–1520 & 1526; Wallace et al. 2019). Available updated compilations for DSDP/ODP/IODP wells were also used here (Ayress 1994; Kulhanek and Morgans 2013; Sutherland et al. 2020). These biostratigraphic and palaeoenvironmental data are displayed as point data. For each map, strata are classified as 'present' where there is high biostratigraphic confidence, 'possibly present' where there is low confidence, or 'missing' where there is high confidence that the time interval is absent at that locality.

Dated volcanic samples, both onshore and offshore, were extracted from PETLAB (Strong et al. 2016), and are also shown on the relevant maps. Active faults are taken from existing palaeogeographies, and other studies where relevant (e.g. Giba et al. 2013; Ghisetti et al. 2016; Ghisetti 2021). Additional faults may be present in areas where insufficient data are available to constrain their orientations, so the absence of faults on a map does not necessarily imply an absence of faulting. Faults are omitted from the regional Zealandia maps (Figures 4–18) for clarity, but are shown on the maps centred on New Zealand (see supplementary material). Also shown are folds and areas of uplift where known (e.g. Bache et al. 2013; Sutherland et al. 2020). Faults from the present day map are from the New Zealand active faults database (Langridge et al. 2016).

Palaeobathymetric contours, representing boundaries between the palaeo water depth zones of Hayward (1986), are drawn using existing palaeogeographic mapping or updated based on new palaeoenvironmental data and to fit the reconstructed geometries. In areas outside of existing mapping, new contours have been drawn based on the compiled palaeoenvironmental data. Palaeofacies boundaries are drawn to mark significant lithological changes, although necessarily simplified at this scale. These boundaries were used to construct both palaeobathymetric and palaeofacies polygons, covering the entirety of Zealandia in a reconstructed geometry for each map time. In some areas, there are sufficient data to subdivide the shelf into inner, middle and outer shelf zones, elsewhere these are undivided and identified only as shelfal. The palaeobathymetry has been simplified on Figures 4–17 for clarity; all shelfal zones are combined, as are uppermost/upper bathyal, as well as lower/deep lower bathyal. All identified palaeobathymetric zones are shown on the maps in the supplementary data.

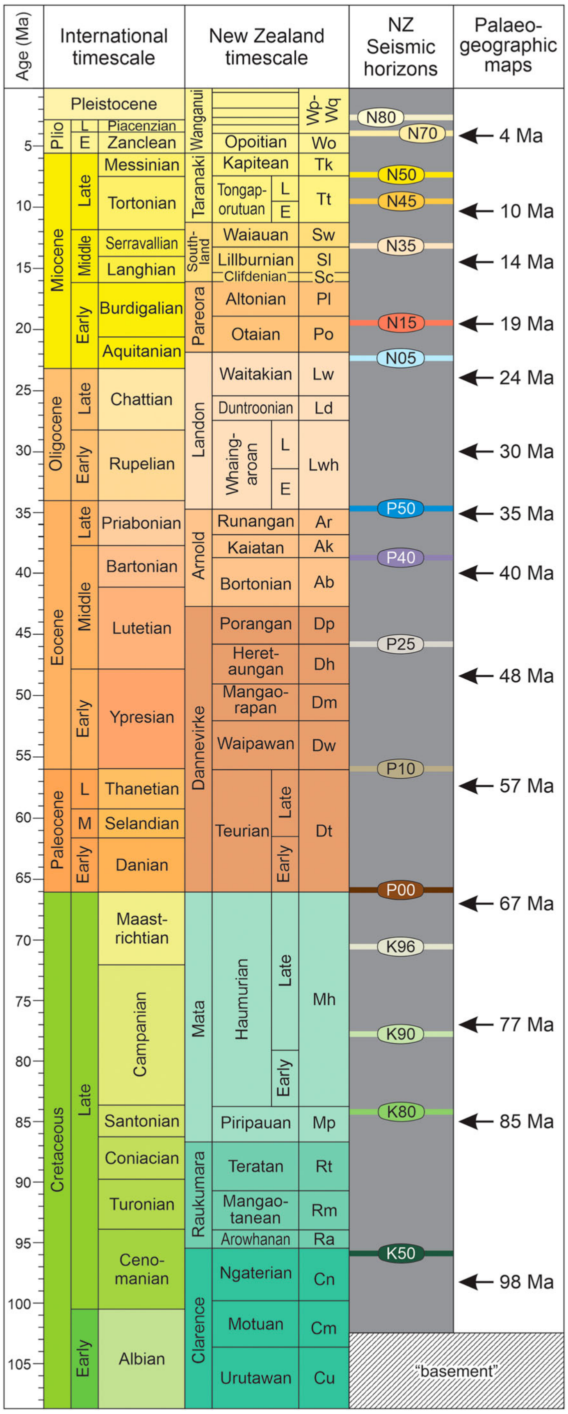

Figure 3. Comparison of the international and New Zealand timescales (Raine et al. 2015), and regional New Zealand seismic reflectors (Strogen & King 2014). The ages of the 15 palaeogeographic maps produced in this study are indicated.

Global tectonic features provided with GPlates include; isochrons, spreading ridges and areas of continental crust (Müller et al. 2016), fracture zones (Matthews et al. 2011) and Australian palaeogeography (Totterdell et al. 2001). In some cases, we have replaced these where more detailed or improved data are available. These include seafloor spreading isochrons between the Campbell Plateau and West Antarctica and in the Adare Trough-Emerald Basin (Croon et al. 2008; Wobbe et al. 2012; Granot et al. 2013) and in the South Fiji Basin (Herzer et al. 2011). The extent of Zealandia continental crust is from Mortimer et al. (2020c), and in the Ross Sea its extent is revised using the 1000 m isobath to include Iselin Bank. Sedimentary basins for Zealandia are from Mortimer et al. (2020c), for the Ross Sea from Brancolini et al. (1995), and for Australia from Raymond (2018). The present-day extent of the Hikurangi Plateau is from Mortimer et al. (2020c), after Reyners et al. (2017b), ultimately modified from that of Wood and Davy (1994). Where no palaeogeographical interpretation has been made, the maps are left blank, or coloured grey where continental crust is interpreted. The modern coastlines are also shown for all regions, for reference.

Palaeogeographic evolution

The series of 15 palaeogeographic maps (see Figure 3 for their ages) presented herein (Figures 4–18) were chosen to illustrate phases of the c. 100 Myr evolution of the Zealandia megasequence. The maps are assigned an age, rounded to the nearest million years (Ma), based on the current New Zealand geological timescale of Raine et al. (2015). However, the majority of biostratigraphic ages upon which maps are constructed are accurate only to the NZ stage level, with stage durations of c. 1–10 Myr. Therefore, the maps are a synthesis of data from an only very approximate snapshot in time. The maps are at c. 10 Myr intervals in the Cretaceous–Eocene and c. 5 Myr intervals from the Middle Eocene to present. They also depict the depositional sequences bounded by regionally mapped seismic horizons (Figure 3) in New Zealand basins (Strogen & King 2014) and are the same ages as those chosen for regional APP studies (Arnot et al. 2016; Sahoo et al. 2017; Arnot et al. 2018), with the addition of new maps for 40 and 30 Ma.

Each of the palaeogeographic maps produced are shown (Figures 4–18) along with a brief description of the tectonics and geological evolution at this time and any major points of interest or issues. We have grouped the map descriptions into four major phases of Zealandia evolution. Significantly more detailed descriptions of each map and its data sources are given in the supplementary material. For the sake of clarity, not all data used can be displayed clearly for the entirety of Zealandia, at a scale of 1:17M. An additional set of maps covering onshore/nearshore New Zealand at a larger scale (1:6M) have been produced, displaying additional data, such as outcrop data, well/outcrop sample data, active faults and more detailed lithofacies. These maps, as well as full-size regional maps, are provided in the supplementary material along with the relevant map descriptions. For the Zealandia-wide maps (1:17M), the only point data shown are DSDP/ODP/IODP wells, outcrop sections from outlying islands and New Caledonia and dated volcanic samples. Faults are omitted for clarity from these regional maps.

Mid- to Late Cretaceous 'Zealandia rifting' (98–85 Ma maps)

These maps (Figures 4–5) illustrate the 'Zealandia rifting' phase (Strogen et al. 2017), with extensional

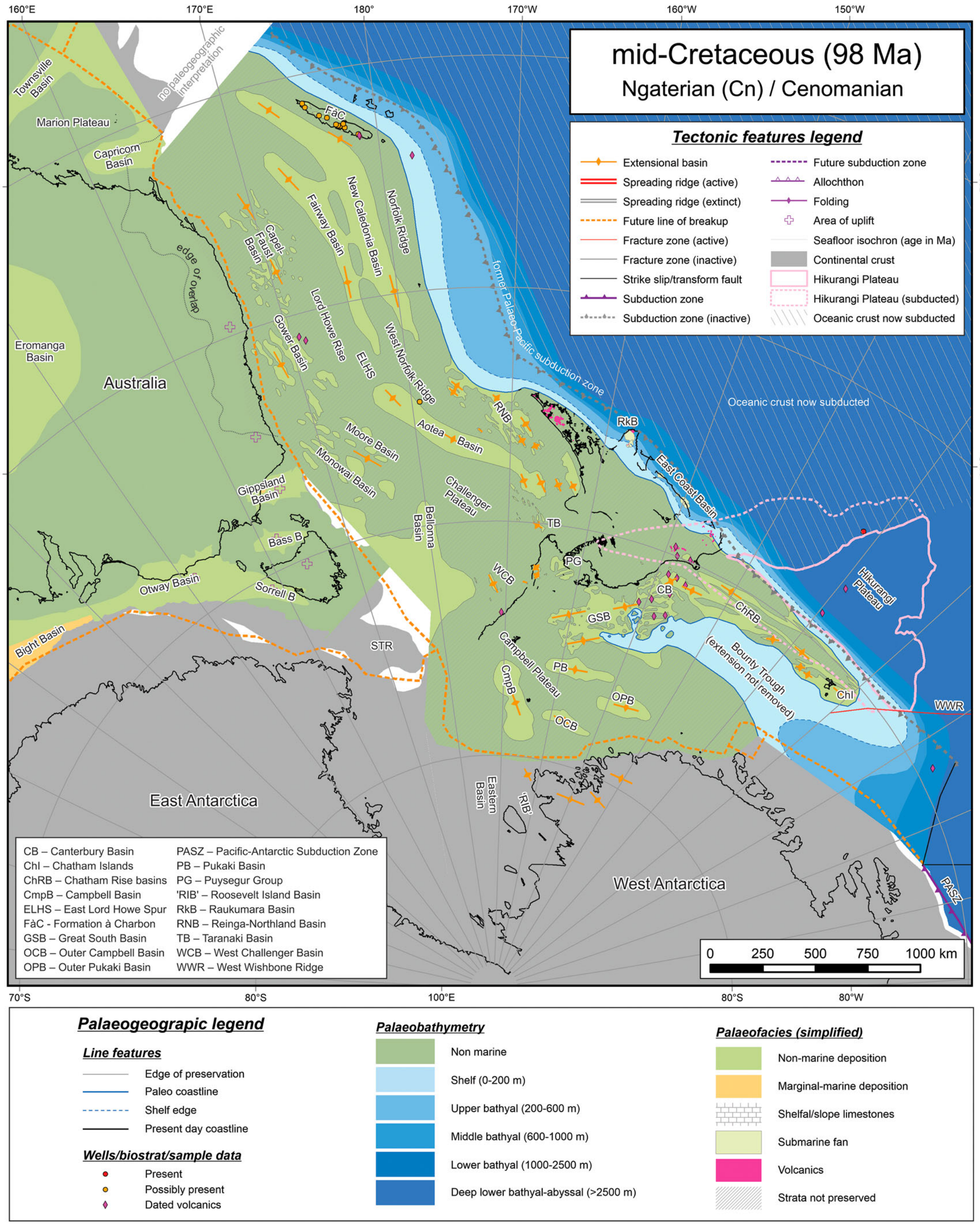

Figure 4. Mid-Cretaceous regional palaeogeographic map of Zealandia (c. 98 Ma). Key applies to all maps. The overlap between Northern Zealandia and Australia in the current reconstruction is also shown, see text for discussion. Australian palaeogeography from Totterdell et al. (2001).

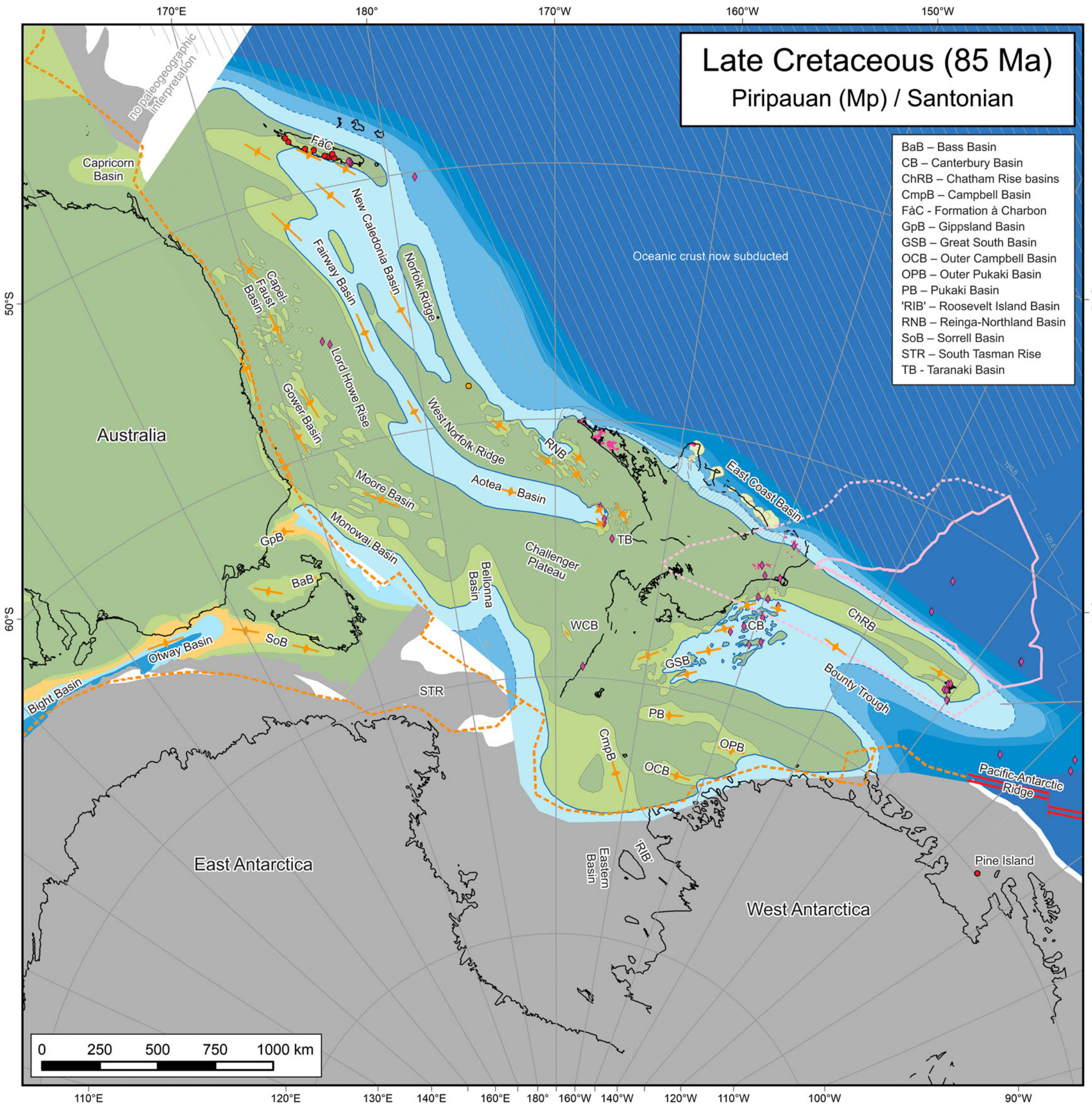

Figure 5. Late Cretaceous regional palaeogeographic map of Zealandia (c. 85 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

basins forming across much of Zealandia. Further detailed descriptions of the tectonics and geological evolution during this interval, as well as sets of both regional and New Zealand-focused maps, are given in the supplementary material. It follows the end of subduction along the palaeo-Pacific margin of Gondwana (e.g. Crampton et al. 2019), which ran along the present-day eastern margin of Zealandia. This followed the collision and partial subduction of the Hikurangi Plateau (a fragment of a large igneous province) with the Chatham Rise (Davy et al. 2008; Bland et al. 2015; Riefstahl et al. 2020a). The present-day eastern margin of Zealandia, then more north facing, was a passive margin dominated by deep-marine deposition, although some minor tectonic events are recognised within this sequence (Crampton et al. 2019). There was widespread syn-rift deposition of initially generally non-marine facies (Figure 4) in many basins across Zealandia from the Campbell Plateau to New Caledonia (Strogen et al. 2017; Maurizot et al. 2020a; Barrier et al. 2022; Sahoo et al. 2022). Through this time interval the later part of this syn-rift succession became more widespread and increasingly marine influenced in many basins (Figure 5). The age of the rift succession in many undrilled basins is poorly constrained, especially in western Northern Zealandia (Totterdell et al. 2014; Bland and Strogen 2018). Crustal extension accrued during the 'Zealandia' rift phase has not been removed from these maps, and there are a number of refinements that remain poorly constrained with respect to reconstructions of this time (see discussion section and the supplementary material).

Late Cretaceous–Early Eocene Tasman Sea opening (77–57 Ma maps)

These maps (Figures 6–8) mark a phase characterised by active seafloor spreading in both the Tasman Sea and between Southern Zealandia and West Antarctica

(Gaina et al. 1998b; Riefstahl et al. 2020b). Detailed discussion of the tectonics and geological evolution, as well as sets of both regional and New Zealand-focused maps, can be found in the supplementary material. Initial spreading in the Tasman Sea propagated northwards, to the west of the Dampier Ridge by the end of the Cretaceous (Figure 7), and finally further northwards until there was full separation of Northern Zealandia and Australia, through the Cato Trough into the Coral Sea, in the Paleocene (Figure 8). Spreading continued into the Early Eocene (c. 52 Ma, Gaina et al. 1998b; Gaina et al. 1999).

Most areas were dominated by post-rift thermal subsidence, with continued marine transgression across most of Zealandia through the Late Cretaceous to Paleocene (Figures 6–8). Non-marine facies remained only in proximal basins, and shelfal facies deepened to bathyal conditions in many areas (Strogen et al. 2017; Maurizot et al. 2020a; Sahoo et al. 2022). Many of the major highs, such as the Lord Howe Rise-Challenger Plateau, West Norfolk and Norfolk ridges and Campbell Plateau, which separated the former rift basins, were slowly transgressed through this interval and only relatively small areas remained emergent by the end of the Paleocene, although much of central Zealandia remained above sea level (Figure 8). The present-day eastern margin of Zealandia (then north facing), remained in a deep-marine passive margin setting (Field et al. 1997; Crampton et al. 2019).

Extension had ended in most basins, but minor rifting in central Zealandia during the Haumurian–Teurian, was orientated roughly perpendicular to previous rifts and occurred in parts of Taranaki, West Coast, and Ohai (Western Southland) basins ('West Coast-Taranaki' rift phase of Strogen et al. 2017). It is also likely that rifting in basins in the northwest of Zealandia preceded the onset of seafloor spreading, although this is poorly constrained (Uruski 2010; Totterdell et al. 2014).

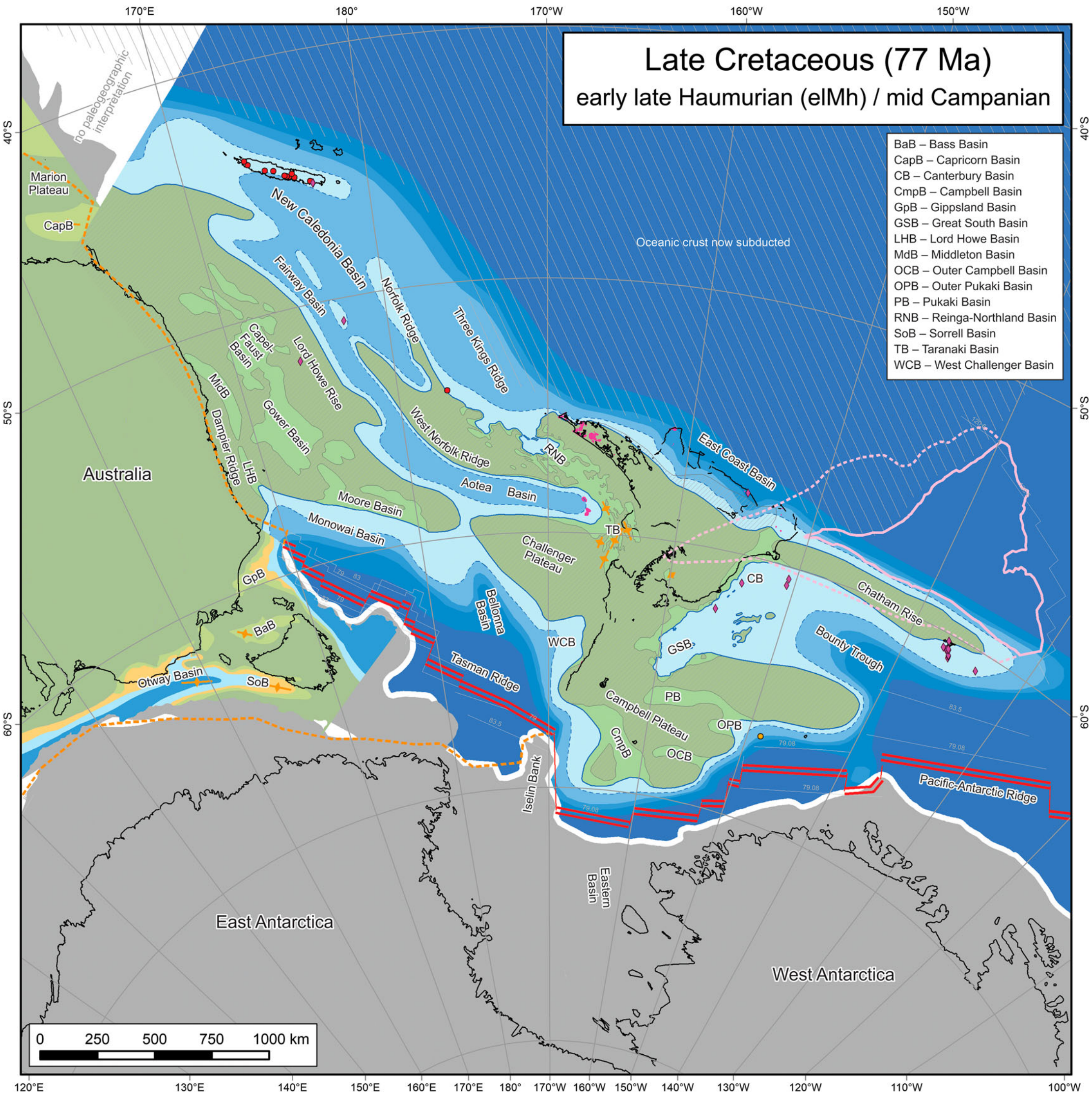

Figure 6. Late Cretaceous regional palaeogeographic map of Zealandia (c. 77 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

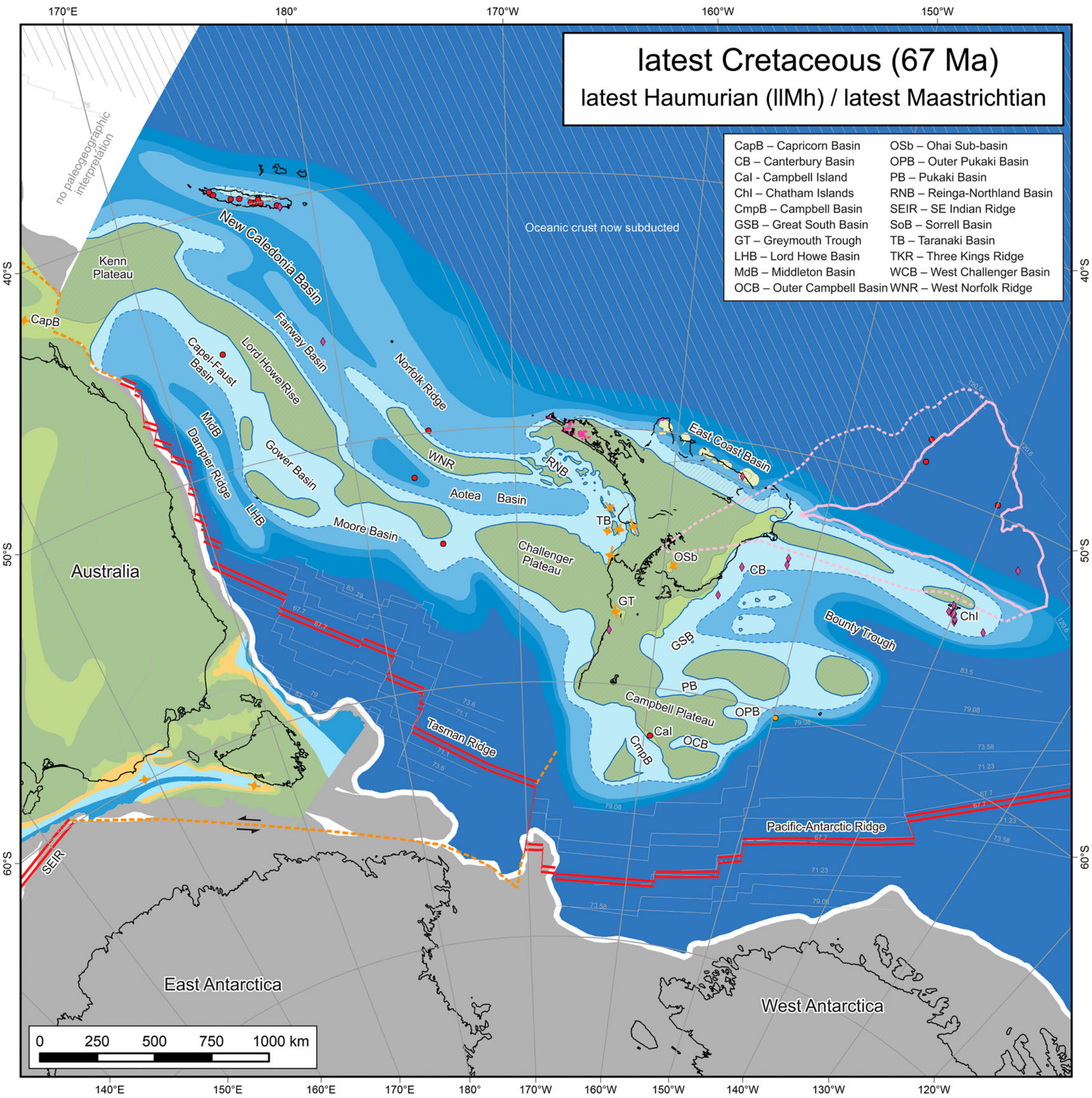

Figure 7. Latest Cretaceous regional palaeogeographic map of Zealandia (c. 67 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

Early Eocene–Oligocene subduction inception in Northern Zealandia (48–24 Ma maps)

This interval marks a period of plate boundary formation, with subduction initiation focused on Northern Zealandia and seafloor spreading to the south of Zealandia (Figures 9–13). Comprehensive descriptions of the tectonics and geological evolution during this interval, as well as sets of both regional and New Zealand-focused maps, are given in the supplementary material. Spreading in the Tasman Sea-Coral Sea was complete by the Early Eocene (c. 52 Ma, Gaina et al. 1998b; Gaina et al. 1999). There is evidence for subduction initiation along the northeast margin of Zealandia from c. 48 Ma (Figure 9) from the oldest arc-related rocks in Tonga (Meffre et al. 2012). This subduction system propagated south along the eastern margin of Northern Zealandia (Sutherland et al. 2020), so that by the end of the Eocene it had extended south to the east of the Three Kings Ridge (Figure 11). Through the Oligocene (Figures 12 and 13), this subduction system rolled back resulting in the complex opening of the South Fiji Basin and later also the Norfolk Basin from c. 25 Ma (Herzer et al. 2011). We do not attempt to restore the complex tectonics of the South Loyalty Basin, given the conflicting models (see Collot et al. 2020; Sutherland et al. 2020) that exist for its formation, geometry and extent (see discussion section and supplementary material). The closure of the South Loyalty Basin was complete c. 34 Ma and was marked by final ophiolite obduction in New Caledonia (Maurizot et al. 2020b). To the south of Zealandia, a new spreading centre propagated northwards through the Emerald Basin during the Mid to Late Eocene (Figures 10 and 11). Spreading continued during the Oligocene (Figures 12 and 13), although becoming more strike-slip in nature with small disconnected ridge segments (Sutherland 1995).

A period of uplift in the northern Lord Howe Rise and Kenn Plateau (Figure 9) at c. 50 Ma is recognised by Sutherland et al. (2020), and likely related to subduction onset. Facies changes in onshore New

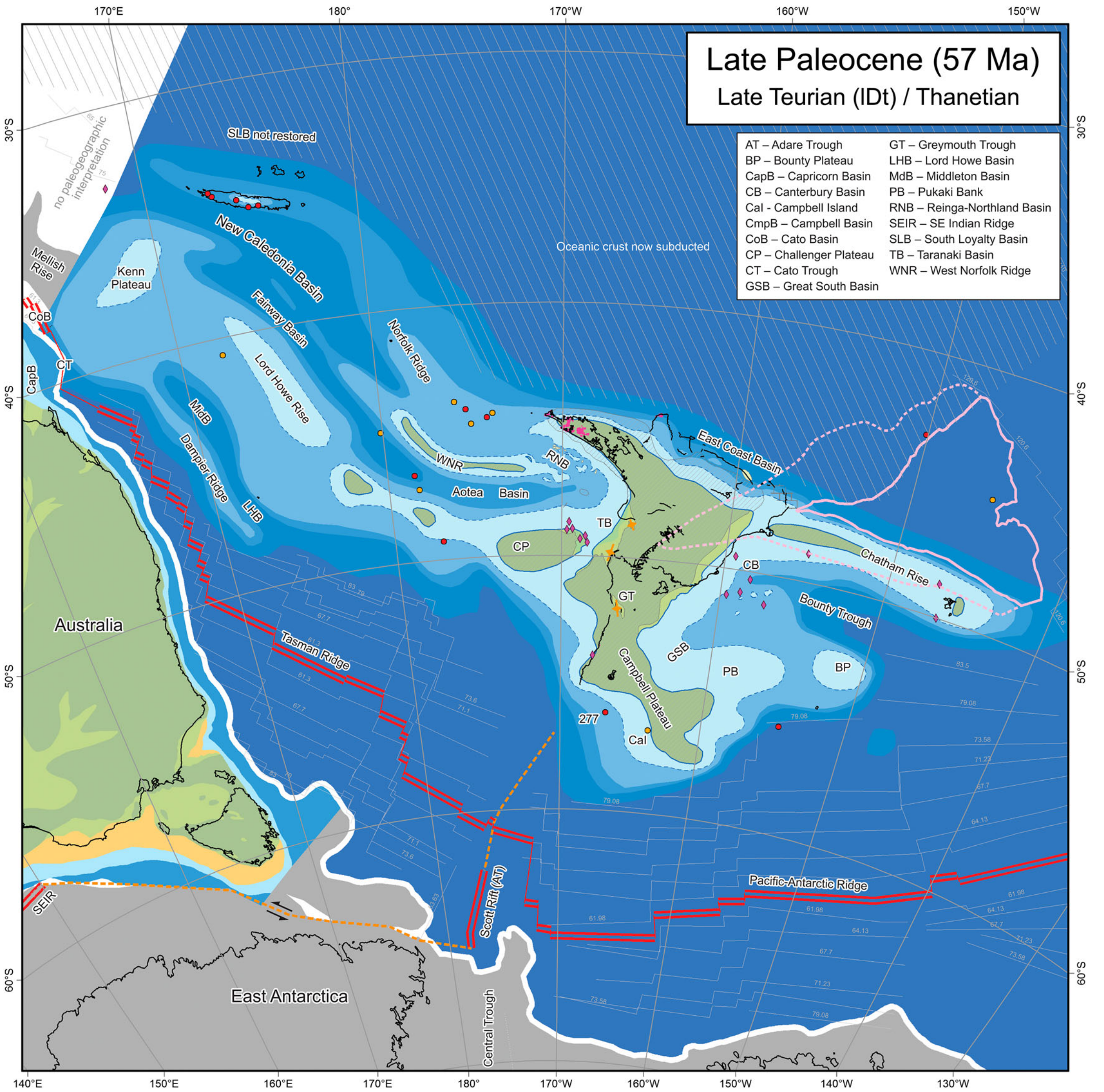

Figure 8. Late Paleocene regional palaeogeographic map of Zealandia (c. 57 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

Caledonia from c. 46 Ma (Dallanave et al. 2020) also indicate the onset of uplift and imminent tectonism that would intensify through the Mid to Late Eocene with increasingly coarse-grained sedimentation (Maurizot et al. 2020a; Bordenave et al. 2021). Following final ophiolite obduction at c. 34 Ma, New Caledonia would remain a relatively stable high (Sevin et al. 2020; Maurizot et al. 2020b).

There was tectonic quiescence throughout much of central Zealandia during most of the Eocene. Continued, gradual, passive-margin transgression and bathyal conditions occurred across much of Zealandia, with increasingly fine-grained and calcareous facies deposited in distal areas (Figures 9 and 10). There was significant Early Eocene progradation of deltaic to shallow-marine facies in both the Taranaki Basin (King and Thrasher 1996; Higgs et al. 2017) and the Great South Basin (Constable and Crookbain 2011), fed from non-marine topographic highs in central Zealandia.

Compressional deformation would reach the Reinga Basin by the Late Eocene (Figure 11), with intense uplift and folding (Bache et al. 2014; Orr et al. 2020) and uplift of the Norfolk Ridge, Lord Howe Rise and Challenger Plateau (Sutherland et al. 2020). This deformation would reach as far south as northern Taranaki Basin (Figure 11) by the end of the Eocene (Strogen et al. 2014; Strogen et al. 2019). The boundary between compressional tectonics in the north and extension in the south lay within Taranaki Basin during the Late Eocene and Oligocene, with compressional tectonics migrating into southern Taranaki Basin in the Early Oligocene in response to activity along the length of the Taranaki Fault System (Stagpoole and Nicol 2008; Strogen et al. 2014).

A new phase of rifting related to Emerald Basin opening is recognised through much of Western Southland and West Coast basins from the Bortonian (Figure 10). Facies were initially non-marine

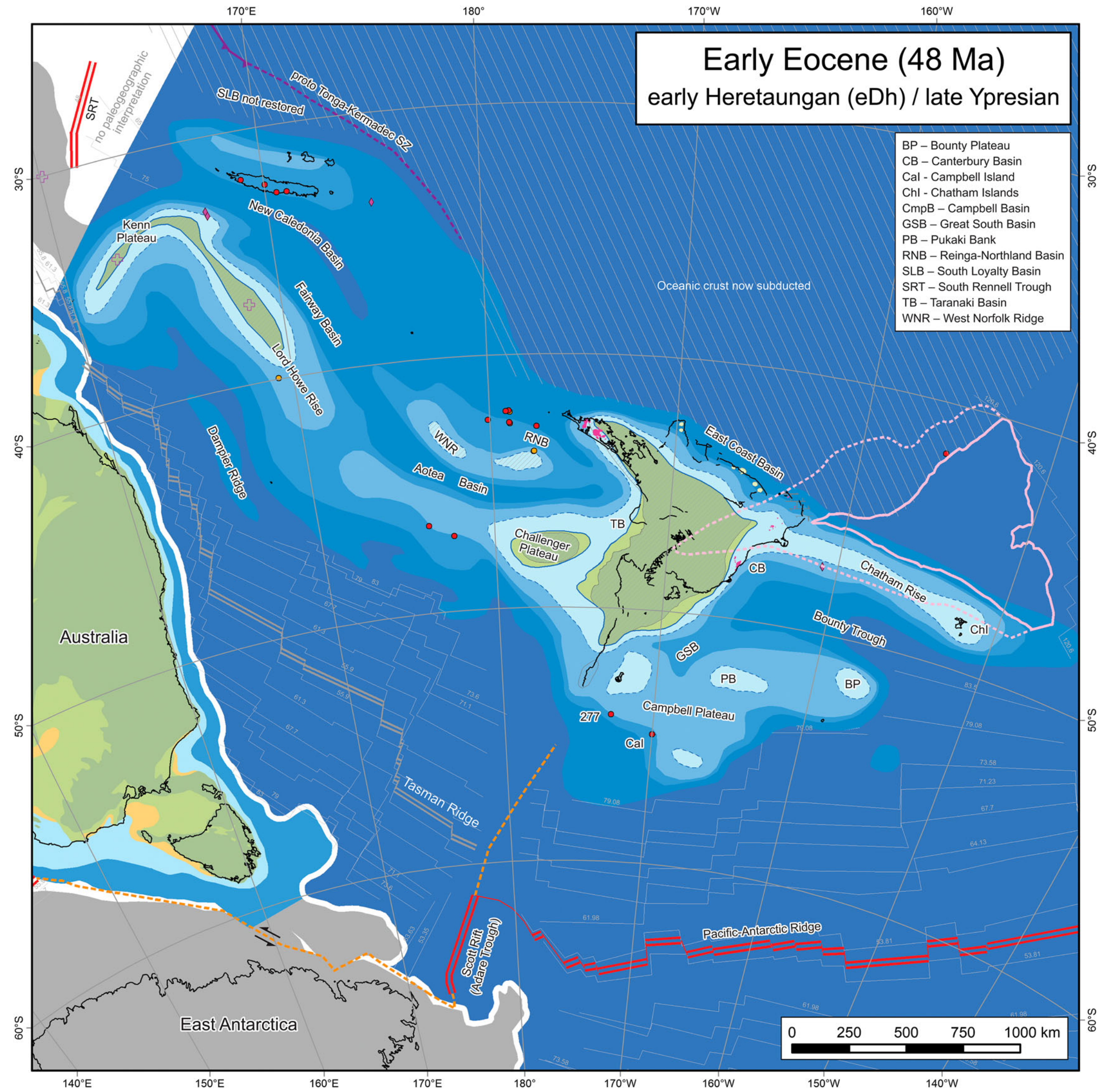

Figure 9. Early Eocene regional palaeogeographic map of Zealandia (c. 48 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

in the Middle Eocene, but deposition would spread and become increasingly marine through the Late Eocene and Oligocene (Nathan et al. 1986; Turnbull et al. 1993). Although poorly constrained, extension in this rift likely reduced during the Oligocene due to sea-floor spreading in the Emerald Basin becoming more strike-slip dominated (Sutherland 1995).

Although active tectonics dominated the plate boundary zone, away from this region, passive subsidence still dominated across much of Zealandia (Field et al. 1997; Morgans 2016). By the Late Oligocene (Figure 13) there was maximum transgression of Zealandia (Landis et al. 2008) with only relatively small land areas preserved, and although there was widespread deposition of carbonate facies, there was still significant clastic input in areas close to the plate boundary zone (e.g. Nathan et al. 1986; Strogen et al. 2014).

Earliest Miocene to present-day plate boundary in central Zealandia (21–0 Ma maps)

This interval marks the propagation of the present-day plate boundary in the New Zealand region (Figures 14–18). Detailed descriptions of the tectonics and geological evolution during this interval, as well as sets of both regional and New Zealand-focused maps, are located in the supplementary material. In the earliest Miocene, the Hikurangi subduction zone propagated along the entire length of the East Coast Basin, bringing a major change to the tectonics in central Zealandia (Figure 14). The Northland and East Coast allochthons were emplaced in this interval (c. 23–19 Ma). The Northland Allochthon was likely formed due to transpression on the Veining-Meinesz Fracture Zone as the Norfolk Basin opened (Herzer and Mascle 1996). Complex seafloor spreading continued in the South Fiji and Norfolk basins until c. 16 Ma (Herzer et al. 2011),

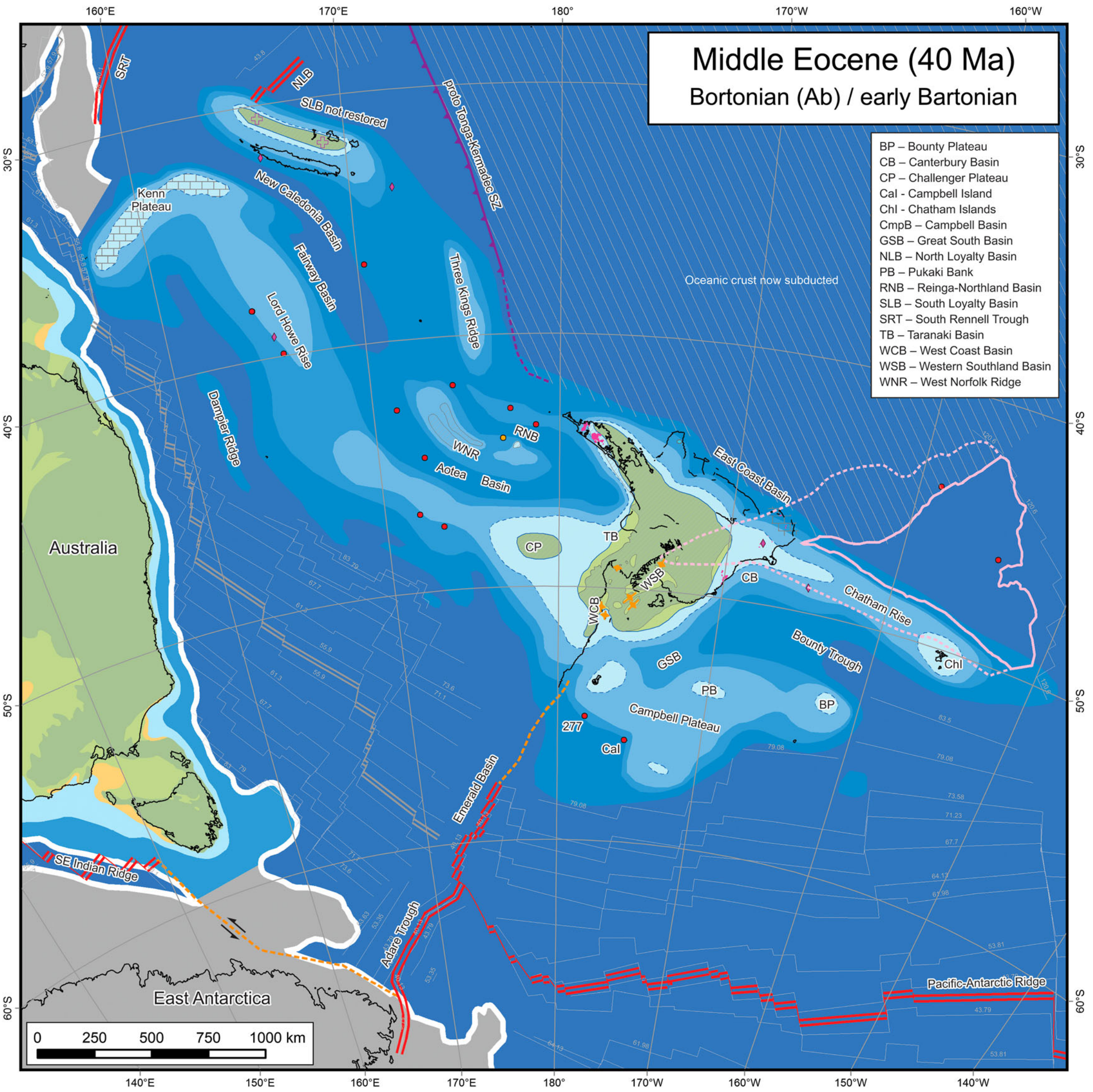

Figure 10. Middle Eocene regional palaeogeographic map of Zealandia (c. 40 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

when rollback of the Colville-Lau arc paused. The East Coast Allochthon, and numerous smaller olistostromes through the East Coast were likely related to the propagation of the subduction margin throughout the region, apparently synchronously (Chanier and Ferrière 1991; Rait et al. 1991; Delteil et al. 2006; Bland et al. 2022). There was also a change in depositional style throughout the East Coast Basin with an abrupt increase in clastic sedimentation, and widespread deposition of thick flysch deposits (Field et al. 1997) that indicate the onset of active tectonism all along this part of the margin. There was an also an intensification of deformation on the Taranaki Fault System in the Early Miocene (King and Thrasher 1996), and thick flysch packages were deposited within a piggyback basin in the King Country region (Nelson and Hume 1977; Kamp et al. 2004) and the pulldown of the Waitematā Basin (Isaac et al. 1994). Punctuated increases in sedimentation rate, grain size and progradation of shelfal facies (Figures 14–16) during the Miocene in the West Coast through Taranaki basins can be linked to the increasing plate boundary convergence (Bull et al. 2019) as can intensification in compressional deformation (Ghisetti et al. 2016).

Arc volcanism migrated through northern New Zealand (Figures 14–16), initially in Northland (Early Miocene), moving south-eastwards through the Coromandel to Taranaki Basin (Middle to Late Miocene) and to the Tauranga-Kaimai area in the Pliocene (Hayward et al. 2001; Seebeck et al. 2013). Back-arc extension began in northern Taranaki Basin from the Middle Miocene, and gradually propagated into central Taranaki Basin during the Late Miocene to Pliocene (Giba et al. 2010).

Whilst significant sea-floor spreading had finished in the Emerald Basin (Sutherland 1995), minor highly oblique spreading likely continued as late as c. 15 Ma (Shuck et al. 2021). The plate boundary through central Zealandia, linking the Hikurangi

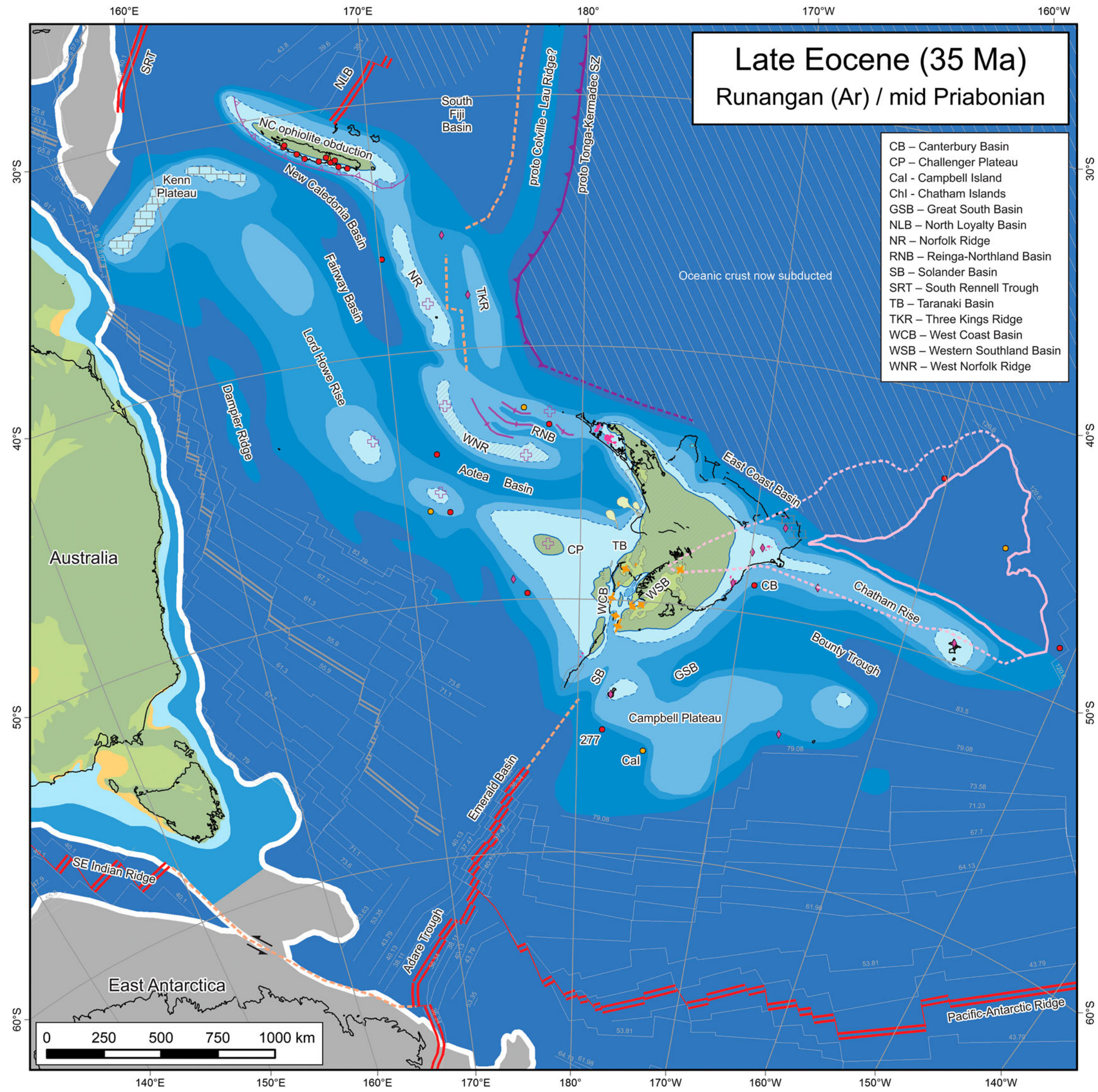

Figure 11. Late Eocene regional palaeogeographic map of Zealandia (c. 35 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

subduction margin and the Emerald Basin, was initially a zone of distributed deformation (Figure 14). A through-going Alpine Fault (Figure 15) had likely formed by the Middle Miocene (Cox and Sutherland 2007; Reyners 2018). Highly oblique subduction on the Puysegur subduction margin had likely begun during the Middle Miocene (Sutherland et al. 2006) although the precise geometry and the timing of onset of this subduction and associated deformation is somewhat ambiguous (Shuck et al. 2021). There was an increase in coarse sedimentation in many basins (Nathan et al. 1986; Norris and Turnbull 1993), including for example, an intensification of convergence and rapid uplift in the Marlborough Fault System (Little and Roberts 1997; Little and Jones 1998).

By the Pliocene (Figure 17), spreading or crustal extension had begun in the Havre Trough (Caratori Tontini et al. 2019). This linked into spreading in the Lau Basin to the north (Taylor et al. 1996), and resulted in separation of the Colville-Lau and Tonga-Kermadec arcs. By c. 2 Ma volcanism had migrated into the present-day Taupō Volcanic Zone with extension linked to the Havre Trough (Figure 18). There has been significant strike-slip motion through the North Island Fault System since c. 2 Ma, with mountain building, and intense deformation in the forearc (Beanland et al. 1998; Nicol et al. 2007; Bland et al. 2019).

The 0 Ma map (Figure 18) shows the present-day bathymetry and tectonics in the same style as the previous reconstructions. It is included largely to illustrate that the modern bathymetry is considerably more complex than we can hope to reconstruct in any of the previous palaeogeographic maps, and to emphasise that despite our efforts using the best data available, they still represent a gross simplification of the likely palaeobathymetry.

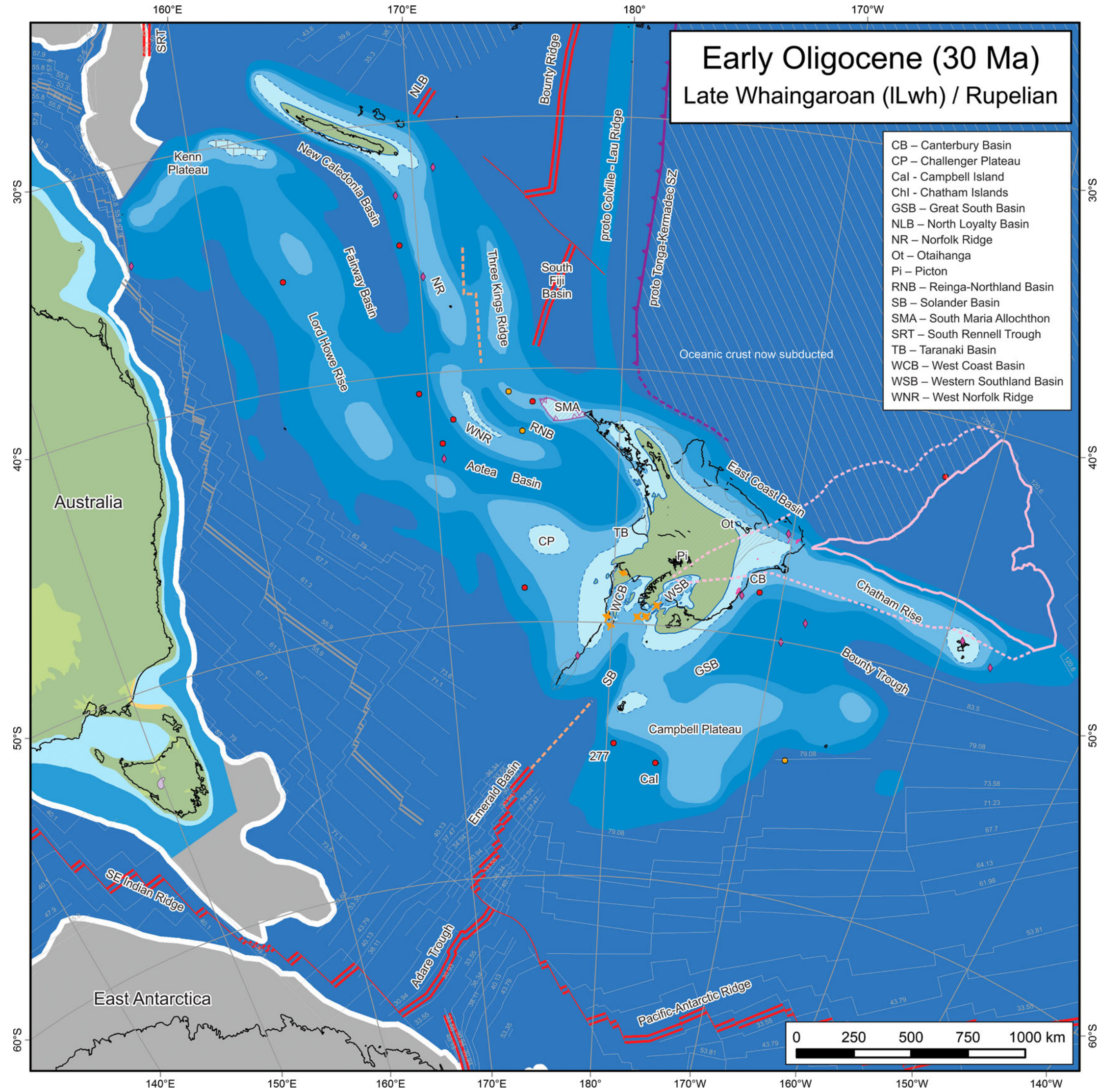

Figure 12. Early Oligocene regional palaeogeographic map of Zealandia (c. 30 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

Discussion

We have produced a set of palinspastically restored palaeogeographic maps for the entirety of Zealandia, from the Cretaceous break-up of eastern Gondwana, through to the present day. Importantly, the tectonic block model (see Hines et al. 2022 for full discussion) that underpins these palinspastic maps is tested and constrained by geological observations, and can be easily updated as required if new data suggest alterations are needed. Although previous studies have provided reconstructed palaeogeographies (e.g. King et al. 1999) and tectonic features (King 2000; Sutherland et al. 2001), these generally cover only the part of Zealandia centred on New Zealand or are focused only on limited time intervals. The majority of these maps were essentially schematic, not located in their restored latitude/longitude as in this study, nor allowing GIS geological datasets to be rigorously restored using a block model tied into the global plate circuit. The study of Cao et al. (2017) did produce palinspastic maps with limited palaeogeographic data, but these were at a global scale, not focused on Zealandia, and contain much less detail that those in our study. Although previous models have addressed the relative positions of the large blocks of Northern and Southern Zealandia well, they failed to capture the complexity of deformation related to the Neogene plate boundary though central Zealandia, which this and a companion study by Hines et al. (2022) have attempted to address. Further iterations capturing more complexity are likely to be produced.

It is possible to analyse the maps produced in this study (Figures 4–18) to look at changes in the area of land and shelfal environments through time (Figure 19), to provide useful insights for palaeo-biogeographers. This shows a rapid decrease in both land and shelf areas from the Late Cretaceous through Paleocene, slowing somewhat in the Eocene–Oligocene, likely due to diminishing post-rift thermal subsidence, but also due to uplift in Northern Zealandia related to subduction initiation processes from c. 50 Ma onwards

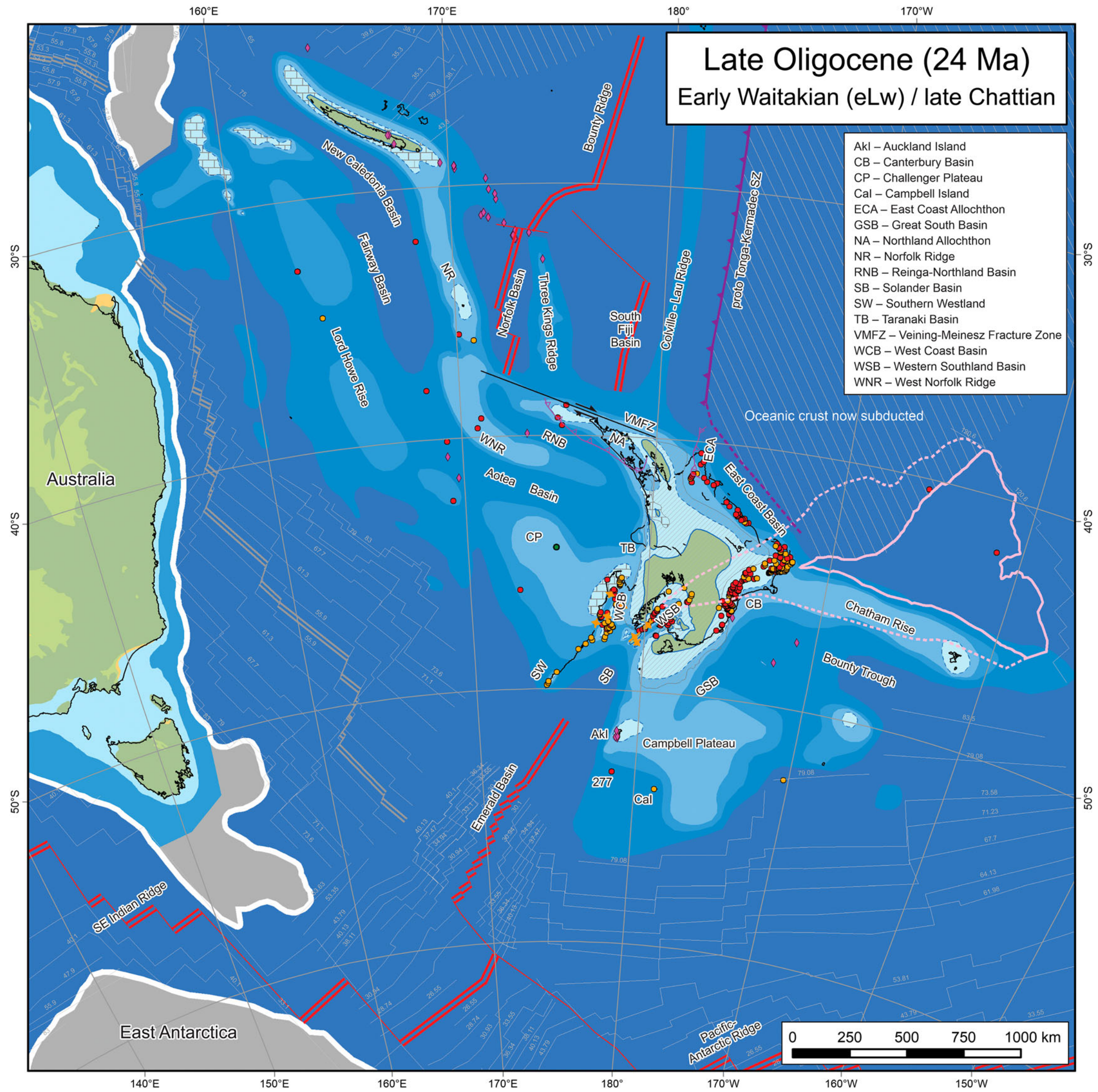

Figure 13. Late Oligocene regional palaeogeographic map of Zealandia (c. 24 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

(Sutherland et al. 2020). Land areas reach a minimum in the Late Oligocene, at the time of supposed total Zealandia drowning (Landis et al. 2008) but, arguably, still with a significant land area present (~150,000 km^2). Since the Neogene plate boundary propagated into New Zealand, the land area has approximately doubled, to around 300,000 km^2. These maps also illustrate the rapid northward migration of Zealandia since the mid-Cretaceous (Figures 4–18); from ~80°S to ~55°S for southernmost Zealandia, and from ~50° to ~20°S for northernmost Zealandia.

A further advance to these maps would be to introduce estimates of palaeotopography, although this is inherently difficult to estimate, given the lack of preservation of non-marine compared to marine facies. However, it may be possible, based on pollen or other flora from sediments in surrounding areas. Attempts have been made to estimate palaeotopography at least for the last 4 Myr in central Zealandia (Nicol 2011; Trewick and Bland 2012), and similar palaeotopography estimates for older strata would help to constrain ecosystem and palaeoclimate models.

Pre-breakup reconstructions

As previously stated, we have taken a simple approach to Cretaceous reconstructions to produce pre-breakup palaeogeographic maps, by maintaining the blocks in their 40 Ma relative positions and using the position of Southern Zealandia within the global plate circuit to drive block positions. Using this model yields a relatively straight palaeo-Pacific subduction margin from Raukumara Basin through to the Chatham Rise, as well as coherent palaeobathymetry and facies belts from Raukumara to Marlborough (Hines 2018; Hines et al. 2022). Neither of these lines of evidence require the major movements between Northern and Southern Zealandia prior to 83 Ma, as suggested by some workers (Lamb et al. 2016; Lamb and Mortimer 2020). Control on the palaeo-Pacific margin of

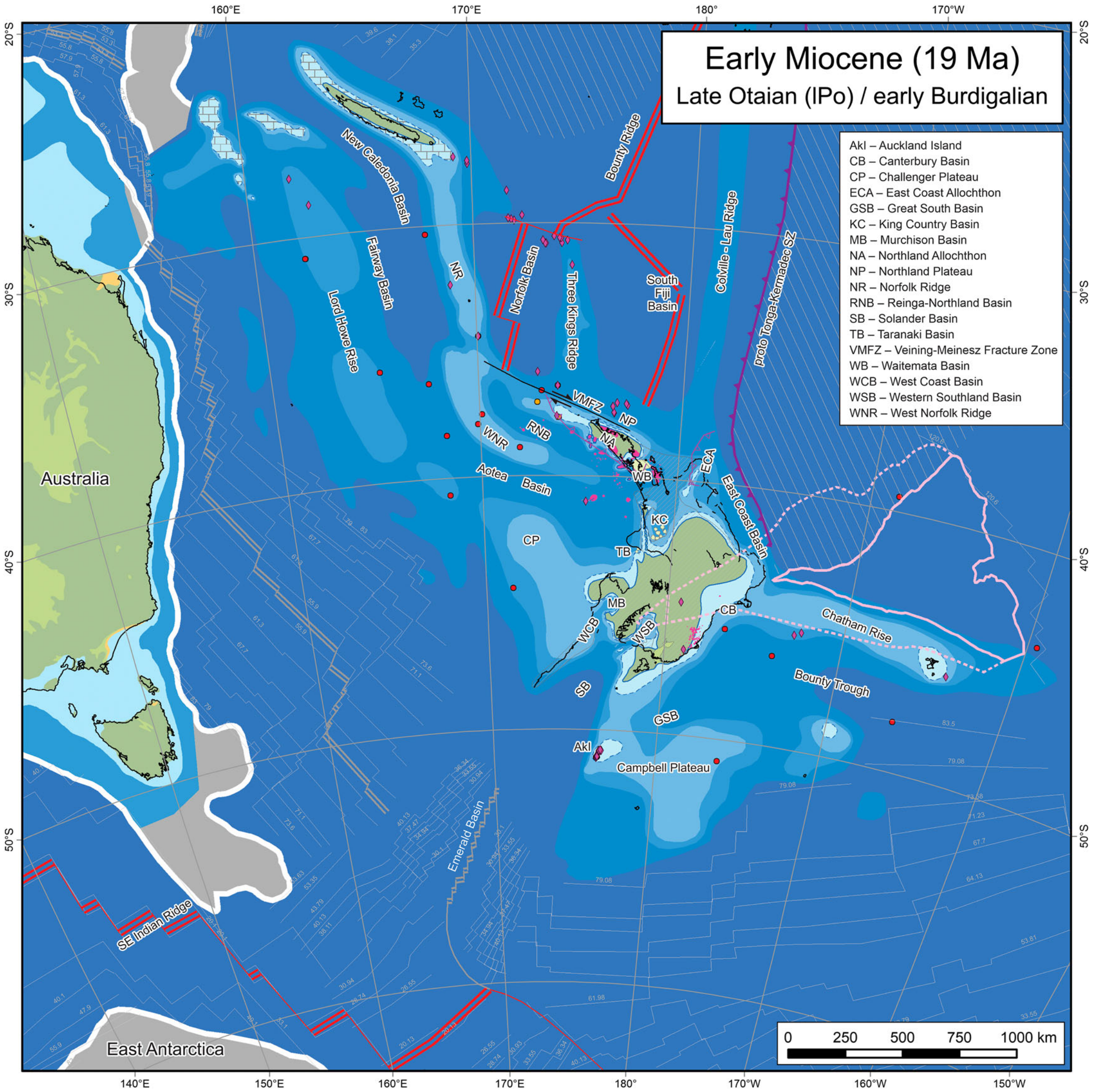

Figure 14. Early Miocene regional palaeogeographic map of Zealandia (c. 19 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

Northern Zealandia from the Three Kings Ridge northwards is very poor.

This simplified model results in a pre-breakup overlap between Northern Zealandia and Australia of roughly 250–350 km, as well as an area of underlap in the southern Tasman Sea (Figure 4), which are obviously in error. One way to reduce this would be the removal of the extension from the basins in Northern Zealandia (present-day width of ~1000–1250 km). Removing this overlap would require extension of ~30–40% across the continent as a whole, which would have been concentrated within the major basins. Retrodeforming this extension may increase gaps present in the southern Tasman Sea although our knowledge of the Tasman Sea facing basins of the middle Lord Howe Rise (LHR) (Totterdell et al. 2014) and Challenger Plateau (CP) (Uruski 2010; Bland and Strogen 2018) is very poor. The effects of removing extension in Southern Zealandia are also unknown, but should result in a better fit of the Chatham Rise against West Antarctica (Figure 4).

Another method to remove overlap is to break Northern Zealandia into multiple blocks. Gaina et al. (1998b) broke the LHR-CP into several blocks, most notably requiring significant sinistral strike-slip between their middle and northern LHR blocks to close the southern Tasman Sea without overlap to the north, and also closure of the Bellona Trough between the middle LHR and CP. It should be noted that Gaina et al. (1998b) only dealt with the fit of the LHR-CP against Australia and not the remainder of Northern Zealandia (Norfolk Ridge) or Southern Zealandia. Our model agrees with Gaina et al. (1998b) from c. 70 Ma onwards, where they have a contiguous LHR-CP in its present configuration. It is beyond the scope of the present study to address this further, but clearly future iterations of any block models for the period prior to the full separation of

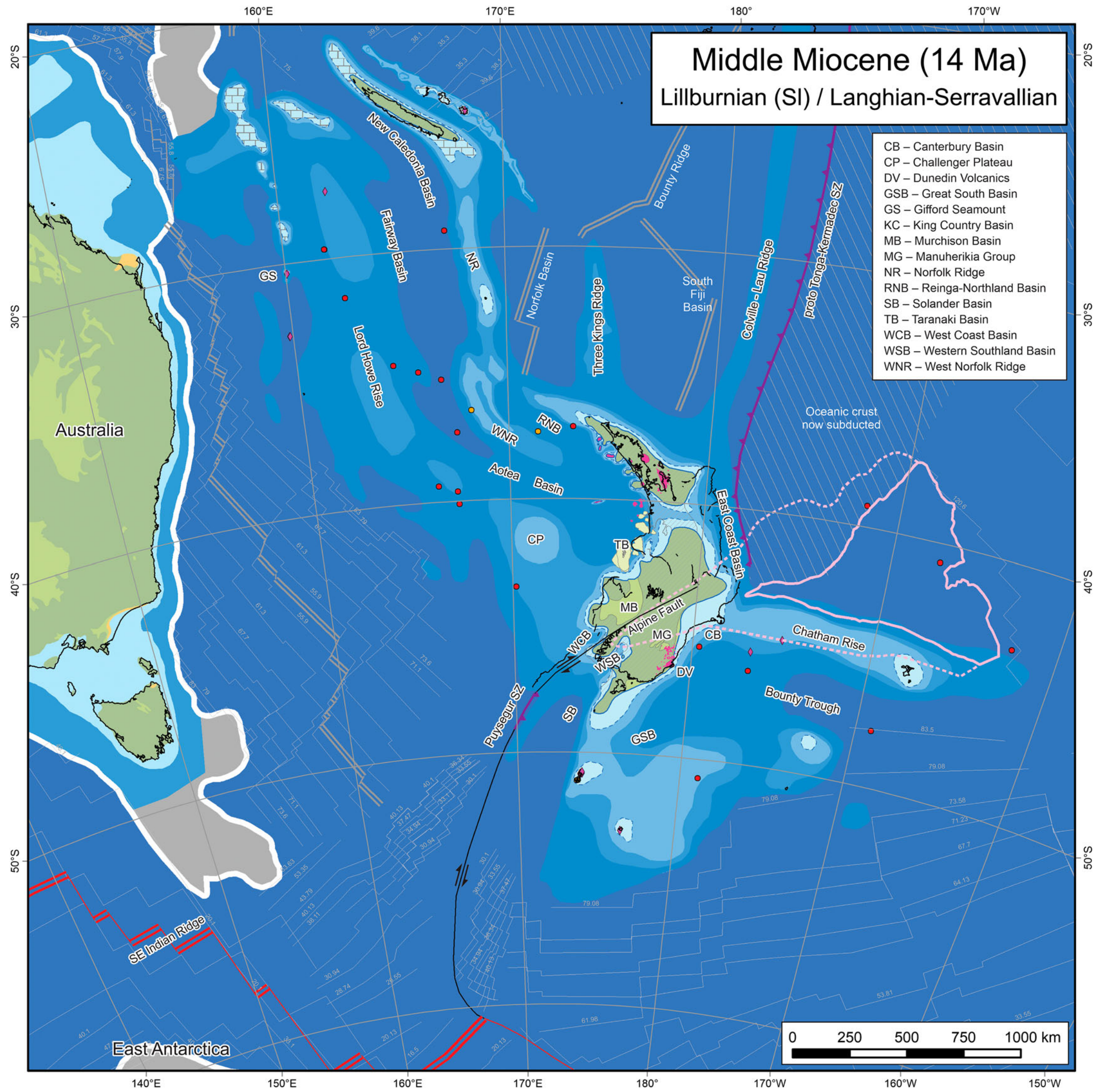

Figure 15. Middle Miocene regional palaeogeographic map of Zealandia (c. 14 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

Zealandia from eastern Gondwana (at c. 62 Ma) will need to address these issues, whether by removing extension, breaking Northern Zealandia into more blocks–assuming there is geological evidence for suitable structures, or more likely some combination of both approaches.

Gondwana breakup

The breakup of Southern Zealandia against West Antarctica appears very different in style than that of Northern Zealandia against Australia. Breakup appears to be much sharper in the south, with a very narrow continental slope, possibly reflecting limited upper-crustal extension in the Campbell Plateau. In comparison, in Northern Zealandia, there is much more distributed crustal extension, particularly in the outer basins on the southwestern side of the LHR. Furthermore, many of the rift basins in Southern Zealandia and the eastern Ross Sea are at a high angle to the line of eventual breakup, unlike in the region adjacent to Tasman Sea opening, where they are generally parallel. An exception is the Bellona Trough (Wood 1991, 1993), which trends at a high angle to the other Tasman Sea basins, and is poorly understood in both its age and mode of origin (Bland and Strogen 2018). The direction of marine flooding into the southern Tasman Sea prior to breakup at c. 83 Ma is unclear. We have suggested a marine connection along the line of subsequent breakup, but this is somewhat tortuous. Other possibilities include through the Bellona Trough and into Aotea Basin, or perhaps to the west of Tasmania, through the Sorrell Basin.

The breakup of Zealandia from eastern Gondwana is often thought of as occurring at c. 83 Ma, and associated with the end of the 'Zealandia' rift phase (Strogen et al. 2017). However, final separation of northern Zealandia with Australia did not occur until c. 62 Ma (Gaina et al. 1998a; 1999), almost 20 Myr later, and almost 40 Myr since rifting first began (Strogen et al. 2017). Also, whilst the eventual separation in the southern Tasman Sea and Southern

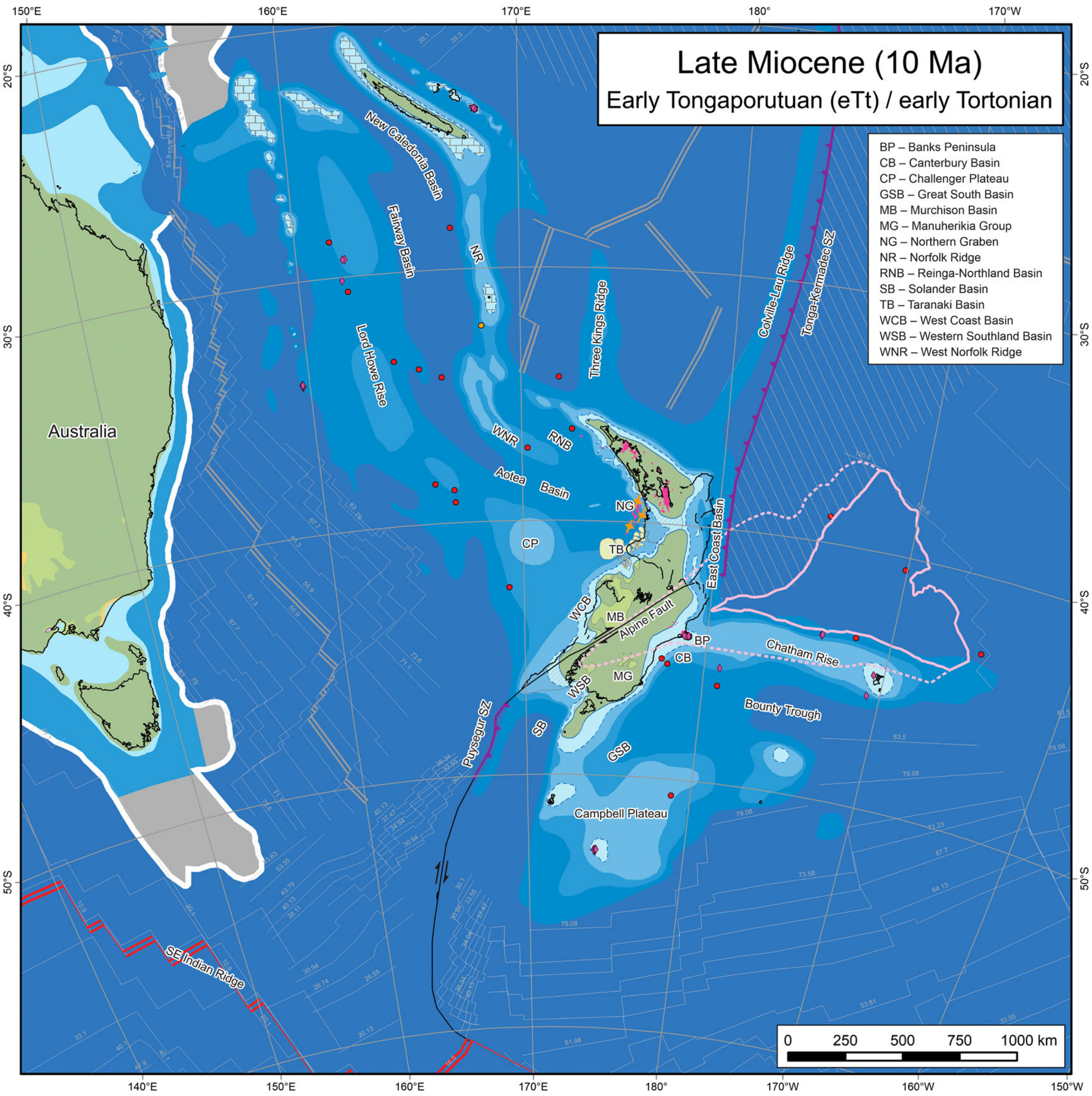

Figure 16. Late Miocene regional palaeogeographic map of Zealandia (c. 10 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

Ocean is wide (>1000 km), the final separation of the Kenn Plateau and Australia through the Cato Trough is extremely narrow (~35 km; Mortimer et al. 2020c). The pre-breakup northern termination of Zealandia (and its sedimentary basins) and its relationship with microplates in the region now forming the d'Entrecasteaux to Coral Sea basins is unclear.

The age of extension in basins in northwestern Zealandia is poorly defined, but inferred to be generally c. 100–83 Ma, the same 'Zealandia' rift phase (Strogen et al. 2017) as recognised elsewhere in Zealandia. This appears to be the case in the eastern basins in Northern Zealandia, such as the New Caledonia Basin (Maurizot et al. 2020a). However, as discussed above, breakup in the northern Tasman Sea continued later than elsewhere in Zealandia, and it is possible that extension in the western basins of Northern Zealandia continued later than elsewhere. As yet there are few constraints on this as only seismic data are available for these rift basins (Totterdell et al. 2014).

Cenozoic plate boundary initiation

Post-breakup, much of the Campbell Plateau deepened rapidly (Sutherland et al. 2010) and was quickly dominated by starved bathyal carbonate sedimentation. Whilst the highs of Northern Zealandia (CP-LHR and Norfolk Ridge) also deepened following the end of rifting, bathymetry in the north is overprinted by the effects of subduction initiation processes from the Early Eocene onwards (Sutherland et al. 2020; Skinner and Sutherland 2022). There was little change in the palaeobathymetry of much of distal Zealandia through the Neogene (Hayward et al. 2004).

An area in central Zealandia close to the present-day plate boundary appears to have supplied coarse sediment to basins to the NW (Taranaki) and SE (Great South) through the Late Cretaceous to Middle Eocene. This supply is cut off immediately prior to Emerald Basin rifting beginning at c. 40 Ma, possibly

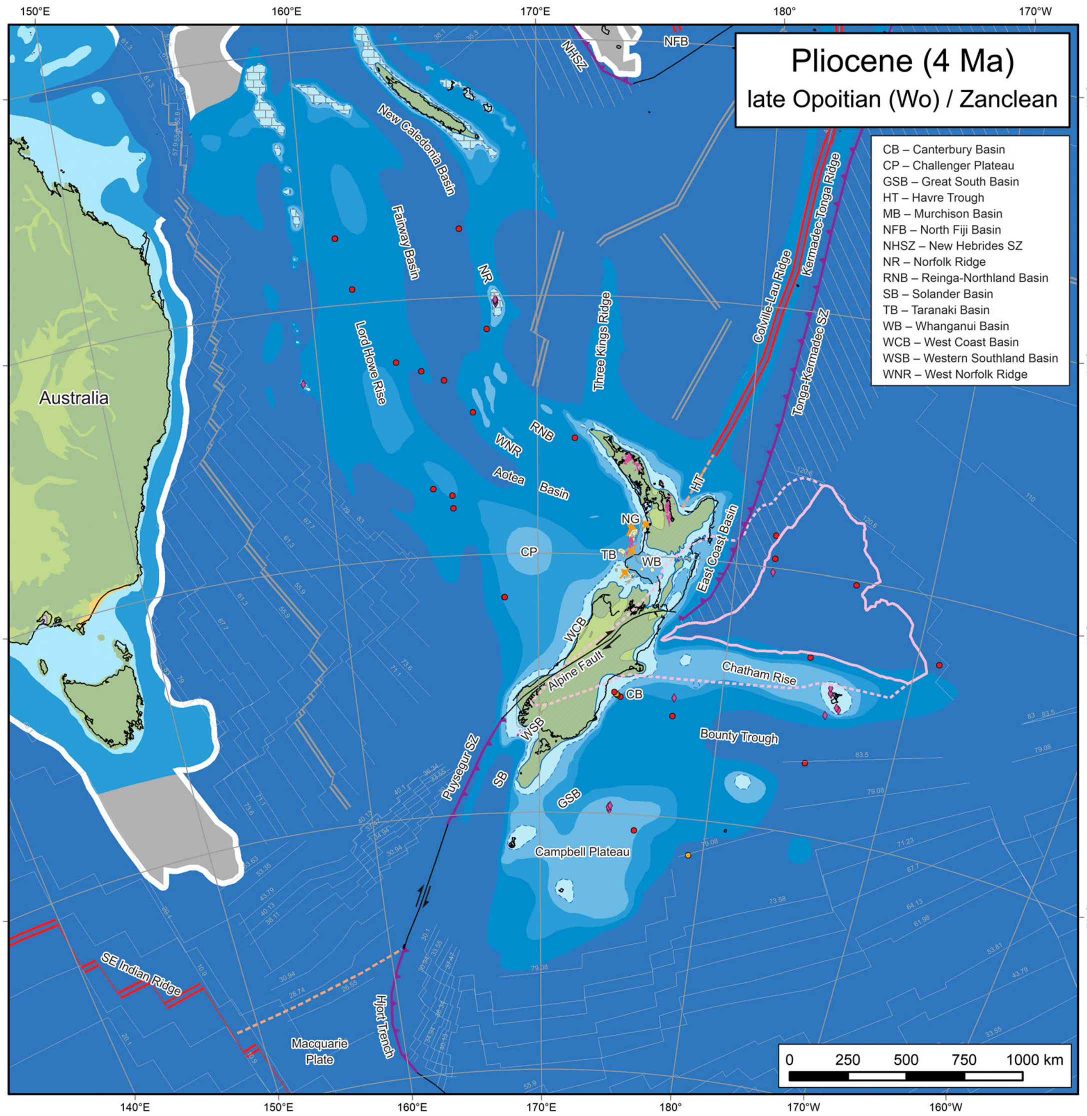

Figure 17. Pliocene regional palaeogeographic map of Zealandia (c. 4 Ma). Australian palaeogeography from Totterdell et al. (2001). See Figure 4 for key.

reflecting topographic changes affecting sediment transport paths. This results in the reduction of coarse clastic sediments into the basins, and the end of long-lived deltaic sequences in both basins–the Farewell/Kaimiro/Mangahewa system in Taranaki Basin (King and Thrasher 1996) and the Tara-Toroa complex in Great South Basin (Sahoo et al. 2022). From the Middle Eocene onwards, the southern part of the West Coast formed part of the western margin facing into the Emerald Basin, the conjugate margin to the western edge of the Campbell Plateau. This explains the distal deep bathyal nature of deposition in southern Westland, which is quite different to further north on the West Coast (Nathan et al. 1986).

There are uncertainties regarding Eocene reconstructions prior to and during Emerald Basin opening. In the current block model, it is difficult to place Fiordland further south, and this places Western Southland to the east of much of the West Coast Basin, with Fiordland tight against Murchison Basin. This has implications for provenance studies in the region (Sagar et al. 2022). Previous models (e.g. King et al. 1999) suggest Western Southland was south of, and contiguous with, the West Coast Basin. Whilst the present block model restores the oroclinal bend in Marlborough, as yet, it does not address inferred oroclinal bending in Fiordland (Lamb and Mortimer 2020).

We favour the model for South Fiji Basin opening of Herzer et al. (2011), which infers younger oceanic crust than many previous models (e.g. Sdrolias et al. 2003; Schellart et al. 2006). Whilst the geometry of spreading centres may be complex, overall it describes a simple rollback of the Tonga-Kermadec subduction system which fits well with our palaeogeographic model. Some details of how the subduction system propagated through this region are still unclear, such as the nature of volcanism on the Norfolk and Three Kings ridges (Mortimer et al. 2020d) and the precise timing of subduction propagation.

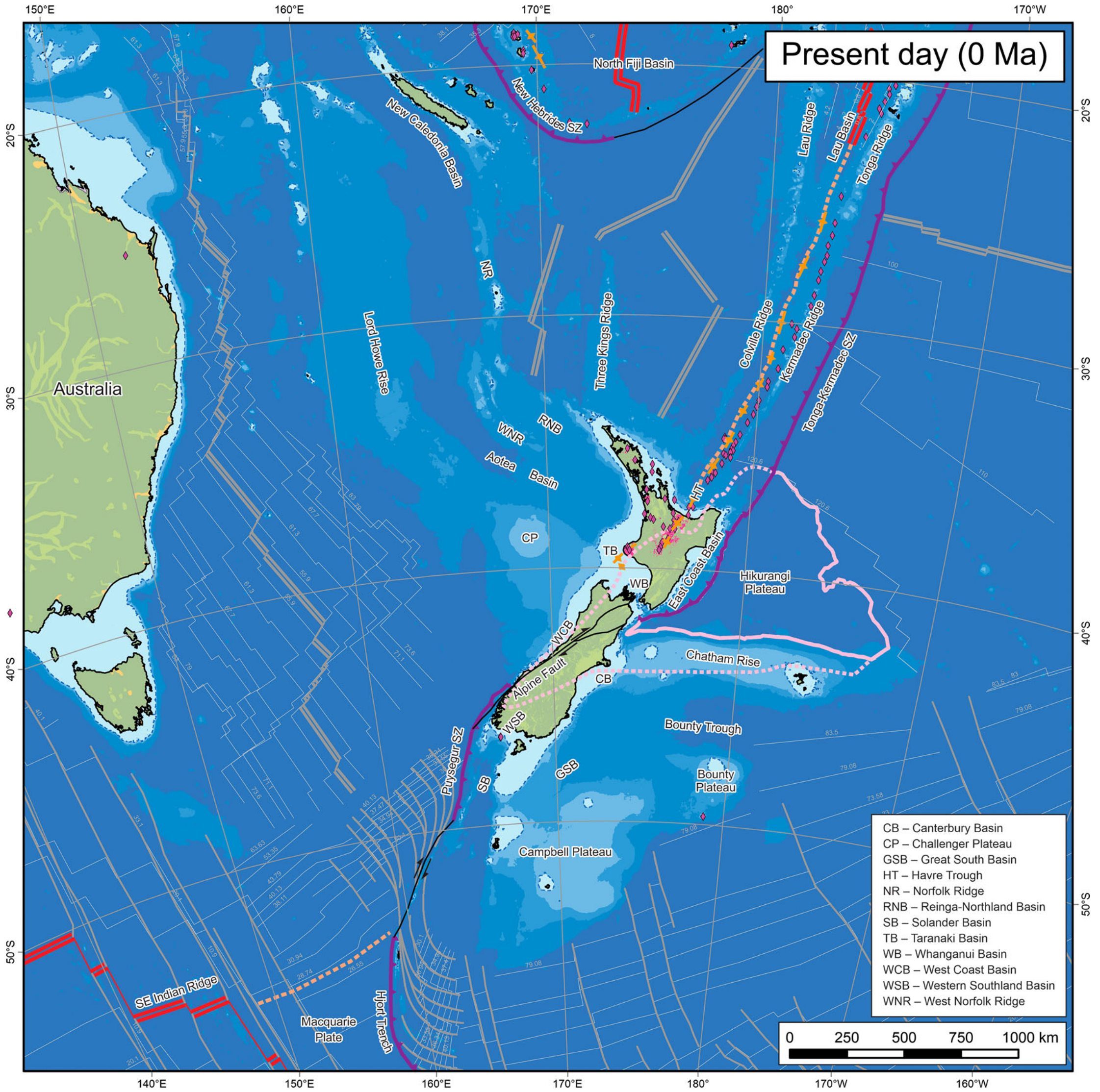

Figure 18. Present day map of Zealandia in the same style as the palaeogeographic maps. Bathymetry courtesy of GEBCO. Australian environments from Totterdell et al. (2001). See Figure 4 for key.

The Northland and East Coast allochthons appear to be similar in age (c. 23–19 Ma). The two allochthons did not form a contiguous single unit and were likely formed by different processes. The Northland Allochthon appears to be related to extension in the South Fiji and Norfolk basins and transpressive deformation along the VMFZ (Herzer and Mascle 1996). The East Coast Allochthon is probably related to transient uplift associated with propagation of the subduction zone south into the area stretching from Raukumara Basin to Marlborough (Chanier and Ferrière 1991; Rait et al. 1991), also reflected in smaller scale olistostromes found further south along this margin (e.g. Delteil et al. 2006; Bland et al. 2022).

It is when rollback in the South Fiji Basin is complete c. 15 Ma (Herzer et al. 2011) that convergence and rotation through central Zealandia intensifies (e.g. Bull et al. 2019), with the formation of a through-going Alpine Fault, and renewed subduction of the Hikurangi Plateau (Reyners et al. 2017a). Neogene subduction of the Hikurangi Plateau under eastern central Zealandia appears to have had a major impact on deformation, uplift and erosion and is seen in significant Middle–Late Miocene increases in sedimentation rates in surrounding basins, particularly the East Coast (Field et al. 1997; Bland et al. 2019) and Taranaki basins (King and Thrasher 1996).

Future work

Further work is needed to reconcile the models of New Caledonia ophiolite obduction and South Loyalty Basin tectonics (for discussion see Collot et al. 2020). As yet, we have not attempted to reconstruct the area to the east of New Caledonia prior to Late Eocene obduction. Future iterations of the block model should aim to more accurately capture the tectonic complexity in this northeastern part of Zealandia, as well as addressing the pre-breakup reconstruction issues already discussed. Further

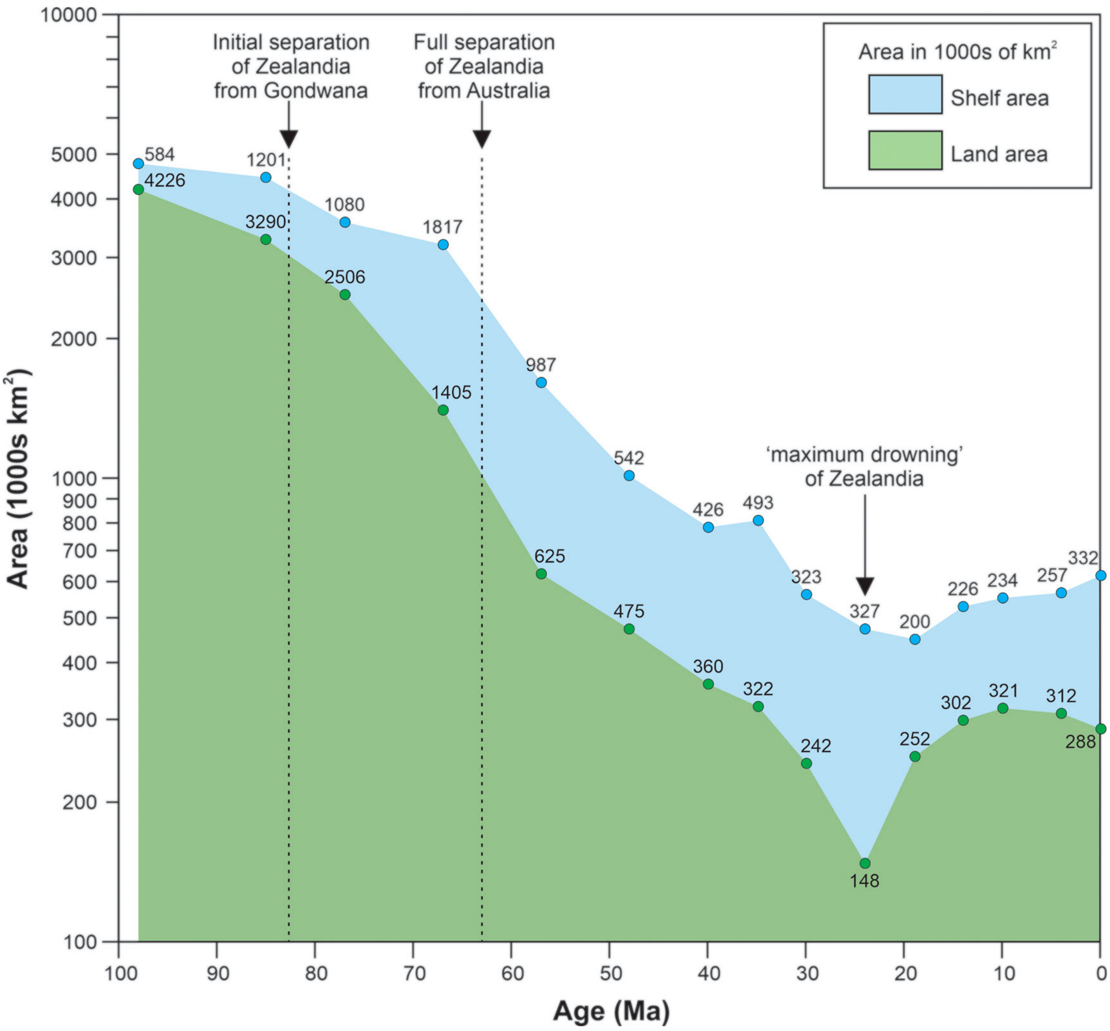

Figure 19. Graph showing the variation in the area of land and shelf (0–200 m) in Zealandia since 98 Ma (note log scale). There was an initially rapid drop in the area of both through the Late Cretaceous and Palaeocene, and slower Eocene–Oligocene, drowning through to a minimum at c. 24 Ma, although there was still significant land area (~148,000 km^2). Since the Neogene propagation of the plate boundary into New Zealand, the land area has roughly doubled from this minimum. Note that Northern Zealandia did not fully separate from Australia until c. 62 Ma (Gaina et al. 1998b). These estimates are approximate with potentially large but difficult to quantify errors.

refinements to the block model in the plate boundary zone are also to be expected, as well as attempts to better capture the ductile deformation occurring there.

Further work is required to fully capture the complex bathymetry and facies in East Coast Neogene accretionary wedge sub-basins as the Hikurangi margin developed (Pettinga 1982; Bailleul et al. 2013), as these have only been mapped at a reconnaissance level in this study. In far-field areas, such as much of Northern Zealandia and the Campbell Plateau, lack of data probably make the construction of more maps untenable at present. However, in areas with better data coverage and higher biostratigraphic resolution, particularly onshore/nearshore New Zealand, the production of further palaeogeographic maps is feasible. This is illustrated by the set of 30 maps produced for the Taranaki Basin by Strogen (2011). It is anticipated that further maps will be constructed to address intervals of interest, particularly the late Neogene of interest in palaeo-climatic studies.

Conclusions

A suite of palaeogeographic maps have been produced for Zealandia, using a new tectonic reconstruction model. These maps mark a major advance in the understanding of Zealandia's palaeogeographic evolution, with the main results summarised below.

(1) The 15 maps (98–0 Ma) illustrate major phases in the tectonic evolution of Zealandia, from initial mid-Cretaceous Gondwana rifting through to the development of the modern Neogene–Quaternary plate boundary. They cover the whole of Zealandia, reconstructed in a rigorous tectonic

framework. The maps provide palaeobathymetric and palaeofacies interpretations along with reconstructed supporting geological datasets and regional tectonics syntheses.

(2) The underpinning retro-deformational block model is geologically constrained and structurally based (see companion paper Hines et al. 2022). It breaks central Zealandia into numerous fault-bounded blocks, reflecting complex Neogene–Quaternary plate boundary deformation. Production of maps using GPlates and GIS allows for simple alteration or refinement of the block model and reconstruction of any geological datasets through time.

(3) Reconstructions are tied to the global plate circuit within a palaeomagnetic reference frame, allowing assessment of palaeo-latitude, critical for palaeo-climatic and palaeo-biogeographic studies. We have also used these maps to estimate variations in the area of land and shelfal environments through time.

(4) Future iterative refinements to the tectonic model are expected. This will include modelling of extensional and contractional deformation, oroclinal bending, particularly to address issues with Cretaceous reconstructions. Palaeogeographic maps will be updated using any improved block model, and also integrating any new regional datasets, as available.

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No potential conflict of interest was reported by the author(s).

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Data availability statement

The palaeogeographic reconstructions presented in this study have utilised open-file and published datasets, which are cited through the paper. All biostratigraphic data used are lodged in the New Zealand Fossil Record File (FRF; Clowes et al. 2021), accessible at https://fred.org.nz/. Data regarding the ages of onshore and offshore volcanic rock samples were extracted from PETLAB (Strong et al. 2016), accessible at http://pet.gns.cri.nz/. Onshore geological map data were derived from the QMAP Seamless 1:250k digital dataset, held by GNS and accessible via https://www.gns.cri.nz/Home/Products/Maps. Digital (GIS) palaeogeographic maps, illustrated seismic transects, and digital (GIS) seismic depth-grids relating to the 'Atlas of Petroleum Prospectivity' (APP) programme, are accessible for download from https://data.gns.cri.nz/pbe/, via digital Petroleum Exploration Data Packs distributed by New Zealand Petroleum & Minerals (MBIE; https://www.nzpam.govt.nz/), or by contacting the authors. A supplemental file providing more detailed descriptions of the palaeogeographic reconstructions presented in this paper and all referenced material used in their construction, is available in figshare via https://doi.org/10.6084/m9.figshare.20500113.

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