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# Introduction to Paleozoic–Mesozoic geology of South Island, New Zealand: subduction-related processes adjacent to SE Gondwana

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## Chapter 1

# Introduction to Paleozoic–Mesozoic geology of South Island, New Zealand: subduction-related processes adjacent to SE Gondwana



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This Memoir presents and discusses recent research mainly concerning the Permian and Triassic geological development of South Island in its regional context, which includes New Zealand as a whole, the continent of Zealandia, eastern Australia and Antarctica. The Permian and Triassic geology of the South Island encompasses several geological units which shed light on fundamental geological processes. These include a well-developed oceanic volcanic arc, a classic subduction-related ophiolite (oceanic crust on land) and a very thick succession of continental margin forearc sediments. These, and other related geological units, constitute the oldest extensively outcropping basement of Zealandia, which can be considered as the world's seventh largest continent, albeit 94% submerged (Mortimer *et al.* 2017). The supercontinent, Gondwana, formed during the Late Neoproterozoic and remained until its progressive break-up into crustal fragments during the Mesozoic. During this prolonged period, New Zealand and adjacent crustal units were located along the SE edge of Gondwana. Subduction took place beneath this margin during the Paleozoic–Mesozoic, until the end of Early Cretaceous time (*c.* 100 Ma) when it halted, followed by rifting of the Tasman Sea Basin.

This volume consists of 14 contributions, comprising a mix of new-data-based papers (and one note) and several review and synthesis papers. The contributions largely concern igneous and sedimentary geology, tectonics and biostratigraphy. Particular emphasis is placed on field geology, petrography and geochemistry. Some aspects are less well covered (e.g. Permian–Triassic geology of New Zealand's Cordilleran-style Median Batholith; metamorphic geology), primarily because there is a large amount of existing and/or recently published data.

While the Permian–Triassic terranes bear imprints of Gondwana break-up and Neogene Alpine Fault development, these topics are outside the scope of this volume. The final chapter discusses various tectonic-based interpretations for the Permian–Triassic development of Zealandia and points the way to an overall synthesis.

In this introductory chapter, we will first set the scene for those with little prior knowledge of New Zealand geology or its regional setting. Many geoscientists are aware of New Zealand geology, primarily for earthquakes, volcanoes and gold. In contrast, the Permian–Triassic 'basement' geology is relatively little known internationally, an omission which this volume aims to correct as far as possible.

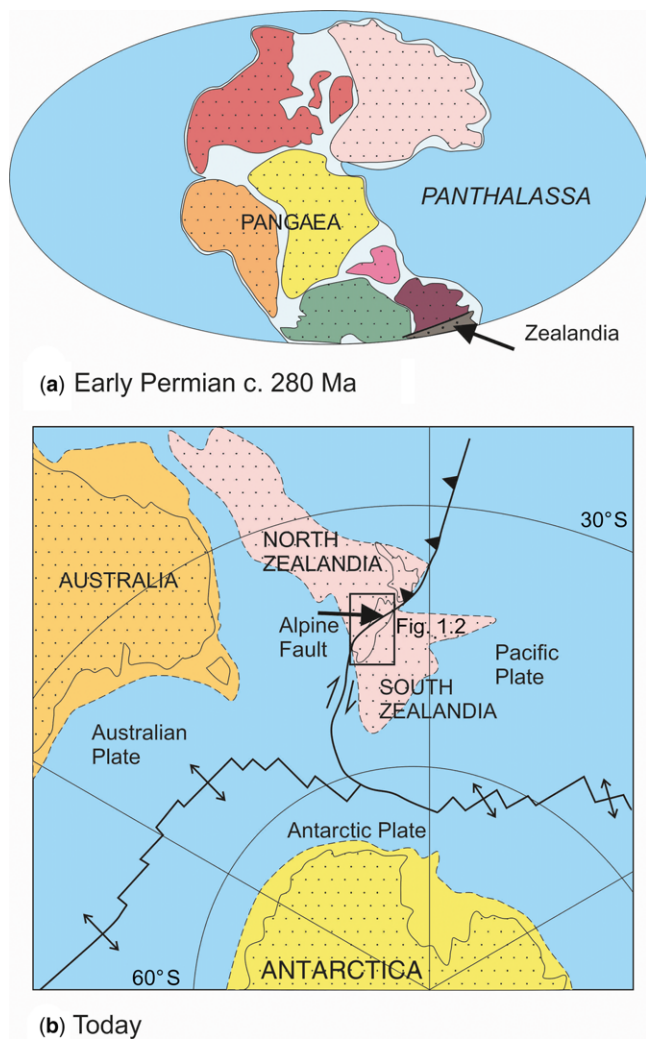
The geological setting and development of New Zealand has been previously reviewed in milestone contributions (e.g. Coombs 1950; Landis & Coombs 1967; Landis & Bishop

1972; Coombs *et al.* 1976; Kimbrough *et al.* 1994), review and synthesis papers (e.g. Mortimer 2004; Mortimer *et al.* 2002) and several books (e.g. Thornton 1985; Mortimer & Campbell 2014; Graham 2015; Ballance 2017) and is only briefly outlined here. We introduce the basic building blocks of the late Paleozoic–early Mesozoic geology of New Zealand, notably the subdivision into the Western Province and the Eastern Province, and the tectonostratigraphic terranes of South Island that are the main subject of this volume (Mortimer *et al.* 2014). We also mention the relevance of conventional stratigraphy, including groups and formations (e.g. H.J. Campbell *et al.* 2003), and the New Zealand timescale (Raine *et al.* 2015). Finally, we briefly introduce the scope and the main findings of each of the contributions.

### Stepping back in time

During late Paleozoic–early Mesozoic time, the geological setting of New Zealand was very different from that of today (Figs 1.1a, b & 1.2). The Late Cretaceous–Holocene plate tectonic development of Zealandia is now quite well understood, taking account of evidence from North and South Island, Zealandia as a whole, and the surrounding oceanic and continental regions (Mortimer & Campbell 2014; Graham 2015). The older rocks of New Zealand form an arcuate oroclinal bend (Mortimer 2014) which is offset by the Late Cenozoic *c.* NE–SW-trending boundary between the Pacific and Australian plates (Fig. 1.3a). Near-orthogonal westward subduction produced the well-known Taupo–Kermadec–Tonga volcanic arc, extending northwards from the NE of the North Island, whereas highly oblique northeastward subduction (beneath the Campbell Plateau) characterizes the Pacific–Australia plate boundary south of New Zealand.

Between the two opposing subduction segments, South Island is cut and offset dextrally by *c.* 450 km along the Alpine Fault and its subsidiary strands (Fig. 1.3a). The rugged Alpine chain, culminating in the Southern Alps, is fundamentally the result of strike-slip and convergence (transpression) along the plate boundary, which has driven uplift at least since the Pliocene (Walcott 1978; Norris *et al.* 1990; Norris & Cooper 2001). The well-known dextral displacement allows the northern and southern segments of South Island to be restored with confidence, an essential prerequisite to understanding the late Paleozoic–early Mesozoic geology as discussed in this Memoir.

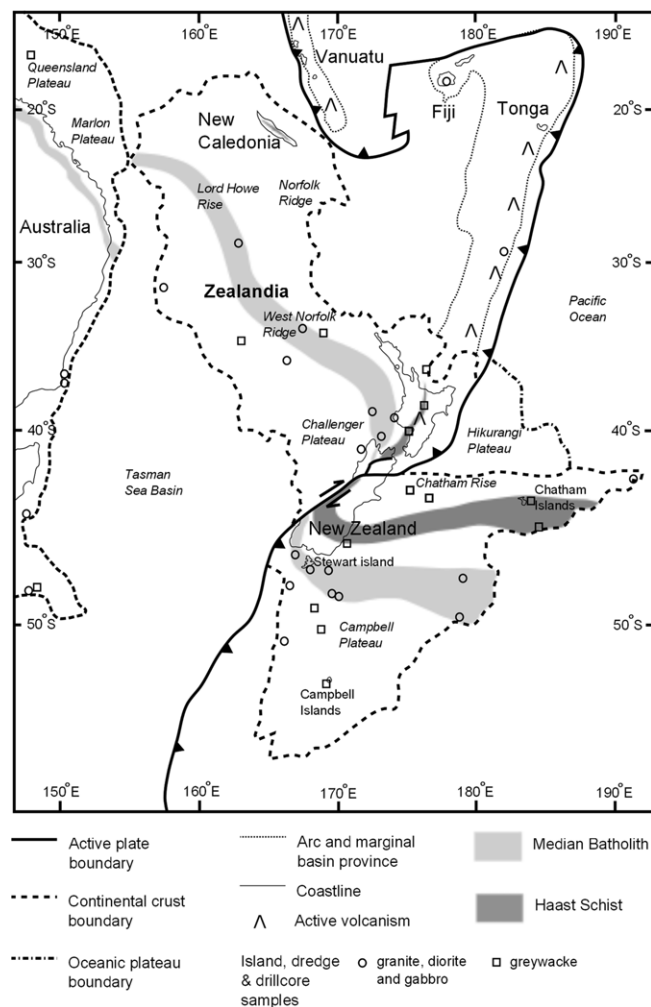


**Fig. 1.1.** Regional tectonic setting of New Zealand. (a) Early Permian (c. 280 Ma), when the oldest rocks discussed in detail in this volume formed. (b) Present day. Modified from Mortimer & Campbell (2014).

Beginning in the Early Eocene (c. 45 Ma), a spreading centre propagated northeastwards from the Southern Ocean to open the Emerald Basin. The spreading tip propagated into Zealandia during the Early Miocene, giving rise to North and South Zealandia (Fig. 1.3b). Prior to this rifting, Zealandia, as a fragment of Gondwana, was relatively intact and encompassed regionally continuous c. NW–SE-trending basement terrane and batholithic trends (Fig. 1.3c). The Late Cretaceous–Recent plate tectonic development is summarized in Figure 1.4a–e.

Prior to its separation from Australia and Antarctica, Zealandia formed part of the eastern continental margin of Gondwana (Figs 1.3 & 1.5). But were Zealandia's constituent Permian and Triassic rocks always part of autochthonous Gondwana? This key issue is considered by several papers in this volume. Restoring the major late Paleozoic–early Mesozoic crustal units (i.e. tectonostratigraphic terranes: Bishop *et al.* 1985; Landis & Blake 1987; Mortimer *et al.* 2014) to their original geological settings is challenging.

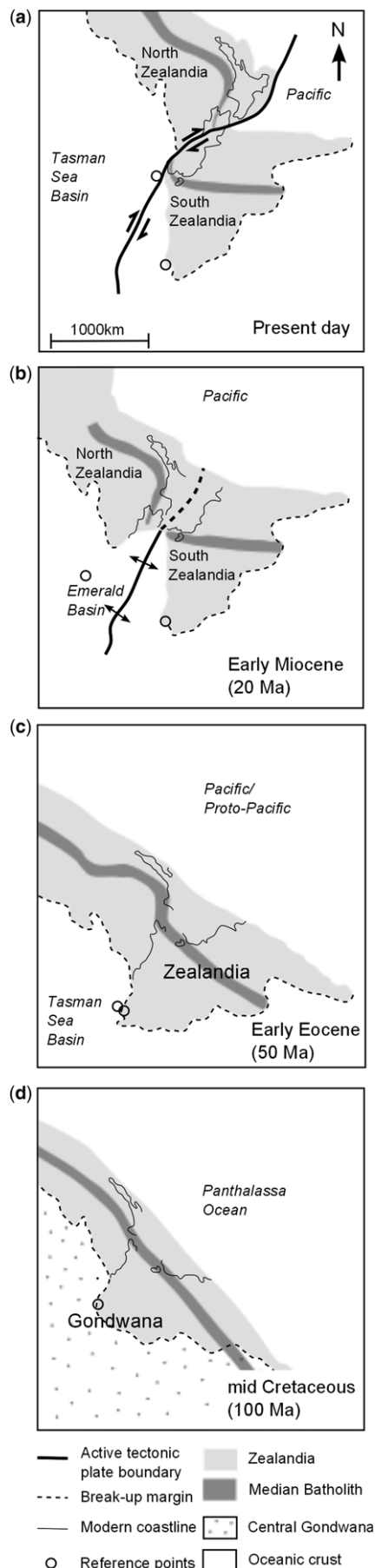
For the New Zealand Permian and Triassic, in particular, dating and thus correlations of the different geological units using fossils is difficult and can be subject to alternative interpretations. Particularly productive is the linking of radiometrically determined detrital sediment ages with potential source rocks. However, even this approach is limited by the potential scale of the source units, submergence or



**Fig. 1.2.** Regional tectonic setting of Zealandia today. Note the size of Zealandia compared to New Zealand. Modified from Mortimer & Campbell (2014).

ice-covering of potential source units, or erosion of source areas. By general agreement, the Permian–Triassic terranes originated somewhere along the eastern continental margin of Gondwana adjacent to eastern Australia or eastern Antarctica (Cawood 1984; Vaughan *et al.* 2005; Vaughan & Pankhurst 2008) (Fig. 1.1a). During Paleozoic–early Mesozoic time the super-ocean Panthalassa was subducting generally westwards beneath Gondwana (Mortimer 2004; Cawood 2005; Torsvik & Cocks 2009), with a consequent history of magmatic arc, trench and forearc processes. During the Permian and Triassic Gondwana was breaking-up, specifically in the Atlantic, Mediterranean and Indian oceans. However, the Permian–Cretaceous terranes of Zealandia remained as part of the easterly active continental margin of Gondwana for c. 450 myr, from the early Paleozoic until the end of the Early Cretaceous.

Subduction-related processes are the dominant topic of this Memoir, including the genesis and accretion of an oceanic island arc, the formation and emplacement of a supra-subduction zone ophiolite, the formation and accretion of seamounts, and also trench sedimentation and accretion. Similar processes characterize subduction systems and active continental margins worldwide, especially in areas such as the western Pacific Ocean. Valuable insights are provided by comparisons of ancient and modern settings involving subduction and ocean–continent interaction.



**Fig. 1.3.** Key stages of tectonic development back through time that restore New Zealand to its tectonic setting during the time interval (mainly Permian–Jurassic) covered by papers in this volume. (a) The crust is offset *c.* 480 km by the Alpine Fault (using the Median Batholith as a reference).

### Tectonostratigraphic terranes of South Island

The basement rocks of New Zealand comprise two contrasting geological provinces, known as the Western Province and the Eastern Province (Fig. 1.6).

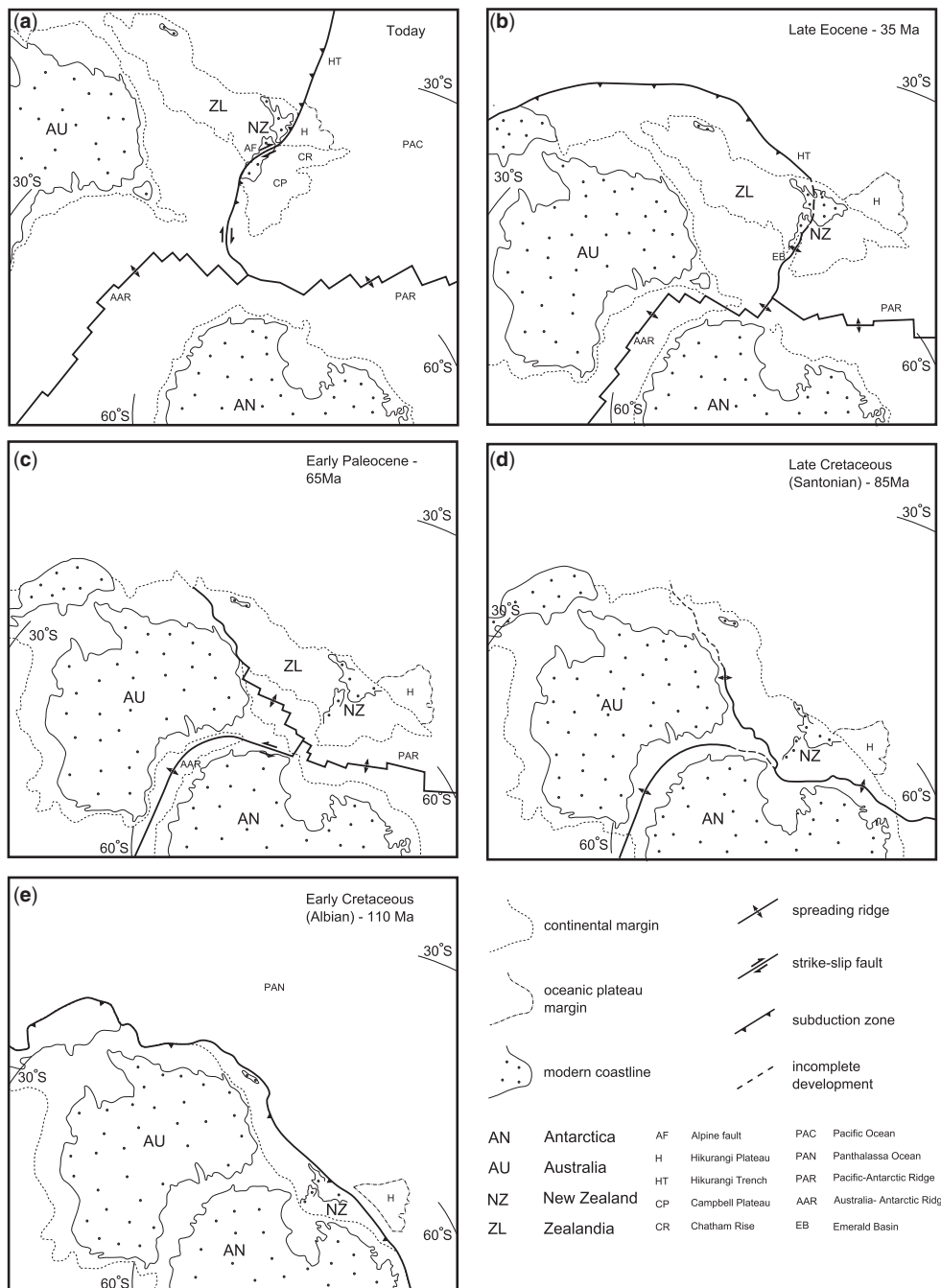
The Western Province is mainly exposed in the NW and SW of South Island, and comprises clastic sedimentary terranes intruded by the Tuhua Intrusives (Mortimer 2004; Mortimer *et al.* 2014). The largest and most voluminous of the Tuhua Intrusives is a composite Cambrian–Early Cretaceous Cordilleran batholith, the Median Batholith (Mortimer *et al.* 1999) (Fig. 1.6), formerly the Median Tectonic Zone (Bradshaw 1993), which straddles the boundary between the western and eastern terranes (Mortimer 2004).

The Eastern Province is extensively exposed in both the South and North islands, where it is dominated by grey quartzofeldspathic sandstones and mudrocks ('greywackes') of Late Paleozoic to (and including) Early Cretaceous age. In the west, there are important Permian igneous bodies which include oceanic crust on land (ophiolite) and remnants of an oceanic island arc. Several of the terranes exposed in South Island (i.e. Murihiku, Caples and Torlesse) also crop out in North Island. The terranes as a whole are separated by high-angle faults, where not obscured by younger geological features.

### Concept of tectonostratigraphic terranes

The papers in this volume broadly follow the currently accepted geological division of South Island into tectonostratigraphic terranes, igneous suites and conventional stratigraphic units (Mortimer *et al.* 2014) (Fig. 1.7). With the emergence of the tectonostratigraphic terrane concept during the 1980s in western USA and its subsequent application to the circum-Pacific region and orogenic belts worldwide (Coney *et al.* 1980; Jones *et al.* 1983; Howell *et al.* 1985; see Howell 2009), the elongate fault-bounded crustal units in New Zealand were classified as terranes (Bishop *et al.* 1985). The tectonostratigraphic terrane concept originally emphasized that fault-bounded crustal units could have been tectonically transported long distances from their place of origin to their site of accretion (i.e. they were allochthonous). More recently, the tectonostratigraphic terrane concept has undergone vigorous debate and some geologists have rejected its application, mainly on the grounds that the fault-bounded nature of terranes is the result of 'normal' plate tectonic processes, especially subduction, which lead to prominent fault contacts between parautochthonous units (Şengör & Dewey 1990). However, in New Zealand the initial terrane nomenclature (Bishop *et al.* 1985) has stood the test of time as a high-level descriptive tectonostratigraphic framework, and has recently been extended and systematized to encompass the entire geological development of New Zealand (Mortimer *et al.* 2014). Possible criticisms of the terrane nomenclature, as applied in New Zealand, can be avoided provided that it is remembered that, in this case, it certainly is non-genetic and does not imply any particular process of terrane assembly or allochthoneity, whether by subduction, strike-slip faulting or another process.

(Continued) This allows the Permian–Triassic terranes to be repositioned with relative accuracy and provides an opportunity for island-wide correlations. (b) *c.* 20 Ma. Zealandia is partially transected by a generally northwards-propagating spreading centre to open the Emerald Basin. (c) *c.* 50 Ma. Zealandia is more or less intact but located away from Australia owing to the opening of the oceanic Tasman Sea Basin. (d) 100 Ma. The oceanic Tasman Sea Basin opens, moving Zealandia away from Antarctica and Australia. Prior to the opening of the Tasman Sea Basin, New Zealand is aligned along the eastern margin of Gondwana, above a continentwards-dipping subduction zone. Simplified from Mortimer & Campbell (2014).



**Fig. 1.4.** Restoring South Island from its present plate tectonic setting back through the Cenozoic and late Mesozoic (in a fixed Antarctica reference frame), back as far as the time interval covered by the contributions to this volume: (a) today; (b) Late Eocene – 35 Ma; (c) Early Paleocene – 65 Ma; (d) Late Cretaceous (Santonian) – 85 Ma; (e) Early Cretaceous (Albian) – 110 Ma. Modified from Mortimer & Campbell (2014).

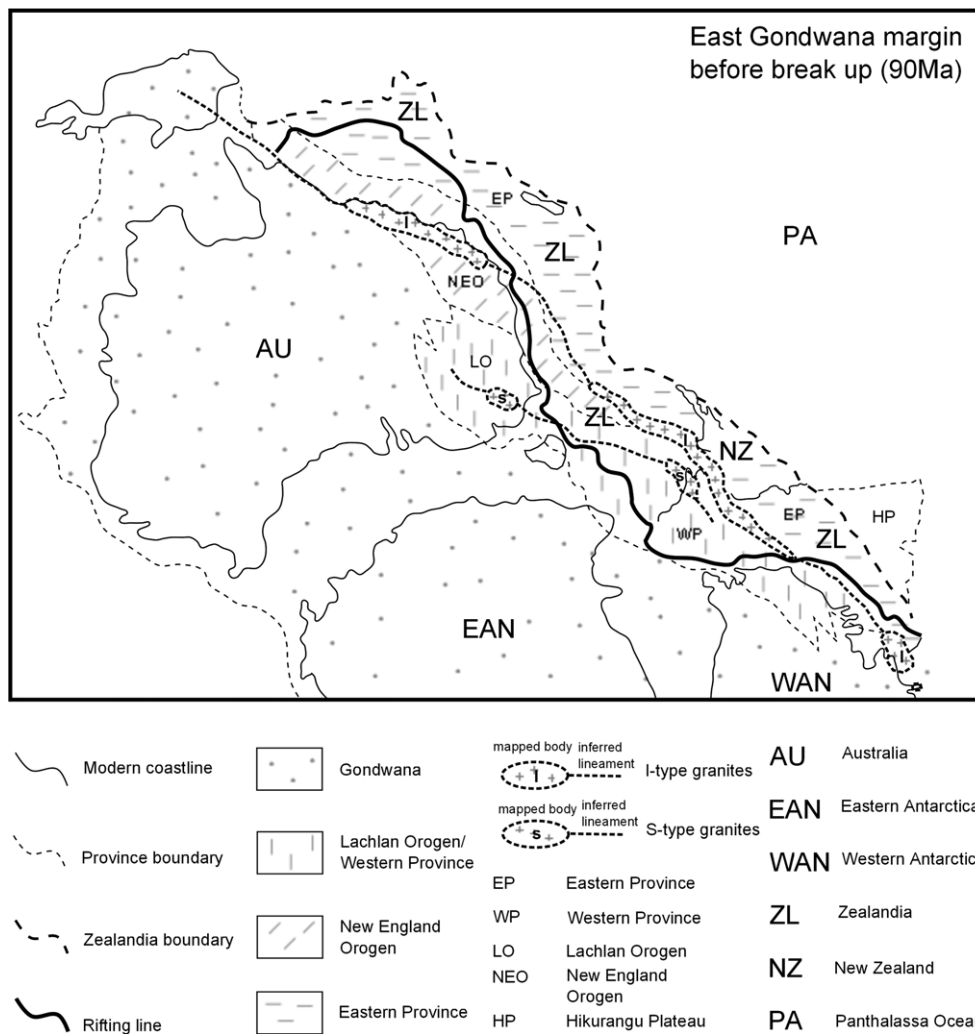
### Terranes of the South Island

The Western Province comprises two units of mostly Early Paleozoic metasedimentary and metavolcanic rocks, known as the Buller and Takaka terranes (Fig. 1.6). By the Permian and Triassic, the Western Province is considered to have been a part of autochthonous Gondwana, part of the Panthalassa margin, along which an active continental margin (Median Batholith and Eastern Province) developed (Mortimer & Campbell 2014). The Western Province, including Median Batholith (or its non-exposed lateral equivalents), is considered in several contributions to this volume as a potential source region for compositionally variable clastic sediments of the Eastern Province.

In South Island, the Eastern Province is made up of six main lithostratigraphic terranes, which are separated by high-angle fault zones, commonly with complex and long-lived displacement.

From west to east the main terranes are:

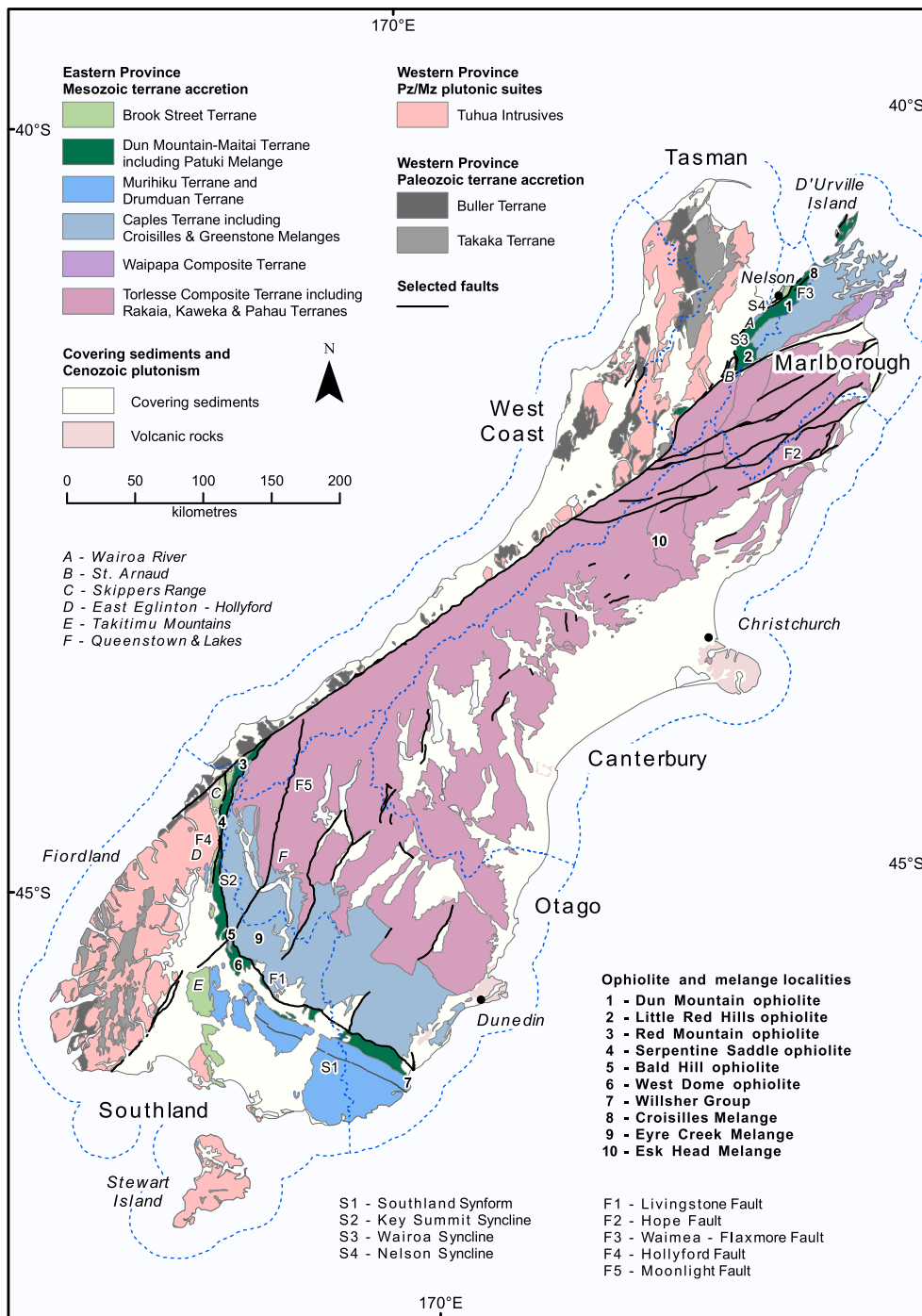
- *Drumduan Terrane* – this terrane occurs as small (less than 20 km<sup>2</sup>), commonly elongate outcrops (Fig. 1.7). North of the Alpine Fault, in Nelson city, the terrane comprises the Drumduan Group of Jurassic volcanogenic, commonly coarsely clastic, plant-bearing sedimentary rocks with tuffs. The group is intruded by igneous rocks of the Median Batholith, and lawsonite indicates that it has been affected by high-pressure–low-temperature (HP–LT) metamorphism in the Nelson city area (Johnston *et al.* 1987; Rattenbury *et al.* 1998). Correlative units occur south of the Alpine Fault, including the earliest Cretaceous Largs Group volcanic rocks in northern Southland (Hollyford–Eglinton area) (Williams 1978; Mortimer *et al.* 1999), and also the Loch Burn Formation outcrops in Fiordland and the Paterson Group on Stewart Island (Turnbull & Allibone 2003).



**Fig. 1.5.** Outline geology of the eastern active continental margin of Gondwana and Zealandia at c. 90 Ma (Late Cretaceous), before spreading of the Tasman Sea Basin. The relative locations of the Eastern and Western provinces of New Zealand are indicated. Note the locations relative to the main orogenic segments of eastern Australia and eastern Antarctica. Simplified from Mortimer & Campbell (2014).

- *The Brook Street Terrane* – this terrane (Fig. 1.7) is made up of very thick (up to c. 15 km) successions of Permian volcanic arc-related rocks (Houghton & Landis 1989; Spandler *et al.* 2005) and, where locally present, an *in situ* Jurassic sedimentary cover (Landis *et al.* 1999). The Brook Street Terrane has five main outcrops (and several smaller ones), which are spatially separated from each other, or at least lack demonstrable continuity due to younger cover or fault displacement (Houghton & Landis 1989; Rattenbury *et al.* 1998; Begg & Johnston 2000; Turnbull 2000; Turnbull & Allibone 2003). From north to south, the main outcrops are: (1) west D’Urville Island, which is c. 12 km long and located c. 50 km north of Nelson city (Begg & Johnston 2000); (2) Nelson city, a c. 20 km-long outcrop (Rattenbury *et al.* 1998); (3) St Arnaud, a c. 20 km-long outcrop located c. 50 km south of Nelson city (Rattenbury *et al.* 1998); (4) Skippers Range, south of the Alpine Fault (Turnbull 2000); (5) East Eglinton–Hollyford and Dunton Range (Turnbull 2000); and (6) the Takitimu Mountains (Houghton & Landis 1989) and near Bluff on the south coast (Turnbull & Allibone 2003). These outcrops, and especially the volcanoclastic and tuffaceous rocks, are discussed in detail in this volume.
- *Murihiku Terrane* – in the South Island, the Murihiku Terrane (Fig. 1.7) is a fossiliferous, Late Permian–Middle Jurassic mostly volcanoclastic succession (up to 13.5 km in aggregate thickness). Through time, this generally evolved from deep-marine gravity-flow deposits, to shallow-marine and near-shore deposits (Ballance & Campbell 1993; H.J. Campbell *et al.* 2003). The Murihiku Terrane is also well-exposed along part of the west coast of North Island,

- where the succession extends into the earliest Cretaceous. The Murihiku Terrane has the most coherent internal stratigraphy and lowest metamorphic grade of any New Zealand terrane (Murihiku Supergroup), which can be correlated laterally for hundreds of kilometres. New chemical data for tuffaceous and volcanoclastic sediments are provided for outcrops both north and south of the Alpine Fault in this volume.
- *Dun Mountain–Maitai Terrane* – this terrane (Fig. 1.7) is made up of three stratigraphic–tectonic parts:
    - The first part is the Dun Mountain ophiolite (Coombs *et al.* 1976), which has previously been radiometrically dated at c. 285–275 Ma (late Early Permian) (Kimbrough *et al.* 1992). The ophiolite is typically dismembered and there is no complete, intact sequence from mantle peridotite to volcanic rocks in any one area. Several massifs expose sections of relatively intact pseudostratigraphy, notably in the Nelson area and the Red Hills, both to the north of the Alpine Fault (Fig. 1.6). Key outcrops to the south of the Alpine Fault include Red Mountain, Little Red Hills, Serpentine Saddle and Bald Hill (Fig. 1.6). In some areas, the ophiolite is represented by ophiolitic melange, or igneous rocks that are completely faulted out. New data and interpretation of the Dun Mountain ophiolite as a whole, including the plutonic rocks and both new and revised radiometric dates, are given in several papers in this volume.
    - The second part of the Dun Mountain–Maitai Terrane is the Middle Permian–Middle Triassic marine sedimentary cover of the ophiolite, known as the Maitai Group (Landis 1974). This is divided into formations that can be



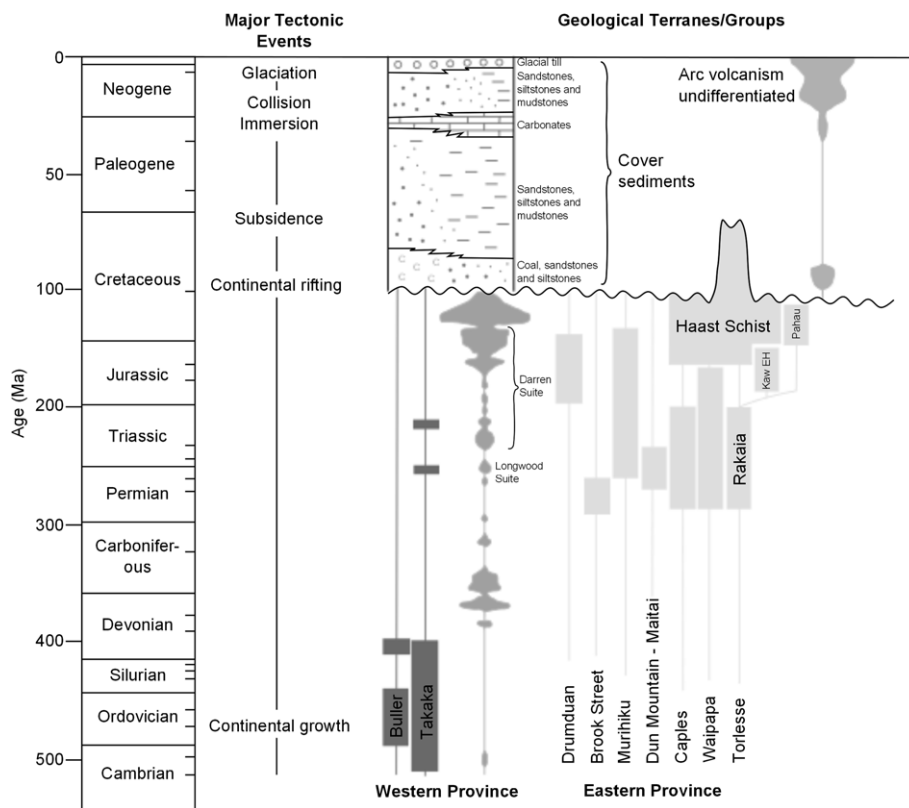
**Fig. 1.6.** Simplified geology of South Island, focusing on Late Paleozoic–Mesozoic lithostratigraphic terranes, offset by the Alpine Fault, indicating the main features mention in the text. Source: GNS Science.

correlated along the length of the South Island. Restoration of the Alpine Fault allows sedimentary patterns and processes to be evaluated on a regional scale. The Maitai Group has been widely interpreted as a continental margin forearc basin (Carter *et al.* 1978; Owen 1995), although other interpretations have been proposed. The Maitai Group is featured in this volume with new data on the sedimentology, petrography and sedimentary geochemistry, coupled with regional to global comparisons, leading to a new overall interpretation.

- The third regional-scale unit that is included in the Dun Mountain–Maitai Terrane (Mortimer *et al.* 2014) is the Patuki Melange which structurally underlies the Dun Mountain ophiolite to the east, where it includes a mixture of clastic sedimentary rocks and ophiolite-related lithologies. The Patuki Melange, named after its type outcrop in the north of D’Urville Island (Begg & Johnston 2000; see

also Sivell & Rankin 1982), has equivalents both north and south of the Alpine Fault. The Patuki Melange is extensively discussed in this volume, with new information on outcrop relationships, petrography and geochemistry leading to a new tectonic model.

- **Kaka Point Structural Belt** – this is a small (*c.* 7 km wide × 20 km long), fault-bounded but stratigraphically intact sedimentary succession that is exposed along the Kaka Point–Nugget Point stretch of the SE coast of South Island. This is composed of a moderately fossiliferous Triassic (Olenekian–Carnian) succession of marine volcanoclastic and tuffaceous sedimentary rocks. Despite the name, this unit is relatively undeformed and little metamorphosed. The succession has been alternatively compared with the Murihiku Terrane and the Maitai Group (Dun Mountain–Maitai Terrane), or considered as a micro-exotic terrane (J.D. Campbell *et al.* 2003). New geochemical data for the



**Fig. 1.7.** Summary of New Zealand's geological development. The Western Province is divided into the Buller and Takaka terranes. Note the geological reorganization during the Cretaceous, which culminated in the spreading of the Tasman Sea Basin and subsidence of most of Zealandia. Modified from Mortimer & Campbell (2014).

clastic and tuffaceous sedimentary rocks are provided, leading to a reassessment of the tectonic affinity of this intriguing, easily accessible, crustal fragment.

- *Caples Terrane* – this terrane (Fig. 1.7) is dominated by very thick (up to 16 km in apparent thickness), mostly low-grade-metamorphosed, poorly fossiliferous, greenish-tinted lithologies that cover large areas to the east of the Dun Mountain–Maitai Terrane (Fig. 1.6). Marine volcanoclastic sedimentary rocks predominate, largely turbidites. The Caples Terrane is separated from the Dun Mountain–Maitai Terrane by the major c. north–south-trending high-angle Livingstone Fault. In places, the Caples Terrane contains lawsonite, evidence of HP–LT metamorphism (Turnbull 1979; Begg & Johnston 2000; Adams *et al.* 2009a).

Large areas, including the Thomson Mountains (Queenstown Lakes District) and parts of Nelson, contain long coherent lithostratigraphical formations of Late Permian–Triassic age (Walcott 1969; Bishop *et al.* 1976; Turnbull 1979). For example, north of the Alpine Fault, two distinctive stratigraphic horizons, one conglomeratic and the other including a red quartzite, can be traced along strike for nearly 50 km (Rattenbury *et al.* 1998). The coherent intervals are, in places, separated by high-strain zones, with localized occurrences of HP–LT metamorphic minerals (Turnbull 1979). Detailed mapping (Turnbull 1979) and U–Pb dating of detrital zircons (Adams *et al.* 2009a) suggest that most of the Caples Terrane is structurally complex, which favours an accretionary wedge interpretation. In North Island and the extreme NE of the South Island, there is a related, volcanoclastic, partly schistose terrane – the Waipapa Composite Terrane (Edbrooke 2017).

The Caples Terrane lithologies, mostly greenish volcanoclastic sandstone and shale, become more schistose and increase in metamorphic grade, generally eastwards, into the greenschist-facies Otago (Haast) Schist before giving way to greyish schistose rocks in the Torlesse Composite

Terrane. Some new chemical data are provided for volcanoclastic turbidites of the Caples Terrane, from both north and south of the Alpine Fault. Whether or not the Caples Terrane represents an overall stratigraphic succession or a subduction–accretion complex is further discussed in this volume.

Within the Caples Terrane there are elongate belts of ophiolitic melange. The most notable of these is the Croisilles Melange, named after its type area around Croisilles Harbour in Marlborough Sounds, north of the Alpine Fault (Landis & Blake 1987). New evidence of the field relationship of this melange, and chemical data for the volcanic and sedimentary rocks within it, are given in this volume, together with a reassessment of its origin compared to the Patuki Melange. South of the Alpine Fault, a potential correlative of the Croisilles Melange is the (thinner) Greenstone Melange, which crops out within the Caples Terrane to the east of the Livingstone Fault. Farther east, the Caples Terrane includes additional narrow melange belts, of which the best known is the Eyre Creek Melange (Pound *et al.* 2014).

- *Torlesse Composite Terrane* – making up much of the east of the South Island, the Torlesse Composite Terrane has been extensively studied in recent decades, concerning its structure, protoliths and metamorphic age (Ireland 1992; Cawood *et al.* 1999, 2002; Roser & Korsch 1999; Wandres *et al.* 2004). No new data for the Torlesse are included in this volume, although its key features are taken into account in the discussion of the regional geological development. The traditional Torlesse Supergroup (MacKinnon 1983; Mortimer 1994) is currently subdivided into three specific terranes, namely from west to east: the Rakaia Terrane, the Kaweka Terrane and the Pahau Terrane (Mortimer *et al.* 2014; Edbrooke 2017) (Figs 1.6 & 1.7). In North Island and the extreme NE of the South Island, there is an additional important unit termed the Waipapa Composite Terrane (Edbrooke 2017).



The Rakaia Terrane is dominated by Permian–Triassic marine clastic sedimentary rocks, broadly similar to, but more quartz- and feldspar-rich, than those of the Caples Terrane. A metamorphosed tectonic contact between the Caples Terrane and the Rakaia Terrane is recognized in the Nelson area (Rattenbury *et al.* 1998) and also in the Otago region (Mortimer & Roser 1992). In places, lenses of meta-basalt (greenschist) and altered (talcose) ultramafic rocks occur near the tectonic contact between the two terranes (Mortimer & Roser 1992).

The Torlesse Composite Terrane includes several distinctive units of melange and broken formation that encompass Triassic–Jurassic sandstone, mudstone, basaltic rocks and pelagic limestone. The most studied of these is the Esk Head Melange (related to the Kaweka Terrane), which includes key evidence of low-latitude fauna (Silberling *et al.* 1988). The Late Jurassic–Early Cretaceous Pahau Terrane includes clastic sedimentary rocks and minor melange-like intercalations.

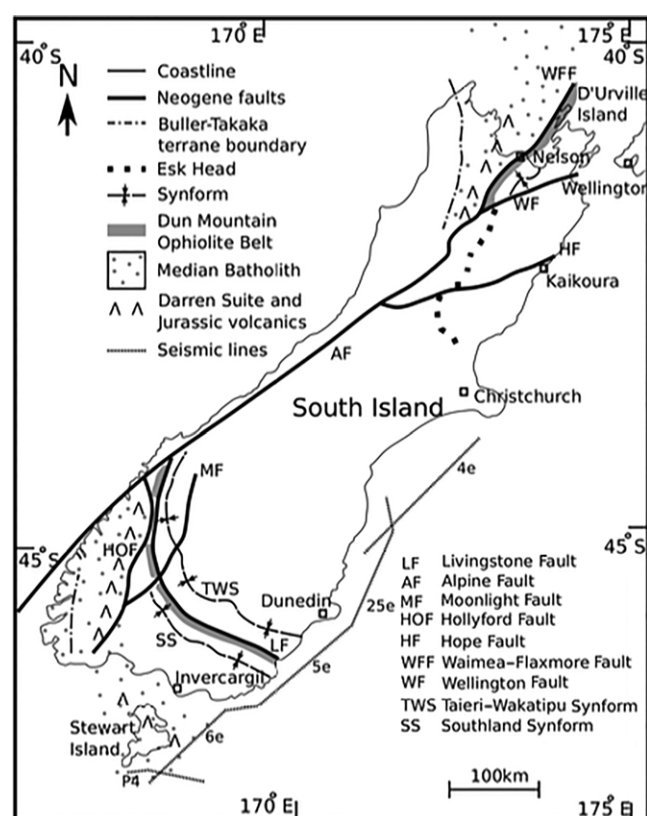
Regional metamorphism of both the Caples Terrane and the Torlesse Composite Terrane (including the Haast Schist) is generally dated as Middle Jurassic–Early Cretaceous, which provides an upper age limit for the tectonic juxtaposition of these two regional-scale units (MacKinnon 1983; Graham & Mortimer 1992; Adams *et al.* 2009b; Mortimer *et al.* 2014). The regional metamorphism accompanied or followed the amalgamation of many of the Eastern Province terranes to near their present relative positions, as over-viewed in the concluding chapter of this volume.

## Structural aspects

Any consideration of the late Paleozoic–early Mesozoic geology of South Island must strip away, as far as possible, the effects of later deformation, which include oroclinal bending, regional-scale folding, and also faulting of diverse distribution, age and type (Fig. 1.8). Both onland and offshore structural and geophysical information needs to be considered (Sutherland 1999; Mortimer *et al.* 2002). The terranes summarized in the previous section were in their present relative positions and metamorphic state, and, except for close to the Alpine Fault, mostly at their present approximate exposure levels before the Late Cretaceous opening of the Tasman Sea Basin (Gondwana break-up).

In one style of interpretation (Fig. 1.9b), the late Paleozoic–Triassic terranes were displaced singly or in concert to their present relative positions mainly during Late Jurassic–Cretaceous time (Adams *et al.* 1998, 2007, 2009a, b). However, the nature and timing of related deformation remain poorly constrained, in part because of the paucity of sedimentary cover or of stitching igneous rocks of appropriate age and distribution. It is likely that the late Paleozoic–early Mesozoic terranes reached their present relative locations before deformation into the present arcuate oroclinal bend, which is dated as mid-Cretaceous (Bradshaw *et al.* 1996; Mortimer 2014) (Fig. 1.8).

The late Paleozoic–early Mesozoic terranes experienced Cretaceous deformation into various regional-scale synclines that were subsequently tightened and rotated associated with oroclinal bending (Fig. 1.6). The most important ones are referred to as synforms below. From south to north, these include the regional-scale Southland Synform (Turnbull & Allibone 2003) and smaller-scale counterparts of this structure that extend northwards (e.g. Key Summit Syncline) and beyond the Alpine Fault (Turnbull 2000). Similar structures, which may be termed the Nelson Synform, persist north of the Alpine Fault, where they have been given different local names (e.g. Roding Syncline; Wairoa Syncline), extending as far as



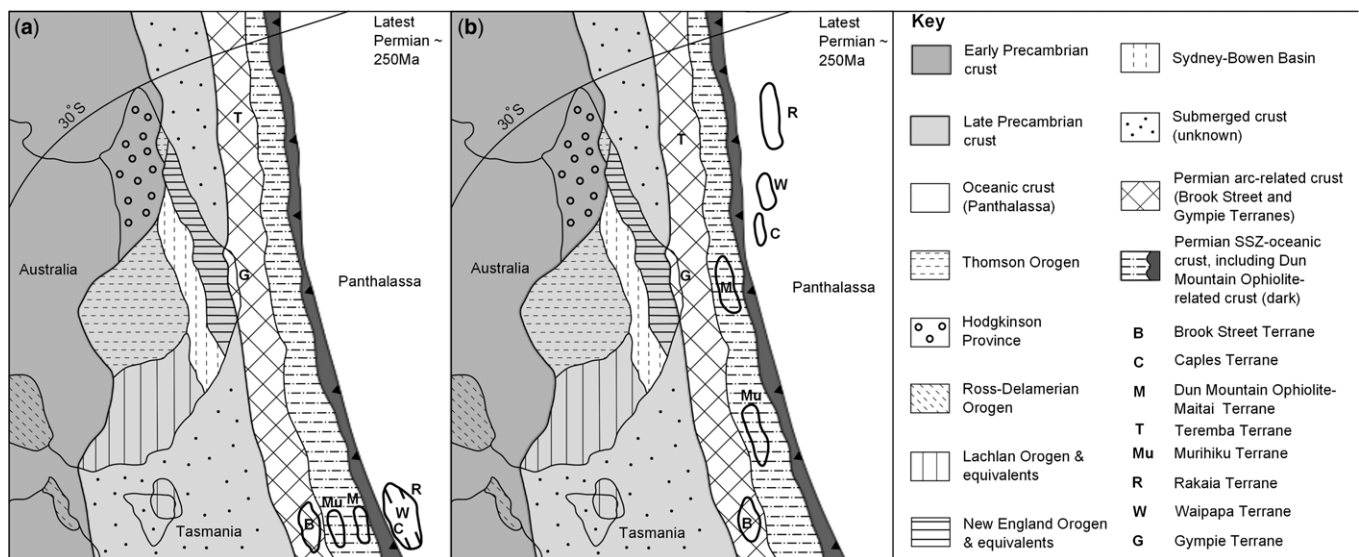
**Fig. 1.8.** Main structural features of South Island, including: the Alpine Fault, which offsets the late Paleozoic–Mesozoic terranes by c. 480 km; the Livingstone Fault, which separates the late Paleozoic–Mesozoic terranes from the Caples Terrane to the east; and the Southland Synform (and counterparts farther north), which folds and partially repeats the Permian–Triassic stratigraphy. The approximate locations of offshore seismic profiles (off the SE coast) are also indicated (Mortimer *et al.* 2002). Modified from Mortimer (2014).

D'Urville Island (Rattenbury *et al.* 1998; Begg & Johnston 2000). These regional structures expose parts of the stratigraphy of the Murihiku Terrane and the Maitai Group on opposing fold limbs, allowing useful comparisons.

Many outcrops are cut by a plethora of local small- to large-scale high-angle faults, as particularly mapped in the Maitai Group (Dun Mountain–Maitai Terrane), where they cut the 'layer-cake' stratigraphy. It is commonly unclear if these faults represent original low-angle contractional structures followed by Neogene rotation to a high angle along the regional synform limbs, or if, instead, they represent primary strike-slip faults, or a combination of both. Pilot-scale microstructural data are given in this volume and serve to indicate the need for additional microstructural studies.

The late Paleozoic–early Mesozoic terranes are, in addition, transected by numerous steep faults on outcrop to regional scale: for example, the Hollyford Fault to the south of the Alpine Fault and the Waimea–Flaxmore Fault System to the north of it (Figs 1.6 & 1.8). Some of these large faults appear to predate the Alpine Fault – for example, the Moonlight Fault and the Delaware–Speargrass Fault Zone (south and north of the Alpine Fault, respectively) – and have undergone reactivation at different times and in different ways (Johnston *et al.* 1987; Rattenbury *et al.* 1998; Turnbull & Allibone 2003; Mortimer 2014). Some faults originated during Jurassic–Early Cretaceous terrane assembly and were reactivated first during the Late Cretaceous rifting of the Tasman Sea Basin and then later, related to the Alpine Fault.

By far the most important of the post-terranes assembly structures is the Alpine Fault (Walcott 1978; Norris *et al.*



**Fig. 1.9.** Alternative end-member reconstructions of the New Zealand terranes: (a) assuming no relative strike-slip displacement; and (b) assuming a more northerly derivation of more outboard terranes (e.g. Adams *et al.* 2007, 2009b). SSZ, supra-subduction zone.

1990; Norris & Cooper 2001). The location and displacements along its major strands (e.g. Hope Fault: Fig. 1.8) are generally well understood. In the present context, the well-known c. 480 km right-lateral displacement of the Alpine Fault allows outcrops to the north and south to be restored and interpreted together.

### The New Zealand geological timescale

The papers in this volume use the New Zealand geological timescale (Raine *et al.* 2015), with reference to the International Geological Timescale (Gradstein *et al.* 2012), where practicable (Fig. 1.10).

A long-term objective has been to produce a unitary timescale that is globally calibrated in absolute time by a combination of fossil and radiometric dating. The International Stratigraphic Commission continuously re-evaluates global reference sections according to the completeness and excellence of dating (e.g. Cohen *et al.* 2012). For any given location, the applicable timescale is controlled by the nature of the rock units present and their determinable age. In many areas, including much of the northern hemisphere, the need for regional timescales has diminished as rock units become better known, better dated and correlated. However, for New Zealand and Zealandia, probably because of pronounced high southern latitude Mesozoic–Cenozoic endemism, there is still a clear need for a regional timescale (Raine *et al.* 2015).

For the Paleozoic–Mesozoic rocks of New Zealand, correlation with the current international reference timescale (e.g. Gradstein *et al.* 2012) is challenging, particularly for several time intervals. Firstly, lithofacies that are dominated by marine clastic sediments are difficult to correlate with corresponding units in surrounding regions. Secondly, potential along-strike correlatives of Zealandian rocks are inaccessible; those in eastern Australia and Antarctica are partially submerged or covered by ice or younger units. Thirdly, some of the Paleozoic–Mesozoic sedimentary units are, at best, sparsely fossiliferous, owing to one or more of: faunal isolation, low biological productivity, burial diagenesis, or regional metamorphism. Fourthly, the age assignments of some key faunal assemblages are still debated, especially for the Permian (e.g. Waterhouse 1964; Campbell & Adams 1999; Campbell 2000), as discussed in this volume. In addition, basic igneous rocks, which

dominate the Brook Street Terrane and the Dun Mountain ophiolite are difficult to date radiometrically (Kimbrough *et al.* 1992). Also, for clastic sedimentary rocks, detrital zircon geochronology gives the ages of crystallization of the source igneous or metamorphic rocks, which may differ from their depositional age (e.g. Adams *et al.* 2007, 2009a, b).

Some parts of the New Zealand timescale (Raine *et al.* 2015) are better correlated with the global timescale (Gradstein *et al.* 2012) than others. For example, the Late Permian–Middle Triassic time interval is finely divided and quite closely correlated with the international scale, based on relatively well-preserved

Ma	International units			New Zealand units			
	Period	Epoch	Age	Series	Stage		
200	TRIASSIC	L	Rhaetian	Balfour	Otapirian	201.3	
					205.7	Warepan	205.7
			Norian		Otamitan	217.0	
					Oretian	221.0	
				227.0	Gore	Kaihikuan	237.5
		Carnian		285.0			
		Ladinian		237.0			
				242.0	D'Urville	Etalian	246.0
		Anisian		247.0		Malakovan	249.0
		Olenekian		251.1		Nelsonian	251.5
		252.2	Makarewan	253.2			
250	PERMIAN	L	Changhsingian	Aparima	Waiitian	254.2	
			Wuchiapingian		Puruhanian	254.2	
				259.8	Flettian		259.8
		Capitanian		265.1			268.0
		Wordian		268.8		Barrettian	276.0
				272.3	Mangapirian		285.0
		Kungurian		283.5			285.0
		Artinskian		290.1			288.5
		Sakmarian		295.0		Pre-Telfordian	
		Asselian		298.9			298.9

**Fig. 1.10.** International Geological Timescale for the Permian and Triassic (Gradstein *et al.* 2012), and the corresponding New Zealand timescale (Raine *et al.* 2015). Some parts of the New Zealand stratigraphy can be better correlated with the International Geological Timescale than others, requiring the regionally based timescale to be retained for the foreseeable future.

faunal assemblages, as in the Murihiku Terrane. However, the Maitai Group (Dun Mountain–Maitai Terrane) lacks the appropriate fauna to achieve such a detailed correlation. For example, the Early–Middle Permian is only broadly subdivided in New Zealand and remains difficult to correlate with the international timescale.

### Outline of contributions

Following this introduction, Mike Johnston discusses the geological development of research concerning the Late Paleozoic–Early Mesozoic central terranes of New Zealand ([Johnston 2019](#)). Knowledge acquired by the Maori and its value to early settlers is outlined. The critical mid-nineteenth century role of Hochstetter as the founding figure of New Zealand geology is explained, as is how work by provincial survey geologists culminated in the first published national map in 1869. Some key contributions and debates during the later decades of the nineteenth century and the early decades of the twentieth century are then discussed (e.g. sediment deposition, geological age determination, metamorphism and the Alpine Fault). The author outlines how our present plate tectonic interpretation of New Zealand and the surrounding region came about, and the presently used terrane classification. Before and after the plate tectonics revolution, knowledge of New Zealand geology greatly benefitted from mapping and related studies by generations of both postgraduate and undergraduate students.

Hamish Campbell next summarizes the palaeontological evidence that can be used to date New Zealand's central terranes; the Brook Street Terrane, the Dun Mountain–Maitai Terrane and the Murihiku Terrane that are the main topics of this volume ([Campbell 2019](#)). The first part of the paper summarizes and tabulates key fossil data, terrane by terrane, while also taking account of constraints from reliable radiometric dating. The second part of the paper presents revised stratigraphic age correlations, correlated with the New Zealand and international geological timescales (see [Fig. 1.10](#)). These age assignments are used in the papers that follow.

In the following contribution, Alastair Robertson and Romesh Palamakumbura provide new field- and laboratory-based data and interpretation for the sedimentology, petrography and geochemistry of volcanoclastic sediments, and some igneous rocks of the Brook Street Terrane ([Robertson & Palamakumbura 2019a](#)). The discussion takes account of the Mid–Late Permian sedimentary cover (Productus Creek Group) of the largest Brook Street Terrane remnant in the Wairaki Hills (Southland), which includes classic bivalve-rich redeposited limestones and volcanoclastic sediments. The type area of the Brook Street Terrane in the north (Nelson) is likely to have a different age and provenance compared to at least some of the outcrops south of the Alpine Fault. An overall interpretation is given, including oceanic arc development and accretion to SE Gondwana.

Next, Dushan Jugum, Eric Stewart, Mike Palin, Nick Mortimer, Dick Norris (deceased) and William Lamb present an integrated review of the Dun Mountain ophiolite, including data from Jugum's PhD thesis which is published for the first time ([Jugum \*et al.\* 2019](#)). The authors begin by outlining the history of research and the relevance of the ophiolite to plate tectonics and seafloor spreading during the 1970s. The various outcrops and lithologies of the ophiolite are summarized and illustrated. Data are provided mainly for igneous petrology, chemostratigraphy, geochemistry and geochronology, leading to an interpretation of the ophiolite as forming in a supra-subduction zone forearc setting. The authors include radiometric age data for several related units, particularly arc-related outcrops in the south and associated melange (see their [Supplementary material](#)).

In a related contribution, Eric Stewart, Julie Newman, Basil Tikoff, Sara Donnelly, Lindsay German, Vasili Chatzaras, William Lamb, Brent Miller and Seth Kruckenberg focus on the fabrics and interpretation of the ultramafic section of the Dun Mountain ophiolite in the Dun Mountain and Red Hills massifs to the north of the Alpine Fault ([Stewart \*et al.\* 2019](#)). Using multiple lines of evidence, they propose a three-phase development applicable to both outcrops which they relate to subduction initiation in a transtensional setting. The data and interpretation have implications for subduction initiation processes in the modern oceans and other ophiolites.

Next, Alastair Robertson gives an integrated account of the igneous and sedimentary rocks associated with the Patuki Melange ([Robertson 2019a](#)). Sedimentological and petrographical data shed light on the origin of sandstones within the melange, while basalt chemical data identify several eruptive tectonic settings for 'blocks'. The Patuki Melange is generally correlated with the Croisilles and Greenstone melanges of the adjacent Caples Terrane, and an overall subduction-related interpretation is proposed that takes account of Cenozoic deformation.

The four papers that follow concentrate on various aspects of the Maitai Group which overlies the Dun Mountain ophiolite within the Dun Mountain–Maitai Terrane.

The first of these, by Alastair Robertson, considers an extraordinary, up to 850 m-thick, regional-scale accumulation of very coarse ophiolite-derived clastic sedimentary rocks of the generally Mid–Late Permian Upukerora Formation, which unconformably overlies the ophiolite ([Robertson 2019b](#)). Building on previous work, new field evidence, mainly from exposures south of the Alpine Fault, is supported by new petrographical and geochemical data. Clastic material was derived from the subjacent ophiolite and an incipient oceanic arc, and accumulated mainly by mass wasting in response to subaqueous faulting. Docking of the supra-subduction zone ophiolite (and its related incipient arc) with SE Gondwana is considered to have initiated the long-lived Maitai forearc basin.

The second of the Maitai Group contributions, by Alastair Robertson and Romesh Palamakumbura, considers the c. 6000 m-thick Mid–Late Permian–Middle Triassic Maitai Group succession of volcanoclastic, terrigenous and carbonate-rich deep-sea sedimentary rocks above the Dun Mountain ophiolite ([Robertson & Palamakumbura 2019b](#)). The main focus is on field facies analysis and optical petrography using thin sections. Facies and compositional variations within the restored basin (pre-Alpine Fault displacement) are highlighted. The succession is interpreted in the context of the long-lived SE Gondwana active continental margin and compared to those in continental margin forearc basins worldwide.

The third of the Maitai Group contributions, also by Alastair Robertson and Romesh Palamakumbura, takes a different approach by comparing the geochemistry of marine sandstones (including rare earth element (REE) data) between the different formations of the Maitai Group ([Robertson & Palamakumbura 2019c](#)). This allows the likely source materials, their tectonic settings and any compositional changes through time to be identified. The interpretation is widened by the inclusion of small suites of marine sandstones from the Murihiku Terrane, the Caples Terrane, the Patuki and Croisilles melanges, and the Willsher Group (south coast). The available data are compared with potential source units, including the Brook Street Terrane, the Dun Mountain ophiolite, the Tuhua Intrusives (Median Batholith) and the Paleozoic country rocks of the Western Province. The overall results point to derivation from the adjacent Gondwana active continental margin, especially from continental margin arc volcanoes and their host rocks.

The final paper concerning the Maitai Group, by Romesh Palamakumbura and Alastair Robertson, utilizes mudrocks

that have been largely ignored in previous studies (**Palamakumbura & Robertson 2019**). Mudrocks encompass mudstone (non-fissile), shale (fissile), argillite (indurated), slate (cleaved), siltstone, claystone and marl. Chemical data (including REE analyses) indicate the nature of source-rock alteration, allow evaluation of the relative contributions of volcanic, terrigenous and other sources, and also highlight major provenance changes through time. Mudstones from several settings associated with the Patuki Melange (see **Robertson 2019a**) are considered for comparison. Red mudrocks (mostly mudstones) in both the Maitai Group and the Patuki Melange are considered in detail. The chemical data from the Patuki Melange suggest a similar provenance and age to the Late Permian of the Maitai Group.

A note by Nick Mortimer, Hamish Campbell, Alastair Robertson and Rose Turnbull then presents a high-quality U–Pb isotopic age for a diorite clast that was collected from a Triassic conglomerate (upper Maitai Group) from near Mossburn (Southland) (**Mortimer et al. 2019**). The new age appears to post-date the Permian volcanic rocks of the Brook Street Terrane (south of the Alpine Fault) but is coeval with Longwood Suite plutons within the Median Batholith. In addition, a less precise Permian U–Pb date is recorded for a small intrusion (Weetwood Andesite) that cuts the Productus Creek Group of the Brook Street Terrane in the Wairaki Hills (Southland). This suggests that Tuhua Intrusive magmatism (Median Batholith) also affected the Brook Street Terrane.

The following contribution by Alastair Robertson, Romesh Palamakumbura and Hamish Campbell explores sedimentological, petrographical, palaeontological and geochemical evidence from marine felsic (siliceous) tuffaceous rocks (**Robertson et al. 2019b**). These lithologies are exposed in the Permian of the Brook Street Terrane, several Triassic formations of the Dun Mountain–Maitai Terrane and also as two mainly tuffaceous intervals of the Murihiku Terrane. Tuffaceous rocks of the south coast Willsher Group are included for comparison. Oceanic v. continental margin arc sources are identified and the results are compared with arc-related felsic volcanism elsewhere (e.g. Cascades, western USA; Izu–Bonin arc, NW Pacific), with implications for the SE Gondwana active continental margin.

In the only contribution in this Memoir concerning the more easterly terranes, Chris Adams, Hamish Campbell, Nick Mortimer and William Griffin present and discuss new detrital zircon age results for northernmost South Island, which enables protoliths of the Marlborough Schist (part of the regional Haast Schist) to be assigned variously to the Caples, Waipapa and Rakaia terranes (**Adams et al. 2019**). The Waipapa–Rakaia terrane boundary can be tracked through the Cook Strait area, whereas the position of the Caples–Waipapa terrane boundary is less certain. The method points the way to using zircon dating for future more precise terrane mapping.

The final chapter by Alastair Robertson, Hamish Campbell, Mike Johnston and Romesh Palamakumbura explores alternative tectonic settings of the terranes making up the Western and Eastern provinces in the regional context especially relative to Australia and Antarctica, indicating preferred options where possible (**Robertson et al. 2019a**). An overall possible interpretation is outlined. Several outstanding geological problems are highlighted as pointers to future research opportunities (see the **Supplementary material**).

Hopefully, publication of this Memoir will prompt an upsurge of interest and research concerning this classic region.

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