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Chapter 15

Construction of a Paleozoic–Mesozoic accretionary orogen along the active continental margin of SE Gondwana (South Island, New Zealand): summary and overview

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Abstract: The Western Province is a fragment of the *c.* 500 Ma SE Gondwana active continental margin. The Eastern Province is a terrane assemblage, which is partly stitched by the Median Batholith. Fragments of the batholith are preserved in the adjacent Drumduan and Brook Street terranes. Permian arc magmatism of the Brook Street Terrane involved both oceanic and continental margin settings. The Permian (*c.* 285–275 Ma) supra-subduction zone Dun Mountain ophiolite records subduction initiation and subsequent oceanic-arc magmatism. The Permian Patuki and Croisilles melanges represent detachment of the ophiolitic forearc and trench–seamount accretion. The Murihiku Terrane, a proximal continental margin forearc basin, received detritus from the Median Batholith (or equivalent). The south coast, Early–Late Triassic Willsher Group is another proximal forearc basin unit. The sediments of the Dun Mountain–Maitai Terrane (Maitai basin) represent a distal segment of a continental margin forearc basin. The Caples Terrane is a mainly Triassic trench accretionary complex, dominantly sourced from a continental margin arc, similar to the Median Batholith. The outboard (older) Torlesse and Waipapa terranes are composite subduction complexes. Successively more outboard terranes may restore farther north along the SE Gondwana continental margin. Subduction and terrane assembly were terminated by collision (at *c.* 100 Ma), followed by rifting of the Tasman Sea Basin.

Supplementary material: Additional structural and petrographical information, a discussion of terrane displacement, petrographical features, a geochemical discrimination plot, summary of lawsonite occurrences and suggestions for future work are available at https://doi.org/10.6084/m9.figshare.c.4399448

With its exceptional *c.* 500 myr subduction history, Zealandia, especially the South Island, is a natural laboratory for the study of fundamental geological processes, especially related to subduction and terrane kinematics (Vaughan *et al.* 2005; Vaughan & Pankhurst 2008; Mortimer *et al.* 2017) (Figs 15.1 & 15.2). Subduction, probably oblique, was the main driver of likely terrane displacement, relative to the active continental margin of SE Gondwana. Restoration of the terranes to their former positions is challenging because similar tectonic environments and processes recur along different parts of the active margin. The geological setting of the individual terranes is increasingly well understood but their mutual relationships are debatable.

Many key advances during the 1970s–80s, stimulated by the plate tectonics revolution, have stood the test of time. However, some early solutions (e.g. ophiolites as ocean crust; magmatic arcs as subduction products) now prompt more specific questions: for example, how, where and when did the ophiolite lithosphere form? Are arcs of continental or oceanic origin, and how, when and where did they form? Many of the interpretations in this chapter build on previous work, while in some cases new, or revised, interpretations are proposed. Preferred interpretations are indicated and related to the overall geological development of the Panthalassa Ocean and SE Gondwana, especially in eastern Australia and East Antarctica (Cawood 1984, 2005; Mortimer & Campbell 2014; Mortimer *et al.* 2017).

Readers unfamiliar with New Zealand geology will find background information in Johnston (2019) and in Robertson *et al.* (2019a), which draws on key literature (e.g. Thornton 1985; Bradshaw 1989; Mortimer 2004; Ballance 2009; Graham 2011; Mortimer *et al.* 2014).

Here, we utilize the global timescale of Gradstein *et al.* (2012) and the New Zealand timescale of Cooper (2004), as perfected by Raine *et al.* (2015).

Application of tectonostratigraphic terrane nomenclature to New Zealand

Several of the late Paleozoic–early Mesozoic terranes recognized in New Zealand (Figs 15.2 & 15.3) conform well to the concept of a tectonostratigraphic terrane, arguably as well as any other comparable rock assemblages worldwide (Coombs *et al.* 1976). The individual terranes are mostly highly elongate, stretching for hundreds of kilometres: for example, the Murihiku Terrane (J.D. Campbell *et al.* 2003) and the Dun Mountain–Maitai Terrane (Coombs *et al.* 1976; Kimbrough *et al.* 1992). The terranes are, in general, internally coherent but geologically different from adjacent terranes, and are separated by steep continuous tectonic contacts with uncertain displacement.

A tectonostratigraphic terrane (or simply terrane) consists of a geological unit or assemblage, typically bounded by faults or fault zones, that can be mapped on a regional scale and which contrasts with neighbouring crustal blocks (Coney *et al.* 1980). Tectonostratigraphic terranes were widely recognized in the western USA during the 1980s (Blake *et al.* 1982; Jones *et al.* 1983). Since then, terrane nomenclature has been applied to many parts of the world, including the circum-Pacific (Howell *et al.* 1985; Howell 2009). Most terranes are substantially allochthonous and are commonly of uncertain origin. The formation and displacement of terranes are controlled by plate

Late Permian (260Ma)
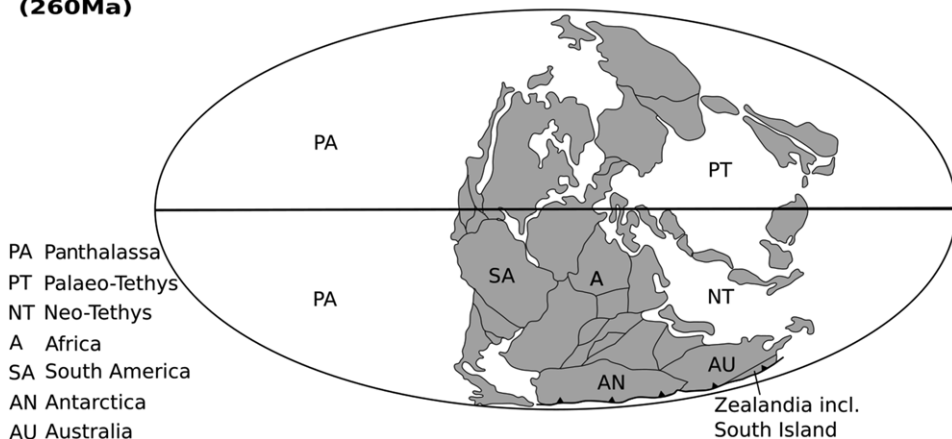
PA Panthalassa
PT Palaeo-Tethys
NT Neo-Tethys
A   Africa
SA South America
AN Antarctica
AU Australia

Fig. 15.1. Palaeogeographical setting of New Zealand during the Late Permian. Note the sublinear, thousands of kilometres-long active continental margin bordering SE Gondwana (eastern Australia and East Antarctica). This contrasts with farther north where the Neotethys was already opening (in the east). Modified from Scotese (2014).
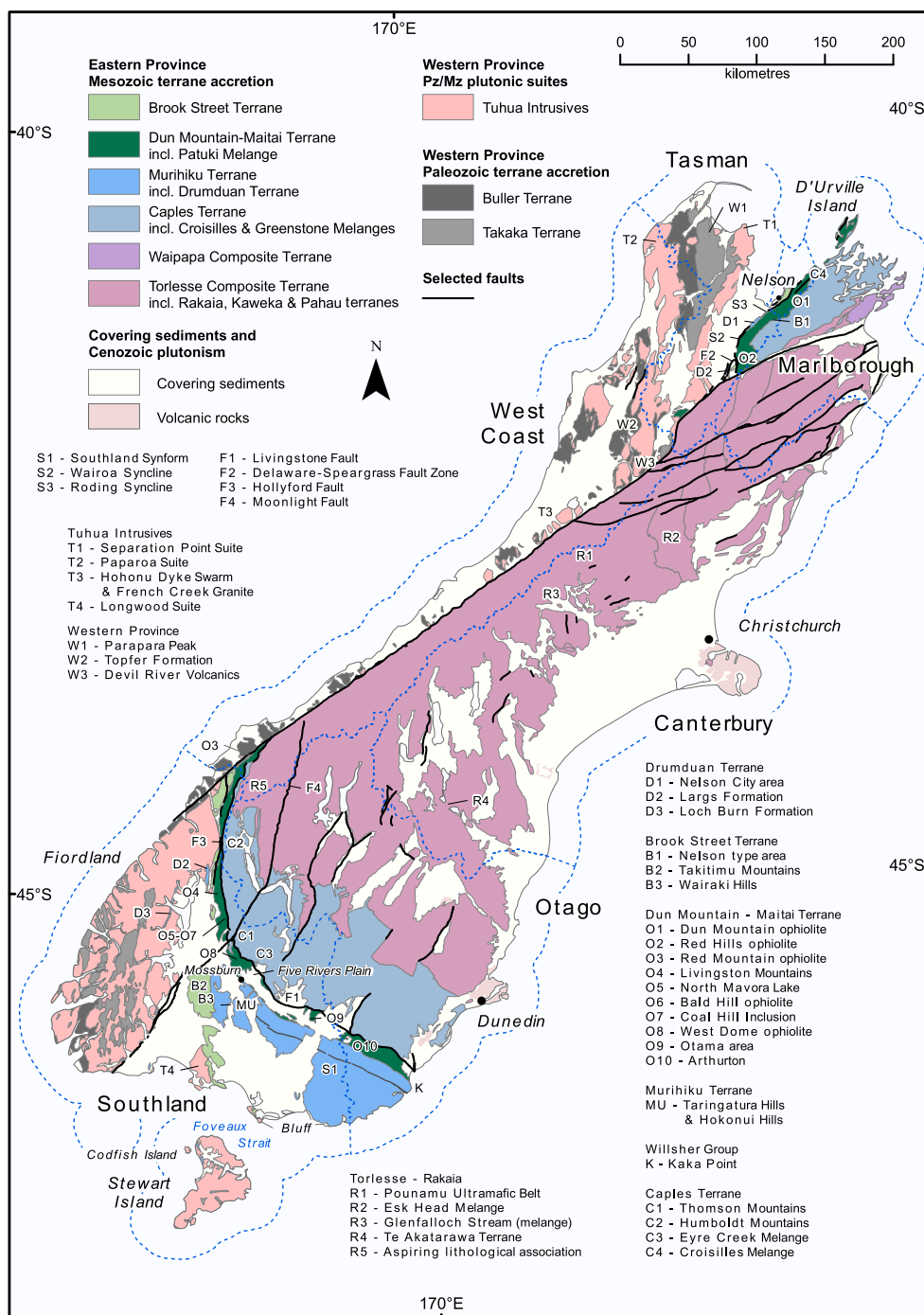
Eastern Province
Mesozoic terrane accretion

- Brook Street Terrane
- Dun Mountain-Maitai Terrane incl. Patuki Melange
- Murihiku Terrane incl. Drumduan Terrane
- Caples Terrane incl. Croisilles & Greenstone Melanges
- Waipapa Composite Terrane
- Torlesse Composite Terrane incl. Rakaia, Kaweka & Pahau terranes

Covering sediments and Cenozoic plutonism

- Covering sediments
- Volcanic rocks

Western Province
Pz/Mz plutonic suites

- Tuhua Intrusives

Western Province
Paleozoic terrane accretion

- Buller Terrane
- Takaka Terrane

— Selected faults

S1 - Southland Synform
S2 - Wairoa Syncline
S3 - Roding Syncline

F1 - Livingstone Fault
F2 - Delaware-Speargrass Fault Zone
F3 - Hollyford Fault
F4 - Moonlight Fault

Tuhua Intrusives
T1 - Separation Point Suite
T2 - Paparoa Suite
T3 - Hohonu Dyke Swarm
       & French Creek Granite
T4 - Longwood Suite

Western Province
W1 - Parapara Peak
W2 - Topfer Formation
W3 - Devil River Volcanics

Drumduan Terrane
D1 - Nelson City area
D2 - Largs Formation
D3 - Loch Burn Formation

Brook Street Terrane
B1 - Nelson type area
B2 - Takitimu Mountains
B3 - Wairaki Hills

Dun Mountain - Maitai Terrane
O1 - Dun Mountain ophiolite
O2 - Red Hills ophiolite
O3 - Red Mountain ophiolite
O4 - Livingston Mountains
O5 - North Mavora Lake
O6 - Bald Hill ophiolite
O7 - Coal Hill Inclusion
O8 - West Dome ophiolite
O9 - Otama area
O10 - Arthurton

Murihiku Terrane
MU - Taringatura Hills
        & Hokonui Hills

Willsher Group
K - Kaka Point

Caples Terrane
C1 - Thomson Mountains
C2 - Humboldt Mountains
C3 - Eyre Creek Melange
C4 - Croisilles Melange

Torlesse - Rakaia
R1 - Pounamu Ultramafic Belt
R2 - Esk Head Melange
R3 - Glenfalloch Stream (melange)
R4 - Te Akatarawa Terrane
R5 - Aspiring lithological association

Fig. 15.2. Summary of the lithostratigraphic terranes of South Island, with the main places and locations mentioned in the text indicated. For each terrane, locations are marked generally from north to south.
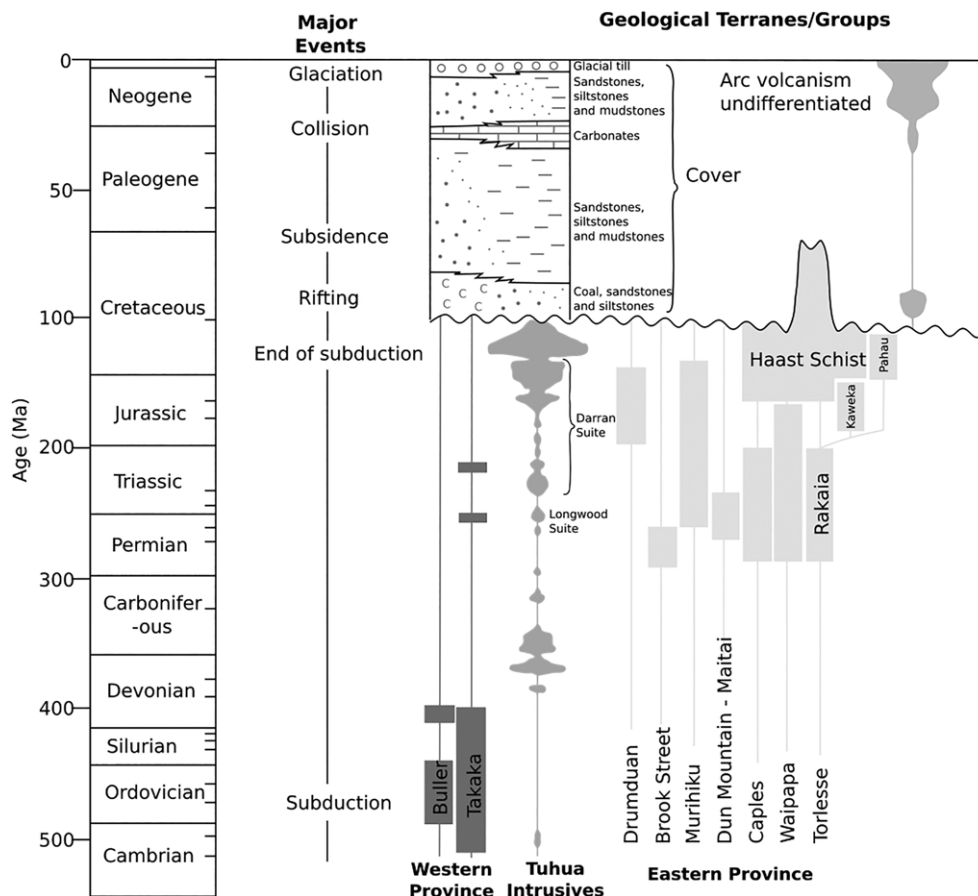
Fig. 15.3. Summary of the age ranges of the tectonostratigraphic units making up the Western Province and the Eastern Province. The Tuhua Intrusives, which are largely represented by the Median Batholith (see Fig. 15.2), cut the Takaka and Buller terranes of the Western Province, and also the Brook Street and Drumduan terranes of the Eastern Province. The Haast Schist encompasses several related metamorphic units in different areas. Modified from Mortimer & Campbell (2014).

tectonics. Plate tectonics has its own nomenclature for identifying tectonic units and processes (e.g. passive margin; subduction complex; spreading centre), raising questions concerning the inherent usefulness of terrane nomenclature, especially for collisional orogens (e.g. the Alps; Himalayas). For example, the classic terranes of the Franciscan Complex, western USA (Blake *et al.* 1982) may be interpreted simply using plate tectonic nomenclature (e.g. subduction–accretion complex: Snow *et al.* 2010).

Despite some trenchant criticism of the principle (e.g. Şengör & Dewey 1990), the tectonostratigraphic terrane concept aids understanding of the Paleozoic–Mesozoic geology of New Zealand and Zealandia as a whole. However, the terrane nomenclature of New Zealand is not entirely without difficulties. The nature and character of several of the individual terranes differ in significant respects including scale, nature of tectonic boundary and internal heterogeneity: (1) terranes such as the Brook Street Terrane, the Dun Mountain–Maitai Terrane and the Torlesse Composite Terrane (Figs 15.2 & 15.3) represent fundamentally different crustal units which are likely to have undergone major tectonic displacement relative to each other (Mortimer *et al.* 2002; Mortimer 2004); in contrast, the Buller and Takaka terranes of the Western Province represent contrasting, mainly Paleozoic, successions that, although tectonically assembled, may represent less fundamentally different tectonic units (Cooper & Tulloch 1992; Bradshaw 1993; Roser *et al.* 1996; Adams 2004); (2) the key boundary between the Eastern and Western provinces is difficult to define because of the rarity or absence of host rocks between intrusions (Tuhua Intrusives); (3) the Brook Street Terrane (Eastern Province) includes several different volcanic arc-related units of possibly different age and uncertain relative tectonic displacement (Robertson & Palamakumbura 2019a); (4) the Drumduan Terrane (assigned to the Eastern Province) includes sedimentary and volcanic assemblages that underwent either high

pressure–low temperature (HP–LT) or low temperature–high pressure (LT–HP) metamorphism in different outcrops (see below), suggesting that it is a composite unit; and (5) the more outboard (easterly) terranes, notably the Torlesse Composite Terrane, include sandstone turbidites, polygenetic melanges and volcanic rocks of different origins that are generally interpreted as subduction complexes but which are difficult to define as discrete fault-bounded tectonostratigraphic terranes.

Should the terrane classification of New Zealand, therefore, be replaced by a combination of conventional stratigraphy and plate tectonic interpretation? Conventional stratigraphy (groups, formations, etc.) works well for several of the regional geological units where a coherent stratigraphy exists throughout, notably the Murihiku Supergroup (H.J. Campbell *et al.* 2003) and the Maitai Group (Landis 1974). However, traditional stratigraphy is ineffective at classifying structurally assembled units, notably the Caples Terrane and the Torlesse Composite Terrane (e.g. Bradshaw 1972; Adams *et al.* 2009b, 2013a, b c). Also, the Brook Street Terrane cannot be effectively defined as a single stratigraphic unit. As alternatives, terms such as Brook Street volcanic arc, Maitai forearc basin, Caples accretionary complex might be used, although such terms would be over-interpretative.

Overall, the existing terrane classification (Mortimer *et al.* 2014) represents a reasonable compromise between terrane classification and stratigraphy, and also facilitates geological interpretation and tectonic reconstruction.

Western Province: very long-lived active continental margin

The geological development of the Western Province and the associated Median Batholith, especially the Tuhua Intrusives

(Fig. 15.2), is critical to an understanding of the Eastern Province because the westerly units in particular are potential sources of detrital material. The South Island exposures represent a preferentially exposed segment of the *c*. 5000 km-long Gondwanan active continental margin (e.g. Cawood 1984, 2005; Torsvik & Cocks 2009). Variation in magmatism, sedimentation and metamorphism are to be expected along this active margin but are impossible to evaluate because most of this area is now submerged, including beneath the Lord Howe Rise.

Tectonostratigraphy and origin

The Western and Eastern provinces were initially seen as being separated by a tectonic boundary, termed the Median Tectonic Line (see Johnston 2019). The two provinces were later interpreted as being separated by an elongate, *c*. north–south belt of mainly Cambrian–Early Cretaceous plutonic igneous rocks (*c*. 10 000 km^2), known as the Median Tectonic Zone (e.g. Bradshaw 1993). However, some plutonic rocks (Tuhua Intrusives) intrude both the Western Province to the west of the traditional Median Tectonic Zone and also the adjacent Eastern Province (Drumduan and Brook Street terranes). The fundamental crustal boundary between the Western Province and the Eastern Province separates essentially intact Gondwanan crust to the west from the allochthonous crustal units of the Eastern Province (Scott 2013). The belt of magmatic rocks which stitches the key crustal boundary between the Western and Eastern provinces has recently become known as the Median Batholith (Mortimer *et al.* 1999a, b; Mortimer 2004) (Figs 15.2 & 15.3).

There is general agreement that the Western Province formed part of the Gondwana active continental margin during Paleozoic to end-Early Cretaceous time (*c*. 100 Ma) when the Tasman Sea Basin rifted (Mortimer *et al.* 1999a, b; Mortimer 2004; Mortimer & Campbell 2014). Direct correlations have been established between geological units exposed in the Buller Terrane (Western Province) and in eastern Australia and Antarctica. Early Paleozoic metasedimentary rocks (Greenland Group) and Devonian granites of the Buller Terrane have counterparts in the Wilson Terrane of the Ross and Adelaide orogens of SE Australia, and within both northern Victoria Land, East Antarctica (Robertson Bay Group) and in Marie Byrd Land, West Antarctica (Swanson Formation) (Bradshaw *et al.* 1983; Adams 2004; Bradshaw 2007). Low- to intermediate-grade regional metamorphism took place within the Buller Terrane prior to the oldest cross-cutting Tuhua Intrusives (Late Ordovician, *c*. 440 Ma). Permian (and possibly Triassic) transgressive clastic successions of the Buller Terrane, as exposed at Parapara Peak (Tasman District), have counterparts in western Australia, potentially including Tasmania (Wysoczanski *et al.* 1997a, b) and eastern Australia (Waterhouse 2015a, b). Elsewhere, a tiny outcrop of mainly felsic volcaniclastic sandstones (Topfer Formation) is correlated with regionally extensive Triassic successions in SE Australia and West Antarctica (Mortimer & Smale 1996). The more easterly Takaka Terrane of the Western Province is a mostly Ordovician, internally sliced, composite unit that lacks Paleozoic regional metamorphism. Lithologies include Cambrian arc-related volcanics (Devil River Volcanics) and Cambrian–Devonian meta-clastic and carbonate rocks (see Adams 2004). The Buller and Takaka terranes were thrust together prior to the intrusion of batholiths (Tuhua Intrusives). The Paleozoic batholiths (e.g. Karamea Batholith) include inherited zircon populations as old as 1.7 Ga, which match the ages of some granites in the Lachlan Orogen, and also Ordovician sedimentary rocks in both the Western Province and SE Australia (King *et al.* 1997). Detrital zircon populations from the Late Paleozoic–Early Mesozoic sandstones of the Western Province support an origin in SE Australia or East Antarctica (Wysoczanski *et al.* 1997a, b).

Cambrian arc-type volcanism in the Takaka Terrane (Münker & Cooper 1999) was followed by basement-derived detrital input during the Cambrian–Devonian. These sediments have been interpreted as a passive-margin setting, based on geochemical evidence (Roser *et al.* 1996). However, an ongoing active margin setting (with or without coeval arc magmatism) is now preferred on wider regional grounds (Cawood 2005; Torsvik & Cocks 2009).

Back-arc rifting took place widely in SE Australia as Panthalassa subducted generally westwards (Cawood 1984; Münker & Cooper 1999; Mortimer 2004; Glen 2005; Kemp *et al.* 2009; Korsch *et al.* 2009). Silurian–Devonian basalts and gabbros of the Lachlan Orogen in SE Australia are interpreted to have formed in an extensional setting on relatively thin lithosphere (<30 km thick) (Collins 2002). Lithospheric extension during the Ordovician–Middle Devonian was associated with basaltic volcanism, then S- or I-type silicic magmatism in different areas, and was in turn followed by a pulse of lithospheric thickening later during the Devonian (Collins 2002).

In summary, the Paleozoic geological development of the Western Province relates to early-stage development of the SE Gondwana active continental margin.

Tuhua Intrusives and Median Batholith

The Tuhua Intrusives include all of the plutonic rocks of the Western Province. The Tuhua Intrusives are dominated by I-, S- and A-type plutons of Middle Devonian, Carboniferous, latest Permian, Triassic, Jurassic and Early–mid-Cretaceous age (Mortimer *et al.* 1999b; Tulloch *et al.* 2009a; Decker *et al.* 2017). The plutonic rocks include the Paleozoic Karamea Suite and the Early–mid-Cretaceous Rahu Suite (e.g. Paparoa and Hohonu batholiths), which are less relevant to the time frame of this Memoir. In general, the Early–mid-Cretaceous batholiths relate to late-stage arc activity, collision and transition to an extensional tectonic setting (Muir *et al.* 1994, 1996; Waight *et al.* 1998a, b; Mortimer *et al.* 1999b; Tulloch *et al.* 2009a).

The Median Batholith is dominated by three main assemblages. The first is the Longwood Suite, which is exposed in a relatively easterly position, mainly in the far south of the South Island. This includes chemically primitive Permian intrusions: for example, at Bluff and Oraka Point (Kimbrough *et al.* 1994; Mortimer *et al.* 1999b; Spandler *et al.* 2000, 2003). High-precision radiometric dating confirms that several of the plutons (Hekeia Gabbro; Pourakino Trondjemite) have latest Permian ages (McCoy-West *et al.* 2014). These Permian plutons were traditionally assumed to represent part of the adjacent Permian Brook Street Terrane (Kimbrough *et al.* 1994; Mortimer *et al.* 1999a; Spandler *et al.* 2005). However, recent more accurate dating suggests that they instead represent Cordilleran-type arc magmatism, because the ages are relatively young relative to the Early Permian Brook Street Terrane (south of the Alpine Fault) (McCoy-West *et al.* 2014). The second major assemblage in the Median Batholith is the I-type Darran Suite, comprising a wide range of mafic-, intermediate- and felsic-composition intrusive rocks, which generally young westwards (Price *et al.* 2011). These intrusive rocks date from *c*. 232 Ma (Middle Triassic) (McCoy-West *et al.* 2014), but are mostly mid-Jurassic–Early Cretaceous in age (168–137 Ma) (Kimbrough *et al.* 1994; Muir *et al.* 1998; Mortimer *et al.* 1999b; Allibone & Tulloch 2004; Allibone *et al.* 2009). The Darran Suite, like the Longwood Suite, is relatively primitive in composition and shows little or no evidence of crustal involvement based on Nd and Sr isotopic evidence (Muir *et al.* 1994, 1995; Price *et al.* 2011). The third major assemblage, which is exposed north of the Alpine Fault, is the Early Cretaceous

(135–100 Ma) Separation Point Suite, which includes adakitic magmas related to late-stage subduction (Tulloch & Rabone 1993; Muir *et al.* 1995; Bolhar *et al.* 2008).

The Tuhua Intrusives and the Median Batholith are potential sources of detrital material in the Eastern Province. Some geochemical data relevant to the provenance of sedimentary rocks within the Eastern Province are shown in Figure 15.4. On a mid-ocean ridge basalt (MORB)-normalized spider plot (Fig. 15.4a), basic igneous rocks of the Darran Suite (felsic rocks excluded) are well grouped, similar to those of the older Longwood Suite (see Robertson & Palamakumbura 2019a). The well-defined negative Nb anomaly, together with the spikey pattern and the enrichment in large ion lithophile elements (LILEs), are indicative of a subduction influence. The

normalized patterns are similar to the reference oceanic Izu–Bonin arc, more so than to the reference Cascades continental margin arc. However, the Darran and Longwood suites could both represent continental margin-arc magmatism that, unusually, exhibits oceanic-arc chemical affinities (Fig. 15.4b). Possible explanations are that the magmas represent melting of strongly thinned lithosphere and/or accreted oceanic or oceanic-arc crust (see below). The Darran Suite is chemically similar to many of the metasedimentary rocks of the Western Province (Fig. 15.4c, d) with important implications for their interpretation (see Robertson & Palamakumbura 2019c). Mafic and felsic rocks of the Drumduan Terrane (see below) plot similarly (Fig. 15.4e), supporting a genetic link with the Median Batholith (see below).
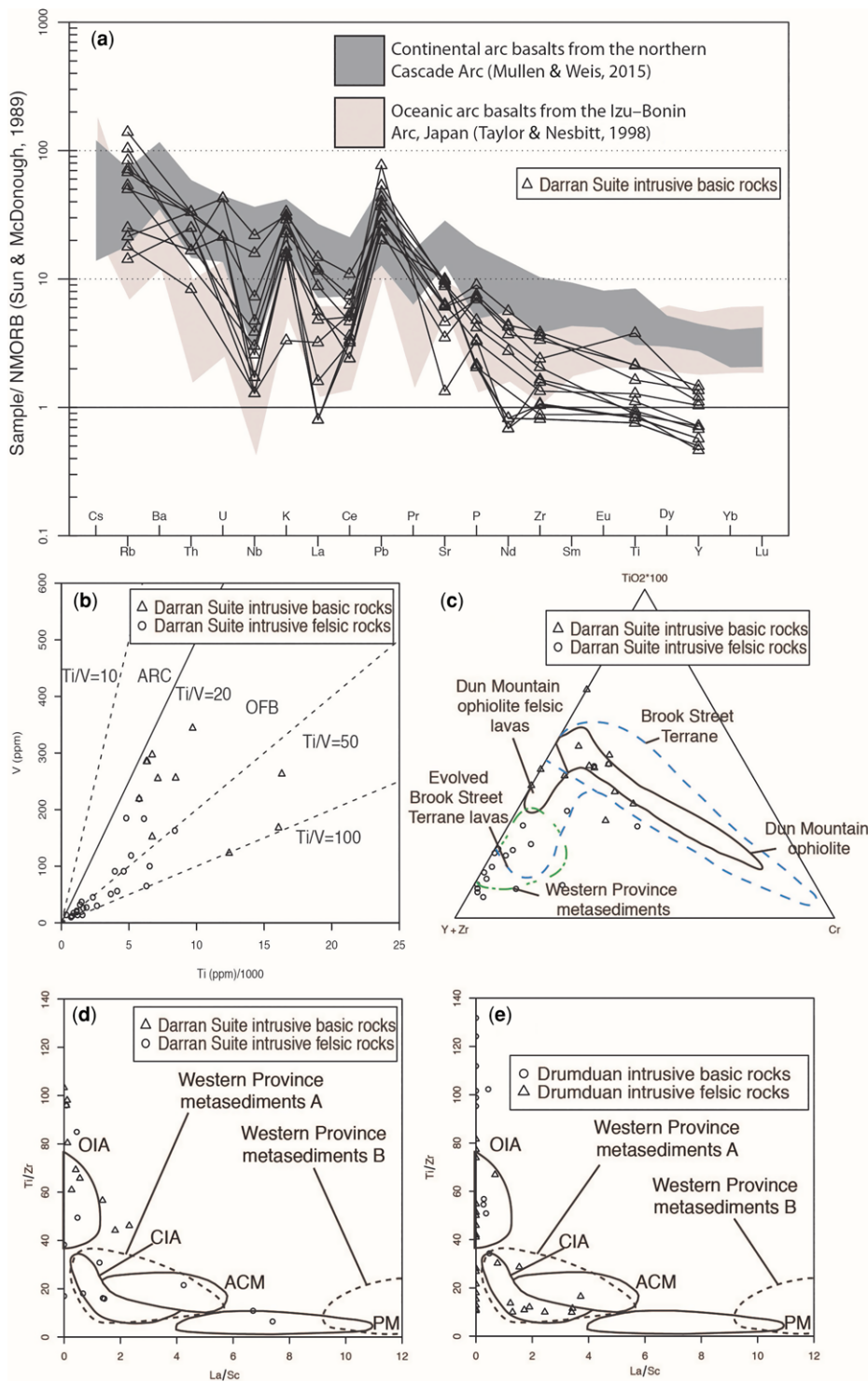

Fig. 15.4. Comparisons of igneous geochemical data for the Darran Suite (Median Batholith), the Drumduan Terrane (Eastern Province) and reference continental and oceanic-arc basalts. (**a**) MORB-normalized plot (Sun & McDonough 1989) of basic intrusive igneous rocks (<55% SiO$_2$) from the Darran Suite, compared with the oceanic Izu-Bonin arc (Taylor & Nesbitt 1998) and the Cascades continental margin arc (Mullen & Weis 2015). (**b**) V v. Ti plot (Shervais 1982) for the Darran Suite (data as above). (**c**) TiO$_2$ × 100 v. Y + Zr v. Cr plot for the Darran Suite (data as above), with fields of other regional igneous units. The Permian Dun Mountain ophiolite and the Brook Street Terrane predate the mid-Triassic–Early Cretaceous Darran Suite, but are potential sources of detritus in the Eastern Province sedimentary rocks (see Robertson & Palamakumbura 2019a) for data sources. (**d**) Ti/Zr v. La/Sc plot for the Darran Suite. (**e**) Ti/Zr v. La/Sc plot for the Drumduan Terrane (fields as in d). All analyses are from the GNS Science Petlab database. ACM, active continental margin; CIA, continental island arc; OFB, ocean-floor basalt; OIA, oceanic island arc; PM, passive margin.

Alternative tectonic settings of the Median Batholith

Two main alternatives can be considered for the latest Permian–Early Cretaceous Median Batholith.

In the first interpretation, the Median Batholith represents the distal (easterly) edge of a Cordilleran-type active continental margin, based mainly on regional tectonic considerations (Scott 2013; Mortimer *et al.* 1999*a*, *b*; Mortimer 2004). In the second interpretation, the Median Batholith is interpreted as an accreted oceanic arc, based on igneous petrological and geochemical evidence. It should be noted that some plutons that are included in the Darran Suite, as defined above, were placed within the Longwood Intrusive Complex, as defined by Price & Sinton (1978) and Price *et al.* (2006, 2011).

Several lines of evidence are inconsistent with an oceanic-arc origin: (1) plutons of the Median Batholith intrude the Takaka Terrane (Western Province) at several localities (Mortimer *et al.* 1999*a*, *b*), supporting a continental margin setting; and (2) the oceanic-arc interpretation implies the former existence of both inboard and outboard margins (e.g. accretionary material or volcanogenic apron). However, there is no preserved evidence of an inboard (westerly) arc margin within or adjacent to the Median Batholith.

Overall, the evidence best fits a continental margin-arc origin for the Median Batholith (Mortimer *et al.* 2014; Schwartz *et al.* 2017). This interpretation is crucial to sedimentary provenance interpretation because it implies that detritus that is chemically discriminated as 'oceanic' in the Eastern Province could instead have a continental margin-arc origin. Robertson & Palamakumbura (2019*a*) propose that oceanic (or oceanic-arc) lithosphere (non-radiogenic) accreted or became trapped along the East Gondwana active continental margin, causing the adjacent subduction zone to step oceanwards. The Median Batholith intrusives (latest Permian–Early Cretaceous) were then constructed on this marginal crust, explaining their oceanic arc-like geochemistry, including isotopic characteristics.

The presently exposed batholiths (Tuhua Intrusives) are likely to have encompassed volcanic carapaces that are now eroded. Volcaniclastic detritus within the Maitai Group is generally consistent with derivation, at least partially, from the Median Batholith, or a (non-exposed) inferred lateral equivalent, based on petrographical, geochemical and geochronological evidence (Adams *et al.* 2007; Robertson & Palamakumbura 2019*c*). Cretaceous andesitic to felsic extrusions (Loch Burn Formation) and conglomerates (Ewing *et al.* 2007) within the Drumduan Terrane (Eastern Province) are interpreted to relate to the Median Batholith (see below). Detritus that is petrographically, chemically and geochronologically similar to that of the Darran Suite also contributed extensively to the Early Cretaceous sediments of the more easterly Pahau Terrane (Wandres *et al.* 2004*a*, *b*; Adams *et al.* 2009*c*; see below). The relatively oceanic arc-like composition of both the Longwood and Darran suites explains why, on discrimination diagrams, some sandstones of the Maitai Group (Dun Mountain–Maitai Terrane), the Murihiku Terrane and the Caples Terrane plot in the oceanic volcanic-arc field (Robertson & Palamakumbura 2019*c*) (Fig. 15.4).

Drumduan Terrane: remnant of the eastern margin of the Median Batholith

In places, the Western Province is separated from the Brook Street Terrane (see below) by fault-bounded crustal fragments, collectively termed the Drumduan Terrane (Johnston *et al.* 1987) (Figs 15.2 & 15.3). The Drumduan Terrane is included in the Eastern Province (Mortimer *et al.* 2014), mainly because a multi-phase tectonic contact separates it from the Median

Batholith. The outcrop is variable and discontinuous, and includes Cretaceous intrusive rocks, which can be interpreted as part of the easterly fringe of the Median Batholith (Scott 2013) or, possibly, a non-exposed along-strike equivalent.

The type outcrop of the Drumduan Terrane is north of the Alpine Fault, in the coastal Nelson area, where it is made up of several small, fault-bounded units (*c.* 12 km long × 2 km across, collectively). Pyroclastic and epiclastic sedimentary rocks include Jurassic plant debris, suggesting subaerial deposition. One formation (Marybank Formation) is mostly tuffaceous breccia, sandstone, mudstone and siltstone, whereas another (Botanical Hill Formation) is dominated by crystal lithic tuff and tuff breccia, with minor sandstone and siltstone. The volcanic rocks are mainly intermediate (andesitic) to locally felsic in composition and have an arc-like chemistry, with a pronounced negative niobium anomaly (Cipriano 1984; Cipriano *et al.* 1987; Tulloch *et al.* 1999) (Fig. 15.4e). In the Nelson area, the Drumduan Terrane is separated from the Brook Street Terrane by a through-going shear zone (Delaware–Speargrass Fault Zone). This boundary contains slivers of highly deformed rocks (e.g. Wakapuaka Phyllonite) that were derived from one, or other, of the two adjacent terranes. The Marybank Formation includes patchy occurrences of the HP–LT mineral lawsonite. The Drumduan Terrane in the Nelson area is intruded by plutons (Median Batholith), resulting in a broad zone of hydrothermal alteration.

South of the Alpine Fault, the Drumduan Terrane is most obviously represented by a structurally coherent, large outcrop (Largs Group). This is separated from the Brook Street Terrane ('Plato unit') by intrusive rocks (Mackay Intrusives) that are again affected by hydrothermal alteration (Williams 1978). Low-grade-metamorphosed andesitic to dacitic rocks include pyroclastic sediments, flows and andesitic dykes. Granitoid clasts are rarely present. Subaerial formation is inferred, as in the Nelson area. Part of the succession (Largs Ignimbrite) is dated as Early Cretaceous (U–Pb zircon: 140 ± 2 Ma) (Mortimer *et al.* 1999*a*).

Fragmentary successions correlated with the Drumduan Terrane in Fiordland (Loch Burn Formation) include fine- to coarse-grained clastic rocks, tuff and minor andesitic rocks (Paterson Group), of inferred latest Jurassic age (<148 Ma) (Bradshaw 1993; Ewing *et al.* 2007). Meta-andesitic to dacitic tuffaceous sedimentary rocks and lava flows farther south, on Stewart and Codfish islands, of inferred Early Cretaceous age, are also included within the Drumduan Terrane (Ewing *et al.* 2007; Edbrooke 2017). The volcanogenic material (extrusive rocks and clasts) is correlated with the Darran Suite. However, Carboniferous-aged clasts (*c.* 355 and 327 Ma) are chemically dissimilar to known Tuhua Intrusives, suggesting a complex origin (Ewing *et al.* 2007).

Overall, the Drumduan Terrane is interpreted to have a Carboniferous (or older) plutonic rock basement, cut and overlain by arc-related plutons and volcano-sedimentary rocks, which are mainly correlated with the Jurassic–Early Cretaceous Darran Suite. The various crustal slivers of Carboniferous–Early Cretaceous age making up the Drumduan Terrane experienced unknown lateral (*c.* north–south) displacement, potentially before, during and certainly after emplacement of the Median Batholith.

Brook Street Terrane: magmatic arc and sedimentary cover

The Permian Brook Street Terrane crops out to the east of the Drumduan Terrane, where exposed (Figs 15.2 & 15.3). The outcrops have previously been interpreted as the remnants of a regional-scale oceanic magmatic arc and (where present) its

sedimentary cover (Williams 1978; Houghton 1981, 1986a, b; Houghton & Landis 1989; Landis et al. 1999; Spandler et al. 2005; Nebel et al. 2007). The ages of the various volcanic remnants are debatable, in part owing to the present lack of reliable radiometric age data. However, the volcanogenic successions to the south of the Alpine Fault (Takitimu and Skippers supergroups) are dated as Early Permian based on fossil evidence (see Waterhouse 1964, 1980; Campbell 2019). The outcrops in the Wairaki Hills, east of the Takitimu Mountains (Southland), include a classic, relatively shallow-water, sedimentary cover succession of inferred late-Early–early-Late Permian age, and associated melange-like units (Begg 1981; Landis et al. 1999; Waterhouse 2002).

Alternative debatable tectonic to magmatic settings for the volcanic-arc rocks of the Brook Street Terrane are shown in Figure 15.5. Lithosphere beneath the Brook Street Terrane (not exposed) could be represented by pre-existing MORB (Fig. 15.5a) and/or depleted supra-subduction zone crust (Fig. 15.5b). The arc could have formed in an open-oceanic setting, followed by accretion to SE Gondwana (Fig. 15.5c), or it might have formed near Gondwana: for example, on accreted or trapped oceanic lithosphere (Fig. 15.5d).
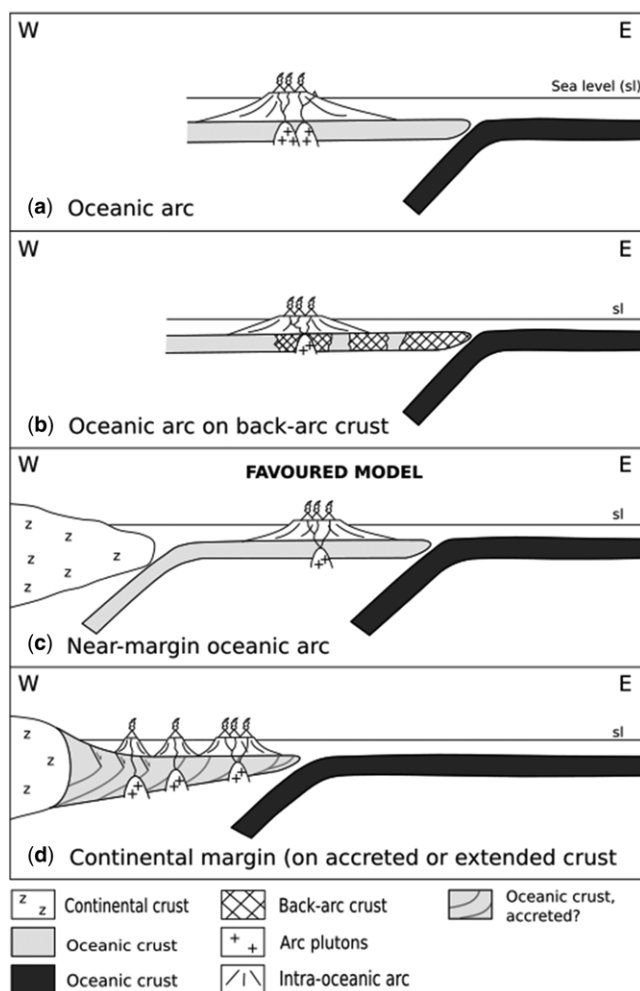

Fig. 15.5. Alternative tectonic settings of the Permian Brook Street Terrane arc. (**a**) Intra-oceanic arc located an unknown distance from a continent, with unknown basement, based on Spandler et al. (2003). (**b**) Intra-oceanic arc constructed on a pre-existing back-arc basin crust, intruded by incipient arc crust, based on Sivell & McCulloch (2000). (**c**) Intra-oceanic arc simultaneously subducting westwards beneath Gondwana, based on Nebel et al. (2007). (**d**) Continental margin arc constructed on (non-radiogenic) accreted oceanic crust or oceanic-arc crust; see the text for discussion.

Nature of the unexposed arc basement

Nd isotopic evidence from four samples of volcanogenic sedimentary rocks indicates a chemically primitive source, without interaction with evolved continental crust (Frost & Coombs 1989). Hf–Nd–Pb isotopic compositions are similar to Pacific-type mantle (for the Takitimu Mountains), but dissimilar to Indian-type mantle that is inferred to underlie Australia–Antarctica, the Western Province and much of the Median Batholith (Nebel et al. 2007).

Comparison of southerly and northerly outcrops

One sample (MAIVX1) of volcaniclastic sandstone from the Grampian Formation, which is mapped as the lowest part of the succession in the Nelson area (Johnston 1981), contains detrital zircons of dominantly Permian age (59 zircons). There are also six zircons of Carboniferous age, and several of Devonian–Silurian and Precambrian ages (Adams et al. 2007). The age population, although small, suggests a Gondwanan origin. Also, the sample analysed from the Grampian Formation contains zircons as young as latest Permian (c. 256 Ma: Adams et al. 2007), which contrasts markedly with the Early Permian age inferred for the Brook Street Terrane igneous rocks south of the Alpine Fault, based on palaeontological evidence (Williams 1978; Waterhouse 1982; Landis et al. 1999; see Campbell 2019). In addition, the volcaniclastic sandstones and tuffaceous sediments of the Grampian Formation contain abundant felsic volcanic material and felsic fallout tuff that plot in the continental island-arc field on tectonic discriminant diagrams (Robertson & Palamakumbura 2019a). In contrast, volcaniclastic sedimentary rocks from south of the Alpine Fault (e.g. Takitimu Mountains) have oceanic-arc affinities (Robertson & Palamakumbura 2019a). It is, therefore, likely (pending acquisition of additional geochronological data) that the outcrops of the Brook Street Terrane, north and south of the Alpine Fault, have different ages and tectonic settings of formation.

Regional comparisons: Gympie Terrane, Queensland and Téremba Terrane, New Caledonia

Additional clues to the Brook Street Terrane come from the Permian Gympie Terrane of near-coastal central Queensland and from the Téremba Terrane of New Caledonia (northern Zealandia). Comparison of the Gympie Terrane with the Nelson type area of the Brook Street Terrane dates back nearly 150 years (see Johnston 2019). The comparison is based mainly on the occurrences of Permian basaltic, volcaniclastic and tuffaceous rocks in both terranes. Specifically, highly depleted magnesium-rich ankaramites occur in both terranes (Harrington 1983; Sivell & McCulloch 2001; Spandler et al. 2005).

At the base of the succession in the Gympie Terrane (Fig. 15.6) are the Highbury Volcanics, which comprise marine basaltic tuff breccia, agglomerate and mafic volcanics (Harrington 1983; Sivell & McCulloch 2001; Stidolph et al. 2016). The succeeding Alma unit is a deep-marine succession of volcanogenic mudstone, siltstone, fine-grained tuffaceous rocks and hyaloclastite, which is generally similar to the Grampian Formation in the Nelson area (Johnston 1981; Robertson & Palamakumbura 2019a). The Gympie Terrane succession continues with basaltic lavas and tuff breccias (Tozer volcanics), and then (ankaramitic) basaltic lavas and tuff breccia (Mary Hill volcanics), which are broadly similar to the Kaka Formation of the Nelson area (Johnston 1981; Robertson & Palamakumbura 2019a). The Tozer and Mary Hill volcanics are interpreted as shallow-marine to non-marine in origin, whereas
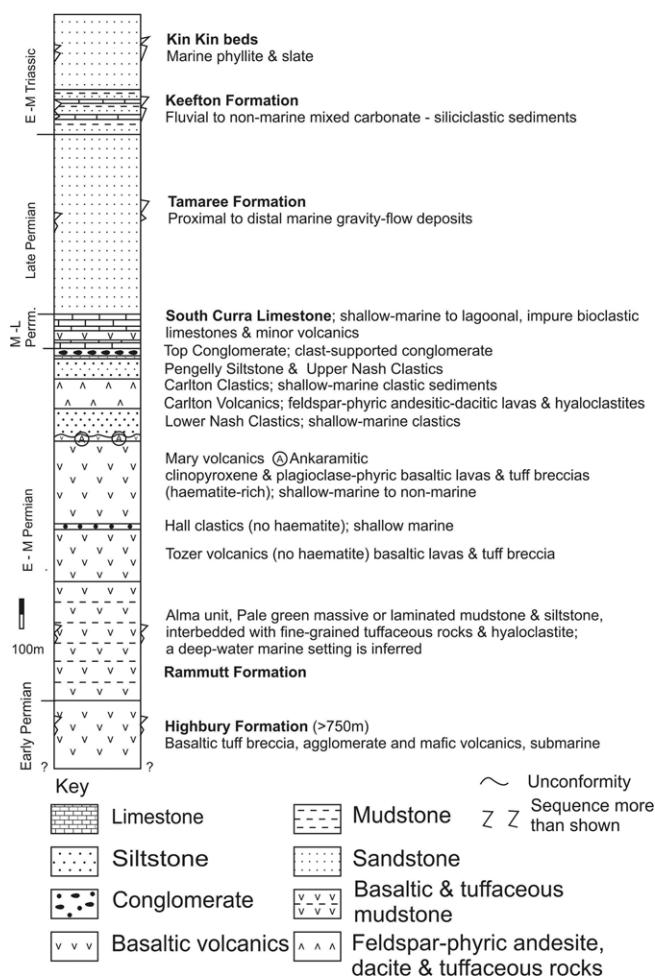
Fig. 15.6. Summary log of the Gympie Terrane, coastal central Queensland (based on Sivell & Waterhouse 1987; Waterhouse & Balfe 1987; Li *et al.* 2015; Stidolph *et al.* 2016).

the Brook Street Terrane volcanogenic rocks as a whole mainly range from deep marine to relatively shallow marine (Robertson & Palamakumbura 2019a). Scattered, to locally concentrated, shallow-marine bioclastic detritus, mainly in the form of brachiopods, bivalves and gastropods, occurs within gravity-flow deposits in the Brook Street Terrane (Waterhouse 1982; Houghton & Landis 1989; Robertson & Palamakumbura 2019a).

Above an unconformity, the Gympie Terrane succession continues with Early–Middle Permian-aged shallow-marine to lagoonal, volcaniclastic and bioclastic sediments, including clast-supported conglomerate, limestone, basaltic lava, tuff breccia and hyaloclastite (Rammutt Formation). This higher interval of the Gympie Terrane succession shows some lithological similarities with the Late Permian Glendale Limestone, which unconformably overlies the highest volcanogenic unit (Caravan Formation) of the Brook Street Terrane in the Wairaki Hills, Southland (Landis *et al.* 1999). However, the upper interval of the Gympie Terrane includes coeval volcanics, which are absent from age-equivalents in the Brook Street Terrane.

Comparative geochemical data for the Gympie and Téremba terranes are summarized in Figure 15.7. On a MORB-normalized spider plot (Fig. 15.7a), the basic igneous rocks of the Gympie Terrane are generally similar in composition to both the Longwood Suite (see Robertson & Palamakumbura 2019a) and the Darran Suite (Fig. 15.4a). The patterns are broadly intermediate between the reference Cascade continental arc basalt and the reference oceanic Izu–Bonin arc basalt (generally more like the Cascades). On a Ti/Zr v. La/Sc plot

(Fig. 15.7b), the majority of the Gympie Terrane samples plot in the ocean island-arc (OIA) field, similar to non-evolved intrusive rocks of the Median Batholith (field a). A few samples lie within the continental island-arc (CIA) and the active margin-arc fields (ACM), similar to the Median Batholith evolved extrusive rocks and to many of the Western Province metasedimentary rocks.

The Gympie Terrane was initially interpreted as an accreted oceanic arc (Sivell & Waterhouse 1987, 1988). More recent field studies have not, however, confirmed the presence of an accretion-related thrust between the Gympie Terrane and the adjacent Late Paleozoic clastic sedimentary rocks of the New England Orogen (Sivell & McCulloch 2001; Shaanan *et al.* 2015; Stidolph *et al.* 2016; Hoy & Rosenbaum 2017). Critically, the Gympie Terrane contains Carboniferous-aged zircons that can be correlated with the New England Orogen, pointing to a near-continental margin rather than open-ocean setting (Li *et al.* 2015). Terrigenous detritus might be carried offshore by gravity flows (up to hundreds of kilometres), but a fully oceanic setting is unlikely. Although of similar age to the Brook Street Terrane south of the Alpine Fault, the Early–Middle Permian interval of the Gympie Terrane is unlikely to have formed in the same geographical and tectonic setting, particularly as the Brook Street Terrane (pre-Jurassic) succession lacks evidence of an equivalent continental influence (in outcrops south of the Alpine Fault).

The Brook Street Terrane has also been compared with the Permian Téremba Terrane, New Caledonia (Spandler *et al.* 2005), which exposes a succession of Late Permian–Middle Jurassic mostly medium-grained, shallow-water arc-derived volcanogenic rocks (Campbell 1984; Campbell *et al.* 1985; Adams *et al.* 2009b). There are, however, some obvious differences with the Brook Street Terrane, as exposed south of the Alpine Fault, notably a relatively young (Late Permian) plagioclase-phyric rather than clinopyroxene-phyric basalt, and a more forearc-like succession (Campbell 1984). Although, terrigenous material is sparse, the Téremba Terrane includes Precambrian–early Paleozoic continentally derived zircon assemblages (Adams *et al.* 2009c), as does the Gympie Terrane (Li *et al.* 2015). A MORB-normalized spider plot (Fig. 15.7c) confirms the arc-like character of the Téremba Terrane basalts, which have patterns similar to many samples from the Gympie Terrane (Fig. 15.7a). A subset of samples for which Cr data are available (relatively evolved extrusive rocks) (Fig. 15.7d) plots similarly to the felsic intrusives of the Median Batholith (Darran Suite: Fig. 15.4c) and also to Western Province metasediments. Overall, the Permian succession of the Téremba Terrane has marked similarities with the Brook Street Terrane to the north of the Alpine Fault, specifically.

Setting of arc genesis

The highly magnesian (ankaramitic) basalts of the Brook Street and Gympie terranes have been interpreted as essentially parental magmas (Spandler *et al.* 2005). However, primitive arc ankaramites are not typical of either early-stage arc magmatism, which can be more boninitic, or of later-stage calc-alkaline magmatism: for example, in the Izu–Bonin–Mariana arc (Reagan *et al.* 2008, 2013). Where present (e.g. Vanuatu), arc ankaramites may form by partial melting of a wehrlite source (rather than lherzolite) (Barsdell & Berry 1990). Experimental studies on ankaramites from Vanuatu show that such highly calcic melts can form by low-degree melting of somewhat refractory mantle that was depleted by previous melt extraction (Schmidt *et al.* 2004). The ankaramatic extrusives and related intrusives might, therefore, be explained by construction of the arc on mantle that was already slightly depleted: for example, accreted (or trapped), oceanic or arc-related lithosphere (Fig. 15.5d).
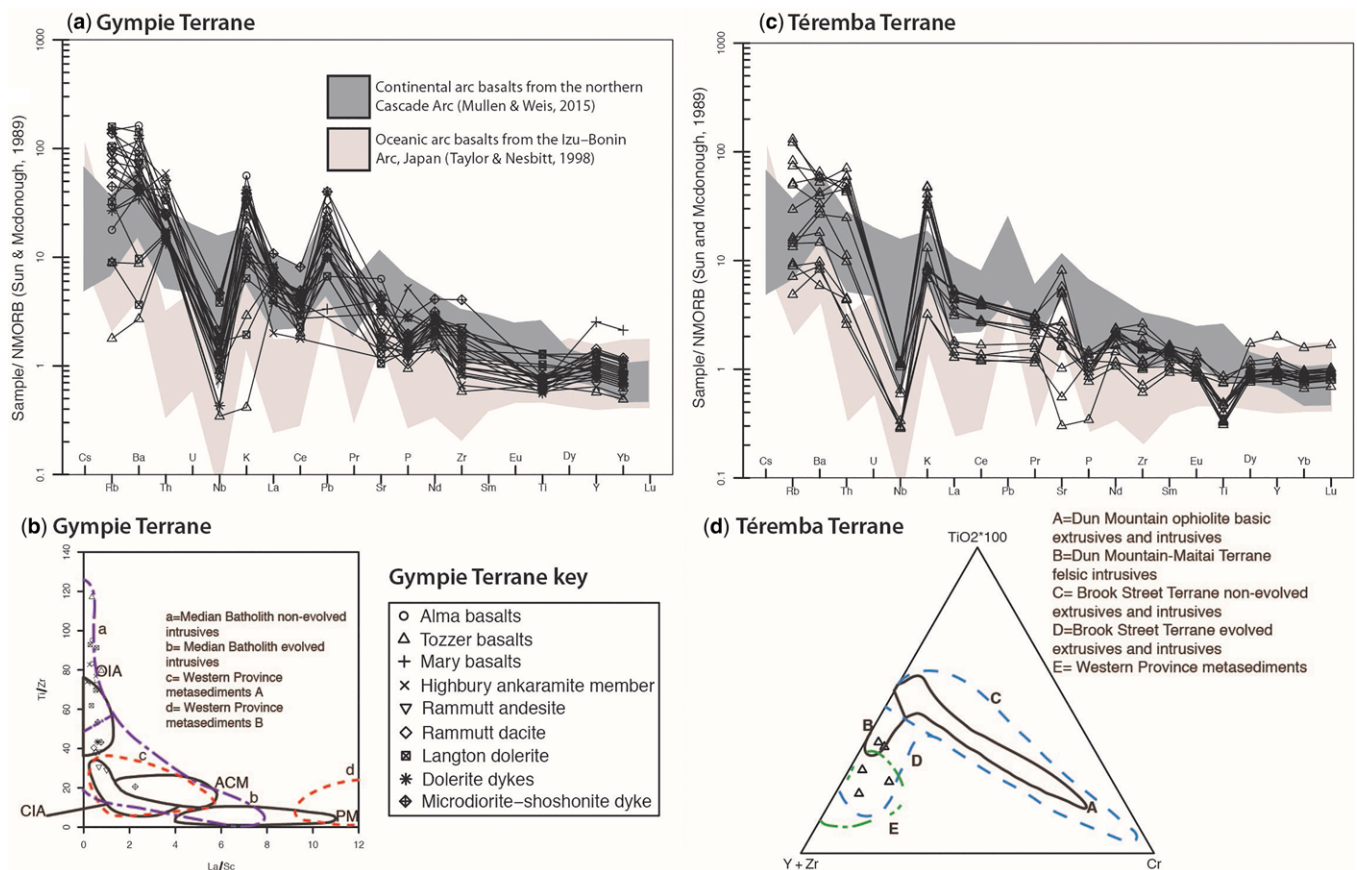
Fig. 15.7. Comparative geochemical data for the Gympie Terrane (Queensland), the Téremba Terrane (New Caledonia), and reference continental margin and oceanic arcs. (**a**) MORB-normalized plot of basic igneous rocks from the Gympie Terrane, compared with the oceanic Izu-Bonin arc and the continental margin Cascades arc; data from Sivell & McCulloch (2000). (**b**) Ti/Zr v. La/Sc plot for basaltic rocks from the Gympie Terrane. Fields: ACM active continental margin; CIA, continental island arc; OIA, oceanic island arc; PM, passive margin; see Robertson & Palamakumbura (2019a) for sources of data for the Median Batholith and the Western Province. (**c**) MORB-normalized plot of basic igneous rocks from the Téremba Terrane (see a); data from Adams *et al.* (2009c). (**d**) TiO₂ × 100 v. Y + Zr v. Cr plot for relatively evolved extrusive rocks of the Téremba Terrane (limited by available Cr data); from Adams *et al.* (2009b). Note the fields (A–E) of lithologies that can be compared with the Téremba Terrane.

Two alternatives are first that the Brook Street, Gympie and Téremba terranes all formed above a single subduction zone but were located variable distances from Gondwana. This could be comparable to the Miocene–Recent setting of the Izu–Bonin–Mariana arc relative to the Japan active continental margin in Honshu (e.g. Taylor *et al.* 1992). In this option, the Gympie Terrane was located relatively close to SE Gondwana, whereas the Brook Street Terrane (south the Alpine Fault) extended oceanwards for up to hundreds of kilometres, similar to the Izu–Bonin–Mariana arc. A second option is that two west-dipping subduction zones existed (Fig. 15.5c): an oceanic subduction zone which gave rise to the Early Permian arc (south of the Alpine Fault) and a separate continental margin subduction zone that created the Early Permian magmatism of the Gympie Terrane (Highbury Volcanics).

Despite the magmatic similarities (e.g. ankaramites), it is difficult to directly correlate the Early Permian continental margin-influenced Gympie Terrane with the extremely thick oceanic-arc-type rocks of the Brook Street Terrane, south of the Alpine Fault, such that both units probably developed separately, along, and adjacent to, different segments of the SE Gondwana active continental margin. The similarity in age (Early Permian) may reflect the pervasive plate reorganization (and consequent subduction) that affected both the active continental margin and the adjacent Panthalassa Ocean (e.g. Cawood 2005; Cawood & Buchan 2007; see below). Robertson & Palamakumbura (2019a) propose that the Brook Street Terrane arc magmatism south of the Alpine Fault was constructed on Paleozoic oceanic lithosphere that accreted or was trapped along the SE Gondwana active continental margin. On the other hand, the Permian-aged Brook Street Terrane outcrop north of the Alpine Fault (type area), the later Permian (and younger) arc volcanism of the Gympie Terrane (Rammutt Formation and above) and the Téremba Terrane are all interpreted as successor arc magmatism along, or adjacent to, the SE Gondwana active continental margin.

Arc sedimentary cover

The uppermost arc volcanics of the Brook Street Terrane south of the Alpine Fault (Caravan Formation), as exposed in the Wairaki Hills, are overlain, depositionally, by bivalve-rich, redeposited carbonates of the Productus Creek Group (Force 1975; Landis *et al.* 1999). These sedimentary rocks lack terrigenous detritus and are inferred to have accumulated in an unstable relatively shallow-marine setting within the arc edifice (see Robertson & Palamakumbura 2019a). The Productus Creek Group is structurally overlain by two melange-like units (Hawtel–Coral Bluff Melange and Tin Hut Melange). The former (Hawtel Formation) includes Late Permian limestones with bryozoans, atomodesmatinids and corals, whereas the latter (Wairaki Formation) is dominated by Late Permian bryozoan-rich pebbly andesitic conglomerate (Force 1975; Landis *et al.* 1999; see Campbell 2019).

Emplacement of the arc

Assuming that the Brook Street Terrane arc, south of the Alpine Fault, formed near SE Gondwana (see above), only a limited amount of underthrusting of Gondwana was needed to emplace the arc, which is consistent with the absence of an intervening oceanic-derived subduction complex.

First, in the far south (Foveaux Strait area: Fig. 15.2), volcanogenic rocks that are correlated with the Brook Street Terrane are cut by latest Permian (257–251 Ma) plutons of the Longwood Suite (Kimbrough *et al.* 1994). These plutons post-date the arc magmatism of the Brook Street Terrane (south of the Alpine Fault) and instead relate to magmatism along the SE Gondwana active continental margin (McCoy-West *et al.* 2014). In addition, the Productus Creek Group in the Wairaki Hills is cut by minor Late Permian-aged intrusions (Weetwood Formation), which are correlated with the Longwood Suite (Mortimer *et al.* 2019). The above evidence implies that the Brook Street Terrane accreted to Gondwana by latest Permian time.

Secondly, there is more definite evidence of accretion of the Brook Street Terrane at least by the Jurassic. After a hiatus and tilting, the Productus Creek Group was unconformably overlain by the mid-Jurassic Barretts Formation, which includes rounded clasts (up to several metres in size) of mostly basic to intermediate extrusive rocks, granitoid rocks and limestone (Landis *et al.* 1999). Radiometric dating of several igneous clasts yielded ages of *c.* 237–180 Ma (Late Triassic–Early Jurassic) (Tulloch *et al.* 1999), consistent with derivation from the Darran Suite (Landis *et al.* 1999; Turnbull & Allibone 2003). The conglomeratic input reflects uplift and erosion of the Median Batholith, possibly in response to accretion to Gondwana. However, the influx of coarse detritus could also be a response to magmatic underplating (uplift) or regional convergence. The first option (Late Permian accretion) is preferred here in the regional context.

The Brook Street Terrane in the Wairaki Hills is overthrust (westwards) by the Murihiku Terrane along the Letham Ridge Thrust, possibly during Early Cretaceous time (Landis *et al.* 1999). The Hawtel Formation limestone and the Wairaki Formation volcaniclastics are likely to have been detached and bulldozed ahead of the advancing Murihiku Terrane to form the melanges at this stage. This interpretation explains the combined gravitational ('olistostromal') and tectonic features of the melange, as noted by Landis *et al.* (1999).

Early Permian Dun Mountain ophiolite

The Early Permian (*c.* 277 Ma) Dun Mountain ophiolite (Kimbrough *et al.* 1992; Jugum *et al.* 2019) and related igneous rocks (Otama Complex) (*c.* 269 Ma) are exposed on both sides of the Alpine Fault (Fig. 15.2). Dense ophiolitic rocks are inferred to continue northwards and southwards for hundreds of kilometres based on subsurface geophysical evidence (Hatherton 1966; Hatherton & Sibson 1970; Mortimer *et al.* 2002). Nowhere is an intact pseudostratigraphy exposed but the ophiolitic belt (excluding melange) can be traced almost continuously in outcrop (Coombs *et al.* 1976; Davis *et al.* 1980; Sinton 1980; Kimbrough *et al.* 1992; Jugum 2009; Jugum *et al.* 2006; Stewart *et al.* 2019).

The ophiolite belt traces southwards from D'Urville Island to the Red Hills and is then offset by the Alpine Fault to near Red Mountain (Fig. 15.2). Different parts of the ophiolite pseudostratigraphy are exposed in different outcrops: for example, cumulates crop out from the Maitai River southwards (at least to Hacket River), whereas depleted mantle is well exposed at Red Hills, and basaltic flows occur in many outcrops (Stewart

et al. 2016; Jugum *et al.* 2019). One-hundred per cent sheeted dykes are only rarely mappable: for example, in the Nelson area (e.g. Tinline River, United Creek; upper West Branch of Wairoa River) (Johnston 1981; Rattenbury *et al.* 1998). The Dun Mountain and Red Hills massifs are exceptional in that they include extensive unserpentinized ultramafic rocks, providing insights into primary magmatic and tectonic processes (Stewart *et al.* 2016, 2019).

Typical ophiolitic rocks extend southwards from the Alpine Fault as far as Five Rivers Plain (Southland) (Fig. 15.2). The Red Mountain outcrop includes intact ultramafic rocks, surrounded by serpentinite melange (Sinton 1980). Southwards (e.g. Barrier River, Diorite Stream and Olivine River areas), thick, relatively continuous outcrops of upper-crustal rocks include mafic lavas, volcaniclastic sediments, gabbro and diabase dykes (Turnbull 2000). Farther south again, intact outcrops are sparse and mainly comprise upper-crustal rocks (e.g. Livingstone Mountains and West Dome), although sheared and disrupted serpentinized mantle rocks also occur widely (Craw 1979).

Ophiolite remnants as regionally coherent oceanic crust

Do the ophiolite outcrops represent a single, evolving tectonic–magmatic setting or are they an amalgam of different oceanic crustal units? A case in point is Dun Mountain itself, which exposes a large body of ultramafic rocks, notably dunite. The peridotite outcrop is surrounded on three sides by the ophiolite-related melange (Patuki Melange; see below). On the remaining, fourth, side, the Dun Mountain massif is separated by a high-angle fault from the regional ophiolite outcrop to the west, which includes similar ultramafic rocks (Johnston 1981). The Dun Mountain ultramafic massif is within the mapped Patuki Melange (Rattenbury *et al.* 1998), and so might have a different origin to the more intact ophiolite section farther west. Also, in many areas (e.g. northern Southland), the ophiolite belt is represented by serpentinite melange or basalt–diabase–gabbro ('spilitic') melange (Craw 1979; Sinton 1980) of debatable origin (see below). In places, ophiolitic rocks are structurally reduced or missing entirely, as locally in Southland (Turnbull 2000; Turnbull & Allibone 2003), questioning whether an intact ophiolite was originally ever present in all areas.

Should the ophiolite, therefore, be viewed as accretionary melange on a regional scale? On the contrary, petrological and chemical similarities indicate that all of the ophiolite outcrops, including the Dun Mountain ultramafic massif, represent remnants of the same overall body of emplaced oceanic lithosphere. The major ophiolitic sections (e.g. Red Hills massif) lack the distinctive structural imprint and the mixing of different sedimentary and igneous components that characterize the structurally underlying Patuki Melange (see below). Large ophiolitic fragments in the Patuki Melange, where present (e.g. Dun Mountain massif), can be interpreted as fragments of the regional-scale Dun Mountain ophiolite that were locally detached and entrained within the melange (Robertson 2019*b*).

Although commonly assumed to have formed in a mid-ocean ridge (MOR)-type oceanic setting (Coombs *et al.* 1976; Sinton 1980; Sano & Kimura 2007; Kimura & Sano 2012) (Fig. 15.8a), it is now becoming increasingly clear that the Dun Mountain ophiolite formed in a supra-subduction zone setting (Sivell & McCulloch 2000; Jugum 2009; Jugum *et al.* 2006, 2019; Stewart *et al.* 2016, 2019; Brathwaite *et al.* 2017; Robertson 2019*b*) (Fig. 15.8b). The petrology, geochemistry and structure of the crustal and mantle sections, taken as a whole, differ from MOR lithosphere (Jugum *et al.* 2019; Stewart *et al.* 2016, 2019). The ophiolite south of the Alpine Fault includes MOR-type crustal rocks low in the lower part of the
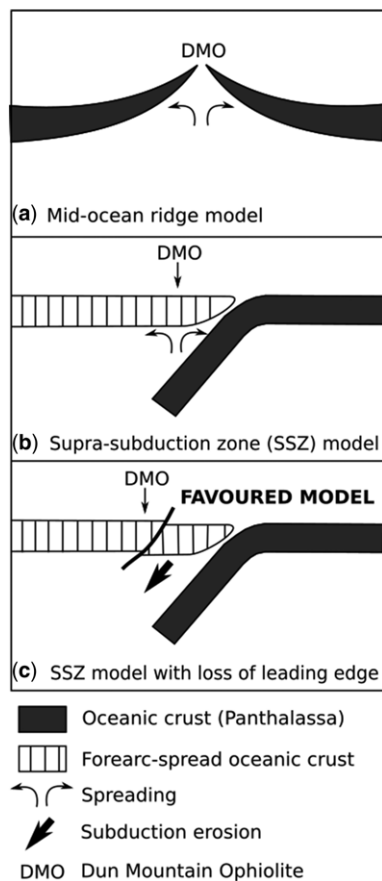
Fig. 15.8. Alternative tectonic models for the Dun Mountain ophiolite. (**a**) Mid-ocean ridge (generalized); based on Coombs *et al.* (1976) and Sinton (1980). (**b**) Forearc genesis above a westward-dipping subduction zone (in current coordinates), as generally favoured by Jugum *et al.* (2019) and Robertson (2019*a*). (**c**) As for (b) but with the removal of the leading edge of the supra-subduction slab, part of which is now preserved in the Patuki Melange, as proposed by Robertson (2019*a*); see the text for discussion.

pseudostratigraphy (Jugum *et al.* 2019). This is compatible with supra-subduction zone genesis because similar MOR-type basalts are known to occur in the Izu–Bonin forearc (Reagan *et al.* 2017). The Dun Mountain ophiolite is generally comparable to ophiolites worldwide (e.g. Troodos Ophiolite, Cyprus; Coast Range Ophiolite, California; Bay of Islands Ophiolite, Newfoundland; Semail Ophiolite, Oman) that are widely interpreted to have formed by spreading above a subduction zone (e.g. Pearce *et al.* 1984; Pearce & Robinson 2010). However, supra-subduction zone ophiolites are not all identical, and can record different settings of genesis, stages of development and emplacement (Shervais 2001). The Dun Mountain ophiolite contributes to an understanding of subduction-initiation processes, including petrogenesis (Jugum *et al.* 2019) and synmagmatic deformation. Stewart *et al.* (2019) propose subduction initiation in an oblique transtensional setting with interesting ramifications for the regional tectonic development.

Supra-subduction zone ophiolites can form in both 'pre-arc' settings related to subduction initiation (prior to typical calc-alkaline arc magmatism) and also in rifted back-arc settings. Back-arc genesis has been proposed for the Dun Mountain ophiolite (Sano *et al.* 1997; Sivell & McCulloch 2000; Jugum *et al.* 2006) mainly on geochemical grounds. However, there is no evidence of the expected precursor volcanic arc (e.g. intercalated arc detritus) that would have split to form a marginal basin, based on a comparison with modern arc-marginal basin systems (Taylor & Karner 1983; Taylor & Martinez 2003). Recent evidence from D'Urville Island suggests that

previously inferred marginal basin ophiolitic rocks (Sivell & McCulloch 2000) can instead be interpreted as fragments of the supra-subduction zone Dun Mountain ophiolite that were incorporated into the Patuki Melange (Johnston 1996; see Jugum *et al.* 2019; Robertson 2019*a*).

Tectonic setting of genesis and emplacement

The best-documented ophiolites, represented by Tethyan-type supra-subduction zone ophiolites, have similar crustal organizations despite different ages and locations. These ophiolites are characterized by a well-developed sheeted complex of 100% regularly orientated diabase dykes. The Late Cretaceous Troodos Ophiolite, Cyprus (e.g. Malpas 1990), the Late Cretaceous Semail Ophiolite, Oman (Lippard *et al.* 1986), the Jurassic Vourinos Ophiolite, northern Greece (Moores 1969) and the Ordovician Bay of Islands Ophiolite, Newfoundland (Jenner *et al.* 1991), to name a few examples, have similar lithologies and crustal organization.

The Dun Mountain ophiolite has similarities and differences with typical Tethyan-type ophiolites (Fig. 15.9a, b). Both have extensive depleted mantle harzburgites, and include layered cumulates, massive gabbros, widespread dykes and basaltic volcanics. The Troodos extrusive sequence, for example, begins with high-Si, moderate-Fe tholeiites (Lower Pillow Lavas), followed by boninites (Upper Pillow Lavas) (e.g. Pearce & Robinson 2010). The Dun Mountain ophiolite also shows an upward change from MOR-like extrusives to more clearly subduction-influenced extrusives, especially south of the Alpine Fault (Jugum *et al.* 2019).

On the other hand, the Dun Mountain ophiolite differs in several respects from typical Tethyan-type ophiolites: (1) The uppermost basaltic rocks of the ophiolite in the Nelson area (north of the Alpine Fault) are comparable with P- or T-type MORB (Jugum *et al.* 2019; Robertson 2019*b*), differing, for example, from the highly depleted Troodos Upper Pillow Lavas (e.g. Pearce & Robinson 2010). (2) The uppermost ophiolite crust unit in Southland (south of the Alpine Fault) is evolved and relatively arc-like (Jugum *et al.* 2019). This contrasts with the highly depleted boninitic Troodos Upper Pillow Lavas but is similar to some other Tethyan ophiolites, including the eastern Albanian ophiolite (e.g. Robertson 2002; Dilek & Flower 2003). (3) The Dun Mountain ophiolite crustal pseudostratigraphy includes several stages of compositionally variable dyke intrusion, including diabase gabbro, plagioclase-phyric dolerite and clinopyroxene-phyric dolerite (Jugum *et al.* 2019). Outcrops of regular 100% sheeted dykes are relatively rare, as noted above. Being extremely robust, it is unlikely that vast sheeted dyke bodies similar to those of the Troodos Ophiolite were selectively cut out, tectonically. Alternatively, the dykes (and related minor intrusions) were largely emplaced as compositionally variable swarms, without regional development of a sheeted dyke complex. Swarms of compositionally variable dykes and minor intrusions that cut all levels of the ophiolite pseudostratigraphy are not a feature of Tethyan-type ophiolites (e.g. Troodos and Oman). (4) Both chromite (Brathwaite *et al.* 2017) and copper mineralization (Johnston 1981) are located within the cumulate zone, as mapped in several exposures north of the Alpine Fault. In typical Tethyan ophiolites (e.g. Troodos), chromites occur within dunite and harzburgite, whereas copper mineralization is mainly located within higher-level basalts and sheeted dykes (e.g. Constantinou 1980; Robertson & Xenophontos 1993). (5) There is no preserved pelagic or hydrothermal metalliferous sediment cover to the Dun Mountain ophiolite, in contrast with, for example, the Troodos and Oman ophiolites (see Robertson 2019*b*). The above differences suggest that the Dun Mountain ophiolite relates to subduction initiation in a specific tectonic setting, which could differ
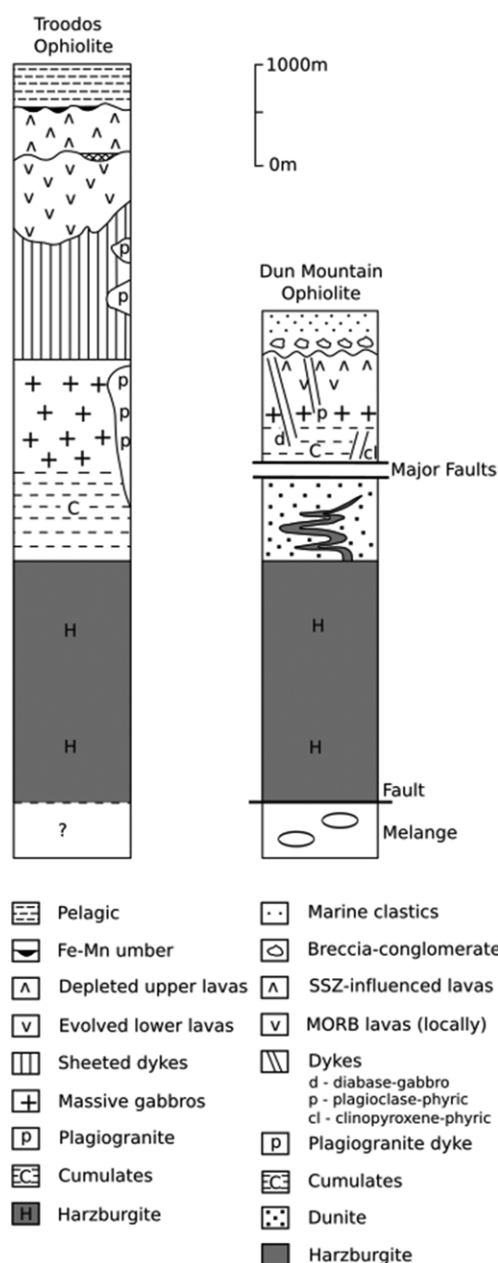
Fig. 15.9. Comparison of the Late Cretaceous Troodos Ophiolite with the Permian Dun Mountain ophiolite (including contrasting sedimentary covers). MORB, mid-ocean ridge basalt; SSZ, supra-subduction zone. Data sources: Troodos Ophiolite: Malpas (1990); Dun Mountain ophiolite: Coombs et al. (1976), Kimbrough et al. (1992) and Jugum (2009); see the text for discussion.

from other well-documented supra-subduction ophiolites (e.g. Troodos and Oman ophiolites).

The Dun Mountain ophiolite can also be compared with Cordilleran-type ophiolites (Moores 1982) that have accreted along an active continental margin: for example, the Jurassic Coast Range Ophiolite, western USA (Metzger et al. 2002; Shervais et al. 2004), or the late Precambrian ophiolites (e.g. greenstones) of SE Australia (Cawood & Buchan 2007; Cawood et al. 2009). Both Tethyan- and Cordilleran-type ophiolites can, in principle, undergo similar petrogenesis related to subduction initiation. However, Cordilleran-type ophiolites commonly lack a well-defined sheeted dyke complex: for example, the majority of Proterozoic–Cenozoic ophiolites described from China (Zhang et al. 2008). Also, these ophiolites lack a typical metamorphic sole or structural

evidence of obduction onto continental crust. Although an intensively deformed 'protoclastic zone' is present in places in the Dun Mountain ophiolite (see Walcott 1969; Coombs et al. 1976), this may not be obduction-related. Recent work points instead to multiple overprinting fabrics within the upper mantle (Webber et al. 2008).

The Dun Mountain ophiolite is interpreted as a Cordilleran-type ophiolite, mainly because accretionary emplacement is in keeping with the regional tectonic setting (Robertson 2019b). In principle, emplacement could be achieved either by westward (continentward) or by eastward (oceanward) subduction. However, Tethyan-type ophiolites that relate to oceanic-directed subduction are emplaced as enormous intact thrust sheets, in response to subduction zone–passive continental margin collision (e.g. Oman Ophiolite). However, the Dun Mountain ophiolite is strip-like (>1000 km), typical of Cordilleran ophiolites (e.g. Coast Range Ophiolite), in contrast to the sheet-like Tethyan ophiolites. Also, evidence of nappe-like ophiolite emplacement has not been reported from the East Gondwana continental margin.

Ophiolite genesis related to west-facing subduction

The ophiolite outcrop is too narrow (<10 km) to preserve a compositional variation that could be indicative of subduction polarity. However, subduction polarity is generally assumed to have been west-dipping in present geographical coordinates (Sivell & McCulloch 2000; Jugum 2009; Jugum et al. 2019; Robertson 2019a, b). Three main circumstantial lines of evidence favour westward-dipping subduction: (1) The Patuki Melange, which is broadly interpreted as a subduction complex (Kimbrough et al. 1992; Malpas et al. 1994; Jugum 2009; Jugum et al. 2019; Robertson 2019a; see below), is located along the eastern side of the ophiolite, whereas the western side is covered by the intact Permian–Triassic Maitai Group sedimentary rocks (see below). (2) Westward subduction is the simplest option because subsequent Permian–Early Cretaceous subduction is inferred to have been in this direction (Adams et al. 2007; Mortimer & Campbell 2014); oceanward subduction would have emplaced the Dun Mountain ophiolite as a regional-scale thrust sheet for which there is no evidence.

Subduction initiation model for the Dun Mountain ophiolite

The Dun Mountain ophiolite can be interpreted as an incipient (poorly developed), irregularly spreading, supra-subduction zone spreading centre. The plutonic lithologies and geochemical evidence suggest a relationship to subduction initiation (see Jugum et al. 2019; Stewart et al. 2019). Many other supra-subduction ophiolites are related to subduction initiation (e.g. Troodos: Pearce & Robinson 2010). Recent deep-sea drilling of the Izu–Bonin outer forearc, NW Pacific (Reagan et al. 2015, 2017) has revealed MORB (forearc basalt: FAB) in a distal (near-trench) setting and low Ca-boninites several kilometres behind this (Fig. 15.10). Sheeted dykes have been identified beneath both types of extrusive rock, although how extensive these are is unknown. Gabbro appears to be present beneath boninite on the adjacent trench slope (Reagan et al. 2010). The MOR-type basalts of the Dun Mountain ophiolite can be compared to forearc basalt. However, there are no confirmed petrographical records of boninites in the Dun Mountain ophiolite extrusive sequence unlike many (but by no means all) supra-subduction zone ophiolites elsewhere (e.g. Pearce 1982; Pearce et al. 1984). Despite this, boninitic-composition melts are inferred to have been generated at depth (see Jugum et al. 2019), comparable to those of the Troodos Ophiolite (Pearce & Robinson 2010).
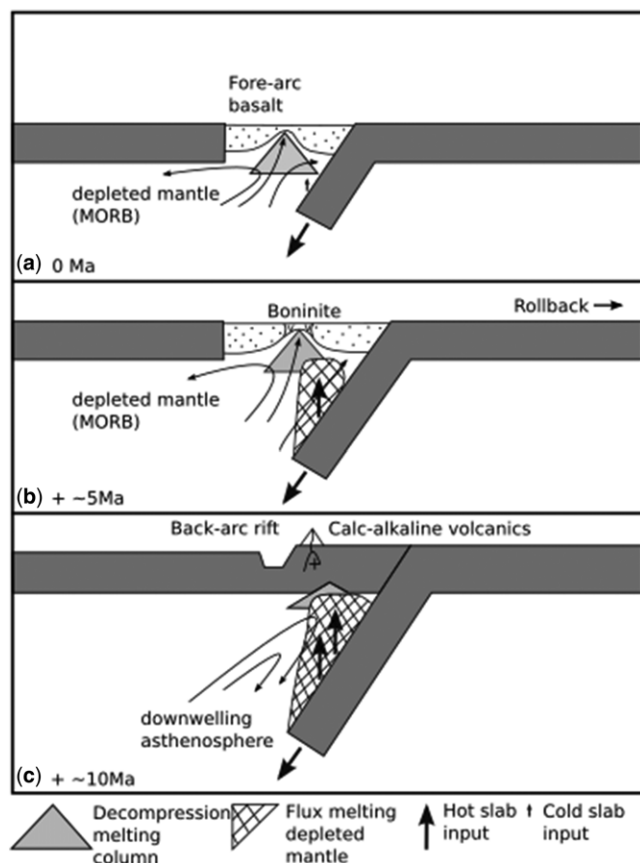
Fig. 15.10. Model of ophiolite genesis based on the Izu–Bonin forearc, NW Pacific (modified from Reagan *et al.* 2017), which has both similarities and differences with the inferred genesis of the Dun Mountain ophiolite. (**a**) Subduction initiation results in roll-back of pre-existing oceanic crust. Depleted mantle decompresses and melts in a water-poor setting, generating near-MORB composition magma, which erupts as forearc basalt (FAB). (**b**) *c.* 3 myr later, with continuing subduction, increasing water flux results in higher degrees of partial melting and genesis of highly magnesian, low-Ca boninite. (**c**) <1.2 myr later (Reagan *et al.* 2019), greatly increasing seawater flux gives rise to large-scale melting of depleted mantle and the onset of conventional calc-alkaline arc volcanism. Note the inferred change in mantle convection direction between (b) and (c). See the text for discussion.

Setting of subduction initiation and incipient arc genesis

Subduction of the >1000 km-long Dun Mountain ophiolite is likely to have initiated sub-parallel to the SE Gondwana continental margin (Fig. 15.11). A popular hypothesis is that subduction initiation takes place along oceanic fracture zones (Stern & Bloomer 1992). In this case, the fracture zone would need to parallel the Gondwana margin for hundreds of kilometres, with orthogonal spreading. The spreading fabric of Panthalassa is unknown and could have been highly oblique to the adjacent continental margin. Fracture zones in the eastern part of the Cocos Plate (e.g. Panama Fracture Zone), for example, trend *c.* north–south, almost at right angles to the Central American active continental margin (Barckhausen *et al.* 2001). However, there is no evidence of subduction initiation in this setting. It is instead more likely that subduction initiated within a spreading fabric that was orientated sub-parallel to the Gondwana active continental margin (*c.* north–south in present coordinates). Similarly, subduction in the Izu–Bonin arc, NW Pacific appears to have initiated at *c.* 50 Ma, sub-parallel to a pre-existing Cretaceous active continental margin (Arculus *et al.* 2015; Robertson *et al.* 2017; Reagan *et al.* 2019). Also, several Cenozoic ophiolites appear to have formed adjacent
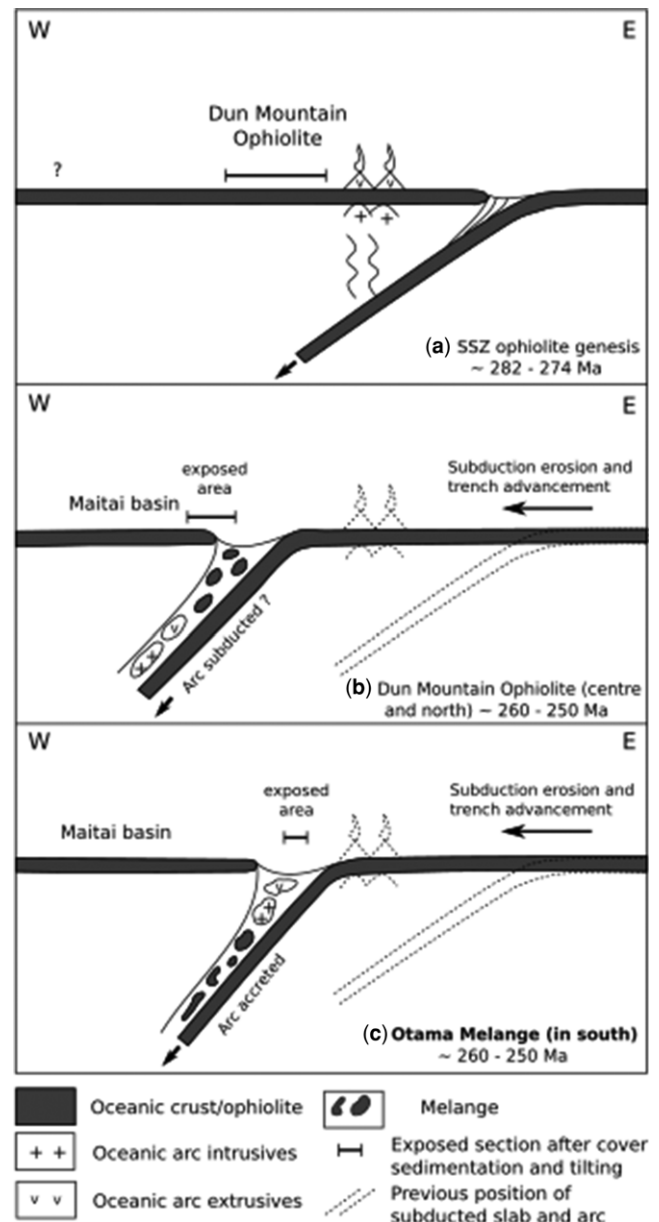

Fig. 15.11. Tectonic model for the genesis of the Dun Mountain ophiolite, the Otama Complex and the Patuki Melange involving variable amounts of subduction–erosion of the overriding oceanic plate from north to south; the relative positions of the inferred incipient oceanic arc are indicated in (a)–(c). (**a**) The Dun Mountain ophiolite forms in a supra-subduction zone forearc setting, transitional westwards to an incipient oceanic arc. (**b**) Related to ongoing subduction, the forearc crust and incipient arc detach and subduct, 'eating into' supra-subduction crust behind (note: the dotted arc and slab indicate the previous setting as in a). (**c**) Farther south (Southland), subduction–erosion is more advanced and fragments of the incipient arc are preserved within the Otama Complex, together with some supra-subduction zone extrusive ophiolitic rocks; see Robertson (2019*a*) and the text for explanation.

(sub-parallel) to relatively young, active continental margins rather than along a transform fault, in an open-ocean setting (Hall 2018).

Subduction initiation is, however, unlikely to have taken place in a very proximal continental margin setting as there is no evidence of terrigenous sediments within the Dun Mountain ophiolite extrusive sequence. Terrigenous material first appears within the Upukerora Formation (as fine-grained muscovite), after the inferred mid-Permian docking with Gondwana (Robertson 2019*b*). The likely scenario is that ophiolite genesis

initiated along a *c.* north–south zone of rheological weakness that was located sub-parallel to, and oceanwards of, the SE Gondwana active continental margin.

Alternative possible settings of the subduction-initiation include: (1) A structural and/or age discontinuity within pre-existing MOR-type crust. For example, subduction is inferred to have begun along a spreading-related detachment fault zone in the Jurassic Albanian ophiolite (e.g. Maffione *et al.* 2015); (2) A crustal discontinuity between a pre-existing earlier-Permian oceanic arc (Brook Street arc or counterpart) that was located inboard (west) of the locus of subduction initiation. Such an age, and thus rheological, contrast is known to be a potential trigger for subduction-initiation, based on modelling (Leng & Gurnis 2015). (3) Preceding continentward subduction was possibly oblique, which would have compartmentalized sub-duction along the Gondwana active continental margin into segments undergoing near-orthogonal subduction and others characterized by transform faulting, similar to the modern Andaman Sea (Cochran 2010). Such a transform segment could have been forcefully converted into a subduction zone, which, once nucleated, propagated along the active margin.

Supra-subduction zone spreading implies compensating roll-back of relatively dense, descending oceanic lithosphere (Fig. 15.8b). Regional evidence of a switch from extensional to contractional (convergent) accretionary orogenesis during the Permian (Cawood 2005; Cawood & Buchan 2007) suggests that subduction initiation is likely to have been forced, rather than occurring spontaneously (see Stern 2004). In such a setting, slab roll-back may not have readily taken place, which in turn would have inhibited the establishment of a well-developed (steady-state) spreading axis. In this case, limited extension was instead largely accommodated by localized sheeted dyke intrusion and by ubiquitous, irregular intrusion of small gabbroic bodies and multiple dyke swarms.

The highest levels of the ophiolite sequence in many areas to the south of the Alpine Fault (e.g. Livingstone Mountains) include arc-like extrusive rocks and related evolved arc-like intrusive rocks (Pillai 1989; Jugum *et al.* 2019; Robertson 2019*b*). This implies that as subduction continued, a nascent arc developed near or above the initially formed supra-subduction crust. This contrasts with, for example, the Izu–Bonin–Mariana arc, where the related arc developed several hundred kilometres away from the locus of subduction initiation (Reagan *et al.* 2008, 2013).

In summary, the Dun Mountain ophiolite is interpreted as relating to a setting of subduction initiation (possibly oblique: Stewart *et al.* 2019). However, this did not proceed directly to a well-developed spreading axis generating large volumes of oceanic lithosphere. Instead, only incipient spreading took place, largely accommodated by multi-stage dyke intrusion. With continuing subduction, an incipient arc developed directly above, or adjacent to, the preserved ophiolite (at least in the south). Assuming an age of *c.* 277 Ma for the ophiolite (based on plagiogranites) and of *c.* 269 Ma for the arc (based on granitic rocks) (Jugum *et al.* 2019), the incipient seafloor spreading is likely to have been followed by arc magmatism after up to *c.* 8 myr.

Permian Otama Complex: emplaced incipient oceanic arc

In the south (south of Five Rivers Plain; Fig. 15.2), the exposure of the Dun Mountain ophiolite is replaced by dominantly arc-related magmatic rocks. This assemblage has been given different names by different authors (Coombs *et al.* 1976; Cawood 1986, 1987; Jugum 2009; Jugum *et al.* 2019). The term Otama Complex (Wood 1956) is favoured by Robertson

(2019*a*) mainly because fieldwork indicates a composite origin, made up of several different lithological components.

The Otama Complex comprises the following main units: (1) a coherent sequence of basic to felsic extrusive rocks (north Lintley Hills), which is interpreted as a southward transition from the Dun Mountain ophiolite to an incipient oceanic arc; (2) large bodies (up to many-kilometre-sized) of arc-type extrusive rocks, with or without enveloping sedimentary rocks (e.g. south Lintley Hills) (Cawood 1986, 1987; Robertson 2019*a*); (3) a *c.* north–south-trending, narrow, elongate belt of mixed terrigenous–volcaniclastic sediments in the NE of the outcrop (unnamed unit of Cawood 1986), which includes scattered detached blocks of basic to felsic extrusive and intrusive rocks, including plagiogranite and granitoid rocks (Coombs *et al.* 1976; Cawood 1986, 1987; Kimbrough *et al.* 1992; Robertson 2019*a*). Rare intercalations of debris-flow conglomer-ates include similar lithologies (Cawood 1986). Widespread atomodesmatinid bivalve fragments (mostly moulds) within the associated sedimentary rocks (unnamed unit of Cawood 1986) suggest a Permian age (Cawood 1986, 1987; Turnbull & Allibone 2003; Robertson 2019*a*).

Where radiometrically dated, the intrusive igneous rocks are similar in age (*c.* 278 Ma) or slightly younger than the Dun Mountain ophiolite (Kimbrough *et al.* 1992; Jugum *et al.* 2019). A granodiorite was dated at 269.3 ± 4.5 Ma, suggest-ing that arc magmatism was active during Middle Permian time (Jugum 2009; Jugum *et al.* 2019). No ultramafic rocks are present in the Otama Complex (Coombs *et al.* 1976; Cawood 1986, 1987). However, the occurrence of a sub-parallel magnetic anomaly (Junction Magnetic Anomaly) sug-gests the presence of dense ultramafic rocks at depth (Hatherton 1966, 1969; Hatherton & Sibson 1970; Mortimer *et al.* 2002). The felsic extrusive rocks and intrusive rocks, including gran-itoids, are interpreted as remnants of an incipient (poorly devel-oped), subaqueous oceanic arc (Coombs *et al.* 1976; Robertson 2019*a*). A juvenile arc is consistent with the relatively short time available for genesis prior to accretion to Gondwana, together with the Dun Mountain ophiolite (Mid-Permian; see below). The arc developed beyond the Otama Complex in the south, at least for 200 km northwards, based on evidence from the ophiolite outcrops and detritus in the overlying Upu-kerora Formation (Pillai 1989; Turnbull 2000; Robertson 2019*b*; see below). The oceanic-arc magmatism represented by the Otama Complex was probably terminated by Mid-Permian accretion to Gondwana, together with the Dun Moun-tain ophiolite.

Two explanations for the overall southward change from the Dun Mountain ophiolite (without arc rocks) to the Otama Complex are: (1) The Dun Mountain ophiolite terminated south-wards abruptly and was replaced by an incipient oceanic vol-canic arc, represented by the Otama Complex (Coombs *et al.* 1976). This implies subduction at a high angle to the overall north–south trend of the Dun Mountain–Maitai Terrane, allow-ing the present outcrop to transect both the supra-subduction ophiolite and the arc in different areas. (2) The Dun Mountain ophiolite and the Otama Complex arc rocks represent differen-tially preserved parts of a single *c.* north–south-trending ophiolite-arc assemblage (Robertson 2019*a*) (Fig. 15.12a–d).

The second option is supported by the following evidence. Extending as far north as the Alpine Fault, the coarse clastic sedimentary rocks of the Upukerora Formation, which uncon-formably overlies the Dun Mountain ophiolite, include both intrusive and extrusive felsic arc-type rocks (Pillai 1989; Rob-ertson 2019*b*). The felsic clasts are chemically similar to the evolved arc-type rocks of the Otama Complex (Robertson 2019*b*). In addition, a *c.* 268 Ma age of detrital zircons from sandstones was obtained from the upper part of the Upukerora Formation in the Alpine area (Jugum *et al.* 2019). This is close to the age of the arc-related magmatism in the Otama Complex
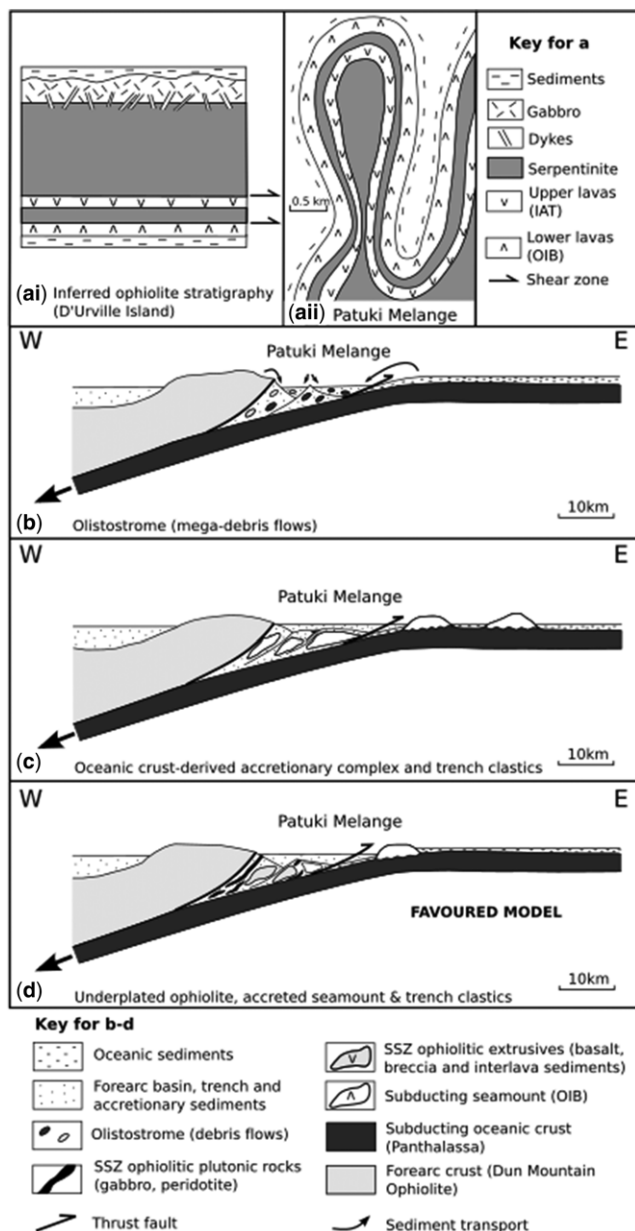
Fig. 15.12. Alternative tectonic models for the Patuki Melange.
(**a**) Original ophiolitic crust (**ai**: restored cross-section), based on outcrops on D'Urville Island. The inferred ophiolite was isoclinally folded (**aii**: map view) to produce the present complex outcrop; based on Sivell (2002).
(**b**) Olistostrome in which sedimentary processes dominate the melange; based on Davis *et al.* (1980) and Sivell (1982). (**c**) Accretionary complex in which the igneous component is subducting oceanic crust, possibly including seamounts; based on Malpas *et al.* (1994). (**d**) Accretionary complex in which most of the igneous rocks detached from the overriding oceanic plate (Dun Mountain ophiolite), whereas a subordinate component of the melange accreted from the downgoing oceanic slab (e.g. seamount crust); based on Robertson (2019*a*).

(*c.* 269 Ma) (Jugum *et al.* 2019). By implication, the arc magmatism extended for a total distance of >350 km, with a >200 km overlap with the exposed ophiolite.

In the second (preferred) interpretation, the apparent southward change from the Dun Mountain ophiolite to the Otama Complex oceanic arc can be explained as follows (see Fig. 15.11a–c). Both ophiolitic and arc rocks originally formed along (and beyond) the entire length of the outcrop but are selectively preserved. With ongoing westward subduction (probably oblique), increasing amounts of subduction erosion

(i.e. tectonic removal of the overriding forearc), took place generally from north to south. In the north, the distal (easterly) edge of the supra-subduction zone ophiolite slab is still largely preserved (Fig. 15.11a), without felsic arc-type rocks (Nelson area). The overlying, coarse clastic sediments of the Upukerora Formation there do not contain arc-derived felsic material (Robertson 2019*b*). However, an oceanic arc may be located to the west, beneath the Maitai Basin (see below). There is possible support for this in the form of clinopyroxene-rich sandstones in the lower part of the cover succession (Bryant Member) in the Nelson area (see Robertson & Palamakumbura 2019*b*).

Southwards, more of the supra-subduction zone slab subducted, such that the preserved crust is nearer to the oceanic arc, as inferred from the arc-type material in both the ophiolite and basal sedimentary cover (Upukerora Formation), south of the Alpine Fault (Fig. 15.11b). Southwards again, still more of the supra-subduction zone ophiolitic slab was removed and the trench began to 'eat into' the oceanic arc behind. The arc then became the leading edge of the (remaining) overriding plate, where it was sliced and intercalated with trench/forearc sediments (e.g. south Lintley Hills). Owing to the attempted consumption of the thickened arc-related crust, the subduction décollement rose; deeper-level ultramafic (ophiolitic) rocks subducted, whereas the remaining overriding plate was sheared and brecciated on a regional scale to form the Otama Complex (Cawood 1986; Jugum 2009; Robertson 2019*b*) (Fig. 15.11c). Fragments of the leading edge of the forearc/arc slab collapsed into the trench as detached blocks and were transported as clasts within debris flows into a deep-water trench or outer forearc setting (Robertson 2019*a*). A possible reason for the inferred north–south difference in the extent of removal of the overriding plate (subduction–erosion) is that subduction (convergence) was oblique to the overriding plate, possibly continuing after subduction initiation (see Stewart *et al.* 2019).

Are the Dun Mountain ophiolite and the Brook Street Terrane arc related?

Before leaving the topic of oceanic crust genesis and emplacement it should be noted that several authors have suggested a formational link between the arc magmatism of the Brook Street Terrane and the Dun Mountain ophiolite (Coombs *et al.* 1976; Sivell & McCulloch 2000; Spandler *et al.* 2005) (Fig. 15.5b). However, no primary relationships are preserved linking these two crustal units (e.g. interfingering lithologies). Also, the Brook Street and the Dun Mountain–Maitai terranes are separated by the Murihiku Terrane, which complicates any attempted correlation (Fig. 15.2).

The palaeontological evidence supports an Early Permian (Sakmarian–Kungurian) age for the Brook Street Terrane arc volcanics (Takitimu Group), as noted above (Waterhouse 1964, 1982, 2002; Johnston & Stevens 1985; Campbell 2000, 2019). The Dun Mountain ophiolite magmatism is radiometrically dated at *c.* 278–269 Ma (Kungurian–Roadian) (Jugum *et al.* 2019). Mafic rocks that were dredged from the inner trench slope of the Izu–Bonin–Mariana forearc (52–45 Ma) are *c.* 2–9 myr older than the associated transitional arc magmatism (high-Mg andesites) (Reagan *et al.* 2010). The time gap represents the period necessary, after subduction-zone initiation, for a large-scale influx of water to induce 'normal' calc-alkaline magmatism (Reagan *et al.* 2017) (Fig. 15.10c). Assuming a subduction-initiation model for the Dun Mountain ophiolite, as discussed above, related arc magmatism should have commenced around 270 Ma (Kungurian), based on comparison with the Izu–Bonin arc. This is inconsistent with the Early Permian (Sakmarian–Kungurian) palaeontological age of the Brook Street Terrane (Takitimu Group) (see Campbell

2019) but corresponds well with the age of the late-stage arc-type magmatism, represented by the Otama Complex. Volcanism within the Brook Street Terrane appears to have climaxed during the Early Permian (Artinskian: c. 290–283 Ma), represented by the Chimney Peaks, Heartbreak and McLean Peaks formations, prior to genesis of the ophiolite (c. 278 Ma) (Jugum et al. 2019).

A second option is that the Brook Street Terrane magmatic arc rifted in a back-arc setting to form the Dun Mountain ophiolite. Back-arc spreading would have needed to be well advanced to accommodate the MOR-like chemistry of the Dun Mountain ophiolite lower extrusives, where present (Jugum 2009; Jugum et al. 2019), by comparison with modern back-arc basins (e.g. Izu–Bonin–Mariana arc system) (Taylor & Martinez 2003; Pearce et al. 2005). A substantial frontal arc should exist between any back-arc (i.e. ophiolitic) basin and Panthalassa oceanic crust (to the east), for which there is no preserved evidence.

The Dun Mountain ophiolite has also been compared with the Yakuno Ophiolite of the Maizuru Terrane in SW Japan (c. 285–282 Ma), which has an early MOR (or Large Igneous Province)-type stage and a later subduction-influenced stage of development (Herzig et al. 1997). Plagiogranites also occur within the composite Koh Terrane in New Caledonia. Correlative ophiolitic rocks along the central chain of New Caledonia have also been compared to the Dun Mountain ophiolite (Aitchison et al. 1998), although published ages (c. 302 and c. 290 Ma) are significantly older. All of these arc and ophiolite units are likely to represent fragments of marginal seas that bordered eastern Gondwana during the Early Permian, potentially extending for several thousand kilometres of palaeolatitude, similar to the modern Izu–Bonin–Mariana arc and back-arc system.

Patuki Melange: subduction–accretion v. subduction–erosion

The Dun Mountain ophiolite is structurally underlain by the Patuki Melange (equivalent to the Windon Melange of Craw 1979), extending from D'Urville Island to Five Rivers Plain (near Mossburn; Fig. 15.2). Farther south, the Otama Complex replaces both the ophiolite and the Patuki Melange. Several lines of evidence indicate a close genetic relationship between the Dun Mountain ophiolite and the Patuki Melange: (1) In some areas (e.g. Dun Mountain, Nelson area) there is an eastward transition from coherent ophiolite, to increasingly disrupted ophiolite, to the mapped Patuki Melange (Johnston 1981). (2) In the Nelson area generally, both the ophiolite and the melange occur side by side; sometimes the former is narrow and the latter wide, and vice versa (Johnston 1981; Rattenbury et al. 1998). However, in some areas farther NE, extending to, and within, D'Urville Island, only melange is exposed (Begg & Johnston 2000). A similar pattern exists south the Alpine Fault, with melange predominating or replacing coherent ophiolite in some areas (e.g. North Mavora Lake–Bald Hill). Overall, the ophiolite–melange zone is essentially continuous. (3) Extrusive and intrusive (mafic and ultramafic) rocks can be broadly matched between the Dun Mountain ophiolite and the Patuki Melange, in terms of lithology, geochemistry and age (Coombs et al. 1976; Kimbrough et al. 1992; Jugum 2009; Jugum et al. 2019; Robertson 2019a).

Robertson (2019a) interprets the Patuki Melange as an accretionary complex (Fig. 15.12d), which is made up of the following main components: (1) ophiolitic remnants (extrusive and intrusive), which are broadly correlated with the Dun Mountain ophiolite; these include serpentinized ultramafic rocks (Coleman 1966), mafic rocks (e.g. gabbro) and felsic rocks (e.g. plagiogranite), together with common subduction-influenced

basaltic rocks (Robertson 2019a); (2) localized alkaline basaltic rocks (Sivell & McCulloch 2000) are interpreted as accreted seamounts (Robertson 2019a); and (3) mixed terrigenous–volcaniclastic sedimentary rocks, mostly sandstones (Robertson & Palamakumbura 2019c) and mudstones (Palamakumbura & Robertson 2019), together with minor conglomerates, are inferred to be of Late Permian age, based on limited fossil evidence and chemical comparisons (Robertson 2019a).

Plagiogranites in the Patuki Melange, from the Livingstone Mountains, are similar in age to those of the Dun Mountain ophiolite (Jugum 2009; Jugum et al. 2019). On the other hand, some mafic extrusive rocks in the Patuki Melange (e.g. Coal Hill Inclusion, northern Southland) are chemically more arc-like than most of the ophiolitic extrusive rocks of the Dun Mountain ophiolite, although similar arc-like rocks occur in the highest levels of the volcanic succession south of the Alpine Fault (e.g. in the Livingstone Mountains) (Robertson 2019a). Sandstones within the melange have yielded detrital zircon ages that are consistent with a Late Permian igneous provenance (Jugum et al. 2019). Petrographical and geochemical evidence suggest a distal equivalence of the melange clastic sediments with the Late Permian Tramway Formation (Maitai Group) (Robertson 2019a; Robertson & Palamakumbura 2019b; Palamakumbura & Robertson 2019). The clastic sediments accumulated in a deep-sea trench and/or trench-slope basin setting. Initially, coherent successions were dismembered and variably mixed with ophiolitic and other igneous rocks (seamounts) to form melange (Robertson 2019a).

Robertson (2019a) proposes a tectonic model (Fig. 15.12d) in which ophiolitic lithologies were detached from the overriding (supra-subduction zone) forearc wedge, intercalated with mixed terrigenous–volcaniclastic sediments, underplated at shallow depths within the subduction zone and then exhumed as melange. The Patuki Melange was finally juxtaposed with the Caples Terrane to the east along the Livingstone Fault, potentially with entrainment of fragments of one, or the other, or both, lithotectonic units along the fault zone in some areas.

North of the Alpine Fault, within the Caples Terrane, there in another melange known as the Croisilles Melange (Dickins et al. 1986; Landis & Blake 1987; Rattenbury et al. 1998; Begg & Johnston 2000) (Fig. 15.2). Ophiolitic basalts in this melange are MOR-like, similar to some of the 'lower basalts' of the Dun Mountain ophiolite (Jugum et al. 2019). Also, plagiogranites in both the Dun Mountain ophiolite and the Croisilles Melange have similar ages (Kimbrough et al. 1992).

The Croisilles Melange (Landis & Blake 1987) shows many features in common with the Patuki Melange, such that the two units can be correlated, although minor differences exist (e.g. basalt chemistry) (Robertson 2019a). The Patuki and Croisilles melanges (and equivalents) are interpreted to have originated as a single, regionally developed Late Permian subduction complex (Robertson 2019a).

South of the Alpine Fault, the comparable Greenstone Melange within the Caples Terrane is likely to be an extension of the Croisilles Melange and thus basically part of the Patuki Melange. Specifically, the Eyre Creek Melange is essentially a broken formation of gabbro, basaltic lavas and chert. This is interpreted as emplaced oceanic crust that could be significantly older than the presumed age of the melange, based on a possible Carboniferous conodont occurrence (Pound et al. 2014).

The accretionary melange as a whole was dismembered after the Triassic, related to regional-scale, thick-skinned thrusting. As a result, the structural fabric of the Croisilles Melange is cut by the dominant structural fabric (cleavage) of the adjacent Caples Terrane (Johnston 1993; Rattenbury et al. 1998; Begg & Johnston 2000). Part of the melange remained with the overriding ophiolite (Patuki Melange), whereas other parts were sliced into the Caples Terrane (Croisilles and Greenstone melanges).

This style of deformation is comparable to the large-scale, out-of-sequence thrusting that affects many accretionary wedges, such as Nankai, in southern Japan (Park *et al.* 2002). However, outcrops of the Greenstone Melange close to the Alpine Fault may have been reactivated diapirically during late Cenozoic time (Bishop *et al.* 1976).

Maitai basin: distal forearc

The mid–Late Permian to Middle Triassic Maitai Group, which unconformably overlies the Dun Mountain ophiolite (Landis 1974; Owen 1995; Campbell & Owen 2003), has been variously interpreted as a continental margin forearc basin (Carter *et al.* 1978; Owen 1995), a rifted back-arc basin (Pillai 1989; Adams *et al.* 2009c), or an oceanic arc-related succession (Aitchison & Landis 1990). In this Memoir, the Maitai Group is extensively discussed and interpreted as the relatively distal part of a continental margin forearc basin, which generally evolved from underfilled to filled, or even overfilled (Palamakumbura & Robertson 2019; Robertson 2019b; Robertson & Palamakumbura 2019a, b). The sedimentary succession was variously derived from an evolving continental margin arc, its associated country rocks and from contemporaneous shallow-water carbonates. A forearc basin setting (Fig. 15.13a) is preferred rather than one in which the Maitai Group represents a back-arc basin (Fig. 15.13b).

Sandstone petrography and chemistry (Robertson & Palamakumbura 2019c), and also mudrock (shale) geochemistry (Palamakumbura & Robertson 2019), chart an evolution of the Maitai basin from a relatively evolved active continental margin-arc signature in the Late Permian to a less evolved but still continental margin-arc signature during the Early–Middle Triassic. The provenance broadly mirrors the evolution of

the Longwood Suite during the latest Permian and of the Darran Suite beginning around the mid-Triassic (see Fig. 15.4). However, there is little record of active magmatism within the Median Batholith during the Early Triassic (Mortimer *et al.* 2014). Assuming derivation from the Median Batholith (or an along-margin equivalent), this could suggest that the copious volcaniclastic material in the Early Triassic interval of the Maitai Basin is likely to be mainly erosional (epiclastic), potentially from any part of the preceding Tuhua-related arc rocks. On the other hand, the abundance of felsic fall-out tuff within the Maitai Basin (Stephens Subgroup) during the Early–Middle Triassic (Robertson *et al.* 2019b) confirms that arc magmatism was active during this time, regionally.

Prograding clastic sediments include channelized conglomerates that have rounded arc-derived granitic clasts in some sections, including the Wairoa River (Richmond area) and near Mossburn (Southland) (Fig. 15.2). A Late Permian radiometric age for a diorite clast from the Stephens Subgroup near Mossburn suggests a provenance link with the Longwood Suite or a non-exposed lateral equivalent (Mortimer *et al.* 2019). The presence of the channelized conglomerates suggest that the ophiolitic basement subsided with time, allowing very coarse debris to prograde across the basin.

During the Late Permian, the Maitai basin was fringed by a substantial carbonate platform which fed large volumes of bioclastic carbonate into the succession by gravity-flow processes, as mainly recorded in the Wooded Peak Formation. As with the inferred Permian and Triassic volcanic sources, no trace of the Permian carbonate source remains within the Western Province. A smaller-scale Early Triassic successor carbonate platform is recorded by the presence of exotic blocks within the upper part of the Maitai Group (see Robertson & Palamakumbura 2019b, c).

Relationship of the basal Upukerora Formation to the ophiolite beneath

The basal Upukerora Formation constitutes a critical link between the Dun Mountain ophiolite and the overlying Maitai Group. Unfortunately, this formation, which is dominated by breccias and conglomerates, remains poorly dated, in part, because it lacks age-diagnostic fossils. As a result, two main, alternative 'age models' have been considered. Model 1 assumes a direct continuity of volcanism between the Dun Mountain ophiolite and the overlying Upukerora Formation (Pillai 1989; Adamson 2008). However, this is not supported by field evidence from Southland or from north of the Alpine Fault: for example, feeder intrusions have not been reported anywhere (Robertson 2019b). Model 2 assumes the existence of an unconformity and a major time gap (Kimbrough *et al.* 1992). A *c.* 20 myr hiatus following ophiolite volcanism was suggested by Kimbrough *et al.* (1992). The youngest evolved arc-type intrusions in the Otama Complex are dated at *c.* 269 Ma (Jugum *et al.* 2019). Detrital zircons from sandstone of the Upukerora Formation south of the Alpine Fault (Heu Member) have yielded an age grouping at 267.8 ± 4.7 Ma (Jugum 2009; Jugum *et al.* 2019). Robertson (2019b) proposes that the duration of the hiatus was variable in different areas; up to *c.* 9 myr in areas where the Upukerora Formation overlies oceanic crust without associated arc magmatism (e.g. Nelson area) but much shorter (*c.* 3 myr) where this formation originally overlay arc-type rocks (Otama Complex) in the south.

Faulting and Maitai Basin initiation

The Upukerora Formation is interpreted as being the result of pervasive extensional growth faulting of the underlying Dun
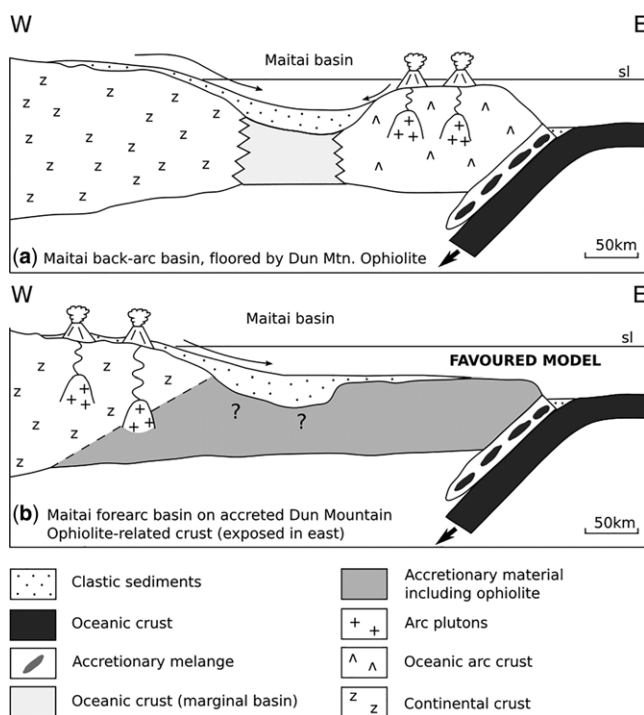

Fig. 15.13. Alternative interpretations of the Permian–Triassic Maitai Group (Dun Mountain–Maitai Terrane). (**a**) Maitai Group as a back-arc basin, with the Dun Mountain ophiolite as part of the floor of this basin (Dun Mountain marginal basin); based on Adams *et al.* (2009b). (**b**) Maitai Group as a continental margin forearc basin. The basin could be underlain by accretionary material (including ophiolite); based on Robertson & Palamakumbura (2019b, c) (preferred model); see the text for explanation.

Mountain ophiolite (Robertson 2019*b*). Three main alternative settings can be considered for this fault-related genesis: (1) back-arc rifting (Fig. 15.14a). This is questioned by the absence of observed coeval volcanism, and the hiatus (albeit variable) between magmatism and clastic deposition. (2) Oceanward-facing forearc extensional faulting (Fig. 15.14b) as in the Eocene Izu–Bonin oceanic forearc (e.g. Robertson *et al.* 2017). However, an eastward-dipping palaeoslope is inconsistent with the stratigraphy and provenance of the Maitai Group as a whole. Also, a distal, open-ocean setting is incompatible with the presence of terrigenous material (e.g. muscovite) in mudrocks of the Upukerora Formation, where rarely deposited (Pillai 1989; Palamakumbura & Robertson 2019; Robertson 2019*b*). (3) Robertson (2019*b*) proposes that the inferred faulting was triggered by the docking of the ophiolite/oceanic arc with the Gondwana active continental margin (Fig. 15.14c). Such docking implies the shutdown of a continental margin subduction zone and the transfer of convergence to the remaining more oceanic subduction zone, outboard (east) of the newly accreted ophiolite. This major regional kinematic change could have resulted in a pulse of accelerated subduction, with

associated uplift of the distal (easterly) margin of newly created forearc basin. This would explain the evidence (e.g. well-rounded clasts) of a relatively shallow-water source for some of the detritus in the Upukerora Formation (Robertson 2019*b*).

Timing and settings of Permian bioclastic deposition

Distinctive atomodesmatinid (bivalve)-rich limestones characterize the Maitai Group, the Brook Street Terrane and, to a lesser extent, the Murihiku Terrane (see below). Did these carbonates form in a single or in multiple depositional settings and are they all of similar age?

The atomodesmatinid-rich limestones of the Maitai Group, mainly within the Wooded Peak and Tramway formations, have previously been correlated with the Permian atomodesmatinid-rich limestones of the Productus Creek Group of the Brook Street Terrane in the Wairaki Hills (Southland) (Waterhouse 1964, 1980, 2002). The Productus Creek Group overlies the uppermost basaltic lavas (Caravan Formation) (Force 1975; Landis *et al.* 1999), as noted above. The limestones of the Wooded Peak Formation are intercalated with Gondwana-derived, mixed terrigenous–volcaniclastic sediment (Robertson & Palamakumbura 2019*b*), which is absent from the Productus Creek Group (Force 1975; Landis *et al.* 1999; Robertson & Palamakumbura 2019*a*), ruling out a common provenance. Both units are entirely redeposited and source bioherms are not exposed in either case. The limestones of the Wooded Peak Formation are interpreted as Late Permian (Wuchiapingian), whereas the Productus Creek Group (together with the associated Hilton Limestone) are dated as Early–Late Permian (Kungurian–Changhsingian) (Campbell 2019). However, the upper unit of the Productus Creek Group (Glendale Formation) is likely to be broadly contemporaneous with the Wooded Peak Formation (Campbell 2019).

The Wooded Peak and Tramway formations (Maitai Group) are characterized by very-high-abundance but low-diversity fauna, dominated by the atomodesmatinid bivalves. The Glendale Formation is similarly dominated by atomodesmatinid fragments, with only rare brachiopods, gastropods, corals and bryozoans (Waterhouse 1964, 1980, 2002; Landis *et al.* 1999). On the other hand, the Wooded Peak Formation includes coarse clastic sediments with ophiolitic debris, both near the base (Anslow Member) and also the top (Waitaramea Member) of the succession (in different areas). These clastic units include a relatively diverse fauna, including atomodesmatinids, bryozoans, brachiopods, gastropods and echinoderms (Owen 1995; Stratford *et al.* 2004).

The atomodesmatinid-dominated fauna of the Wooded Peak and Tramway formations originated from a carbonate platform that fringed the adjacent Gondwana active continental margin. A likely setting would be marine lagoons that were protected from open-ocean storm activity (and consequent nutrient supply) by off-margin barriers, specifically the recently accreted Dun Mountain ophiolite. Carbonate accumulation was followed by repeated redeposition by gravity flows on a seaward-sloping ramp, with final accumulation in fault-controlled depocentres (Robertson & Palamakumbura 2019*b*). In contrast, ophiolite debris with diverse faunal elements (Anslow and Waitaramea members) was redeposited from small, localized off-margin ophiolitic highs that formed as a result of the inferred mid-Permian ophiolite accretion (Robertson 2019*b*). With open ocean to the east, greater nutrient availability would have supported a relatively diverse fauna in these off-margin carbonate deposits, compared to the large-scale, more inboard, facies mainly represented by the Wooded Peak Formation.

Coarse conglomerates within the Early–Middle Triassic upper part of the Maitai Group (Stephens Subgroup) commonly contain rounded clasts (up to cobble sized) of extrusive and

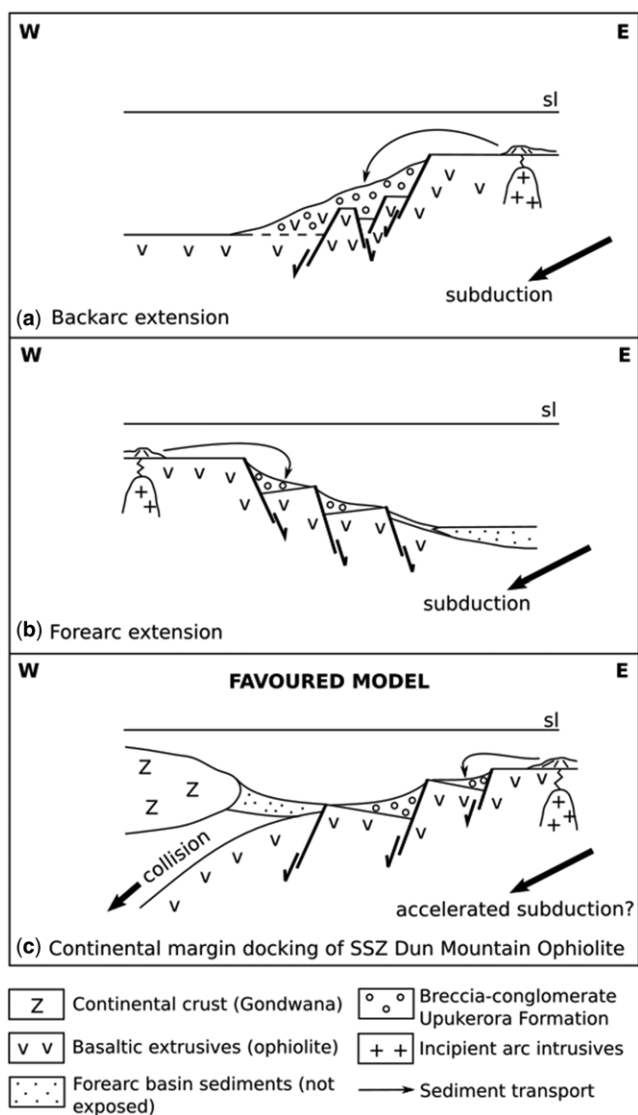**Fig. 15.14.** Alternative interpretations of the mid–Late Permian Upukerora Formation (lowermost Maitai Group). (**a**) & (**b**) Faulting in an open-ocean setting, either back-arc or forearc. (**c**) Faulting relates to docking of the Dun Mountain ophiolite with the SE Gondwana continental margin and related change in the subduction kinematics; based on Robertson (2019*b*) (preferred interpretation); see text for explanation.

intrusive rocks. These conglomerates locally (e.g. Mossburn Quarry) include large boulders of Permian atomodesmatinid limestone, together with Triassic bioclastic debris (Mortimer *et al.* 2019). The bioclastic debris was probably carried into the Maitai basin, together with igneous material, from the Median Batholith (or an along-strike equivalent), as supported by the latest Permian age of a diorite clast from Mossburn Quarry (Mortimer *et al.* 2019).

In summary, atomodesmatinid bivalves and related fauna flourished at various times during the Permian, associated with three main identifiable tectonic settings: (1) active continental margin (e.g. Wooded Peak Formation); (2) fringing (by then) inactive oceanic-arc volcanoes (Productus Creek Group); and (3) locally around small outer-arc highs created by ophiolite accretion (e.g. Anslow and Waitaramea members). The atomodesmatinid sediment contribution appears to have peaked during the Late Permian, but also contributed to both older (Middle Permian) and younger (Early–Middle Triassic) sedimentation (Campbell 2019).

Termination of the Maitai forearc basin

Preserved deposition within the Maitai Group terminated at an indeterminate time during the Middle Triassic, both north and south of the Alpine Fault (Campbell & Owen 2003; Campbell 2019). In contrast, sedimentation in the adjacent Murihiku Terrane persisted until the earliest Cretaceous in North Island (J.D. Campbell *et al.* 2003; see below). Possible reasons for the termination of sedimentation in the Maitai basin are: (1) the forearc basin overfilled leading to non-deposition, although there is no evidence of shallowing upwards or emergence; (2) the forearc basin uplifted and deposition ceased; for example, as a result of changed subduction rate or direction but again there is no obvious evidence for this; and (3) and sedimentation continued (possibly paralleling that of the Murihiku Supergroup) but is not preserved owing to later erosion, subduction, or tectonic dismemberment, which is the preferred option.

Metamorphism affecting the Maitai basin sediments

The Brook Street Terrane (Houghton 1982), the Murihiku Terrane (Coombs 1950) and also the south coast Willsher Group (Paull *et al.* 1996; see below) underwent metamorphism that is consistent with stratigraphic burial, albeit variable, as supported by experimental studies (Cho *et al.* 1987). In contrast, the Drumduan Terrane (Nelson area) and the Dun Mountain–Maitai Terrane in some areas show evidence of HP–LT metamorphism in the form of sporadic lawsonite (Landis 1974; Johnston *et al.* 1987; Owen 1995). In the Nelson area, lawsonite occurs preferentially within cleaved argillaceous facies of the Early Triassic Greville Formation, suggesting a compositional influence on mineral growth or preservation. The Greville Formation in Nelson is largely within the Roding Syncline, which could suggest a structural influence (locally increased burial). However, lawsonite is reported more widely from south of the Alpine Fault (e.g. Livingstone Mountains), although it is not recorded from the lowest or the highest levels of the succession. Lawsonite (of uncertain origin) has also been detected by X-ray diffraction in mudrocks within the Patuki Melange (from Bald Hill) within a little-deformed clastic succession (Palamakumbura & Robertson 2019). In general, there is no obvious correlation of lawsonite with zones of high strain (Landis 1974; see Supplementary material).

Alternative explanations of the lawsonite are: (1) very deep stratigraphic burial; and (2) subduction. Based on experimental data, the lowest pressure–temperature conditions of lawsonite formation remain poorly defined but are likely to be equivalent to >12 km burial, assuming normal geothermal gradients (Comodi & Zanazzi 1996). Given that lawsonite also occurs within the upper kilometre or so of the Maitai Group (Landis 1974; Owen 1995), >17 km of sediment equivalent (above this) would be needed to generate lawsonite by simple sedimentary burial. This is excessive assuming stratigraphical burial within a continental margin forearc basin (Dickinson 1995).

The lawsonite is instead interpreted to have formed beneath a major tectonic load: that is, within a subduction zone. Despite this, an origin as a typical subduction–accretion complex (e.g. the Jurassic Franciscan Complex) (e.g. Blake 1984; Snow *et al.* 2010) is improbable for both the lawsonite in the Maitai Group, the Drumduan Terrane (Nelson area) and the Patuki Melange. The Maitai Group retains a coherent stratigraphic succession, with no evidence of structural repetition as in typical accretionary complexes. If the Maitai Group was buried sufficiently deeply to form lawsonite, this must also apply to the unconformably underlying Dun Mountain ophiolite, although HP–LT minerals have not been reported within it (e.g. Coombs *et al.* 1976). Either lawsonite never formed in the ophiolitic rocks or it entirely retrogressed. The lawsonite preservation is unusual and can be satisfactorily explained by subduction, followed soon afterwards by exhumation, thereby limiting both prograde and retrograde neomorphism (e.g. Clarke *et al.* 2006; Tsujimori *et al.* 2006).

The timing of lawsonite formation within the Maitai Group and the Drumduan Terrane is poorly constrained, although metamorphism related to Early Cretaceous collisional orogenesis (i.e. traditional Rangitata Orogeny: Carter *et al.* 1978) has been suggested for the Drumduan Terrane (Nelson) (Johnston *et al.* 1987) and is also likely for the Maitai Group (Landis 1974). Lawsonite formation in the Drumduan Terrane was previously explained by eastwards (oceanwards) subduction beneath the Brook Street Terrane (Johnston *et al.* 1987). This would require a *c.* 150 km-wide downgoing plate, assuming a subduction geometry similar to the modern Nankai Trench (e.g. Kodaira *et al.* 2000). However, eastward (oceanward) subduction would appear to conflict with the regionally inferred westward subduction during Permian–end-Early Cretaceous time (Mortimer & Campbell 2014). A possible explanation of the lawsonite is that during Early Cretaceous collision, which terminated subduction (see below), the Maitai forearc basin as a whole and part of the marginal Drumduan arc-related volcanogenic unit detached and briefly lodged beneath the Gondwana active continental margin; this was soon followed by exhumation related to rifting of the Tasman Sea Basin (*c.* 100 Ma).

Murihiku Terrane: proximal forearc basin

The Late Permian–earliest Cretaceous Murihiku Terrane is extensive in both South Island and North Island (Campbell & Coombs 1966; H.J. Campbell *et al.* 2003). Some new geochemical data are given in this Memoir for Triassic felsic tuffaceous sedimentary rocks (Robertson *et al.* 2019b), and a small number of Late Permian and Triassic sandstones (Robertson & Palamakumbura 2019c). Comprehensive reviews of the Murihiku Terrane can be found in, for example, Coombs *et al.* (1976), Ballance & Campbell (1993), Roser *et al.* (2002), H.J. Campbell *et al.* (2003), Turnbull & Allibone (2003) and Adams *et al.* (2007). Numerous sedimentary breaks are suggested by the stratigraphical record (see Campbell 2019). However, the Murihiku represents an overall shallowing-upward succession, which developed from moderately deep marine (several hundred metres) in the Late Permian–Middle Triassic to shallow-marine, paralic and fluvial subsequently (Noda *et al.* 2002; J.D. Campbell *et al.* 2003; Turnbull & Allibone 2003). Gravity-flow deposition (mass flow and turbidity current) dominated

during the Late Permian–Late Triassic in slope to base-of-slope settings, as indicated by the sedimentology of the Kuriwao and North Range groups.

Based mainly on the literature, three main alternative tectonic settings can be considered for the Murihiku Terrane (Fig. 15.15a–c):

1. Off-margin arc: westward subduction: pilot-scale Nd isotopic analysis of sandstones has suggested a change from early-stage (Late Permian–Early Triassic) input from relatively non-evolved volcanic sources to later-stage more felsic volcanic sources, with a contribution from continental crust (Frost & Coombs 1989). Geochemical data, including rare earth elements (REEs), from a wide range of localities and different stratigraphic intervals support and develop this overall interpretation (Roser et al. 2002; Robertson & Palamakumbura 2019c). Sand-sized terrigenous detritus is not reported until after the Middle Triassic
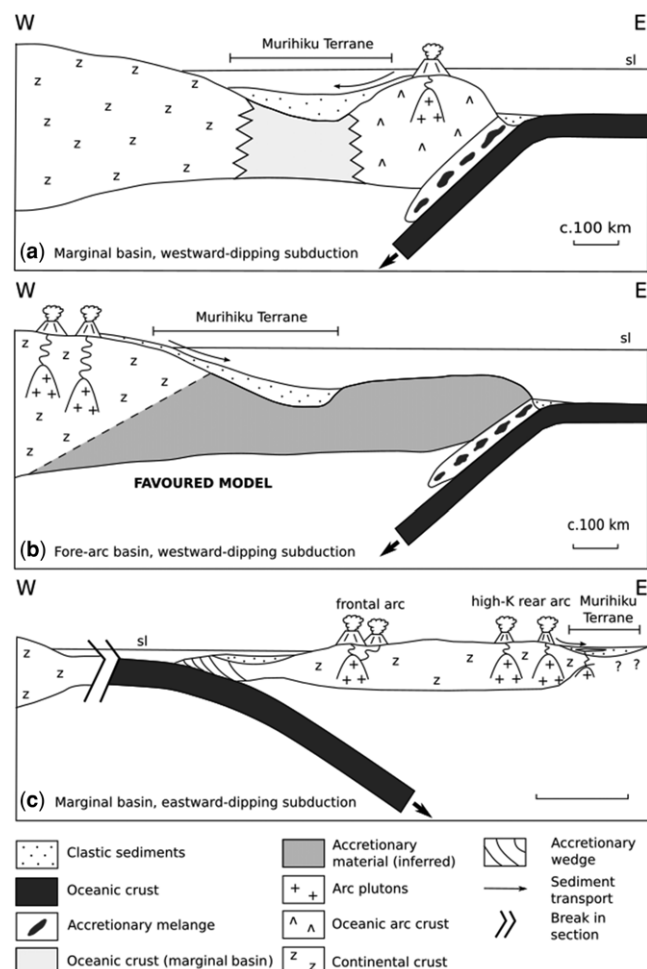

Fig. 15.15. Alterative interpretations of the Murihiku Terrane. (**a**) As a proximal part of a rear-arc apron, within a back-arc marginal basin. The marginal basin was floored by oceanic crust, potentially the Dun Mountain ophiolite. Similar to Figure 15.13a, but possibly in a more southerly position along the Gondwana margin; based on Roser et al. (2002) and Adams et al. (2009b). (**b**) As a proximal part of a continental margin forearc basin. The basin is assumed to be underlain by (non-radiogenic) accreted (or trapped) oceanic crust, similar to Figure 15.13b but in a more proximal setting. No trace of the inferred basement remains; based on Robertson & Palamakumbura (2019c) (preferred interpretation); see the text for explanation. (**c**) As a back-arc basin behind an inferred (off-margin) microcontinent, related to eastward (oceanward) subduction. High-K magmatic rocks (Park Volcanic Group) characterize the Late Triassic of the Murihiku Terrane, possibly representing a back-arc setting; based on Coombs et al. (1992).

(Roser et al. 2002). This evidence has been used to support an off-margin, arc-like depositional setting, similar to the modern Aleutian or Taranaki back-arc basins (Roser et al. 2002; Adams et al. 2009c; Strogen et al. 2017) (see Fig. 15.15a).

The provenance of the Murihiku Terrane is broadly comparable with that of the Téremba Terrane, New Caledonia and there are similarities in fauna (Campbell et al. 1985; Adams et al. 2009c; Ullmann et al. 2016; see above). Nd and Sr isotopic data from the Téremba Terrane indicate an oceanic source with little evidence of a continental crust or sediment influence, except in sparse samples (Cluzel & Meffre 2002; Adams et al. 2009c). However, there is no requirement for the two terranes to originate in geographical proximity (see Supplementary material Fig. S3 for two alternatives).

The first appearance of copious continental detritus (e.g. metamorphic quartz; lithic fragments; muscovite) within the Late Triassic–earliest Cretaceous time interval of the Murihiku Terrane has previously been explained by the juxtaposition of an oceanic arc-related unit with the Gondwana continental margin, by accretion or strike-slip (Roser et al. 2002). Such an abrupt change in tectonic setting is, however, difficult to reconcile with the overall progressive facies trends throughout the Murihiku Terrane from the Late Permian onwards (Boles 1974; Noda et al. 2002).

2. Off-margin arc with eastward subduction: back-arc rifting took place above an eastward (oceanward)-dipping subduction zone in this suggested alternative (Fig. 15.15c). This setting was proposed largely to explain the chemical composition of Late Triassic medium- to high-K shallow intrusions and/or flows within the Murihiku Terrane, in widely spaced areas (Park Volcanics Group) (Coombs et al. 1992). A back-arc rift setting could be consistent with mainly eastward-directed palaeocurrent evidence in the Murihiku Terrane (Boles 1974), assuming that this was located to the east of the arc. The back-arc interpretation is difficult to evaluate geochemically because any volcaniclastic input from the Park Volcanics Group is not easily distinguishable from volcaniclastic input from the Western Province Paleozoic terranes or the Median Batholith (see the Supplementary material). In the regional context, there is no independent evidence of east-directed subduction or of the implied existence of a related subduction–accretion complex to the west of the Murihiku Terrane

3. Continental margin forearc basin (favoured model): the Murihiku Terrane represents a proximal segment of a continental margin forearc basin (Ballance & Campbell 1993; Frost et al. 2005; Robertson & Palamakumbura 2019c), for which the Median Batholith, or a possible non-exposed lateral extension, represents the likely source (Fig. 15.15b). The commonly coarse nature of the sediments, including channelized conglomerates and shallow-marine deltaic sediments in the higher parts of the succession (Noda et al. 2002; Turnbull & Allibone 2003), indicate a proximal depositional setting. Muscovite, of presumed terrigenous origin (i.e. plutonic or metamorphic), occurs throughout the Murihiku Terrane, even in the Late Permian–Middle Triassic interval that lacks obvious sand-sized terrigenous detritus (Boles 1974; Roser et al. 2002; Robertson et al. 2019b). Nd isotopic data from several clasts, and also from the matrix of a Late Triassic conglomerate, indicate the presence of both mafic and felsic arc-type and also continental crust-type contributions (Frost et al. 2005). The mainly Permian–Early Cretaceous age range of detrital zircons and the presence of minor Devonian detrital zircon populations are consistent with a source related to the Tuhua Intrusives in the Western Province

(or lateral equivalents) (Adams *et al.* 2007). In addition, clastic sedimentary rocks of the Murihiku Terrane have similarities with the Gondwana-like Triassic volcaniclastic sandstones (Topfer Formation) of the Western Province (Mortimer & Smale 1996; see above) and with the Jurassic Barretts Formation (Wairaki Hills) of the Brook Street Terrane (Landis *et al.* 1999).

On tectonic discrimination diagrams, the Late Permian and Triassic sandstones of the Murihiku Supergroup commonly plot in the continental island-arc fields (Robertson & Palamakumbura 2019c). These sedimentary rocks are similar to the composition of the Western Province metasediments and average terrigenous shale (Robertson & Palamakumbura 2019c). The igneous source contribution of the Murihiku Terrane during the Permian–Triassic broadly parallels that of the Median Batholith, from the Late Permian onwards. Felsic tuffs make a significant contribution during the Early–Middle Triassic and the Late Triassic (Boles 1974; Robertson *et al.* 2019b).

In summary, the Murihiku Terrane is interpreted as a proximal, generally prograding forearc succession during its entire Late Permian–earliest Cretaceous development (Fig. 15.15b). A possible explanation of the lack of coarse terrigenous sediment during the Late Permian–Middle Triassic is that the continental margin arc was blanketed by arc-related volcanogenic rocks which were erosionally dissected by Late Triassic time, allowing deeper-level sourcing from the Western Province and Tuhua Intrusives (and/or possible equivalents along strike).

The position of the Murihiku Terrane along the Gondwana active continental margin during its prolonged accumulation remains uncertain mainly because of the absence of provenance-diagnostic zircon populations (Adams *et al.* 2007). However, there are marked sedimentary and faunal differences with the Maitai Group (Owen 1995; Adams *et al.* 2007; Robertson & Palamakumbura 2019c), and it is unlikely that the two crustal units originated adjacent to the same stretch of the East Gondwana active continental margin. Fauna of the Téremba Terrane (New Caledonia) and the Murihiku Terrane share many features in common, as noted above (Campbell *et al.* 1985; Adams *et al.* 2009c). However, rather than restoring these two terranes geographically in close proximity, it is possible that the faunal similarities reflect similar depositional conditions along the Gondwana margin. Fossils were preferentially preserved in relatively shallow and rapidly deposited forearc basin sediments (e.g. Murihiku and Téremba terranes) compared to the deeper-water, more distal deposits (Maitai Group), where bottom currents were also colder (favouring carbonate dissolution).

The Murihiku Terrane was thrust, presumably westwards, over the Brook Street Terrane in the Wairaki Hills (Southland), as noted above, and probably also in the Nelson area (Johnston 1981; Rattenbury *et al.* 1998). This emplacement probably took place after Murihiku Supergroup deposition ended regionally (Early Cretaceous). The Brook Street Terrane was probably already near its present relatively southern position by the latest Permian. This would, in turn, imply that the Murihiku Terrane was near its present relatively southerly position at least by Early Cretaceous time. In summary, a relatively southerly position (similar to the Brook Street Terrane) is favoured for the Murihiku Terrane.

How then did the Brook Street Terrane come to be located between the Murihiku Terrane and the Median Batholith/Drumduan Terrane? The proximity of the Median Batholith and the Brook Street Terrane (Takitimu Group), at least by the Jurassic, is implied by the presence of the transgressive arc-derived detritus (Barretts Formation) (Landis *et al.* 1999; see above). A possible explanation of the relative positions is that, after accretion to the Gondwana active continental margin

during latest Permian time, the Brook Street Terrane remained submerged in a proximal forearc setting where it did not shed detritus to the adjacent forearc basin, including the Murihiku Terrane. Later, associated with Early Cretaceous regional convergence, both terranes were reactivated and the Murihiku Terrane was thrust westwards over the Brook Street Terrane.

Willsher Group: proximal forearc basin fragment

This well-exposed Triassic south-coast exposure is more important than its small size would suggest because it potentially represents an otherwise unknown Triassic forearc basin fragment. Known stratigraphically as the Willsher Group, or structurally as the Kaka Point Structural Belt (H.J. Campbell *et al.* 2003), the succession has been interpreted either as mainly relatively deep-water turbidites (J.D. Campbell *et al.* 2003) or as shallow-water coastal deposits (Jeans *et al.* 1997, 2003). Geochemically, the succession is rich in evolved arc-type volcaniclastic detritus including numerous ash layers (Roser & Korsch 1999). Tectonically, it is interpreted as the southernmost and youngest extension of the Maitai Group (Turnbull & Allibone 2003), or as a possible exotic micro-terrane (J.D. Campbell *et al.* 2003). The Willsher Group is specifically dated as late Early Triassic (Olenekian)–early Late Triassic (Carnian) (J.D. Campbell *et al.* 2003), implying that it covers much the same age range as the Stephens Subgroup (Maitai Group).

The dominant sedimentary rocks are dark-coloured, planar-laminated muddy siltstones (*c.* 80% by volume), notably the Karoro Formation, Bates Siltstone, Tilson Siltstone, Potiki Siltstone and Waituti Siltstone. There are also several intervals of fine-grained sandstone (*c.* 80 m-thick Kaka Point Volcanic Sandstone; *c.* 6 m-thick Pilot Point Sandstone). Bioturbation is common (e.g. *Chondrites*). Soft-sediment instability, slumping and dewatering structures characterize parts of the succession (J.D. Campbell *et al.* 2003). Plant debris is widespread. Palynomorphs and oxygen isotope data indicate an important terrestrial/freshwater input. Spores are abundant relative to saccate pollen, as in many nearshore settings. Spores, leaf and stem cuticle were assumed not to survive transport to a distal deep-water setting and, therefore, suggest an inshore, shallow-marine setting (Jeans *et al.* 1997, 2003). Some fine-grained ash beds contain plant detritus, suggesting rapid redeposition from land during flood events (J.D. Campbell *et al.* 2003), which is also consistent with a near-coastal environment. Overall, the succession has been explained by cyclic transgression–regression in a shallow-marine (<50 m), proximal prodelta setting (Jeans *et al.* 1997). On the other hand, the succession has also been interpreted as a deep-marine, mainly turbiditic succession, possibly on a distal basin plain (Bishop & Force 1969; J.D. Campbell *et al.* 2003).

The two alternative interpretations (near-coast v. deeper water, off-margin) can be evaluated based on facies evidence and comparison with modern and ancient depositional settings, as follows.

The Willsher Group facies show many features suggestive of an origin as prodelta deposits. In general, prodelta deposits are variably lenticular, undulose, cross-stratified and may show evidence of instability, slumping, dewatering or storm influence. They are commonly dominated by monotonous regular, thin- to medium-bedded muds, with or without bioturbation, and are mostly unaffected by waves and tides (Reading & Collinson 1996). Turbidites commonly occur and muds may be interbedded with proximal delta-front or deeper-water facies. Most studies have focused on the prodeltas of major rivers (e.g. Mississippi, Po, Yangtze) (e.g. Trincardi & Syvitski 2005). In contrast, most prodeltas on active continental margins, comparable to Gondwana during the Triassic, represent outbuilding of small deltas from numerous relatively

small rivers; these drain adjacent forearc terrains: for example, the Oregon Coast Range (Chan & Dott 1986) or the SW Japan forearc (Takano et al. 2013). In some cases, prodelta deposits lie behind a ridge which forms a trench-slope break (e.g. Tokai-oki–kumano-nada basins, SW Japan), producing a relatively quiet, ponded slope basin.

The presence of radiolarians, especially in the upper part of the succession (Potiki Siltstone) (Campbell 1996; Hori et al. 2003), indicates an open-marine influence. Also, the most common fossils in several of the siltstone units are cephalopod beaks and opercula, which could have been 'recycled' related to faecal input from fish and/or mososaur/nothosaur marine reptiles (H.J. Campbell unpublished data). The 80 m-thick Kaka Point Sandstone, specifically, could represent a prograding turbiditic sand lobe. The individual thick sandstone intercalations appear abruptly, with large (up to 60 cm-long) rip-up clasts near the base (J.D. Campbell et al. 2003), which is suggestive of a control by relative sea-level change (i.e. local tectonic and/or eustatic). The siltstones are likely to have been rapidly redeposited in a slope setting, which could explain the survival of spores, leaf and stem cuticle. Overall, the facies evidence and the fossil remains point to sediment accumulation in a relatively quiet, open-marine, outer prodelta setting, at variable water depths (c. 100–300 m).

The Willsher Group succession is similar to that of partially filled to overfilled forearc slope basins (Fig. 15.16a, b). For

Fig. 15.16. Interpretation of the south-coast outcrop of the late Early–early Late Triassic-aged Willsher Group (near Kaka Point): (**a**) map view; (**b**) cross-section. Felsic volcanism was highly active in the forearc hinterland; erosional products mixed with extrusive and some exposed intrusive rocks, and supplied detritus via a channel to a small delta; this periodically prograded seawards over oxygenated, silty and muddy, moderately deep, prodelta deposits. Felsic tuffs repeatedly rained down, both onshore and offshore, and were variably reworked downslope, mostly by low-density turbidity currents.

example, a close comparison can be drawn with the Mid-Pleistocene of the Tokai-oki-Kumano-nano forearc basins in SW Japan, as inferred from seismic reflection data. This setting is characterized by small fan/sheet turbidite infill during overall sediment progradation (Takano et al. 2013). Possible counterparts on land include the Plio-Pleistocene of the Boso Peninsula, Japan (Ito & Katsura 1992) and the Late Jurassic of Alaska (Tropaff et al. 2005).

Problematic, however, for both of the above interpretations are sedimentary structures and slumps in the Willsher Group that are reported to indicate a generally west-dipping palaeo-slope, which is opposite to that inferred for both the Murihiku and Maitai successions (J.D. Campbell et al. 2003). However, definite measurements remain to be made. If such a direction is confirmed, then it could be explained by landward current reworking (e.g. storm surges), downslope motion away from a seaward marginal ridge or tectonic rotation. Sediment flow directions can be very variable in forearc basins, with near-axial transport, especially during periods of overall subsidence when new accommodation space is continuously being created (e.g. Takano et al. 2013).

The Willsher Group can alternatively be compared with either the Murihiku Terrane or the Maitai Group on different grounds, as follows.

On lithological and chemical evidence, the sandstones of the Willsher Group have been compared with those of the Murihiku Supergroup (Campbell & Coombs 1966; Jeans et al. 2003; Roser & Coombs 2005). New chemical data for sandstones of the Murihiku Terrane from nearby Roaring Bay (Robertson & Palamakumbura 2019c) do, indeed, indicate some general chemical similarities with the Willsher Group sandstones (but see below). However, the metamorphic grade of the Willsher Group is slightly lower than the zeolite-facies grade of equivalent-aged facies within the Murihiku Supergroup (Coombs 1950; Boles & Coombs 1975; J.D. Campbell et al. 2003; Jeans et al. 2003).

On the other hand, several lines of evidence suggest a closer comparison with the Maitai Group: (1) the Willsher Group succession youngs northwards, in the same direction as the adjacent Maitai Group, but opposite to the Murihiku Terrane, which youngs to the SW (H.J. Campbell et al. 2003; Turnbull & Allibone 2003). (2) The outcrop abuts the Dun Mountain ophiolite, with no mapped equivalent of the Maitai Group, as mapped further north. Comparable, relatively felsic sandstones of Triassic age occur within the Stephens Subgroup, north of the Alpine Fault (Wairoa–Lee River area) (Owen 1995; Robertson & Palamakumbura 2019c). (3) Chemical diagrams indicative of the relative contributions of mantle, v. crustal sources (e.g. Th/Sc v. Zr/Sc: Bhatia & Crook 1986) suggest a closer similarity of the tuffaceous sandstones in the Willsher Group to similar lithologies in the Maitai Group rather than to those of the Murihiku Terrane (Robertson et al. 2019b).

Nevertheless, there are significant differences in age, facies and depositional setting between the Willsher and Maitai groups: (1) the age of the Willsher Group is likely to overlap with that of the Greville and Waiua formations, and the Stephens Subgroup (Maitai Group) (Campbell 2019), but lithologies differ markedly. (2) Prodelta deposition is inferred for the Willsher Group, in contrast to the inferred more distal, deep-water deposition for the Triassic of the Maitai Group as a whole (Robertson & Palamakumbura 2019b). (3) The Willsher Group has undergone minimal burial to temperatures of <100° C, based on the colour indices of a conodont element (Paull et al. 1996; Jeans et al. 1997). Also, white mica crystallinity is indicative of low anchizone to diagenetic zone conditions (Jeans et al. 1997, 2003). This contrasts with the phrenite–pumpellyite and higher-grade metamorphism of the Maitai Group (Coombs et al. 1976; Cawood 1987). (4) The Willsher Group contains a rich and diverse fauna of brachiopods, bivalves,
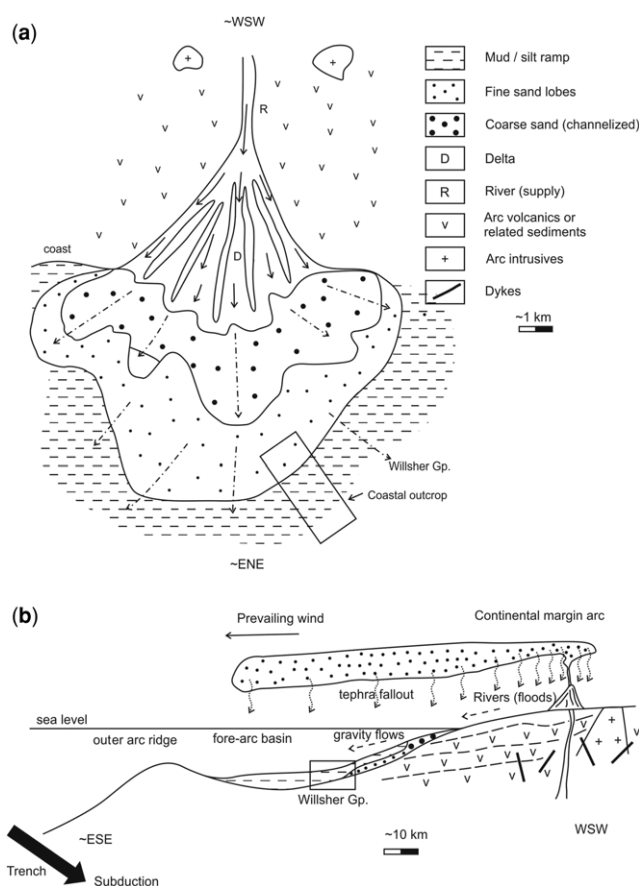
gastropod, crinoids, and ammonoids and crustaceans (Campbell 1996; H.J. Campbell et al. 2003), whereas the Maitai Group is only sparsely fossiliferous (Campbell & Owen 2003).

Taking all of the evidence together, the Willsher Group could be considered as a relatively proximal equivalent (distal prodelta) of the Maitai Group, which is otherwise not preserved regionally (Fig. 15.16a, b). This outcrop could be relatively in situ but only if the proximal to distal facies trend in the Maitai Group runs obliquely across the c. north–south Dun Mountain–Maitai Terrane (i.e. preserving much more proximal facies in the south). However, no such southward facies change is indicated by the Maitai Group, as exposed farther NE in the Otama and Arthurton areas (Cawood 1987; Robertson & Palamakumbura 2019b). Alternatively, the Willsher Group represents an exotic crustal fragment that was entrained between the Dun Mountain–Maitai and Murihiku terranes, probably during pre-Late Cretaceous terrane displacement (J.D. Campbell et al. 2003). Proximal equivalents of the Maitai forearc basin must have existed regionally, of which the Willsher Group could be the only known remnant.

Caples Terrane as a subduction–accretion complex

The most important issues concerning the mapped Middle Permian–Middle Triassic Caples Terrane are whether it is mainly a strongly deformed stratigraphic succession (Caples Group: Turnbull 2000) or a subduction–accretion complex, and also its timing of formation. New data for the Caples Terrane (Fig. 15.2) in this Memoir are restricted to some field and chemical evidence, including REE data, mainly from outcrops in the west, adjacent to the Dun Mountain–Maitai Terrane (Robertson & Palamakumbura 2019c). The summary below begins with the westerly belt of the Caples Terrane, for which some new data are available, and then considers the terrane as a whole, making use of existing chemical analyses and the literature generally.

The Caples Terrane, both north and south of the Alpine Fault, is dominated by deep-sea gravity-flow deposits, mainly sandstone turbidites (Turnbull 1979a, b, 1980). There are also subordinate amounts of both coarser- and finer-grained pelagic and hemipelagic facies. Localized volcanogenic material includes mafic to andesitic lava, lava breccia and hyaloclastite. The Caples Terrane is strongly deformed and metamorphosed up to regional greenschist facies, with instances of lawsonite–albite–chlorite-facies HP–LT metamorphism (Turnbull 2000).

Evidence for accretion in the west

In the west, adjacent to the Dun Mountain–Maitai Terrane (south of the Alpine Fault), the westerly outcrop of the Caples Terrane includes meta-volcanogenic rocks that extend discontinuously from the Humboldt Mountains (Kawachi 1974; Turnbull 2000) in the north, through the North Mavora Lake area (Craw 1979) to Bald Hill c. 10 km farther south (Ramsbottom 1986). Although a small part of the Caples Terrane, this is a convenient area to evaluate the possible role of accretionary tectonics and sedimentation (Fig. 15.2).

The North Mavora Lake outcrop encompasses a laterally extensive, heterogeneous body of rocks known as the West Burn semischists (Craw 1979). Lithologies include meta-pillow lava that are associated with partly recrystallized, foliated meta-sandstone and meta-siltstone, red and green phyllite, minor meta-conglomerate, and hematitic chert (Fig. 15.17a). Pillow lava cores include titanaugite, suggestive of alkaline volcanism. A single available analysis of basaltic rock indicates relatively high values of TiO_2 and Zr (Ramsbottom 1986), consistent with a within-plate setting.

Two contrasting lithological assemblages are mapped in the Bald Hill area, east of the Livingstone Fault (Ramsbottom 1986; Turnbull 2000). First, on the eastern slopes of West Bald Hill, a kilometre-sized lenticular body is made up of stratiform, foliated meta-argillite, meta-sandstone and meta-basalt, and has been metamorphosed under HP–LT (lawsonite–albite–chlorite-facies) conditions (Ramsbottom 1986). The lithologies are foliated, sub-parallel to major bounding faults (e.g. Livingstone and Moonlight faults) (Ramsbottom 1986). Five available X-ray fluorescence (XRF) analyses of meta-basalts indicate TiO_2 values of 1.08–2.85% and Zr values of 88–185 ppm (Ramsbottom 1986), consistent with MORB to
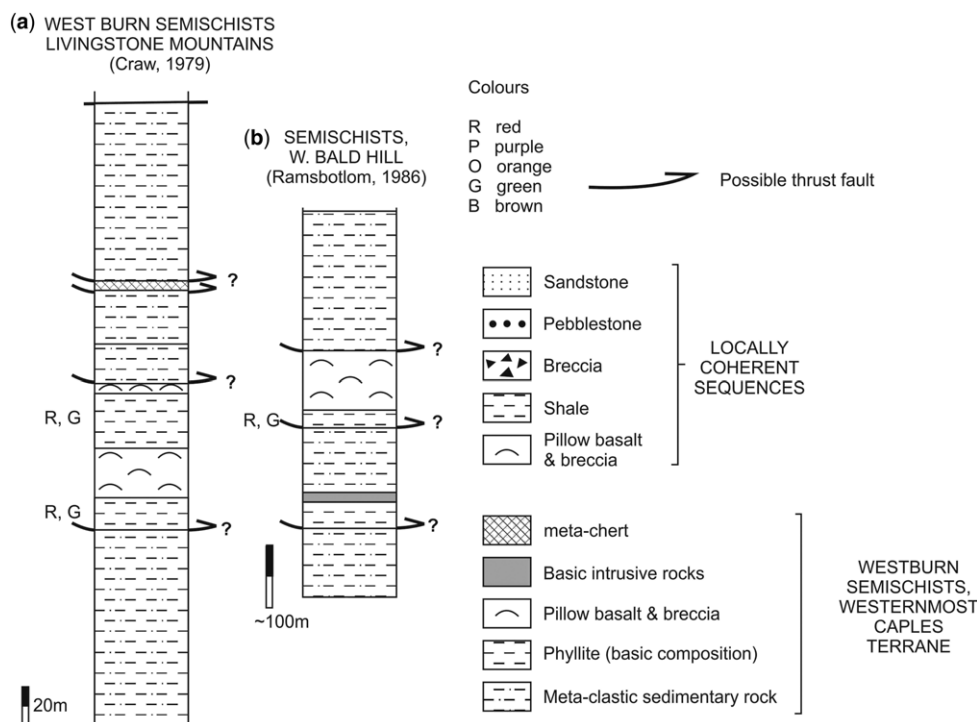

Fig. 15.17. Generalized lithological logs of: (**a**) West Burn semischists in the North Mavora Lake area (based on Craw 1979); and (**b**) semischists in the east Bald Hill area farther south (based on Ramsbottom 1986 and this study). An accretionary origin is proposed (see the text).

enriched MORB (E-MORB) compositions. Secondly, farther east, on east Bald Hill, a partially recrystallized succession (semischists of Ramsbottom 1986) is dominated by green and grey semischist (undated), estimated as up to 2.3 km thick (Fig. 15.17b). These lithologies also belong to the HP–LT law-sonite–albite–chlorite facies and can be correlated with the West Burn semischists of the North Mavora Lake area (Craw 1979; Ramsbottom 1986). Petrographical study indicates partially recrystallized clastic sedimentary textures, complex folding and shearing (see the Supplementary material). Chemical ana-lysis of the meta-sandstones suggests that they were sourced from a non-evolved volcanic arc, in strong contrast to the mid-ocean-ridge, to within-plate setting of the analysed metaba-saltic rocks (Robertson & Palamakumbura 2019c).

Taken together, the mix of compositions, together with the HP–LT metamorphism, is consistent with formation of the semischists by tectonic accretion of a seamount adjacent to a little-evolved volcanic arc. The semischists form a belt of rela-tively high-grade rocks, with lower grade rocks of the Caples Terrane farther east (Turnbull 2000). The Dun Mountain–Mai-tai Terrane to the west (or an equivalent along strike) could have acted as the backstop to an accretionary prism, bounded by the Livingstone Fault. Backstops are known to be zones of diapir-ism and exhumation in other areas, including the Mediterranean Ridge accretionary complex (e.g. Camerlenghi *et al.* 1995), and such a setting would have favoured localized exhumation of the deeper levels of an accretionary prism.

Regional continental margin-arc provenance

Petrographical study (Turnbull 1979b) and both major- and trace-element chemical analysis of Caples Terrane lithologies, regionally (Roser *et al.* 1993; Mortimer & Roser 1992) shows that some basalt–andesite-rich, quartz-poor sandstones (Harris Saddle Formation; West Burn semischists and equiva-lents; see above) were derived from a relatively immature island-arc setting. Other sandstones were derived from more-evolved, calc-alkaline continental island-arc magmatic rocks (e.g. Bold Peak Formation), or a quartz-rich continental setting (Momus Sandstone). The chemical compositions of the sandstone differ significantly from the clastic sedimentary rocks of the adjacent Maitai, Murihiku and Brook Street ter-ranes (Mortimer & Roser 1992; Roser *et al.* 1993; Robertson & Palamakumbura 2019c).

To obtain a regional overview, available analyses of Caples Terrane lithologies, as recorded in the GNS Science Petlab database, were plotted and compared with previously published fields of metasedimentary rocks from the Caples and Torlesse terranes (Mortimer & Roser 1992). The Caples Terrane rocks in the database are classified as metabasites, metamorphic rocks (undifferentiated), sedimentary rocks (undifferentiated) and Permian sedimentary rocks (although a Triassic age may be more likely; see below) (Fig. 15.18a–d).

On tectonic discrimination diagrams (see Robertson & Pala-makumbura 2019c for the explanation), the Caples Terrane sedimentary rocks (mostly low-grade meta-sandstones) mainly plot near, or within, the combined ocean island-arc (OIA) field, whereas the Caples Terrane metamorphic rocks (mostly higher-grade meta-sandstones) mostly lie within the continental island-arc field (CIA) field (Fig. 15.18a, b). The metamorphic rocks are generally more evolved than the lower-grade sedi-mentary rocks (undated and 'Permian') (Fig. 15.18a–c). A small group made up of metamorphic rocks and metabasites is similar to the composition of the Dun Mountain ophiolite extrusive rocks (see Robertson 2019b for comparative data). The Caples Terrane rocks as a whole largely overlap with the composition of the Median Batholith (Fig. 15.18d). The major-ity of the less-evolved Caples Terrane rocks also overlap with
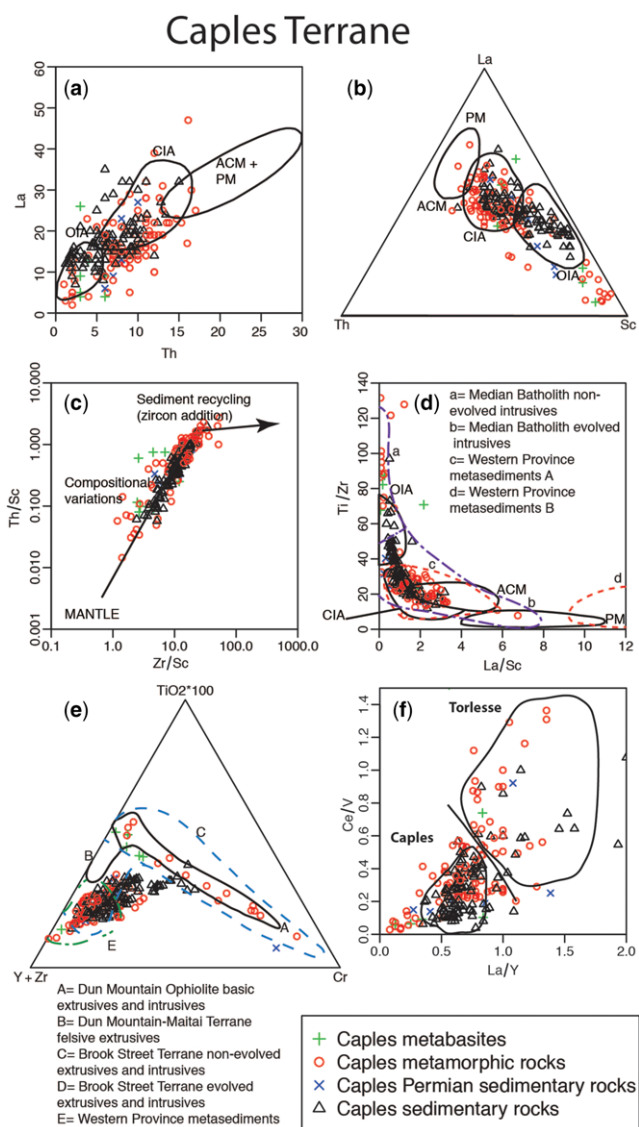

Fig. 15.18. Geochemical data for sandstones, meta-sandstones and metabasites from the Caples and Torlesse terranes (from the GNS Science Petlab database). The data are plotted on well-known tectonic–magmatic discrimination diagrams (see Robertson & Palamakumbura 2019c for the explanation): (**a**) La v. Th; (**b**) La v. Th v. Sc; (**c**) Th/Sc v. Zr/Sc; (**d**) Ti/Zr v. La/Sc; (**e**) TiO₂ × 100 v. Y + Zr v. Cr; (**f**) Ce/V v. La/Y. Published fields in (f) for Caples and Torlesse terrane clastic metasedimentary rocks (Mortimer & Roser 1992).

the composition of the late Paleozoic–early Mesozoic meta-sandstones of the Western Province (Campbell *et al.* 1998; see Robertson & Palamakumbura 2019c) (Fig. 15.18c). Few of the sandstones overlap with the composition of the basic vol-canic rocks of the Early Permian Brook Street Terrane south of the Alpine Fault (Fig. 15.18e). However, many of the Caples Terrane lithologies are compositionally similar to the volcani-clastic sandstones and tuffaceous sediments of the Permian Grampian Formation (Brook Street Terrane), north of the Alpine Fault, which relate to a continental margin arc (see above; Robertson & Palamakumbura 2019a). In summary, the Caples Terrane lithologies are likely to have been derived from a continental margin arc, similar to the Median Batholith, and the Western Province (or a lateral equivalent), with a pos-sible ophiolitic contribution.

Most of the Caples Terrane lithologies plot within the recog-nized Caples v. Torlesse Composite (Rakaia) Terrane fields (Mortimer & Roser 1992) (Fig. 15.18f). However, a significant

number of the Caples Terrane samples (of all categories) lie within the previously recognized Torlesse Terrane field, which is dominated by terrigenous sediments (Price *et al.* 2015; see below). The likely explanation is that the Torlesse-like sandstones are equivalent to the terrigenous, quartzo-feldspathic units within the Caples Terrane (e.g. Momus Sandstone).

Tectonic assembly

There are two end-member interpretations for the assembly of the Caples Terrane (Fig. 15.2).

The Caples Terrane has been interpreted as an infilled, deformed trench or forearc basin, with a variably deformed but overall coherent stratigraphy. An overall stratigraphic succession (Caples Group) (Fig. 15.19a) has been mapped in several areas to the south of the Alpine Fault, especially in the

Fig. 15.19. Caples Terrane. (**a**) Stratigraphy of the Caples Terrane as five main successive formations, based on the mapping of key well-exposed areas, notably the Thomson Mountains (Turnbull 1979*a*, *b*, 1980), and the Humboldt Mountains (Kawachi 1974; Bishop *et al.* 1976), south of the Alpine Fault (Turnbull 2000). The key ages of detrital zircons from these units are indicated approximately, based on Adams *et al.* (2009*a*). (**b**) & (**c**) Two alternatives to explain published field and radiometric age evidence: (b) forearc basin between a continental margin arc to the west and an accretionary complex to the east. Detrital zircon ages indicate Early–mid-Triassic ages both near the base and the top of the regional tectonostratigraphy; also basic to intermediate-composition igneous rocks are intercalated, which is atypical of a continental margin forearc basin; and (c) composite accretionary complex. The Caples Terrane as a whole is interpreted as a subduction–accretion complex, including trench sediments, oceanic-derived accretionary melange and fragments of an adjacent volcanic arc (preferred interpretation); see the text for discussion.

Thomson Mountains (Queenstown Lakes District) (Turnbull 1979*a*, *b*) and also in the Humboldt Mountains, NW Otago (Kawachi 1974; Turnbull 2000). North of the Alpine Fault, a coherent stratigraphy has also been mapped locally (e.g. Walcott 1969), separated by large areas that are almost unmappable due to lithological similarity and structural complexity (Turnbull 1980; Johnston 1993; Begg & Johnston 2000).

There are several difficulties with any interpretation involving a variably deformed but otherwise intact succession: (1) the implied >15 000 m thickness is anomalously high compared to modern and ancient forearc basins (Dickinson 1995) (Fig. 15.19b); (2) particularly north of the Alpine Fault, the stratigraphy is affected by kilometre-scale isoclinal folding and thrusting; (3) detrital zircon data indicate the existence of relatively young populations, both near the base and the top of the rock pile (Adams *et al.* 2009*a*) (Fig. 15.19a), which is difficult to explain assuming a layer-cake succession, even if deformed by thrusting and folding; and (4) the succession includes basaltic pillow lava, andesitic flows, volcanic breccia and hyaloclastite (e.g. Harris Formation; West Burn semischists and equivalents; see above), which are not typical of a low heat-flow forearc/trench setting.

Building on evidence from the western outcrop (e.g. Bald Hill area; see above), the Caples Terrane can be interpreted as a regional-scale subduction–accretion complex, which underwent later-stage (post-Triassic) thick-skinned re-thrusting (Fig. 15.19c). This model readily explains the great structural thickness, the zircon population distributions, the intercalated volcanic rocks and the presence of polygenetic melanges. Studies of accretionary prisms in other regions (e.g. Franciscan Complex, northern California; Blake 1984) indicate that parallel stratal units on various scales may conceal bedding-parallel thrusts. Such displacement may be barely recognizable in the field, and it may even take microfossil dating to reveal significant age repetitions and other discontinuities. Also, some accretionary terranes include large tracts of coherent stratigraphy, as in northern California and some Tethyan melanges. Detailed structural mapping in the Thomson Mountains, north Southland (Turnbull 1980) revealed numerous features that are typical of accretionary prisms, including zones of intense shearing and folding between intact intervals of sandstone turbidites, broken formation, melange zones, and soft-sediment deformation (e.g. within the Bold Peak Formation). Folds are commonly subhorizontal, tight to isoclinal, with steep axial planes, as in many accretionary complexes, including Japan (Taira *et al.* 1989). The sandstones are readily interpreted as trench or trench-slope deposits, and the numerous small bodies of mafic volcanic rocks as off-scraped seamount-type crust. Lawsonite–albite–chlorite-facies assemblages are preserved, particularly along major shear zones, confirming the existence of HP–LT metamorphism, as in many subduction complexes. This also emphasizes that the Dun Mountain ophiolite (and Patuki Melange) represent a major tectonic boundary in the Eastern Province between the stratigraphically intact Brook Street Terrane, the Murihiku Terrane and the Maitai Group to the west and accretionary complexes to the east.

Setting relative to the Dun Mountain–Maitai Terrane and Gondwana

Detrital zircon assemblages in the Caples Terrane are generally comparable in age to those of the Maitai Group, which has been restored to a position off central Queensland, although minor differences in the zircon populations do exist (Adams *et al.* 2009*a*). However, it is unlikely that the various gravity-flow deposits of the Caples Terrane simply resulted from overspill from the adjacent Maitai forearc basin. In particular, the sediments within the Tramway Formation are generally finer-
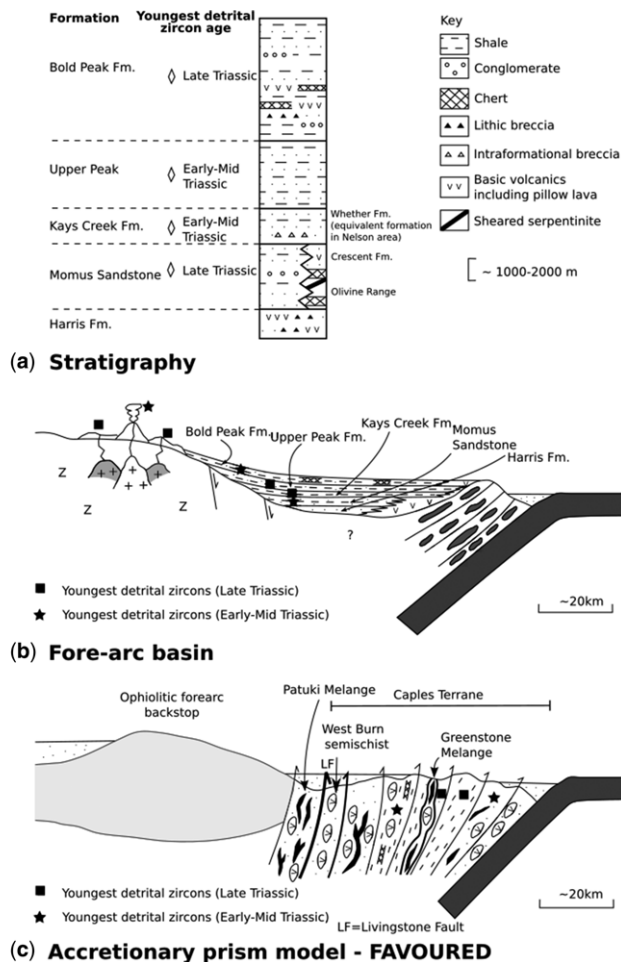
grained and more terrigenous than the commonly coarser-grained, arc-derived, volcanogenic detritus within much of the Caples Terrane (Robertson & Palamakumbura 2019*c*). Any interpretation needs to bear in mind that long-distance axial-sediment transport (hundreds of kilometres) can take place in subduction-trench settings and so juxtapose sediments of different provenance (e.g. Moore *et al.* 1982).

The Caples Terrane is mapped as having an overall mid-Permian–Mid-Triassic age (Rattenbury *et al.* 1998; Begg & Johnston 2000; Turnbull & Allibone 2003; Cooper 2004; Mortimer *et al.* 2017). The Caples Terrane sedimentary rocks are mostly unfossiliferous but very rarely contain atomodesmatinids within limestone clasts and also as scattered shell fragments (Turnbull 1979*a*). Micritic limestone blocks (metre-sized) within melange units exceptionally contain conodonts, along with atomodesmatinid fragments, indicating ages as old as Early Permian (Kungurian) (Ford *et al.* 1999). Plant material of probable Triassic age is also recorded (Johnston 1993). Triassic radiolarians are reported from the SE coastal Chrystalls Beach–Brighton block (Coombs *et al.* 2000). Triassic-aged macrofossils are not reported from the Caples Terrane regionally (Turnbull 2000; Adams *et al.* 2009*a*; Campbell 2019), despite the Triassic ages of the detrital zircons in the sandstones (Adams *et al.* 2009*a*). On the other hand, Permian zircons appear to be largely absent from the voluminous sandstones (Adams *et al.* 2009*a*), possibly because Permian igneous source rocks were simply zircon-poor.

An alternative explanation is that the Permian macrofossils could be within, or reworked from, accretionary material that was emplaced within Triassic trench-type turbidites (together with some Triassic accretionary material). This would explain why the Caples Terrane sandstones are systematically different in composition from the Late Permian sandstones of the Maitai Group, the Otama Complex, and both the Patuki and Croisilles melanges (Palamakumbura & Robertson 2019; Robertson & Palamakumbura 2019*c*). In this case, the Caples Terrane is essentially a Triassic accretionary complex, although the presence of a minor proportion of material accreted during the Permian remains possible.

Torlesse Composite Terrane: a long-lived, evolving accretionary complex

The Torlesse Composite Terrane makes up much of the eastern part of South Island (Fig. 15.2), where it includes some of the variably metamorphosed rocks known as the Haast Schist (and regional equivalents) (Landis & Bishop 1972). From west to east generally, the Torlesse Composite Terrane includes the Rakaia Terrane (itself subdivisible; see below), the Kaweka Terrane (largely equivalent to the Esk Head Melange; see below) and the Pahau Terrane (Fig. 15.3). Detrital zircon geochronology and geochemistry facilitate regional terrane mapping and correlation.

No new data concerning the Torlesse Composite Terrane are included in this Memoir. However, some key evidence and basic interpretations are outlined below to help understand the overall Late Paleozoic–early Mesozoic regional tectonic development. The Rakaia Terrane is Permian–Triassic, whereas the Kaweka and Pahau terranes are Jurassic and Early Cretaceous, respectively (e.g. George 1992; Mortimer 2004; Mortimer *et al.* 2014; Edbrooke 2017).

The most westerly segment of the Rakaia Terrane, adjacent to the Caples Terrane and formerly included within it (Craw 1984), is the Aspiring lithological association (or assemblage). This encompasses oceanic lithologies: for example, meta-pillow lava, meta-chert (up to 100 m thick) and rare ultramafic lenses (Craw 1984; Begg & Johnston 2000). This unit is treated
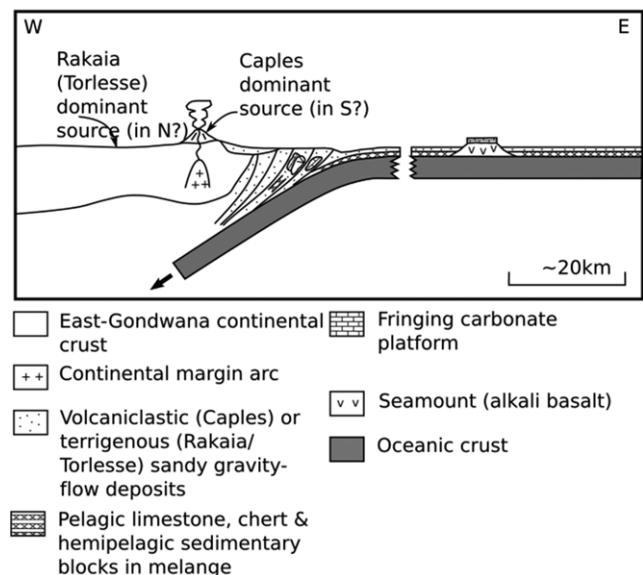

Fig. 15.20. Schematic diagram indicating the main compositional difference between the Caples Terrane and the Rakaia–Waipapa terranes. The Caples Terrane accreted adjacent to a continental margin arc, interpreted as the Median Batholith, whereas the Rakaia Terrane accreted adjacent to a more craton-influenced margin segment, possibly further north. The two accretionary complexes were juxtaposed by Early Cretaceous time when they both contributed detritus to the more outboard (easterly) Pahau Terrane. See the text for references and discussion.

either as accreted oceanic crust that now happens to be located between the Caples and Rakaia terranes or as the separate Aspiring Terrane (Norris & Craw 1987; Cox 1991; Cooper & Ireland 2013).

Deposition and assembly

The Rakaia Terrane is dominated by quartzo-feldspathic gravity-flow deposits, mostly greywacke turbidites, of Permian–Late Triassic age (Fig. 15.20). The sandstones are felsic, rich in quartz and have an average rhyodacitic composition. In contrast, the Caples Terrane sandstones are generally more volcaniclastic and less felsic (Mortimer & Roser 1992) (Figs 15.18 & 15.20). The Rakaia Terrane lithologies include sparse conglomerates that mainly derived from granitoid rocks of a continental margin-arc affinity (MacKinnon 1983; Bishop *et al.* 1985; Adams *et al.* 1998, 1999, 2009*b*). The presence of a volcanic clast of late Early Permian age within an early Late Permian conglomerate is specifically indicative of near-contemporaneous arc magmatism and conglomerate deposition (Wandres *et al.* 2004*a*, *b*, 2005). The sedimentary rocks are interpreted to have accumulated in a deep-sea, trench-type setting (Bishop *et al.* 1985). The various terranes of the Torlesse become generally younger eastwards, consistent with progressive accretion. Detrital zircon geochronology indicates a *c.* 200 Ma minimum age (Triassic–Jurassic boundary) for detrital igneous material in the Rakaia Terrane (Ireland 1992; Adams & Kelley 1998; Wandres *et al.* 2004*a*, *b*). The clastic lithologies are structurally thickened by thrusting and are generally of prehnite–pumpellyite facies, grading eastwards into pumpellyite–actinolite facies (Adams & Kelley 1998).

The Caples and Rakaia terranes both pass laterally into the Haast Schist, and are inferred to have been contiguous by the Jurassic (Mortimer & Roser 1992). Detrital zircons from near the boundary between the Caples Terrane and the Aspiring lithological association (or Aspiring Terrane) have yielded minimum detrital zircon ages of 160–154 Ma (Late Jurassic)

(Jugum et al. 2013). This constrains the maximum depositional ages of the Caples and/or Rakaia terranes to within the known Jurassic age range of the Haast Schist regional metamorphism (Little et al. 1999). The Aspiring lithological association is suggestive of a rifted ocean-ridge origin.

In addition, Cretaceous detrital zircons have been recognized from the more northerly Pounamu Ultramafic Belt, close to the Alpine Fault (Cooper & Ireland 2013). Oceanic meta-serpentinite, dyke-intruded metagabbro and metabasite are interpreted as an intact (but undated) ophiolite and its former deep-water sedimentary cover (meta-chert and marble). The lithological association and the geochemistry as a whole are suggestive of a mid-oceanic ridge setting, although the depletion in high field strength elements in some basalts points to a supra-subduction zone forearc setting (Cooper et al. 2018). Overlying biotite schist (possibly derived from felsic tuff) contains late Early Cretaceous zircons (c. 108 Ma) (Cooper & Ireland 2013). These zircons significantly post-date the known Jurassic tectonic assembly and accretion of the Haast Schist. The simplest explanation is that after formation of the Haast Schist, these rocks were underplated beneath the Gondwana active margin during late-stage subduction or collision. Diapiric exhumation possibly took place much later, related to Alpine Fault displacement (Cooper & Ireland 2013).

Melange is an important component of the Rakaia Terrane, as exposed at two particular localities in central north Otago: Te Akatarawa and Glenfalloch stream (c. 150 km to the NE). Associated limestones include coral and warm-water benthic foraminifera (fusulines) (Hada & Landis 1995; Leven & Campbell 1998; Cawood et al. 2002). The melange units originated as volcanic seamounts, together with associated pelagic sediments and redeposited neritic sedimentary rocks, and accreted in a deep-water subduction-trench setting near to an active continental margin (Howell 1980; Leven & Campbell 1998).

South of the Alpine Fault, a NE–SW-trending belt (c. 25 km-wide) of predominantly low-grade sandstone turbidites (greywackes) is located between the Rakaia and Pahau terranes. These rocks extend from the Alpine Fault southwards through the north Canterbury region, where distinctive detrital zircon populations imply a general correlation with the Jurassic Kaweka Terrane of North Island (Adams et al. 2011, 2013b). In North Island, the Early–Middle Jurassic-aged Kaweka Terrane is exposed from SW of Wellington, northwards to the Bay of Plenty, where it includes minor melange-like units (Edbrooke 2017).

In South Island, the belt of rocks now correlated with the Kaweka Terrane (Adams et al. 2011, 2013b) encompasses a litho-tectonic assemblage mapped as the Esk Head Melange (e.g. Bishop et al. 1985; Johnston 1990) or as the Esk Head Subterrane, which forms a tectonized zone between the Rakaia and Pahau terranes (Silberling et al. 1988). In north Canterbury and Marlborough, the melange belt (up to 12 km across by >60 km long) includes pillow lava, and both shallow- and deep-water-derived sedimentary lithologies (e.g. chert and pelagic limestone). Sedimentary blocks variously contain radiolarians, conodonts, bryozoans and also macrofossils (e.g. bivalves, brachiopods, crinoids) of overall Permian–Triassic age. The melange is widely interpreted to have an accretionary origin, similar to the melange units of the adjacent terranes (Howell 1980; Botsford 1983; Bishop et al. 1985). The Kaweka Terrane can, therefore, be considered to extend through South and North Island, with variable amounts of accretionary melange in different areas.

The Early Cretaceous Pahau Terrane ('younger Torlesse') (Mortimer 2004) is widely exposed, mainly in the north Canterbury and Marlborough areas. Outcrops are of great extent, complexly folded and faulted, and apparently of similar age over large areas, based mainly on microfossil dating (Bishop et al.

1985; Rattenbury et al. 1998; Begg & Johnston 2000). The sediments are predominantly deep-water sandstone turbidites of similar quartzo-feldspathic composition to those of the Rakaia Terrane farther west. Thick, lenticular conglomerates locally contain deformed and metamorphosed clasts that are interpreted to have a Rakaia Terrane source (Wandres et al. 2004a, b; Wandres & Bradshaw 2005). The inferred depositional ages mainly range from Late Jurassic to Early Cretaceous, with detrital zircons as young as c. 100 Ma (Albian–Cenomanian boundary) (Adams et al. 2013a, b).

Chert, limestone, basalt and dolerite are rarely present in the Pahau Terrane (Bishop et al. 1985; Edbrooke 2017). Specifically, a melange unit (up to 7 km wide × 50 km long) in the Kaikoura area (between the Waihopai and Spray rivers) contains igneous rocks and rare limestone. These melange units are generally similar to the Esk Head Melange (Kaweka Terrane) and indicate that accretion of oceanic-derived material continued from Jurassic to Early Cretaceous time. The Pahau Terrane in Marlborough (Awatere Valley) includes basalts, some of which appear to be contemporaneous with adjacent sediments. Overall, the Pahau Terrane sediments are inferred to have accumulated in a trench setting, together with oceanic-derived material (e.g. seamount-related igneous and sedimentary rocks), in part coeval with metamorphism and exhumation of the Rakaia Terrane to the west.

SW of the Esk Head Melange belt, deformed lithologies of the Rakaia Terrane are locally covered by fluvial to shallow-marine facies of similar age and composition to the Pahau Terrane (Bishop et al. 1985). These paralic sediments are interpreted as a surviving fragment of a forearc basin that was contemporaneous with trench accretion (Bishop et al. 1985; Cawood et al. 1999; Adams et al. 2013b).

Petrographical, geochemical and radiometric age data support derivation of the Pahau Terrane partially from a continental margin arc, similar to the Darran Suite of the Median Batholith. In contrast to the Rakaia Terrane, tuffs are widespread (Bishop et al. 1985), which could reflect a surge in magmatism within the Median Batholith. Additional material was derived from the by-then deformed and metamorphosed Rakaia Terrane. The Rakaia and Pahau terranes were, therefore, contiguous and adjacent to the Median Batholith during the Early Cretaceous (Roser & Korsch 1999; Wandres et al. 2004a, b; Wandres & Bradshaw 2005; Adams et al. 2013c).

Waipapa Composite Terrane: Jurassic accretionary complex

The Waipapa Composite Terrane makes up a significant part of the 'basement' of North Island, particularly in the NE (especially around Hamilton) (Black 1994; Mortimer 1994; Adams & Maas 2004; Adams et al. 2009b; Edbrooke 2017). In North Island, the Waipapa and Torlesse composite terranes are separated by the inferred extension of the Alpine Fault, implying substantial Neogene–Recent offset (Edbrooke 2017). The Waipapa Composite Terrane is dominated by sandstone turbidites (greywacke) and includes small, scattered melange units. The sandstones are felsic, rich in quartz, have an average rhyodacitic composition and differ somewhat in chemical composition from the Jurassic sandstones of the Rakaia Terrane in South Island (Price et al. 2015).

The sediments of the Waipapa Composite Terrane accumulated during the Jurassic, based on fossils and also detrital zircon dating (Cawood et al. 1999; Adams et al. 2013b). Small melange outcrops include basalt, chert and siliceous mudstone (Hunua facies) (Edbrooke 2017). Warm-water Permian fusuline foraminifera are locally documented (Leven & Grant-Mackie 1997; Leven & Campbell 1998). Radiolarians

are typically Tethyan (Aita & Spörli 1992). However, a Late Triassic radiolarian assemblage in the Wellington area is reported to have a high-latitude origin (Aita & Sporli 1994). A separate suite of quartz-poor sandstones in North Island (Waioeka petrofacies) is compositionally similar to that of the Waipapa Terrane. This unit has recently been defined as the Waioeka Terrane based on map relationships on the peninsula east of the Bay of Plenty and related evidence from detrital zircon populations. The Waioeka Terrane may have been displaced relative to the Waipapa Terrane (Adams *et al.* 2013*b*).

The Waipapa Composite Terrane is now known to extend into South Island in the area east and NE of Picton (Marlborough District), as far south as the Alpine Fault (Adams *et al.* 2009*a*, *b*; Edbrooke 2017). The Marlborough Schist, a northern South Island equivalent of the Haast Schist, is divisible into a western part with Caples Terrane protoliths and an eastern part with protoliths that are generally interpreted as a southward extension of the Waipapa Terrane from North Island, based on detrital zircon geochronology (Adams *et al.* 2019). The contact within the schist between the Caples and Waipapa terranes has indications of high-strain conditions, including bands of greenschist, lesser amounts of grey pelitic schist and very rare talcose schist. The presence of ultramafic material can be correlated with the Aspiring lithological association or Aspiring Terrane (Norris & Craw 1987; Cox 1991; Cooper & Ireland 2013). This in turn implies that similar oceanic crust accreted along hundreds of kilometres of the active margin.

Identification of continental sources in the outboard terranes

Any interpretation of regional provenance needs to take account of the probability that one or more relevant sources were buried by younger units, eroded, or covered by sea or ice. Sediment chemistry alone has not so far proved effective at unambiguously identifying the source areas of the more easterly terranes (Roser & Korsch 1999). Radiometric dating of detrital minerals, although informative, has produced varied results for different lithologies, including sandstone and conglomerates, in different units and areas. Early U–Pb detrital zircon dating of the 'Torlesse' was permissive of origins in Antarctica or the New England Orogen (Ireland 1992). More recent studies identify potential source areas but cannot discount all other regional possibilities. In general, zircon age populations are a powerful provenance indicator, although zircons may survive crustal melting (e.g. Bhattacharya *et al.* 2018) and so do not always accurately indicate the age of the magmatic rocks in which they occur. This might, in certain circumstances, give a false impression of multiple sources rather than a single arc source (e.g. Median Batholith) in certain cases.

The granitoid terranes of the New England Orogen in NE Australia (Terra Australis Orogen of Cawood 2005) and its hinterland have been identified as a suitable source for the Rakaia Terrane clastic sediments. Single-crystal ^{40}Ar/^{39}Ar ages of detrital muscovite from the Rakaia Terrane of North Island are consistent with a source in NE Australia or adjacent older orogens of eastern Queensland (Adams & Kelley 1998). A source in SE Australia is unlikely because of the strong mismatch of source mica ages in this area (375–330 Ma) compared to the Rakaia Terrane (Adams & Kelley 1998).

The majority (65%) of the U–Pb detrital zircon ages from the Rakaia Terrane (and also some from the Waipapa Composite Terrane in North Island) have yielded Permian–Mesozoic ages that are generally consistent with derivation from the SE Gondwana active continental margin (Cawood *et al.* 1999). Zircon populations from sandstones of the small exotic faultbounded Te Akatarawa unit (treated as either a formation or a terrane in the literature) in south Canterbury are also consistent

with a source in the New England Orogen (Cawood *et al.* 2002). Crucially, the Te Akatarawa unit includes distinctive fusulines (large benthic foraminifera; e.g. *Parafusulina* sp.) which are convincingly interpreted to have originated at a low latitude, as part of an oceanic seamount that later accreted to Gondwana (Hada & Landis 1995). Overall, the strongest evidence for provenance is the low-latitude fauna within melange units in both the Torlesse and Waipapa Composite terranes (Hada & Landis 1995; Cawood *et al.* 2002). However, this evidence does not indicate the depositional palaeolatitude of the tectonically associated deep-sea trench-type deposits.

On the other hand, some reported detrital zircon populations of sandstones and igneous rocks from the Rakaia Terrane are consistent with derivation from SE Australia and/or East Antarctica, including the Lachlan Orogen and equivalents in South Island, especially the Karamea Batholith (Cawood *et al.* 1999). Also, coarse-grained sedimentary rocks have yielded detrital zircon ages that are consistent with an Antarctic source (e.g. Amundsen and Ross provinces) (Wandres *et al.* 2004*a*, *b*; Wandres & Bradshaw 2005). However, conglomerates may sample small, relatively proximal source areas (e.g. the walls of canyons cutting the forearc) and may not be representative of the regional hinterland; similar local source areas may exist elsewhere but may not now be exposed. For the Pahau Terrane, Sr–Nd ages, supported by chemical data, suggest that igneous clasts in conglomerates were derived from lithologies similar to the Darran Suite of the Western Province (Adams *et al.* 2013*b*). Some clasts appear to have been recycled from older conglomerates (Wandres *et al.* 2004*a*, *b*). However, as noted above, Darran-type arc rocks could exist widely along the SE Gondwana active margin, in common with other potential sources and the above evidence does not pinpoint one specific source area.

Taking the evidence as a whole, four main interpretations of the provenance of the Torlesse Composite Terrane can be considered (Fig. 15.21). First, equatorial Pacific seamounts (with warm-water biota) subducted during the Permian–Triassic and accreted orthogonally to northern Queensland (1 in Fig. 15.21); this was followed by southward translation prior to the Early Cretaceous formation of the Pahau Terrane (preferred interpretation). Secondly, Panthalassa crust subducted obliquely during Permian–Triassic time, bringing equatorial material near to its present relative position by the Early Cretaceous (2 in Fig. 15.21). This seems unlikely because of the lack of a match of key sandstone detrital zircon populations with SE Australia geology (Adams *et al.* 2013*a*, *b*). Thirdly, equatorial Panthalassa subducted obliquely, reaching East Antarctica before being accreted, followed by northward translation (3 in Fig. 15.21). However, southward migration across *c.* 60° of latitude seems excessive. Fourthly, orthogonal accretion adjacent to East Antarctica (4 in Fig. 15.21) but this precludes the preservation of warm-water fauna.

Assuming option 1 (1 in Fig. 15.21), initial northerly accretion followed by southward margin-parallel displacement, why do the Caples and Rakaia–Waipapa clastic sediments differ, with the former being mainly arc-derived and the latter (both) mainly craton-derived? One possibility is that an Early–Middle Permian accretionary prism developed in a northerly position and was translated southwards to near its present position as early as mid-Permian time. The Rakaia–Waipapa trench sediments accordingly derived much of their clastic material from the truncated active continental margin in the north (Adams *et al.* 2013*a*). However, the identity and location of the inferred Early–Middle Permian accretionary prism are debatable. Why did a successor continental margin arc not simply develop in the north, equivalent to the Median Batholith, and supply new arc-derived sediment to the 'Rakaia–Waipapa trench' during the Permian–Jurassic? Alternatively, could subduction adjacent to the 'Rakaia–Waipapa active margin segment'

Metamorphism of the Caples and Torlesse terranes

The regional metamorphism sheds light on terrane assembly and collisional processes. Metamorphism of both the Caples and the Rakaia terranes ranges from pumpellyite–actinolite to greenschist facies (Bishop 1972; Graham & Mortimer 1992; Grapes & Watanabe 1992; Mortimer 2000; Turnbull 2000; Turnbull *et al.* 2001). Maximum temperatures are estimated as 390°C (Yardley 1982). Metamorphic grade in the Otago (Haast) Schist, is particularly indicated by metamorphic foliation development and white mica grain size, increases generally towards the NE (Turnbull *et al.* 2001). In places, the Caples Terrane and the Rakaia Terrane are mapped simply as the regional Haast Schist (Otago Schist, Alpine Schist and Marlborough Schist in different areas), although they are generally distinguishable (Mortimer 1993; Edbrooke 2017). After reaching a maximum, the metamorphic grade in the schists generally decreases northeastwards, suggesting an overall domal shape to the isograds (Bishop *et al.* 1976, 1985). The metamorphism of both the Caples and Rakaia terranes occurred after local sedimentation ended, mainly during the Jurassic (Graham & Mortimer 1992; Turnbull 2000; Adams *et al.* 2009a, b, d; Jugum *et al.* 2013). The schist units of both terranes show localized evidence of high-temperature metamorphism during Late Cretaceous time, increasing the complexity (Mortimer & Cooper 2004).

The Caples and Rakaia terranes also exhibit local evidence of HP–LT metamorphism, as indicated by the localized presence of sodic amphibole and rare jadeitic pyroxene, mainly within metabasites and metacherts (e.g. Queenstown Lakes District). Lawsonite–albite–chlorite assemblages are specifically reported from major shear zones within the Caples Terrane, as noted above (Turnbull 1980). In general, moderately high-pressure conditions (c. 6.4 kb) were succeeded by lower-pressure greenschist-facies metamorphism (Yardley 1982). The HP–LT metamorphism is likely to relate to subduction–exhumation of accreted oceanic lithologies. The regional metamorphism generally relates to thickening and crustal-scale warping of the assembled accretionary wedges mainly during the Jurassic. A possible trigger for Jurassic regional metamorphism could have been the westward bulldozing of the accretionary prism by the arrival of a large body of exotic oceanic crust (e.g. seamount or Large Igneous Province). More plausibly, given the enormous scale of the metamorphism, crustal thickening was driven by a regional change in plate kinematics.

Cessation of subduction

Within the Median Batholith, from *c.* 130 to 125 Ma, there was a major change to large-scale intrusion of sodic adakitic, high Sr calc-alkaline magmas, mostly in the west (Mortimer 2004). The main intrusion occurred around 125–120 Ma, continuing sparsely until *c.* 105 Ma. Additional magmatism farther inboard at *c.* 110 Ma (Rahu Suite, Hohonu Batholith) may also have an adakitic component, although masked by an older crustal component (Waight *et al.* 1998b). The switch to adakitic magmatism corresponds to a regional transition from crustal thickening (contraction) to crustal thinning (extension) (Muir *et al.* 1995; Waight *et al.* 1998a; see below). The scale of the Early Cretaceous intrusion implies a magmatic surge which could have resulted from slab tear or ridge subduction around 136–128 Ma (Decker *et al.* 2017). Subduction apparently continued until *c.* 100 Ma, based on the youngest detrital zircon ages from near Wellington (Kamp 2000).

The inferred Early Cretaceous crustal thickening could be explained in four main ways (not necessarily mutually exclusive): (1) major crustal shortening (thrusting) (Muir *et al.* 1995); (2) shallowing of the subduction zone (Mortimer *et al.* 1999a, b); (3) subduction underplating with increased
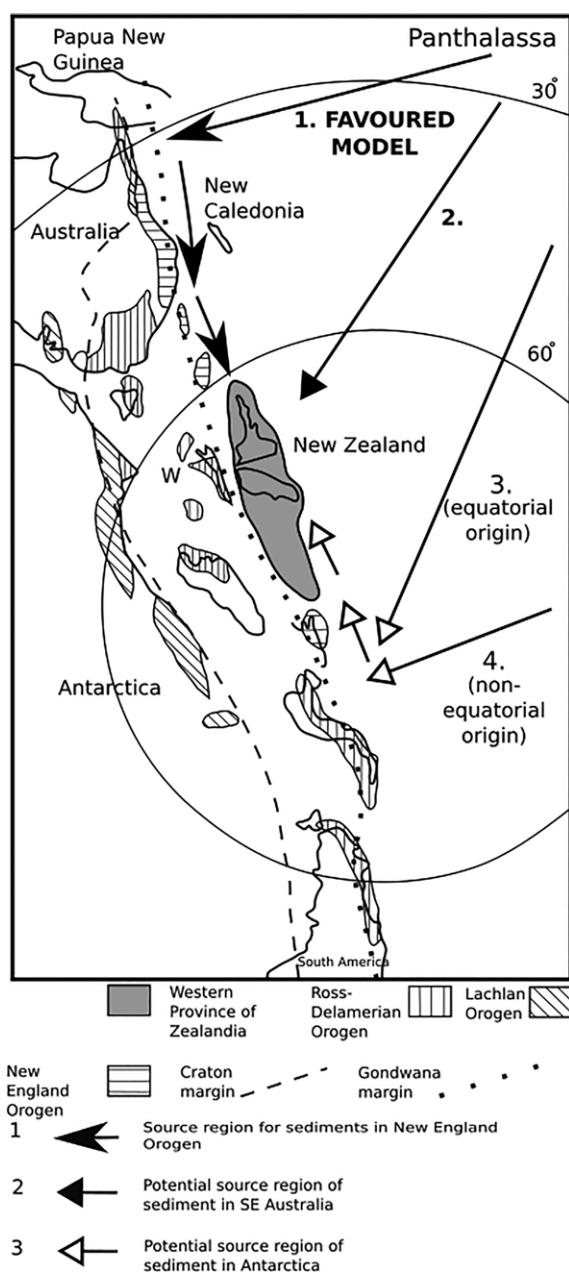

Fig. 15.21. Options for the accretion of the Torlesse and Waipapa composite terranes (and related units): 1, orthogonal subduction–accretion in the north, then southwards transport (preferred model); 2, long-distance oblique subduction to the present relative position; 3, long-distance oblique transport from far north to far south, then northward transport; and 4, orthogonal subduction, then northward transport. The positioning of Gondwana is based on Adams *et al.* (2007). See the text for discussion.

have been oblique, comparable to the modern Andaman Sea (Curray 2005), thereby suppressing continental margin-arc magmatism? Oblique subduction could also have helped to detach accretionary material and relocate it elsewhere, possibly within a regional-scale embayment farther south, allowing an unusually wide, composite accretionary wedge to develop in New Zealand.

In summary, the Torlesse and Waipapa composite terranes are likely to have accreted somewhere adjacent to northern Queensland, beginning in the Middle Permian (*c.* 270 Ma) and finally reached their present relative position, together with the Pahau Terrane, by Early Cretaceous time (*c.* 100 Ma) when subduction terminated.

interplate friction (Tulloch & Kimbrough 2003); and (4) collision of the Hikurangi Plateau (or a similar edifice) (Mortimer 2004). The longevity of the adakitic magmatism (*c.* 25 Ma), although waning, and the apparent absence of large-scale coeval thrusting, question the first explanation. The second interpretation is consistent with the subduction of increasingly young, buoyant crust (Defant & Drummond 1990). Cessation of subduction has been explained by the arrival of the spreading ridge between the Phoenix and Pacific plates (Bradshaw 1989). However, ridge subduction is self-limiting and unlikely to cause major crustal thickening or collisional effects by itself (Luyendyk 1995). The orogenesis was both convergent and collisional (Bradshaw 1989). Collisional effects could have been caused by attempted subduction of the Hikurangi Plateau or an equivalent (Mortimer *et al.* 2006). Regional collision is the most likely explanation of the inferred crustal thickening and cessation of subduction. As noted above, regional collision-related subduction and then extension could also have triggered the genesis of HP–LT lawsonite-bearing metamorphism affecting the Dun Mountain–Maitai Terrane and part of the Drumduan Terrane.

By *c.* 100 Ma, extensional basin development began, onshore and offshore, coupled with localized alkaline magmatism (Laird & Bradshaw 2004; Tulloch *et al.* 2009*b*; Strogen *et al.* 2017), which was related to rifting of the Tasman Sea Basin. The cogenetic, alkaline Hohonu Dyke Swarm and the French Creek Granite (*c.* 82 Ma) formed during late-stage rifting, coeval with the oldest oceanic crust in the Tasman Sea (Waight *et al.* 1998*a*). Relatively inboard (westerly) alkaline magmatic rocks, dated *c.* 92–84 Ma, reflect the melting of a heterogeneous subduction-influenced mantle, with a contribution from a relatively enriched mantle source, similar to that which existed beneath the Hikurangi Plateau (van der Meer *et al.* 2017).

The subsequent Late Cretaceous–Cenozoic development is outside the scope of this Memoir (see Mortimer & Campbell 2014).

SE Gondwana in eastern Australia and Antarctica

Unsurprisingly for a subduction-dominated setting, some parts of the geological record appear to be missing. These include an inferred distal (outboard) Murihiku forearc basin, an inner (proximal) Maitai forearc basin (other than possibly the south-coast Willsher Group) and Jurassic–Early Cretaceous equivalents of the Maitai forearc basin. This emphasizes the need for a close integration with the geology of eastern Australia and Antarctica in order to obtain an overall picture.

Taking account of evidence mainly from SE Australia, the overall geological record in the South Island can be divided into, first, an extensional phase (Cambrian–Early Permian) and then an (overall) contractional phase (Middle Permian–Early Cretaceous) related to the development of an accretionary orogen. Generally, the East Gondwana active margin migrated oceanwards from Neoproterozoic to Recent, if the Cenozoic Tasman Sea Basin is included (Cawood *et al.* 2009).

The following main stages of tectonic development can be recognized in eastern Australia/Antarctica.

Cambrian–Carboniferous continentward subduction and inboard craton formation (c. 530–360 Ma)

Panthalassa began to subduct beneath Gondwana around 530 Ma (Cawood 2005), establishing an active margin that remained until *c.* 100 Ma (Early Cretaceous) (Cawood 1984; Cawood & Buchan 2007). Early subduction events included widespread genesis and emplacement of supra-subduction zone ophiolitic rocks (535–529 Ma greenstones), as exposed

in the southern New England Orogen and elsewhere in SE Australia (Aitchison *et al.* 1992; Cawood & Buchan 2007). Slope facies accumulated in an outboard, marginal setting, as exposed in the Ross and Delamerian orogenic segments of Antarctica and SE Australia, respectively (Gray & Foster 2004; Glen 2005). These sedimentary rocks can be correlated, specifically, with the Buller Terrane (Greenland Group) and more generally with the more outboard (overthrust) Takaka Terrane (Laird & Shelley 1974; Adams 2004). Crustal development was characterized by short-lived deformation pulses, including the Late Ordovician Benambran orogenic event in the Lachlan Orogen, although interpretations differ (Aitchison *et al.* 1994; cf. Collins 2002). Ordovician regional metamorphism affected both SE Australia and the Buller Terrane but not the Takaka Terrane (Chappell & White 1992; Mortimer 2004). During the Devonian–early Carboniferous, an overall transition took place from lithospheric extension to lithospheric thickening and cratonization. Peripheral subduction was accompanied by outboard migration of the active margin, as documented from the New England Orogen (Collins 2002; Glen 2005; Cawood 2005; Cawood *et al.* 2011).

Early Permian oceanic plate roll-back and outboard arc genesis (c. 300–285 Ma)

The Early Permian of the New England Orogen was dominated by crustal extension, including localized eruption of MORB (e.g. Nambucca Belt) (Asthana 1984). Extension was accompanied by the intrusion of both S- and I-type granites, and related mafic and siliceous volcanics (e.g. Halls Peak Volcanics: Korsch *et al.* 2009; Cawood *et al.* 2011). The S-type granites fingerprint a switch to extension. Overall, the active arc migrated eastwards, in response to back-arc extension (Cawood 1984; Cawood *et al.* 2011). The calc-alkaline arc rocks of the Brook Street Terrane correlate in time with pervasive, regional Early Permian extension in eastern Australia (e.g. Denison Trough), which includes alkaline magmatism in some easterly areas (Korsch *et al.* 2009). The driving mechanism of the extension was oceanward slab roll-back, which caused the pre-existing Late Paleozoic continental margin arc to retreat oceanwards, giving rise to the arc-type succession in the Gympie Terrane in a distal continental borderland setting. In this context, the absence of pre-latest Permian magmatism in the Western Province (Mortimer *et al.* 1999*b*) could represent a location within the arc–trench gap during this time interval, with coeval arc magmatism farther west in SE Australia.

Later Permian: switch to a convergent accretionary origin (c. 265 Ma)

The progressive consolidation of Gondwana required fundamental plate readjustments which affected SE Gondwana, its borderland and adjacent Panthalassa throughout Permian–Middle Triassic time (*c.* 300–230 Ma) (Cawood 2005; Cawood & Buchan 2007). Convergence refocused along the remaining peripheral continental margin subduction zones. Plate coupling is likely to have increased between the downgoing and overriding plates, eventually triggering a fundamental switch from an extensional to a contractional (convergent) accretionary origin (Cawood 2005; Schellart 2008). The regional tectonic setting was then comparable to the Central Andes today (Norabuena *et al.* 1998). Evidence from the southern New England Orogen, particularly the onset of oroclinal bending (north of Sydney), puts the change to regional convergence at *c.* 270 Ma (early Middle Permian). Soon afterwards, the active continental margin underwent regional-scale oroclinal bending (265–260 Ma: Cawood *et al.* 2011), accompanied by localized

sinistral strike-slip (Cawood 1984). Contractional deformation continued during Mid–Late Permian (*c.* 265 Ma) to early Late Triassic (*c.* 235 Ma). This was associated with I-type calc-alkaline magmatism (Collins 1991; Li *et al.* 2012) and sediment accumulation in the Sydney–Bowen foreland basin (Korsch & Totterdell 2009; Cawood *et al.* 2011), specifically the Esk Trough and the Lorne Basin (Fielding *et al.* 2001). Palaeocurrent data from the Sydney–Bowen Basin (e.g. Esk Trough) indicate mainly west-directed sediment transport along its eastern margin (Fielding *et al.* 2001).

Triassic–Early Cretaceous: on-going convergence

A conventional continental margin arc continued to develop along the East Gondwana active margin, although not necessarily without variation in, for example, subduction rate or obliquity (Cawood 1984, 2005).

Stages of tectonic and magmatic development

After a long period of relatively steady-state, peripheral subduction, Permian plate reorganization, related to the consolidation of Gondwana, had profound effects on New Zealand and Zealandia, including the portions that now comprise New Zealand. The following tectonic evolution is proposed:

- Early Permian arc magmatism (*c.* 295–275 Ma): accelerated convergence triggered arc magmatism, both along the continental periphery (Gympie Terrane) and within the adjacent Panthalassa Ocean (Figs 15.22a & 15.23ci).
- Late Early Permian supra-subduction zone spreading (*c.* 278–274 Ma): accelerated subduction resulted in slab rollback and supra-subduction zone genesis of the Dun Mountain ophiolite within adjacent Panthalassa (Figs 15.22b & 15.23cii).
- Middle-Late Permian accretion of the oceanic-type Brook Street arc to Gondwana: the oceanic Brook Street arc (south of the Alpine Fault) accreted in the south, somewhere off SE Australia–East Antarctica (Figs 15.22c & 15.23di). The exact timing remains uncertain.
- Middle Permian docking of the ophiolite with Gondwana (*c.* 266 Ma): subduction of oceanic crust (not preserved) between Gondwana and the supra-subduction zone Dun Mountain ophiolite caused its accretion (and the associated oceanic arc) by Middle Permian time (*c.* 265 Ma) (Figs 15.22c & 15.23dii).
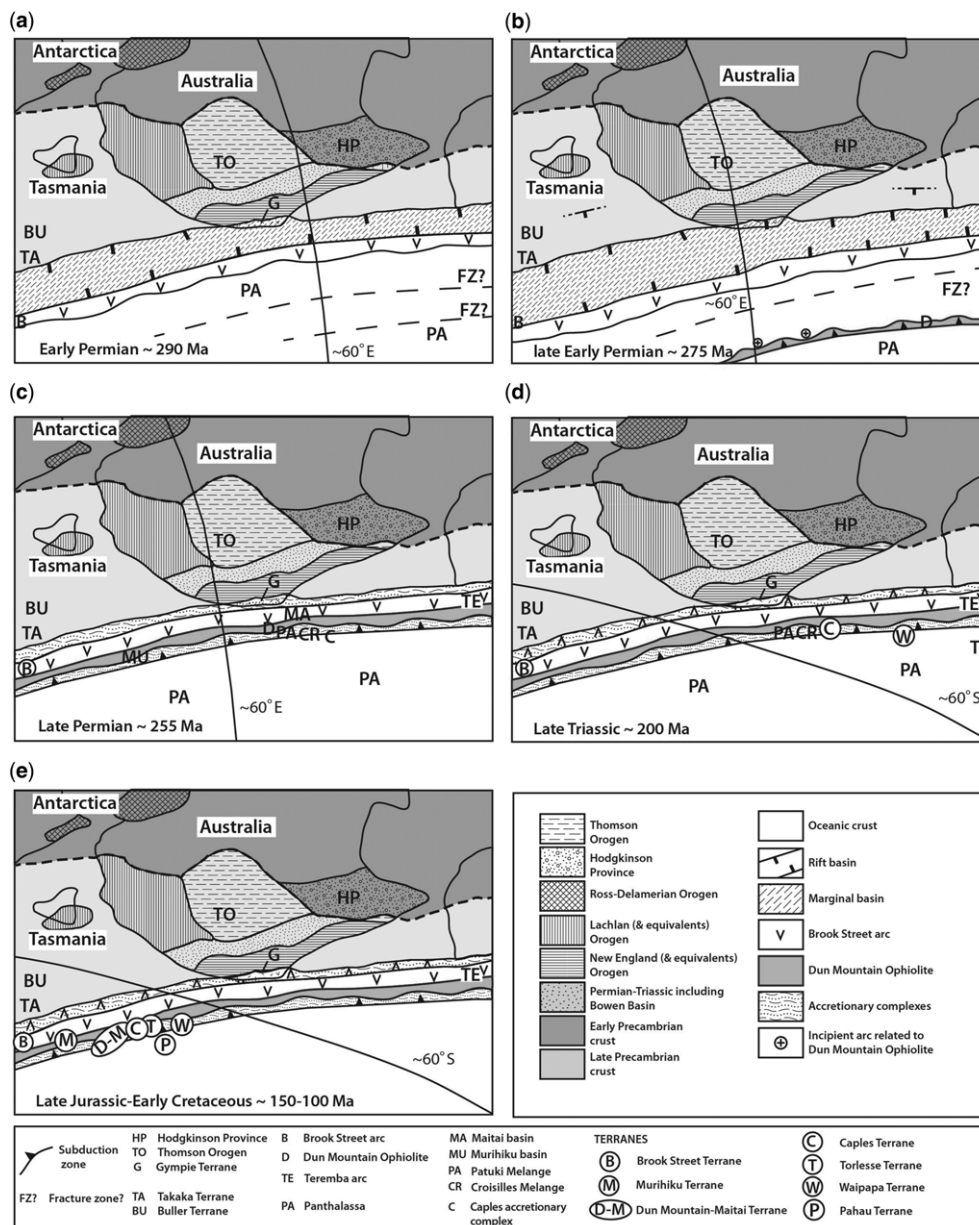

Fig. 15.22. Schematic reconstruction of the SE Gondwana active continental margin. (**a**) Early Permian, (**b**) late Early Permian, (**c**) Late Permian, (**d**) Late Triassic, (**e**) Late Jurassic–Early Cretaceous. Background reconstruction of Gondwana is based on data from Adams *et al.* (2007). Restored geographical coordinates are based on Torsvik & Cocks (2009). See the text for discussion.
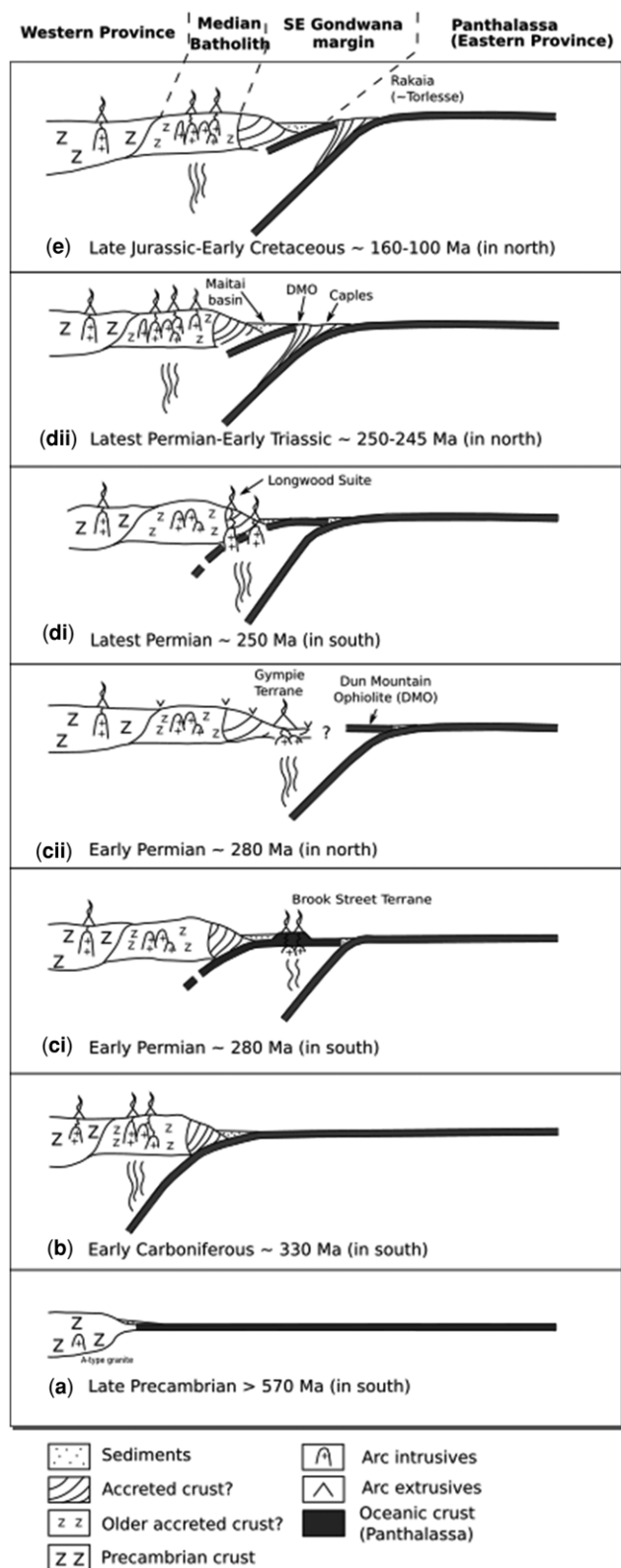
Fig. 15.23. Summary of proposed SE Gondwana continental margin evolution. (**a**) Late Precambrian; (**b**) early Carboniferous (located in a southerly position along the SE Gondwana margin); (**ci**) Early Permian (located in a southerly position); (**cii**) Early Permian (located in a northerly position along the SE Gondwana margin); (**di**) latest Permian (southerly location); (**dii**) latest Permian–Early Triassic (northerly location); (**e**) Late Jurassic–Early Cretaceous (northerly location). Several terranes (Brook Street and Murihiku) are restored to a southerly position (i.e. near the present relative position), whereas others originated from more northerly segments of the SE Gondwana margin, followed by southward displacement (i.e. Dun Mountain–Maitai, Caples and more easterly terranes). See the text for discussion.

- Middle Permian initiation of the Maitai forearc basin (*c.* 265 Ma) and Late Permian initiation of the Murihiku forearc basins (c. 260 Ma): the Murihiku Terrane and the Maitai Group represent proximal and distal forearc basins, respectively, along different segments of the Gondwana active continental margin. The Murihiku forearc basin was located relatively farther south, off SE Australia and East Antarctica, whereas the Maitai Basin was located off central Queensland (Figs 15.22c & 15.23dii).
- Late Permian accretion of the ophiolite-related melanges (*c.* 255 Ma): continuing plate convergence resulted in accretion of the Patuki, Croisilles and Greenstone melanges at the subduction trench to the east of the accreted Dun Mountain ophiolite (Fig. 15.22c).
- Late Permian continental margin-arc magmatism: continental margin-arc magmatism resumed during the latest Permian along the distal edge of the active continental margin (Median Batholith), resulting in batholith intrusion and volcanism which fed the Brook Street Terrane north of the Alpine Fault (Figs 15.22c & 15.23di).
- Triassic–Jurassic: continental margin arc: The relatively primitive I-type magmatism, exemplified by the Longwood and Darran suites of the Median Batholith, may represent intrusion of accreted (or trapped) oceanic crust, explaining the absence of a continental crust chemical signature (Figs 15.22d & 15.23e). Detritus in the adjacent Maitai and Murihiku forearc basins was derived both from the Cordilleran-type arc and from an emergent, bordering crustal block, which included pre-existing accretionary material and older arc-related magmatic rocks. Fragments of oceanic crust and sea-mounts accreted, together with trench sediments, to form the Caples, Rakaia and Waipapa terranes along different segments of the active continental margin (Figs 15.22e & 15.23e).
- Middle Jurassic: crustal thickening and metamorphism (*c.* 170 Ma): the pre-Cretaceous subduction complexes (Caples, Waipapa and Rakaia terranes) thickened, buckled *c.* north–south and metamorphosed up to phrenite–pumpellite facies or greenschist facies in different areas to form the Haast Schist.
- Early Cretaceous stabilization of the accretionary orogen (*c.* 100 Ma): collision of the Hikurangi Plateau (or an equivalent intra-plate edifice) with the trench ended subduction, associated with regional deformation (Scott *et al.* 2011). The Maitai basin and segments of the Drumduan Terrane (Nelson area) subducted, resulting in the lawsonite-bearing HP–LT metamorphism.

Resumption of an extensional accretionary orogen

Crustal extension, related magmatism and sedimentary basin formation culminated in rifting of the Tasman Sea Basin. Initial mafic calc-alkaline magmatism (102–100 Ma) was replaced by strongly alkaline magmatism (92–84 and 72–68 Ma in different areas), consistent with an intra-plate source, with the first oceanic crust appearing around 82 Ma (van der Meer *et al.* 2016).

The allochthonous terranes of the Western Province were close to their present relative positions by the end of the Early Cretaceous (*c.* 100 Ma), although terrane interaction persisted, especially related to Neogene displacement along (and adjacent to) the Alpine Fault (Coombs *et al.* 1976; Norris *et al.* 1978; Johnston *et al.* 1987; Bradshaw *et al.* 1996; Mortimer 2013, 2018; Lamb *et al.* 2015, 2016), although this is beyond the scope of this Memoir.

Conclusions

- Buller Terrane and Takaka Terrane (Western Province): these are correlated with Gondwana continental crust, as

exposed in SE Australia and E Antarctica. They are interpreted to have a relatively southerly origin, without substantial lateral translation along the Gondwana active margin.

The remaining terranes form parts of the Eastern Province:

- Drumduan Terrane (Paleozoic–Cretaceous): this is interpreted as fragments of the eastern margin of the Median Batholith and its country (host) rocks, or a non-exposed equivalent elsewhere along the SE Gondwana active margin. Significant lateral displacement relative to the Western Province is unlikely.
- Brook Street Terrane (Permian arc magmatism): oceanic arc-type rocks accreted to the Western Province in a southerly position during the Middle Late Permian; significant lateral displacement is again not implied. The Mid–Late Permian arc-related succession north of the Alpine Fault relates to early continental margin-arc magmatism.
- Murihiku Terrane (Late Permian–Early Cretaceous): the structural position and sediment provenance evidence suggest a proximal forearc setting along the SE Gondwana active margin. Southerly, or intermediate, positions are likely.
- Dun Mountain–Maitai Terrane (early Late Permian–Middle Triassic): after supra-subduction zone genesis (*c.* 277–269 Ma) above a west-facing subduction zone, the Dun Mountain ophiolite accreted to the SE Gondwana active margin (*c.* 265 Ma). The ophiolite then became the distal basement of the Maitai forearc basin, which accumulated sediment that was probably mainly sourced from central Queensland
- Patuki, Croisilles and Greenstone melanges (Late Permian genesis): these are parts of a regional-scale accretionary complex, combining material derived from the overriding oceanic plate (Dun Mountain ophiolite) and the downgoing Panthalassa oceanic plate (e.g. seamounts).
- Willsher Group (late Early–early Late Triassic): this is a proximal forearc basin, possibly a proximal equivalent of the Maitai Basin or its lateral equivalent.
- Caples Terrane: this represents trench sediments, oceanic seamount-related fragments and continental margin arc margin-related material (Permian and Triassic) that accreted during the Triassic at approximately the same palaeolatitude as the Dun Mountain–Maitai Terrane.
- Waipapa Composite Terrane (Permian–Jurassic); also the Kaweka Terrane (Jurassic): these units probably accreted along the NE Australia active margin segment, north of the terranes summarized above, and migrated to the central Queensland segment of the active margin by Early Cretaceous time (*c.* 150 Ma).
- Rakaia Composite Terrane (Permian–Triassic): this accreted along the NE Australia segment of the SE Gondwana active margin, and also migrated southwards to amalgamate with the other terranes of the Eastern Province by the Early Cretaceous (*c.* 145 Ma).
- Pahau Terrane, also the Waioeka Terrane (Early Cretaceous): these units accreted after displacement of the Waipapa and Rakaia composite terranes to near their present relative positions. Sediment was mainly derived from the older Rakaia Terrane (Torlesse) and from an adjacent continental margin arc, equivalent to the Median Batholith.

Overall, subduction, for much of the period oblique, was the main driver of terrane genesis, displacement and assembly. Relevant factors include changes in the rate, angle and obliquity of subduction, hinge migration (i.e. oceanic slab roll-back or roll-forward), the age of the incoming plate, thermal perturbations (e.g. ridge subduction), and mechanical discordances (e.g. fracture zones, seamounts, large igneous provinces or seamounts).

The vast area of subducted Panthalassa in the Zealandia region still remains virtually unknown, other than for accreted scraps of oceanic seamounts and possible mid-ocean ridge or forearc oceanic crust, together with related deep- and shallow-water sediments (e.g. Esk Head Melange, South Island), leaving many questions unanswered.

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