Gondwana Research 19 (2011) 650–669

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

The Mount Wright Arc: A Cambrian subduction system developed on the continental margin of East Gondwana, Koonenberry Belt, eastern Australia

J.E. Greenfield [a,*], R.J. Musgrave [a], M.C. Bruce [b], P.J. Gilmore [a], K.J. Mills [c]

[a] Geological Survey of New South Wales, Industry & Investment NSW, PO Box 344, Hunter Region Mail Centre, NSW 2310, Australia
[b] Geological Survey of New South Wales, Industry & Investment NSW, W.B. Clarke Geoscience Centre, 947-953 Londonderry Road, Londonderry NSW 2753, Australia
[c] 521 Williams Street, Broken Hill NSW 2880, Australia

ARTICLE INFO

Article history:
Received 6 May 2010
Received in revised form 26 November 2010
Accepted 29 November 2010
Available online 9 December 2010

Keywords:
Mount Wright Arc
Koonenberry Belt
Tectonics
East Gondwana
Delamerian Orogeny

ABSTRACT

The Mount Wright Arc, in the Koonenberry Belt in eastern Australia, is associated with two early to middle Cambrian lithostratigraphic groups developed onto the Late Neoproterozoic volcanic passive margin of East Gondwana. The Gnalta Group includes a calc-alkaline basalt-andesite-dacite suite (Mount Wright Volcanics), interpreted to represent the volcanic component of the arc. Volcaniclastic Gnalta Group rocks now buried in the Bancannia Trough represent the continental back-arc, developed immediately behind the arc in a manner analogous to the modern Taupo Volcanic Zone of New Zealand. East of the Gnalta Group is the Ponto Group, a deep marine sedimentary package that includes tholeiitic lavas (Bittles Tank Volcanics) and felsic tuffs, interpreted as part of a fore-arc sequence. The configuration of these units suggests the Mount Wright Arc developed on continental crust in response to west-dipping subduction along the East Gondwana margin, in contrast with some models for Cambrian convergence on other sections of the Delamerian Orogen, which invoke east-dipping subduction and arc accretion by arc-continent collision.

This convergent margin was deformed by the middle Cambrian Delamerian Orogeny, which involved initial co-axial shortening followed by sinistral transpression, and oroclinal folding around the edge of the Curnamona Province.

1. Introduction

The Neoproterozoic East Gondwana margin in southeastern Australia represents a passive margin developed after the break-up of Rodinia (Scheibner, 1992; Veevers et al., 1997), now marked by a series of salients and recesses that represent a margin boundary modified by later tectonic activity (Direen and Crawford, 2003a; Williams et al., 2009). Renewed extension along the passive margin resulted in significant turbiditic sedimentation during the early Cambrian (Kanmantoo Marginal Basin of Veevers, 2009). Outboard of the passive margin, the presence of Cambrian calc-alkaline and tholeiitic volcanics in a series of linear belts have been interpreted to represent either a fossil volcanic arc (Scheibner, 1974; Sharp and Buckley, 2003) and/or the products of post-collisional volcanism following the Delamerian Orogeny (Crawford and Berry, 1992; Crawford et al., 1996, 1997). Debate about the polarity of the Delamerian convergence has continued between proponents of broadly east-dipping subduction below arcs facing towards the Gondwanan continent (Crawford and Berry, 1992; Münker and Crawford, 2000; VandenBerg et al., 2000; Direen and Crawford, 2003b) and supporters of west-dipping subduction below arcs facing away from Gondwana (Crawford and Keays, 1978; Flöttmann et al., 1993; Finn et al., 1999; Spaggiari et al., 2003; Boger and Miller, 2004; Boger, in press; Foden et al., 2006; Foster et al., 2005; Miller et al., 2005). The middle Cambrian Delamerian Orogeny marked the final stage of accretion for the newly formed Gondwana supercontinent (Li and Powell, 2001) and was responsible for the deformation of the Cambrian volcanic rocks (Mills, 1992), and modification of the passive margin boundary (Williams et al., 2009). Accretion of arcs in the east-dipping subduction models implies arc collision with the Gondwanan continent during the Delamerian Orogeny.

The northwest-trending Koonenberry Belt, in northwest New South Wales (Fig. 1a and b), preserves strongly-weathered, sporadic outcrops of Neoproterozoic to Cambrian volcanic and sedimentary rocks that provide rare exposures of the Delamerian Orogen in eastern Australia. Similar Cambrian volcanic rocks have been described along strike from the study area helping to place the Koonenberry Belt in a wider zone of deformed rocks along the East Gondwana margin preserved in Australia (Glen, 2005). Tracing aeromagnetic lineaments ~200 km to the northwest, the belt appears to extend under cover to the Warburton Basin (Fig. 1), where drilling intersected Early Cambrian calc-alkaline volcanics (the Moorachoochie Volcanics) that have been correlated with the Mount Wright Volcanics (Gatehouse, 1986). To the south, the belt can be traced under cover to the northeast-trending Loch Lilly–Kars Belt (Fig. 1), where drilling has

* Corresponding author. Tel.: +61 2 4931 6728.
E-mail address: john.greenfield@industry.nsw.gov.au (J.E. Greenfield).

1342-937X/$ – see front matter
doi:10.1016/j.gr.2010.11.017

also uncovered Cambrian calc-alkaline and tholeiitic volcanics (Direen, 1999; described herein). Continuing south, the aeromagnetic lineaments of the Loch Lilly–Kars Belt can be traced to the exposed Adelaide Fold Belt (Preiss, 1995; Sharp et al., 2006). In western Victoria, middle Cambrian calc-alkaline volcanics occur in the northwest-trending Dimboola Igneous Complex (Fig. 1; Crawford et al., 1996), and similar Cambrian calc-alkaline and tholeiitic volcanic rocks occur further south again as the Mount Read Volcanics of Western Tasmania (Fig. 1; Crawford and Berry, 1992). Collectively these anatomising belts of deformed rocks are contained within the Delamerian Orogen (Glen, 2005), which also includes deformed Cambrian sedimentary rocks and Late Neoproterozoic volcano-sedimentary sequences.

The southwestern part of the Delamerian Orogen, especially the well-exposed Adelaide Fold Belt, has been extensively studied. Foden et al. (2006) conducted the most recent review of the available data, and concluded that the orogen developed in a compressive regime that was initiated at 514 ± 3 Ma, and was terminated by rapid uplift and extensional magmatism at about 490 ± 3 Ma. Aided by detailed geochemical analysis, Foden et al. (2002) demonstrated a change from extensional margin volcanism and sedimentation in the Late Neoproterozoic to a Cambrian convergent regime that was associated with the onset of subduction-related magmatism.

In the Koonenberry Belt, the early mapping work of Wopfner (1967), Warris (1967), Rose and Brunker (1969) and Mills (1992) established the Neoproterozoic to Cambrian stratigraphy. Based on this mapping Scheibner (1972, 1974) devised the first plate tectonic interpretation of the region, suggesting the Mount Wright Volcanics were part of an extensive volcanic arc associated with west-dipping subduction that developed along the East Gondwana margin in the Cambrian. Leitch et al. (1987) alternatively proposed a terrane model where the Cambrian elements were potentially unrelated to each other and juxtaposed via accretion to the Gondwana margin.

Edwards (1980), Davidson (1981), and Zhou (1992) elucidated the geochemical signatures of the key volcanic rocks. Crawford et al. (1997) built on these geochemical studies to distinguish Neoproterozoic alkaline rift-related Mount Arrowsmith Volcanics from the Cambrian calc-alkaline Mount Wright Volcanics. Although Crawford et al. (1997) determined that the Mount Wright Volcanics were compositionally similar to mature island arc lavas, they interpreted them to have been erupted within an immature continental rift that was unrelated to subduction. This interpretation was based on the small surface extent and the coherent, sparsely-phyric nature of the lavas. The presence of abundant intrusive dolerite dykes and the lack of andesitic pyroclastics were considered to be atypical of modern volcanic arc environments (Crawford et al., 1997).

This paper summarises and extends the results of 15 years of second generation 1:100 000 scale systematic mapping of the Koonenberry Belt. This work included the discovery of further outcrops of Mount Wright Volcanics, prompting a re-evaluation of their tectonic setting as part of an arc system (Sharp and Buckley, 2003). We also include geochemical and geophysical evidence that suggests the Mount Wright Volcanics were part of a volcanic arc and back-arc along the East Gondwana Margin, with the bulk of the back-arc developed in the Bancannia Trough that was protected from the effects of the Delamerian Orogeny behind a relatively stable continental landmass that now provides the spine of the Koonenberry Belt.

2. Geochemical and Geophysical Methods

A compilation of 375 whole-rock major- and trace-element geochemical and 32 Nd–Sr isotopic analyses from a variety of sources was used in this study (Appendix 1). Three hundred fourteen analyses were sourced from Crawford et al. (1997), Zhou (1992), Zhou and Whitford (1994), Edwards (1980), Direen (1999), and Mizow (2006). Sixty-one analyses were obtained by the Geological Survey of NSW over a sustained period of mapping and research using a variety of commercial geochemical laboratories (mainly ALS Chemex and Amdel Ltd.).

Due to the variety of compiled data sources from differing geochemical techniques, interpretations in this paper are largely based on the most recent data analysed by high-precision ICPMS (Inductively coupled plasma mass spectrometry) and TIMS (Thermal Ionisation Mass Spectrometry) methods, supported by the main dataset where appropriate. All rocks used in the analysis here have been variably metamorphosed, from prehnite–pumpellyite facies to lower amphibolite facies. Thus most major elements and some trace elements are potentially mobile during metamorphism. This is particularly true for the alkali elements (e.g. Li, Na, K, Rb and Cs) and other large-ion lithophile elements (LILE: Sr, Ba). In contrast, the high field-strength elements (HFSE; e.g. Th, U, Pb, Ti, Nb, Ta, Y, Zr and Hf) and rare earth elements (REE) are generally immobile. As a result, the least-mobile elements have been used to deduce primary geochemical signatures and relate them to tectonic interpretations.

Geophysical interpretation helped both to define the surface extent of the major tectonic elements of the arc and the framework defining their three-dimensional relationships. Qualitative analysis of aeromagnetic and gravity data comprised recognition of textural styles, and the extraction of major structural elements through the generation of wavelet edges (so-called worms, Hornby et al., 1999). Subsurface structure across the Koonenberry Belt was revealed by a deep seismic reflection line acquired in 1999 by the Australian Geological Survey Organisation (AGSO) and the then New South Wales Department of Mineral Resources (AGSO Line 99AGS-C1; Willcox et al., 2000).

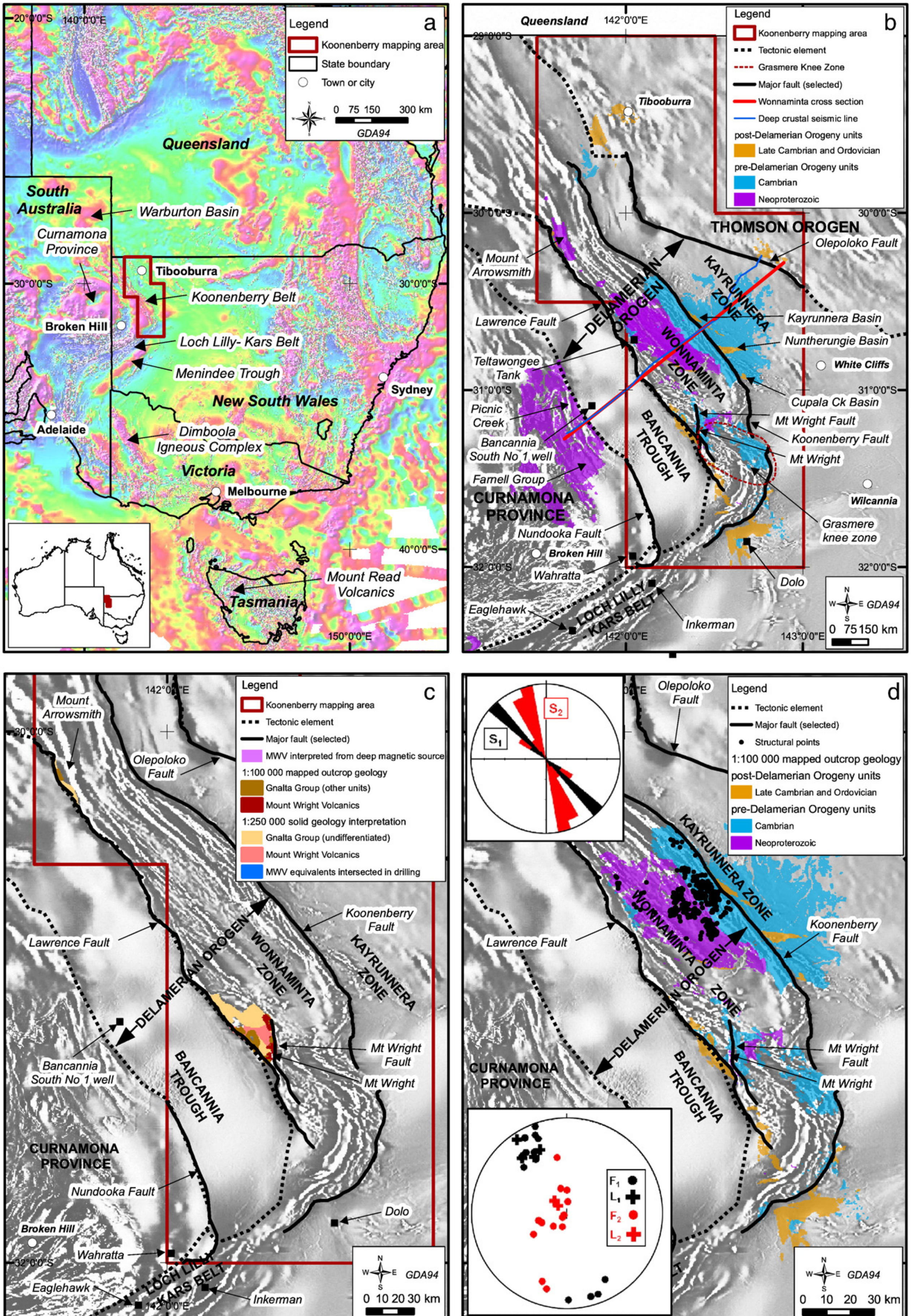
Quantitative geophysical interpretation comprised magnetic and gravity modelling of a series of long (30–160 km) cross-sections oriented perpendicular to the trend of the belt. Modelling took the form of geologically-constrained inversion by iterative forward modelling of discrete parametric bodies (Type III modelling of Oldenburg and Pratt, 2007), and was a sequential process, with the output of earlier modelled sections informing the construction of the starting model for subsequent, neighbouring sections. Density and susceptibility assigned to bodies were allowed to vary within limits set by petrophysical measurements of samples, augmented by field measurements of susceptibility: some composite units (e.g. undifferentiated Grey Range Group or Ponto Group) were allowed a range of values between limits set by constituent lithologies (Appendix 3). Remanence was included, and allowed to vary during the inversion, for sources of negative anomalies, and for a series of large magnetic sources at the base of the Bancannia Trough. A detailed discussion of this modelling approach is found in Musgrave (2010).

3. Geological Setting and Geochemical Analysis

3.1. Regional Setting

The Koonenberry Belt is a 300 km long and up to 80 km wide linear package of Neoproterozoic and Palaeozoic rocks that outcrop in a series of inliers surrounded by Mesozoic (i.e. Eromanga Basin fill), Cenozoic (i.e. Lake Eyre Basin fill) and Quaternary cover sequences east of the Bancannia Trough (Fig. 1b). The Bancannia Trough separates the Koonenberry Belt from the Palaeoproterozoic Curnamona Province (and its Neoproterozoic to Cambrian cover) to the west. The Loch Lilly–Kars Belt to the south is interpreted from geophysics and exploration drilling (including drilling of the Inkerman, Wahratta and Eaglehawk prospects (Fig. 1b) to represent the thrusted and rotated continuation of the sequence observed in the Koonenberry Belt (Direen, 1999; Sharp et al., 2006; this study). To the northwest, the Koonenberry Belt abuts the enigmatic Thomson Orogen along the Olepoloko Fault (Burton, 2010).

Late Neoproterozoic and Cambrian rocks (Fig. 2) of the Koonenberry Belt, Bancannia Trough and the Loch Lilly–Kars Belt preserve a



a
Legend
Koonenberry mapping area
State boundary
Town or city
0 75 150 300 km
GDA94
20°0'0"S
140°0'0"E
Queensland
South Australia
Warburton Basin
Curnamona Province
Tibooburra
Koonenberry Belt
Broken Hill
Loch Lilly- Kars Belt
Menindee Trough
Sydney
New South Wales
Adelaide
Dimboola Igneous Complex
Victoria
Melbourne
Mount Read Volcanics
Tasmania
30°0'0"S
40°0'0"S
150°0'0"E
b
Legend
Koonenberry mapping area
Tectonic element
Grasmere Knee Zone
Major fault (selected)
Wonnaminta cross section
Deep crustal seismic line
post-Delamerian Orogeny units
Late Cambrian and Ordovician
pre-Delamerian Orogeny units
Cambrian
Neoproterozoic
Queensland
142°0'0"E
29°0'0"S
Tibooburra
30°0'0"S
THOMSON OROGEN
Olepoloko Fault
Mount Arrowsmith
DELAMERIAN OROGEN
KAYRUNNERA ZONE
Kayrunnera Basin
Nuntherungie Basin
Lawrence Fault
WONNAMINTA ZONE
Teltawongee Tank
White Cliffs
31°0'0"S
Cupala Ck Basin
Picnic Creek
Mt Wright Fault
Koonenberry Fault
Bancannia South No 1 well
BANCANNIA TROUGH
Mt Wright
Farnell Group
Wilcannia
CURNAMONA PROVINCE
Grasmere knee zone
Nundooka Fault
Broken Hill
32°0'0"S
Wahratta
Dolo
Eaglehawk
LOCH LILLY KARS BELT
Inkerman
142°0'0"E
143°0'0"E
GDA94
0 75 150 km
c
Legend
Koonenberry mapping area
Tectonic element
Major fault (selected)
MWV interpreted from deep magnetic source
1:100 000 mapped outcrop geology
Gnalta Group (other units)
Mount Wright Volcanics
1:250 000 solid geology interpretation
Gnalta Group (undifferentiated)
Mount Wright Volcanics
MWV equivalents intersected in drilling
142°0'0"E
30°0'0"S
Mount Arrowsmith
Olepoloko Fault
Koonenberry Fault
Lawrence Fault
DELAMERIAN OROGEN
WONNAMINTA ZONE
KAYRUNNERA ZONE
Mt Wright Fault
Mt Wright
Bancannia South No 1 well
BANCANNIA TROUGH
CURNAMONA PROVINCE
Nundooka Fault
Dolo
Broken Hill
32°0'0"S
Wahratta
Eaglehawk
LOCH LILLY KARS BELT
Inkerman
142°0'0"E
GDA94
0 10 20 30 km
d
S_1
S_2
Olepoloko Fault
Legend
Tectonic element
Major fault (selected)
Structural points
1:100 000 mapped outcrop geology
post-Delamerian Orogeny units
Late Cambrian and Ordovician
pre-Delamerian Orogeny units
Cambrian
Neoproterozoic
KAYRUNNERA ZONE
Koonenberry Fault
Lawrence Fault
WONNAMINTA ZONE
DELAMERIAN OROGEN
Mt Wright Fault
Mt Wright
CURNAMONA PROVINCE
BANCANNIA TROUGH
F_1
L_1
F_2
L_2
GDA94
0 10 20 30 km

significant segment of the Delamerian Orogenic Cycle (as defined by Glen, 2005) in eastern Australia, and were first deformed in the middle Cambrian Delamerian Orogeny. These rocks record a major igneous rifting event which may represent a second phase of segmentation of this margin of the Rodinia supercontinent following an hypothesised break-up at about 827–755 Ma, or may indeed be the first stage of rifting of the East Gondwana margin (Foden et al., 2001; Direen and Crawford, 2003a,b). Late Cambrian and Ordovician rocks post-dating the Delamerian Orogeny represent the early stages of the Lachlan Orogenic Cycle (Glen, 2005).

In addition, evidence of subsequent orogenic events has been preserved in the Koonenberry Belt. These include deformation events correlated with the Late Ordovician–Early Silurian Benambran Orogeny, the Late Silurian–Early Devonian Bindian Orogeny, the Middle Devonian Tabberabberan Orogeny and the Carboniferous Kanimblan and Alice Springs orogenies (Greenfield, 2010a).

The development of the Mount Wright Arc can be described with respect to the Delamerian Orogenic Cycle, as defined by Glen (2005). Within the Koonenberry Belt, the Delamerian Orogenic Cycle incorporates Neoproterozoic to late Cambrian sedimentation and igneous activity comprising the Grey Range Group, including the Mount Arrowsmith Volcanics, the Teltawongee Group, the Gnalta Group (including the Mount Wright Volcanics), and the Ponto Group (including the Bittles Tank Volcanics; Mills, 1992; Greenfield and Mills, 2010). Deposition in this cycle was terminated by the Delamerian Orogeny. Sedimentation during the early stages of the following Lachlan Orogenic Cycle resulted in the deposition of the late Cambrian to Ordovician Kayrunnera, Mutawintji, and Warratta groups.

3.2. Geophysical Imagery and the Definition of Structural Domains

Images of aeromagnetic total magnetic intensity (TMI) and gravity data (Fig. 3) prompt a division of the Koonenberry Belt into three structural domains, the Bancannia Trough, the Wonnaminta Zone, and the Kayrunnera Zone. Broadly, these domains correspond to the Bancannia Zone, Wonnaminta Zone, and the northern part of the Morden–Stawell Zone of Scheibner and Basden (1996).

Gravity across the Bancannia Trough forms a broad but intense low (amplitude of ~400 μms^{-2}) consistent with the thick fill of Devonian and Mesozoic sedimentary rocks recovered in drilling in the trough. However a series of prominent, deeply-sourced, elliptical magnetic anomalies, spaced about 20–40 km apart and running along the axis of the trough, appear to represent an igneous basement below the trough. Samples of the Cambrian andesite and dacite recovered from below the Devonian sequence in the Bancannia South No. 1 petroleum exploration well (Baarda, 1968) are strongly magnetic (magnetic susceptibility averaging about 1700×10^{-5} SI), and have been considered representative of the sources of the large magnetic anomalies (Mills and David, 2004).

Intense (100–500 nT), short-wavelength (half-width <1 km), linear or curvilinear magnetic highs characterise the Wonnaminta Zone; their sources have been identified through mapping as the Mount Arrowsmith Volcanics, Bittles Tank Volcanics, and magnetic phyllite with intercalated calc-silicate horizons from the Ponto Group. Mount Wright Volcanics also contribute magnetic highs along the south-western flank of the Wonnaminta Zone. Metasedimentary rocks of the Grey Range and Teltawongee groups have a very subdued magnetic signature. Gravity is high over the Wonnaminta Zone, reaching a maximum near the southwestern flank of the zone; local gravity maxima delineate belts of higher-density rocks, comprising Mount Arrowsmith Volcanics and, in the southeastern part of the zone, upper greenschist to amphibolite grade rocks within the Ponto Group.

Short-wavelength linear or curvilinear magnetic anomalies mark metasandstone units of the Teltawongee Group east of the Koonenberry Fault within the Kayrunnera Zone. These are much less intense (amplitudes less than 10 nT) than the prominent anomalies that define the Wonnaminta Zone, matching the observed absence of mafic volcanics in this zone, but have a greater amplitude than the anomalies over the Teltawongee Group west of the Koonenberry Fault, suggesting differences in composition which may reflect contrasting provenance or depositional history. Longer wavelength linear magnetic anomalies, with amplitudes of >50 nT and half-widths of 1–3 km, define a deep-seated structure close to the boundary with the Thomson Orogen in the northern part of the Kayrunnera Zone. Gravity decreases by about 200 μms^{-2} from the Wonnaminta Zone to the Kayrunnera Zone (and still more in the south of the Kayrunnera Zone, where Devonian sedimentary rocks cover the Cambrian basement). Decreased gravity over the Kayrunnera Zone reflects the lower density of the Teltawongee Group east of the Koonenberry Fault compared to rocks of the Teltawongee Group west of the fault.

Wavelet edges in gravity and magnetics reveal the major structural features of the belt. They delineate the principal domain-bounding faults—the Nundooka Fault on the western margin of the Bancannia Trough, the Lawrence Fault defining the eastern boundary of the trough, the Koonenberry Fault between the Wonnaminta Zone and the Kayrunnera Zone, and the inferred extension of the Olepoloko Fault separating the Koonenberry Belt from the Thomson Orogen. Wavelet edges also pick out the major internal structure within the zones, particularly a series of stacked thrust faults in the Wonnaminta Zone.

3.3. Stratigraphy and Geochemistry of the Delamerian Orogenic Cycle

3.3.1. Neoproterizoic Rift Package—the Grey Range Group

The Late Neoproterozoic Grey Range Group (Greenfield and Mills, 2010), which underlies the Cambrian arc elements, consists of shallow marine sedimentary rocks of the Kara Formation, and intercalated alkaline dominantly basaltic submarine lavas and related intrusives of the Mount Arrowsmith Volcanics (Fig. 2). This group is interpreted to be related to platform sedimentation and intracratonic rifting during a late phase of rifting on the eastern Gondwana margin (Foden et al., 2001; Crawford et al., 1997; Direen and Crawford, 2003b; Direen et al., 2009).

SHRIMP II U–Pb analysis of zircons from a rare rhyodacite of the Mount Arrowsmith Volcanics (in the Mount Wright area) yielded an age of 585.5 ± 2.6 Ma (Black, 2007; Appendix 2), which is consistent with a previous SHRIMP I U–Pb zircon age of 586 ± 7 Ma (Crawford et al., 1997) from the same unit. The SHRIMP II dates compare favourably with a Sm–Nd whole-rock isochron age of 578 ± 96 Ma (Bruce, 2010).

According to the Nb/Y versus Zr/TiO2 classification scheme of Winchester and Floyd (1977), the bulk of the Neoproterozoic Mount Arrowsmith Volcanics (n = 168) predominantly overlap the alkali basalt–trachyandesite–trachyte–phonolite fields. Zr/Nb ratios are variable (3–12) which may suggest that the Mount Arrowsmith Volcanics were sourced from a mix of both enriched (low Zr/Nb values) and slightly more depleted (higher Zr/Nb values) mantle reservoirs. Initial $^{143}Nd/^{144}Nd = 0.51212 \pm 7$ corresponding to εNd (578 Ma) = +4.3 ± 1.2, is consistent with average modern rift-related basalts (Hart, 1988). This suggests derivation from a similar

Fig. 1. Location of the Koonenberry Belt in relation to eastern Australia over an image of a total magnetic intensity (a), geological and structural features in the study area (b), the distribution of the Mount Wright Volcanics from mapping and geophysical interpretation (c) and structural measurements (d). Figures b, c and d have a background image of the first vertical derivative of total magnetic intensity. Geological units shown in the Koonenberry mapping area are from 1:100 000 scale outcrop mapping. The geological units shown in the Curnamona Province are outcropping Neoproterozoic units from the NSW 1.5 million scale surface geology compilation.

enriched mantle source, an interpretation supported by trace element data (Fig. 4).

Within the Koonenberry Belt, the greatest area of outcrop of the Mount Arrowsmith Volcanics is at Mount Arrowsmith, with further exposures near Mount Wright (Fig. 1b). The Grey Range Group is interpreted to be equivalent to the Adelaidean Farnell Group west of the Bancannia Trough with respect to age and depositional setting (Gilmore et al., 2007). The basaltic rocks within the Farnell Group share close geochemical affinities to the Mount Arrowsmith Volcanics (Fig. 1b, Greenfield and Mills, 2010).

Basaltic rocks with similar geochemical affinities to the Mount Arrowsmith Volcanics also occur south of the Koonenberry Belt in the Loch Lilly–Kars Belt. Three basalt samples from the Eaglehawk prospect (Fig. 1b) analysed by Direen (1999) have been plotted on a multi-element diagram normalised to N-MORB (Fig. 4) with average ocean island basalt (OIB) data from Sun and McDonough (1989) and

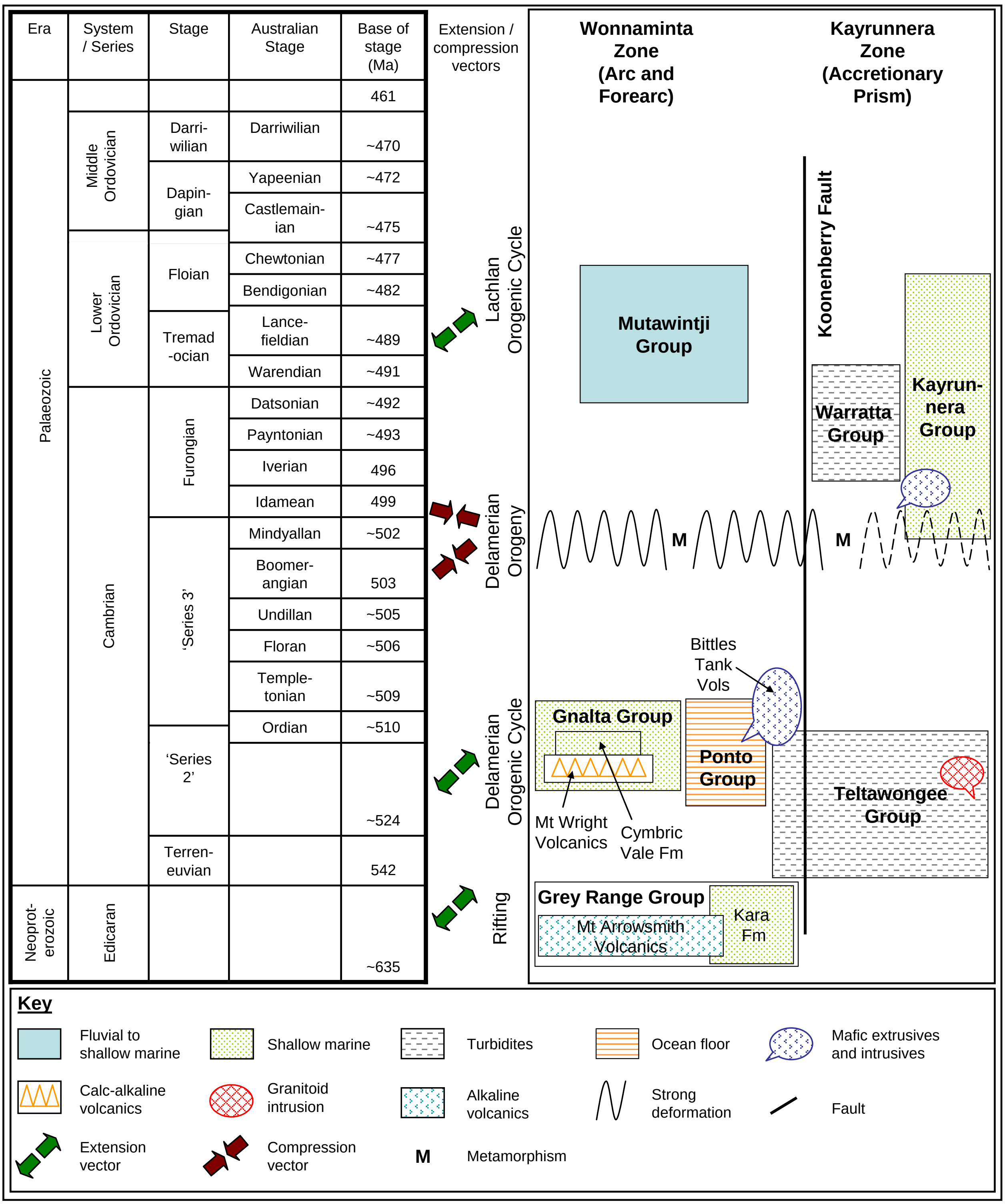


Fig. 2. Schematic time-space plot for the Koonenberry Belt from the Neoproterozoic to Middle Ordovician. Australian stages and ages from Percival (2010b), other terminology from Ogg et al. (2008). Note time-space plot is not to scale and overlap occurs between Australian stages and international subdivisions—see Percival (2010b) for details.

sample MS15C from the Mount Arrowsmith Volcanics. Similarities between all data suggest a similar intra-plate origin. The Eaglehawk basalts are more Th enriched and Nb depleted than the average OIB or MS15C possibly suggesting a greater crustal contribution. Zr/Nb ratios vary (6–14) as do Ti/V = 38–147. Based on La–Y–Nb concentrations the Eaglehawk basalts plot as continental intra-plate basalts on the discrimination diagram of Cabanis and Lecolle (1989).

Therefore there is evidence of rift-related magmatism on both sides of the Bancannia Trough, and to the south in the Loch Lilly–Kars Belt. In addition, magnetic and gravity modelling, coupled with the interpretation of a seismic reflection profile, suggests that large bodies equivalent to the Mount Arrowsmith Volcanics occur at depth in the Wonnaminta Zone (see Section 4.1).

3.3.2. Cambrian Turbidites—the Teltawongee Group

The Teltawongee Group (Fig. 2) is an extensive package of turbiditic sandstones and siltstones deposited along an east-facing continental slope (Mills, 2010a). The Teltawongee Group consists of the Nundora and Wonnaminta formations west of the Koonenberry Fault, and the Bunker Creek, Copper Mine Range and Depot Glen formations east of the Koonenberry Fault. The age of the Teltawongee Group is poorly constrained, although non-diagnostic fossils and trace fossils indicate a likely Cambrian age (Mills, 2010a). This is supported by SHRIMP II zircon dating of the Williams Peak Granite that intrudes the Bunker Creek Formation at 515.1 ± 2.7, Ma, and a laminated felsic tuffaceous bed within the Depot Glen Formation at 504.5 ± 2.6 Ma (Black, 2006; Appendix 2).

At one key outcrop near Teltawongee Tank (Fig. 1b), a sequence of steeply-dipping, laminated slate and graded sandstone beds of the Nundora Formation overlie, with structural concordance (probable disconformity), a series of laminated to cross-bedded feldspathic sandstone of the Neoproterozoic Kara Formation of the Grey Range Group (Mills, 2010b). This relationship indicates a lack of tectonic disturbance between deposition of Neoproterozoic shallow marine sediments and the Cambrian turbidites of the Teltawongee Group.

Dating of detrital zircons suggests a different provenance for sediments for Teltawongee Group units west and east of the Koonenberry Fault. The Nundora Formation rocks west of the Koonenberry Fault have a detrital zircon population that includes peaks at ~1178 Ma and ~1589 Ma, and are interpreted to be proximally derived from the Curnamona Province (Greenfield, 2010a). In contrast, the Copper Mine Range Formation east of the Koonenberry Fault has a detrital zircon population with peaks at ~575 Ma and ~1000 Ma (Greenfield, 2010a). Veevers (2000) interpreted these latter two peaks as evidence that the sediments were derived from a distal source to the south (i.e. Ross Orogen in eastern Antarctica).

3.3.3. Cambrian Mount Wright Arc—the Gnalta Group

The latest early Cambrian to late Cambrian Gnalta Group consists of the Mount Wright Volcanics, a calc-alkaline basalt–andesite–dacite–rhyolite volcanic suite, intercalated with a package of mudstone, siltstone and limestone (Percival, 2010a). The sedimentary parts of the sequence preserves the best early Cambrian fossil record in NSW, and are inferred to represent a shallow marine–shelf setting (Percival, 2010a). Pyroclastic to tuffaceous rocks from the Cymbric Vale Formation (which overlies the Mount Wright Volcanics) have been dated using SHRIMP II zircon analysis at 510.3 ± 3.2 Ma (Black, 2005; Appendix 2) and at 510.5 ± 2.9 Ma (Black, 2007; Appendix 2). A reworked felsic tuff from the Cymbric Vale Formation was dated at 510.1 ± 2.3 Ma (Jagodzinski, 2007). These dates indicate volcanism at ~510 Ma, consistent with age-constraints from the fossil record (Percival, 2010b).

The Mount Wright Volcanics comprise compositionally diverse volcanic rocks—lavas and intrusions are mainly subalkaline as defined

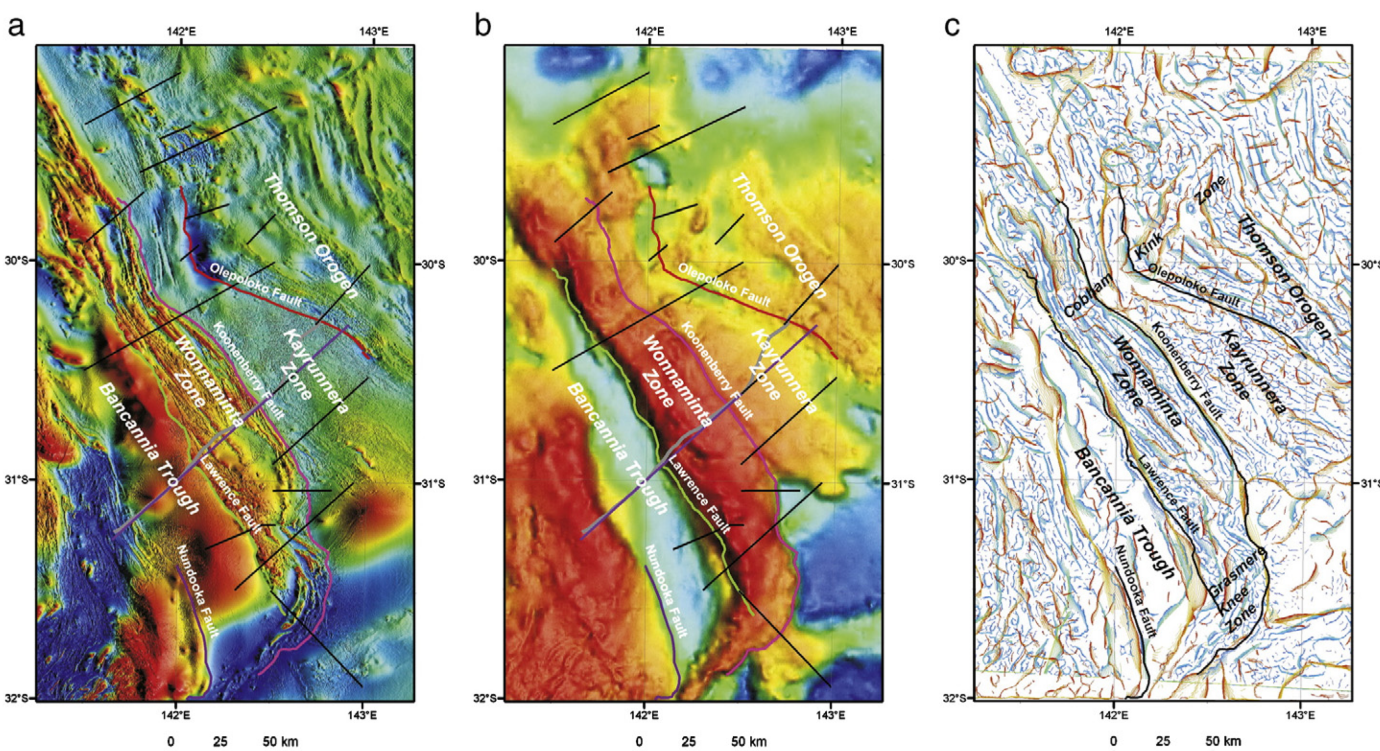


Fig. 3. Images of gridded aeromagnetic and gravity data over the Koonenberry Belt. (a) Total magnetic intensity. Structural terranes and bounding faults indicated. Grey line shows trace of deep seismic reflection profile. Black lines show locations of geophysically modelled cross-sections: purple line shows location of Wonnaminta cross-section, shown in Fig. 7. (b) Isostatically reduced Bouguer gravity. (c) Overlay of magnetic (blue to green) and gravity (red to orange) edges, with location of major cross-strike structural zones.

by Le Bas et al. (1986), with low Nb/Y (<0.6), and span both the tholeiitic and calc-alkaline series (Fig. 5a) as defined by Miyashiro (1974). Notably on this diagram the basalt and andesite appear to have evolved largely along a tholeiitic trend whilst the more differentiated dacite and rhyolite are calc-alkaline in character. Despite the compositional variation, there appears to be no distinction in outcrop distribution between the rock types, although this may be due to structural juxtaposition during subsequent deformation. The geochemical variations are discussed in detail below.

3.3.3.1. Tholeiitic Volcanics of the Mount Wright Volcanics. The more mafic basalt–andesite samples of the Mount Wright Volcanics have mixed geochemical fingerprints transitional between E-MORB-like and arc-like signatures (Fig. 5b). Enrichment in Th and Pb (and to a lesser extent the more mobile Rb, Ba and K), coupled with relative depletion in Nb, are characteristics of arc (Pearce, 1982) or crust-contaminated (Cox and Hawkesworth, 1985) magmas. In the one sample (MW037; Appendix 1) where La data are available, light REE enrichment is apparent with high $(La/Y)_{E\text{-}MORB} = 2.08$. This is also consistent with subduction-related or crust-contaminated magmas. However, a distinct lack of Ti and Zr depletions are characteristics more akin to magmas from enriched mantle sources. Variable Zr/Nb (19–34) ratios overlap the fields of arc magmas and N-MORB. The Ti/V ratio (~30) of two dolerites (MW037 and MW020A) is similar to both N-MORB and backarc basin basalts (BAB). Whole-rock Nd isotopes are available for two of the samples (MW031 and MW089A). They record present-day εNd = -0.1 and −2.6, which are within the range of enriched OIB (with or without crustal input), as well as subduction-related basalts.

Two andesite samples (MW11 and MW12) normalised to E-MORB, show enrichment in Rb, Ba, Th and the light REE ($[Sm/Nd]_{N\text{-}MORB} = 0.63$–$0.7$), coupled with relative depletions in Nb and Ti (Fig. 5c). These are characteristics typical of arc magmas, however slightly elevated Ta (0.8–0.9 ppm) suggests more of an intraplate character.

In summary, a combination of both arc and intra-plate geochemical attributes characterise the tholeiitic basaltic and andesitic samples of the Mount Wright Volcanics.

3.3.3.2. Calc-alkaline Volcanics of the Mount Wright Volcanics. The dacite–rhyodacite samples display a similar trace element pattern to the tholeiitic volcanics (Fig. 5d, cf. b), with characteristic Nb depletions. However, a greater enrichment in light REE ($[La/Y]_{E\text{-}MORB} = 2.6$–$4.7$) supports a calc-alkaline affinity as suggested by major element data (Fig. 5a).

The dacite samples have high Th/Y and Ba/Ti ratios and low Nb/La and Nb/Zr ratios with the majority having HFSE concentrations similar to E-MORB. This, together with light REE enrichment would suggest either the addition of LILE and light REEs to the mantle wedge from a subducted slab (Pearce, 1983) or crustal contamination. A few of the dacite samples have incompatible trace-element abundances similar to the average upper continental crust of Taylor and McLennan (1995), which would imply the involvement of a substantial crustal component. However, significantly higher Th and Pb concentrations, coupled with even more depleted Nb abundances (compared to average upper crust), would argue for the additional role of subduction-related fluids.

Two rhyolite samples normalised to E-MORB display characteristic arc signatures with enrichments in the LILE and light REE ($[Sm/Nd]_{N\text{-}MORB} = 0.47$–$0.55$) and depletion in Nb, Ta, Zr and Ti (Fig. 5e). Part of this signature may be attributed to crustal contamination, an assertion supported by low present-day epsilon Nd values (εNd = −7.5) that are also recorded in a dacite sample (MW061; εNd = −8.0) and are within the range of both crust-contaminated oceanic island arc and continental arc volcanic rocks.

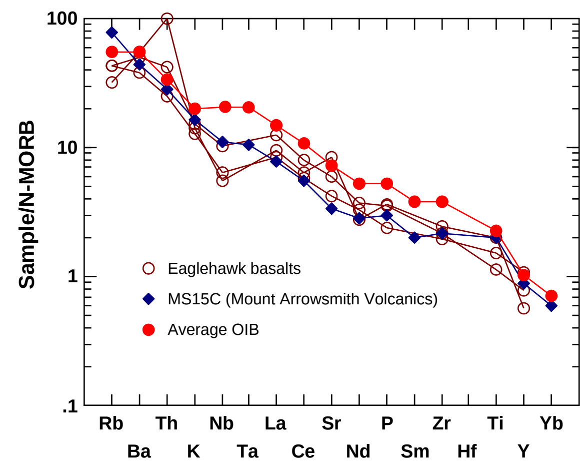


Fig. 4. N-MORB normalised multi-element diagram of basalts from the Eaglehawk prospect. Also plotted for comparison purposes is a basalt from the Mount Arrowsmith Volcanics and an average OIB. Normalisation values and OIB data are taken from Sun and McDonough (1989).

3.3.3.3. Inferred Mount Wright Volcanics Under Cover. Exposure of the Mount Wright Volcanics is confined to the Mount Wright area in the Koonenberry Belt (Fig. 1c), and the limited outcrop of these volcanics led Crawford et al. (1997) to suggest that they were unlikely to represent a volcanic arc (Crawford et al., 1997). However, interpretation of aeromagnetic and gravity images (Fig. 3) suggest that the volume of Mount Wright Volcanics can be significantly extended under cover, and modelling incorporating seismic reflection, aeromagnetic and gravity data indicates that igneous bodies related to the Mount Wright Volcanics occupy very large volumes (approximately 11 000 km^3), buried below 3–7 km of Devonian and post-Palaeozoic sedimentary rocks in the Bancannia Trough (see Section 4.2). Geochemical analyses, petrographic descriptions and age-dating of basement rocks intersected in drilling in parts of the Loch Lilly–Kars Belt and in the Bancannia Trough support this interpretation of the extent of the Mount Wright Volcanics.

The Bancannia South No 1 petroleum well in the Bancannia Trough (Fig. 1b) intersected a 151 m thick package of extrusive volcanic rocks to the end of hole, under ~3250 m of younger rocks. The plagioclase-phyric andesitic lavas, tuffs and dacites intersected are similar in petrography and geochemistry (samples BS10–BS11 in Appendix 1) to outcropping Mount Wright Volcanics. A recent SHRIMP II analysis of an andesitic lava from the Bancannia South No 1 core produced an age of 506.2 ± 2.8 Ma (Appendix 2), consistent with the age of the Mount Wright Volcanics from SHRIMP II analysis of outcropping units to the east.

Eighteen igneous rocks from the Inkerman Prospect in the Loch Lilly–Kars Belt (Fig. 1b) were analysed by Direen (1999) and show a range of subalkaline volcanic lithologies including basalt, andesite, dacite and rhyolite according to the classification scheme of Le Bas et al. (1986). Intrusive rocks are classified as microdiorite to micrograniite using the scheme of Middlemost (1994). To compare the Loch Lilly–Kars Belt volcanic rocks against Koonenberry Belt equivalents, a basaltic sample (sample MW020A in Appendix 1) from the Mount Wright Volcanics was used. This sample was chosen because it has similar Mg# [Mg+/ (Mg+ + Fe2+] (0.53) and Ni content (48 ppm) to the only reported datum of the Inkerman basalt (0.56 and 50 ppm respectively), thus minimising effects due to fractionation. An N-MORB normalised multi-element diagram of the two samples shows a similar trace-element pattern, however a lower Nb and P abundance coupled with higher Ti and Y suggests a greater extent of melting of a more depleted source for the Inkerman basalt. This interpretation is also supported by Zr/Nb ratios (~68 for Inkerman and ~20 for MW020A). Both samples have similar Ti/V ratios (25 and 28 respectively) characteristic of MORB

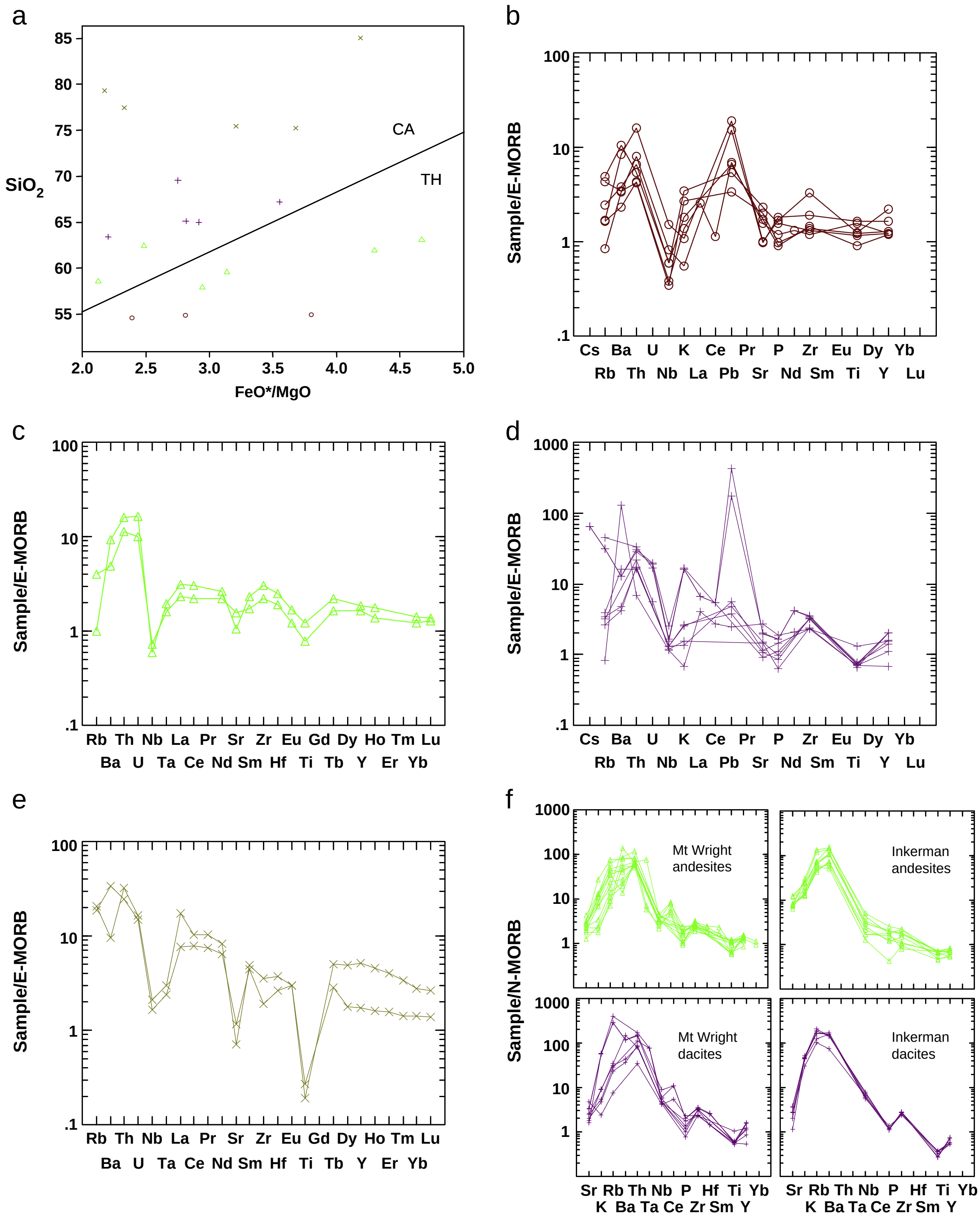


Fig. 5. (a) SiO_2 versus FeO^*/MgO diagram of moderately fractionated basalt (o), andesite (Δ), dacite (+) and rhyolite (×) of the Mount Wright Volcanics. Dividing line separating calc-alkaline (CA) magmas from tholeiitic (TH) magmas is from Miyashiro (1974). FeO^* = total Fe reported as FeO. (b) Multi-element diagram normalised to E-MORB (Sun and McDonough, 1989) plotting basalts of the Mount Wright Volcanics. (c) Multi-element diagram of two andesites from the Mount Wright Volcanics normalised to E-MORB. Normalisation values after Sun and McDonough (1989). (d) E-MORB normalised multi-element diagram of dacites from the Mount Wright Volcanics. Normalisation values after Sun and McDonough (1989). (e) E-MORB normalised multi-element diagram of two rhyolite samples (G06_944 and G06_945; Appendix 1) from the Mount Wright Volcanics. Normalisation values after Sun and McDonough (1989). (f) N-MORB normalised multi-element diagrams comparing andesites and dacites of the Inkerman prospect and Mount Wright Volcanics. Normalisation values after Sun and McDonough (1989).

and back-arc basalts (BAB). A spiked pattern typical of subduction related magmas is observed in both samples, consistent with a BAB origin. Therefore based on the available data the volcanic rocks intersected by drilling at the Inkerman Prospect are very similar to the Mount Wright Volcanics, suggesting a similar origin (Fig. 5f).

At the Wahratta prospect (Fig. 1b) exploration drilling intersected an andesitic volcanic province including shoshonitic volcanics, porphyritic intrusive rocks including monzonites and microdiorite and quartz syenite (Richardson, 1998). SHRIMP I age dating of euhedral, magmatic zircons from coarse-grained monzodiorite (Mills, 2010c) in drillhole DDH96WA3 at the Wahratta prospect resulted in age determinations of 505 ± 5 Ma, 519 ± 5 Ma and 521 ± 5 Ma (Corbett, 2000; Gilmore, 2010). Monzodiorite and syenite intersected in this drillhole have a calc-alkaline affinity (Direen, 1999) and are therefore interpreted to be equivalents of the Mount Wright Volcanics with respect to age and geochemistry (Sharp et al., 2006). As discussed below, tholeiitic dolerites intersected in DDH96WA3 (Direen, 1999) are interpreted to be equivalents to the Bittles Tank Volcanics.

3.3.4. Cambrian Fore-arc—the Ponto Group

The Cambrian Ponto Group mainly consists of fine-grained (dominantly mudstone and siltstone) marine clastic rocks with intercalated exhalative units (quartz–magnetite, quartz–haematite, and quartz–pyrrhotite units) and laterally extensive laminated cherty air-fall tuffs (Mills, 2010d). These strike-extensive rocks are confined to a narrow belt roughly 300 km long against the western side of the Koonenberry Fault, where they are well exposed in the central and southern Koonenberry Belt (Fig. 1b). These rocks attained the highest metamorphic grade in the Koonenberry Belt, reaching lower amphibolite facies in the hanging wall of the east-dipping Mount Wright Fault (Fig. 1c), defined by biotite–muscovite–quartz in phyllite, and epidote–plagioclase (andesine–oligoclase)–hornblende–quartz in mafic schist (Greenfield, 2010b). The Ponto Group is interpreted from aeromagnetic images to extend into the Loch Lilly–Kars Belt (Sharp et al., 2006; Fig. 1b).

The preservation of feldspathic air-fall tuffs intercalated with mudstone and siltstone suggest long, quiet periods with little clastic input, and the group is interpreted to have been deposited in a deep water environment, probably a foot of continental slope or ocean basin margin (Mills, 2010d). The air-fall tuffs have been dated using SHRIMP II zircon analysis at 508.6 ± 3.2 Ma, 512.0 ± 3.1 Ma and 511.7 ± 3.5 Ma (Black, 2005; Appendix 2). The calc-alkaline chemistry of these tuffs (Percival, 2010a; Appendix 1) and their age suggest that the Mount Wright Arc may have been the source of this volcanic ash, and deposition of the Ponto Group was at least partially contemporaneous with volcanic activity of the Mount Wright Arc to the west.

The Ponto Group contains mafic extrusive and intrusive rocks of the Bittles Tank Volcanics (Vickery and Greenfield, 2010). Intrusive rocks of the Bittles Tank Volcanics both pre- and post-date the Delamerian Orogeny based on field relationships including the absence/presence of Delamerian Orogeny-related deformation and fabrics.

The Bittles Tank Volcanics include basalts of both tholeiitic and alkaline affinity, although on the available data ($n = 125$), tholeiites are dominant. The Bittles Tank Volcanics have patterns similar to ocean island tholeiite (OIT) except they are more enriched in the large ion lithophile (LIL) elements and more depleted in the high field strength (HFS) elements, with some affinities to N-MORB (Fig. 6a). This suggests a different setting to classic OIT, with either the addition of subduction zone fluids or crustal contamination. Nd–Sr isotopes for the Bittles Tank Volcanics have been decoupled from the mantle array (Fig. 6b) which is also atypical of ocean island basalts. Most basalts have high $^{143}Nd/^{144}Nd$ relative to bulk earth values, indicating little or no significant crustal contamination. This, combined with high $^{87}Sr/^{86}Sr$ ratios, suggest that they may have been variably contaminated by an influx of a radiogenic Sr-rich fluid (e.g. seawater or other carbonate-rich solution) in addition to the involvement of any subduction related fluids.

Correlation between Zr/Nb and $(La/Sm)_{N\text{-}MORB}$ for basalts of the Bittles Tank Volcanics (Fig. 6c), suggest a binary mixing between a plume source component (OIB) and a depleted N-MORB source may have been important in determining their geochemical characteristics. Those samples that plot off the mixing curve would suggest either the additional influence of subduction zone fluids or crustal contamination. This is supported by anomalously high Ba, Rb, with or without Th, K, and Sr as well as Pb (not shown) combined with Nb depletion in these samples. The relatively high Ta is more akin to OIT, supporting a mixed origin, with Nb/Ta ratios (3–9) even more subchondritic than the bulk continental crust (~11; Taylor and McLennan, 1995). Age-corrected epsilon Nd for the sample (69029; Appendix 1)

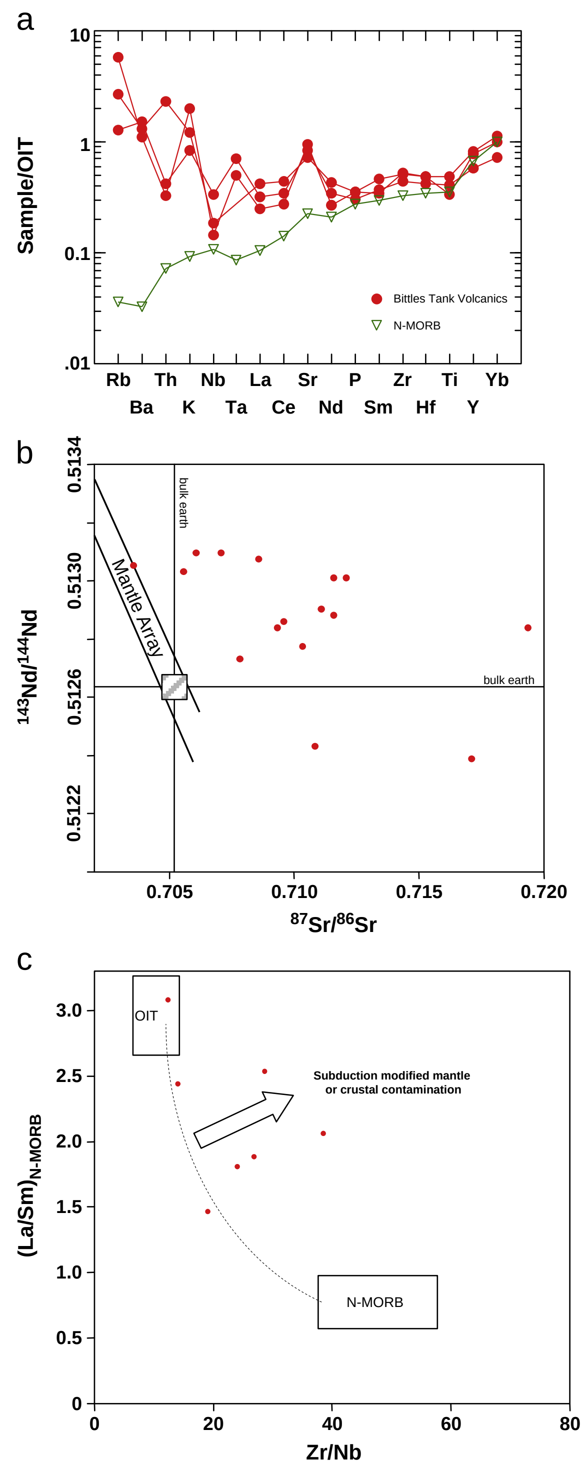


Fig. 6. (a) Multi-element diagram normalised to Oceanic Island Tholeiite (OIT) of basaltic rocks from the Bittles Tank Volcanics. Also plotted the average N-MORB data from Sun and McDonough (1989). Normalisation values after Thompson et al. (1984). (b) Nd-Sr isotope correlation diagram for samples of the Bittles Tank Volcanics. Note that the majority of samples plot in the upper right quadrant indicating alteration by Sr-rich fluids. (c) Zr/Nb vs. $(La/Sm)_{N\text{-}MORB}$ diagram for samples of the Bittles Tank Volcanics. Note that the curve defines a mixing line between N-MORB and OIB.

least altered by radiogenic Sr, ε_{Nd} (510 Ma) = +6.8, indicates a juvenile mantle origin that is slightly more enriched than the depleted mantle (e.g. Nagler and Kramers, 1998). However, even this basalt has anonymously high Rb and Th indicating possible source contamination via subduction zone fluids.

Two dolerite samples (DD96WA3g, DD96WA3h; Appendix 1) intersected from drilling of the Wahratta prospect in the Loch Lilly–Kars Belt (Fig. 1b) have been analysed by Direen (1999) and show a similar petrogenetic signature to the Bittles Tank Volcanics. They have a mixed origin involving a depleted (N-MORB) and enriched component (OIT). Zr/Nb ratios for the Wahratta dolerites are ~15 within the range of ratios typical of E-MORB and OIT (10-20), while Ti/V ratios are >50 characteristic of ocean island basalts. Two trachybasalt samples from the same drillhole (DD96WA3a, DD96WA3b; Appendix 1) are relatively low in Ti, and have characteristics of both OIT and N-MORB (Zr/Nb = 10, Ti/V > 20).

In summary, the Bittles Tank Volcanics of the Ponto Group have a complex geochemical signature, but one which involved mixing between a depleted component (N-MORB) and an enriched component (OIT), with probable contamination from subduction zone fluids. Volcanic rocks from the modern Izu-Bonin Arc show similar features, combining high 143Nd/144Nd ratios with evidence for the addition of variable proportions of slab-derived fluids (Nakamura and Iwamori, 2009).

3.4. Delamerian Orogeny

Fossil and geochronological data constrain deposition of sedimentary and contemporaneous igneous units within the Delamerian Orogenic Cycle to at least Series 3 of the Cambrian (Fig. 2). This is based on SHRIMP II analysis of a population of pristine euhedral zircons from a laminated felsic tuffaceous bed within the Depot Glen Formation (of the Teltawongee Group) dated at 504.5 ± 2.6 Ma (Black, 2006; Appendix 2), and from trilobite-based biostratigraphic zonation in the Gnalta Group in the Templetonian stage (~508 Ma; Percival, 2010a).

Deformation and uplift associated with the Delamerian Orogeny marked the end of the Delamerian Orogenic Cycle. Temporal constraints on the final stages of deformation include:

- Muscovite–biotite schist from the Ponto Group in the Southern Koonenberry Belt with a $^{40}Ar/^{39}Ar$ plateau age of 498.8 ± 1.4 Ma (Greenfield, 2010a),
- Felsic tuff from the Warratta Group, deposited above the Delamerian unconformity, dated by U–Pb SHRIMP II at 497 ± 2.6 Ma (Black, 2006; Appendix 2),
- Post-orogenic trilobite fossils from the Kayrunnera Group (Percival, 2010b), deposited above the Delamerian unconformity, constrained to the Mindyallan Stage of the Late Cambrian (~502–499 Ma),
- Non-foliated felsic intrusive cross-cutting the Delamerian fabric within Ponto Group phyllite, dated by SHRIMP II zircon analysis at 496.3 ± 3.1 Ma (Black, 2005; Appendix 2),
- Muscovite–biotite foliation from the Cambrian Teltawongee Group with a $^{40}Ar/^{39}Ar$ plateau age of 475.3 ± 1.3 Ma (Greenfield, 2010a).

3.5. Lachlan Orogenic Cycle

A new cycle of sedimentation and igneous activity commenced at the end of the Delamerian Orogeny (Fig. 2), and is termed the Lachlan Orogenic Cycle (defined by Glen, 2005). Erosion of uplifted Delamerian landforms and subsequent deposition resulted in a major angular unconformity (the Delamerian unconformity) observed at numerous locations throughout the Koonenberry Belt (Mills, 2010c). Three main rocks packages were deposited onto the unconformity surface during the Cambro-Ordovician: the Kayrunnera, Mutawintji and Warratta groups.

The Cambro-Ordovician (late Mindyallan (~500 Ma) to Chewtonian (~476 Ma)) Kayrunnera Group consists of dominantly shallow marine sedimentary rocks restricted to structurally controlled basins (Kayrunnera, Nuntherungie and Cupala Creek basins) to the east of the Koonenberry Fault. The basin-bounding faults are interpreted to have been active during the final stages of the Delamerian Orogeny and facilitated deposition into the basins during the Lachlan Orogenic Cycle (Greenfield et al., 2010a). Each basin shows a general fining up sequence of basal conglomerates, sandstones and siltstones (Greenfield et al., 2010a).

The Cambro-Ordovician (Datsonian (~491 Ma) to Chewtonian (~476 Ma) Mutawintji Group encompasses a dominantly fluvial to deltaic sedimentary sequence that crops out to the southwest and south of the Koonenberry Belt (Greenfield et al., 2010b). The 600 m thick fluvial-derived Bilpa Conglomerate, the basal unit of the Mutawintji Group, contains clasts of mainly locally-sourced pre-Delamerian Orogeny units such as the Teltawongee and Ponto groups.

The Warratta Group represents a sequence of Late Cambrian to Early Ordovician interbedded siltstone, sandstone and mudstone in the northern part of the Koonenberry Belt (Greenfield, 2010c). The sequence deepens from west to the east, from a shallow marine environment (e.g. minor limestone units in the Jeffreys Flat Formation) to a deep marine environment (e.g. turbidites in the Easter Monday Formation) (Greenfield, 2010c). Uplift and re-deposition of units from the Delamerian Orogenic Cycle into this sequence is evidenced by a SHRIMP II age date of 510.4 ± 3.0 Ma for a rounded boulder of deformed felsic tuff (inferred to be derived from the Ponto Group) within a diamictite unit of the Jeffreys Flat Formation (Black, 2006; Appendix 2).

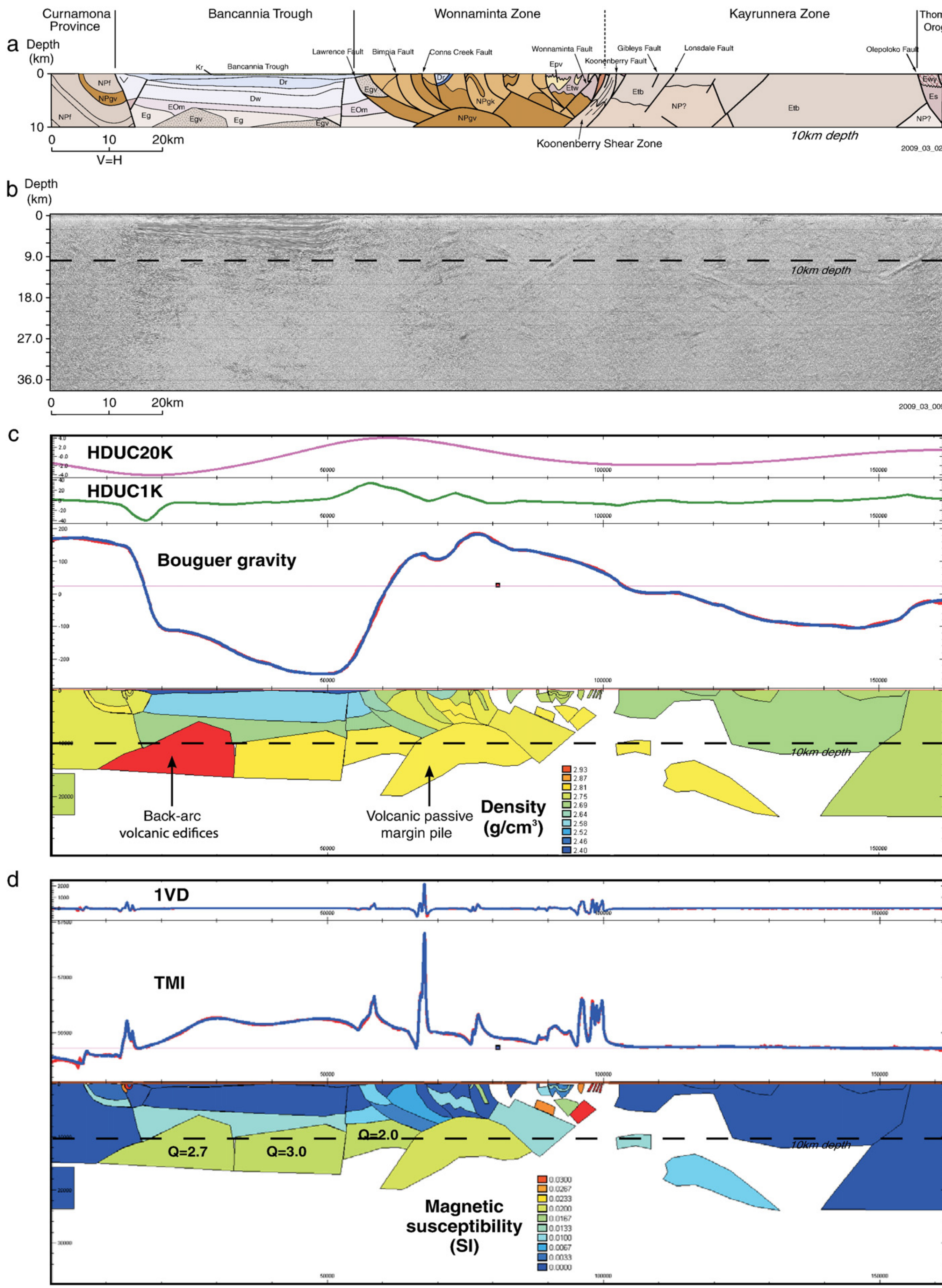
3.6. Tectonic Framework of the Mount Wright Arc

3.6.1. Late Neoproterozoic Volcanic Passive Margin—Curnamona Province and Wonnaminta Zone

Extension directed northeast-southwest characterised the East Gondwana margin throughout most of the Neoproterozoic, as indicated by the northwest-trending strike of mafic dykes, extensional faults and graben sedimentation in the Adelaide Rift Complex (Preiss, 1995, 2000) and in the Curnamona Province (Cooper et al., 1978). In the Koonenberry Belt during the Late Neoproterozoic, extension culminated in the production of a volcanic passive margin (Direen and Crawford, 2003b) with a now-distant conjugate whose identity is uncertain. Break-up volcanism on this margin resulted in the production of the Mount Arrowsmith Volcanics of the Wonnaminta Zone, and their equivalents in the Farnell Group of the Curnamona Province.

Volcanic products on the new continental margin were not restricted to the outcropping alkaline basalts. Direen (1998) recognised the need for large magnetic sources under the Bancannia Trough and Wonnaminta Zone, in order to explain the long-wavelength features of his magnetic and gravity model across the Koonenberry Belt. In his model, completed before the deep seismic reflection profile (Fig. 7) was acquired, the set of deep magnetic sources was interpreted as a single thick package of basaltic composition, with associated ultramafic sheets, that extended from the western edge of the Bancannia Trough to the middle of the Wonnaminta Zone. Direen and Crawford (2003b) suggested that this magnetic source was comprised of rift-related mafic volcanic piles, cogenetic with the outcropping Mount Arrowsmith Volcanics. Our potential field modelling, and our interpretation of the seismic profile, suggest instead that the deep magnetic sources under the Bancannia Trough and Wonnaminta Zone represent two sets of distinct entities with different origins.

The large magnetic source under the Wonnaminta Zone forms a relatively simple, continuous feature that extends along strike for most of the length of the Wonnaminta Zone (Fig. 7). Modelled density and magnetic susceptibility of this deep source (2.75 g/cm^3 and 1500×10^{-5} SI) are similar to those of shallow bodies corresponding to mapped intervals of interbedded Mount Arrowsmith Volcanics and Kara Formation, and are consistent with physical property measurements of samples of these units (Musgrave, 2010). Modelling on the Wonnaminta profile shows this body at the point where it achieves its maximum thickness, and where it shows some degree of open folding. Seismic reflection reveals the magnetic body to comprise a


a
Curnamona Province
Bancannia Trough
Wonnaminta Zone
Kayrunnera Zone
Thomson Orogen
Depth (km)
Lawrence Fault
Bimpia Fault
Conns Creek Fault
Wonnaminta Fault
Koonenberry Fault
Gibleys Fault
Lonsdale Fault
Olepoloko Fault
Koonenberry Shear Zone
10km depth
0 10 20km
V=H
2009_03_020
b
Depth (km)
2009_03_0097
c
HDUC20K
HDUC1K
Bouguer gravity
Back-arc volcanic edifices
Volcanic passive margin pile
Density (g/cm³)
d
1VD
TMI
Q=2.7
Q=3.0
Q=2.0
Magnetic susceptibility (SI)

series of strong, parallel reflectors, consistent with a layered volcanic–sediment package, and similar to the seismic signature of modern seaward-dipping reflectors formed during break-up on volcanic passive margins (Planke and Eldholm, 1994; Planke and Alvestad, 1999). Given the physical properties, seismic character, and geometric setting of this body, it is likely that it does indeed represent a thick pile of equivalents of the Mount Arrowsmith Volcanics. A series of thrust slices of Grey Range Group rocks, including thinner packages of Mount Arrowsmith Volcanics, have been emplaced over this deeper, apparently more rigid body.

3.6.2. Cambrian continental back-arc—Bancannia Trough

By virtue of their northwest trend, the Lawrence and Nundooka faults, which bound the Bancannia Trough, may have been initiated during the Neoproterozoic phase of continental margin extension. Later reactivation of these faults is indicated by their oblique termination of Delamerian structural trends visible in aeromagnetic and gravity images on both sides of the trough, and by the accumulation of 37 km of Devonian sandstone topped by several hundred metres of post-Palaeozoic sedimentary rocks in the Bancannia Trough graben, revealed by drilling and in the seismic profile. Prior to the availability of the deep seismic profile across the Koonenberry Belt, and on the basis of earlier potential field modelling, basement below the Devonian graben was considered to be part of the same volcanic passive margin sequence, continuing below the Wonnaminta Zone, described above (Direen, 1998; Direen and Crawford, 2003b). However, the seismic profile identifies not only that these faults appear to continue below the flat-lying Devonian sequence, and may be imaged at 35–40 km depth and continue to the Moho, but that they also form the boundaries to a basement which extends across the Bancannia Trough and has distinct seismic properties which contrast with those of the interpreted volcanic passive margin package below the Wonnaminta Zone. Unlike the strongly layered reflector package below the Wonnaminta Zone, basement below the Bancannia Trough has a weak and chaotic seismic texture (Fig. 7b; Mills and David, 2004). This basement includes the andesitic to dacitic volcanics with compositional and age affinity to the Mount Wright Volcanics that were intersected by the Bancannia South No 1 well. Within this basement, subtle contrasts in reflectivity define features that appear to correspond to the very large edifices required as the sources of the large elliptical magnetic anomalies that characterise the Bancannia Trough.

In contrast with the deep magnetic sources under the Wonnaminta Zone, the sources of the long-wavelength magnetic anomalies in the Bancannia Trough are arranged as a series of individual deep bodies, defined by elliptical rings of magnetic edges, with a vertical extent of 5 to 8 km and a width of more than 20 km (Figs. 3 and 7). The series of bodies abut each other, and an enveloping set of magnetic edges define the total area of the intrusive system as approximately 3000 km^2: magnetic modelling indicates a total volume of approximately 11 000 km^3. Initially in our study, these bodies were assigned the susceptibility determined for andesite and dacite samples recovered from the bottom of the Bancannia South No. 1 well (1700×10^{-5} SI); however it was found that higher magnetisation was required, so the bodies were assigned a normal remanence with a Königsberger ratio of 2 to 3, reasonable if the body is a volcanic edifice of andesitic composition (Hunt and Smith, 1982). At intervals along the Bancannia Trough, a second set of deep igneous bodies west of the main chain is suggested by a series of three magnetic anomaly lobes extending west from the main magnetic high. Inversion of this western series of bodies suggests a similar susceptibility and Königsberger ratio to the main eastern chain of bodies, but with a higher density (2.95 g/cm^3), contrasting with a best-fitting density of 2.76 g/cm^3 for the eastern chain. This difference in density may indicate a more mafic composition for the western series of deep bodies below the Bancannia Trough, compared to the andesitic and dacitic composition of the samples recovered from the Bancannia South No. 1 well.

Partly on the basis of the samples from the Bancannia South well, the magnetic sources below the Bancannia Trough have been assigned to volcanic edifices related to the Mount Wright Volcanics (Sharp and Buckley, 2003). The transitional arc–backarc geochemistry, and the geometry of the trough, invites comparison with the Taupo Volcanic Zone (TVZ) of New Zealand (Fig. 8), the region of active volcanism and continental back-arc extension that occupies the eastern flank of the Central Volcanic Region (CVR) of the North Island (Stern et al., 2006; Spinks et al., 2005).

3.6.3. Volcanic arc and fore-arc—Wonnaminta Zone

The Wonnaminta Zone refers to the package of rocks comprising (from west to east) the outcropping Mount Wright Volcanics, the Grey Range Group, the Teltawongee Group west of the Koonenberry Fault, and the Ponto Group. Mount Wright Volcanics (both outcropping within the Wonnaminta Zone and inferred deeply buried within the Bancannia Trough) evidently erupted onto and within the existing Neoproterozoic passive margin, and so the polarity of the arc was unequivocally northeast facing, with subduction dipping to the southwest. This geometry places the Wonnaminta Zone in the fore-arc of the subduction system. Grey Range Group rocks provide the continental back-stop. Between the east-dipping upper surface of the continental rift package comprising the Grey Range Group, and the projected subsurface extension of the Koonenberry Belt, rocks of the Teltawongee and Ponto groups form a thrust wedge (Fig. 7). Sediments in this wedge appear to have accumulated in a fore-arc basin, rather than through tectonic accretion (Mills and David, 2004), although thrust stacking has resulted in multiple repetitions of mixed Teltawongee and Ponto group units in the southern part of the Koonenberry Belt. Similar thrust stacking of fore-arc basin sediments is a feature of the modern Luzon Arc in the southern part of the Taiwan collision zone (Malavieille and Trullenque, 2009).

In this context, the mafic Bittles Tank Volcanics, which provide the dominant magnetic signature within the fore-arc thrust wedge, have an apparently anomalous setting. However, the Boring Volcanics, a compositionally similar suite of mafic volcanics, including a range from MORB to OIB chemistry with varying subduction influence (Leeman et al., 2005), occur within the fore-arc of the Neogene Cascadia Arc, which also exhibits intra-arc rifting (Evarts et al., 2009). MORB-like tholeiitic basalt has also been reported as the first volcanic product within the Izu-Bonin and Mariana fore-arcs (Ishizuka et al., 2008).

3.6.4. Accretionary prism?—Kayrunnera Zone

The Kayrunnera Zone comprises the Teltawongee Group rocks northeast of the Koonenberry Fault and south of the Olepoloko Fault. Back-arc extension in the Bancannia Trough suggests trench roll-back, making it likely that a broad accretionary prism would have been

Fig. 7. Profiles across the Koonenberry Belt: see Figs. 1b and 3 for locations. (a) Interpreted geological cross-section for the Wonnaminta cross-section to 10 km depth. (NPf = Farnell Group, NPgv = Mount Arrowsmith Volcanics, NPgk = Kara Formation, NP? = Neoproterozoic?, Eg = Gnalta Group, Egv = Mount Wright Volcanics, Epv = Bittles Tank Volcanics, Etw = Wonnaminta Formation (Teltawongee Group), Etb = Bunker Creek Formation (Teltawongee Group), Es = undifferentiated Thomson Orogen, Ewy = Yancannia Formation (Warratta Group), EOm = Mutawintji Group, Dw = Wana Karnu Group (Devonian), Dr = Ravendale Formation (Devonian), Kr = Rolling Downs Group (Cretaceous). (b) Migrated seismic reflection profile of AGSO Line 99AGS-C1. (c) Gravity model of Wonnaminta cross-section, approximately coinciding with seismic profile. Background density is 2.70 g/cm^3. Red curve shows measured Bouguer gravity anomaly, blue curve shows calculated model gravity response, horizontal red line shows assumed regional gravity. (d) Magnetic model of Wonnaminta cross-section; geometry is identical to the gravity model. Red curve shows measured total magnetic intensity (TMI), blue curve shows calculated model TMI response, horizontal black line shows regional magnetic field, Q is Koenigsberger ratio. The dotted line on b, c and d represents 10 km depth.

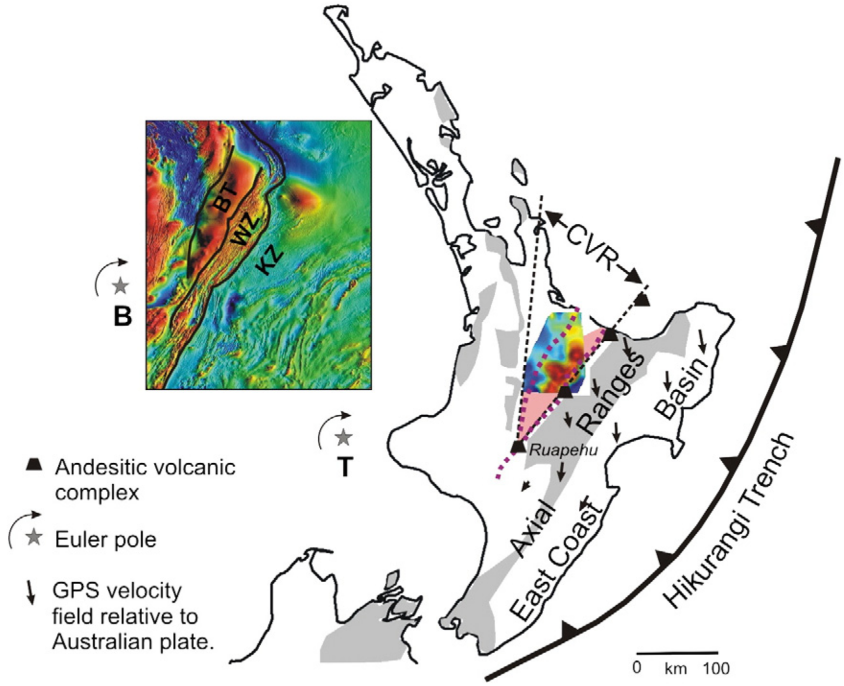


Fig. 8. Comparison of the Koonenberry Belt with modern North Island, New Zealand. The map of North Island, in transverse Mercator projection, shows the Central Volcanic Region (CVR), following Stern et al. (2006). Plotted within this is an image of TMI data for part of the Taupo Volcanic Zone (TVZ), upwardly continued by 5 km to represent the effect of burial to a comparable depth to the magnetic sources under the Bancannia Trough. Pink shading indicates continuation of the TVZ north and south of the TMI data. Grey shading indicates outcropping Mesozoic greywacke basement. Arrows indicate GPS velocity field for North Island east of the TVZ (Wallace et al., 2004). Euler pole for this rotation is labelled T. Inset shows TMI data for the Koonenberry Belt, at the same scale and projection, translated and mirror inverted to facilitate comparison. BT = Bancannia Trough, WZ = Wonnaminta Zone, KZ = Kayrunnera Zone. Euler pole representing proposed extension and crustal growth in the Bancannia Trough is labelled B. Dotted magenta lines superimposed on North Island map are copies of the boundaries of the Bancannia Trough, rotated to align with the TVZ and pinned to the Ruapehu volcanic centre at the southern end of the TVZ.

emplaced behind a trench that had retreated from its initial position along the line of the Koonenberry Fault. If the thrust wedge in the Wonnaminta Zone is a deformed fore-arc basin, then any accretionary prism would lie further outboard, in the position of the Kayrunnera Zone.

3.6.5. Koonenberry Shear Zone

The Koonenberry Fault (Fig. 1b) is another major northwest-trending fault that marks the eastern extent of exposed Proterozoic rocks in the region and marks the eastern extent of near-surface Proterozoic rocks in the region (Mills, 1992). Despite its recognition as a major bounding structure, the Koonenberry Fault is only marked in outcrop by a vertical brittle crush zone that is mainly observed to separate late Palaeozoic rocks (Mills, 1992). However, on a deep crustal seismic image (Figs. 1b and 7b) the Koonenberry Fault at the surface coincides with a moderately-dipping (40° to the southwest) major structure that is at least 7 km wide when extrapolated to the surface, encompassing the strongly deformed Ponto Group, the mapped Koonenberry Fault, and related splay faults, that together comprise the Koonenberry Shear Zone (Fig. 7; Mills and David, 2004). In this paper we refer to the western and eastern Koonenberry Shear Zone as either west or east of the Koonenberry Fault. This structure is at least as old as late Cambrian in age, since it postdates the deposition of the Ponto Group.

3.6.6. Early Delamerian Structures in the Koonenberry Belt (D_1)

A strong belt-parallel structural grain consisting of an intense northwest-trending cleavage and tight to isoclinal folds with vertical to steeply dipping axial surfaces affected Neoproterozoic and Early Cambrian rocks in the Koonenberry Belt and is attributed to the Delamerian Orogeny, since these structures are not present in overlying Cambro-Ordovician rocks. The fold axes are shallow to moderately plunging, dominantly to the northwest. Mapping and geophysical edge detection ("worm") analysis (Fig. 3c) suggests that many major faults west of the Koonenberry Fault dip steeply to the southeast (Fig. 7).

3.6.7. Late Delamerian Structures in the Koonenberry Belt (D_2)

In the southern to central Koonenberry Belt within the Koonenberry Shear Zone (west of the Koonenberry Fault), the early Delamerian foliation (S_1) is overprinted by a later ductile structural fabric (S_2). Davies (1985) recognised the S_2 fabric as a spaced crenulation cleavage overprinting the early Delamerian S_1 foliation in Ponto Group phyllite. He noted that the metamorphic grade in these rocks increased from west to east approaching the Koonenberry Fault, reaching biotite grade (M_2 biotite), chlorite and phengite assemblage. Davies (1985) also noted sinistral-rotated pyrite porphyroblasts, left-stepping en-echelon quartz veins and en-echelon F_2 folds that all infer ductile sinistral transpression in the Western Koonenberry Shear Zone in the later stage of the Delamerian Orogeny.

At a broader scale, aeromagnetic images show the main Delamerian fabric, picked out by magnetite-rich units, wrapping into major northwest trending faults, including the western Koonenberry Shear Zone (Greenfield, 2010a). This is reflected in outcrop in the Western Koonenberry Shear Zone where S_1 has been rotated from a northwest-trend west of the shear zone to a north-trend within the shear zone. The wrapping implies a sinistral-sense of movement along these major faults. These fabrics are overprinted by Cambro-Ordovician units, suggesting a late Delamerian timing.

It is possible that this stress regime was still active in the early stages of the Lachlan Orogenic Cycle. Deposition of the Cambro-Ordovician Kayrunnera Group occurred in restricted, fining-upward sedimentary basins (i.e. Kayrunnera, Nuntherungie and Cupala Creek basins; Fig. 1b) adjacent to fault splays in the eastern Koonenberry Shear Zone. The west to west-northwest trending growth faults are on the northern side of the basins, consistent with a sinistral strike-slip regime in the Koonenberry Shear Zone.

At the southern end of the Koonenberry Belt, the strongly deformed rocks of the Ponto and Teltawongee groups are folded around the southern margin of the Bancannia Trough (Fig. 1b), resulting in an almost 90° clockwise rotation of bedding and foliation. The intense, ductile nature of deformation in these rocks is in contrast to the gently deformed overlying Cambro-Ordovician Mutawintji Group rocks adjacent to and covering the folded Ponto and Teltawongee Group rocks in the Grasmere Knee Zone. This suggests the ductile oroclinal folding of the basement Ponto and Teltawongee group rocks occurred during the late Delamerian Orogeny, after the development of an early Delamerian foliation.

In summary, these observations suggest that following strong belt-parallel deformation in the early Delamerian Orogeny, the Koonenberry Belt experienced a period of sinistral transpression in the late stages of the Delamerian Orogeny. The presence of overlap sequences (Kayrunnera Group) along the eastern Koonenberry Shear Zone in the Late Cambrian to Early Ordovician suggests the later stages of the transpressive strain regime were long-lived and possibly diachronous.

4. Discussion

Geochemical analysis in this study supports the interpretation of Crawford et al. (1997) that the calc-alkaline lavas of the Mount Wright Volcanics have arc affinities. The more mafic end-member compositions have a tholeiitic trend that is more closely related to intraplate basalts. These tholeiites are mostly doleritic dykes whose emplacement we suggest may be an expression of the early stages of rifting during the opening of the Bancannia Trough. Their composition is very distinct from the earlier Neoproterozoic Mount Arrowsmith Volcanics that were clearly related to intraplate rifting. The bulk of the Cambrian Mount Wright Volcanics represents a much more evolved suite with geochemical evidence for both crustal and source (slab dehydration) contamination, typical of a marginal volcanic arc environment.

The preferred scenario for Crawford et al. (1997) was that the Mount Wright Volcanics represented an embryonic continental rift rather than a volcanic arc. This was not based on geochemistry, but rather on the small area of outcrop of the Mount Wright volcanics that they recognised (about 3 km^2) and the coherent, sparsely-phyric nature of the lavas observed in outcrop. We concur with this observation, but note that recent mapping has increased the area of known exposure of Mount Wright Volcanics to about 8.5 km^2 (Sharp and Buckley, in press), while geophysical interpretation suggests that the combined outcrop and subcrop of Mount Wright Volcanics east of the Bancannia Trough represent at least 57 km^2 (Stevens et al., 2000; Gilmore et al., in press). Further, our geophysical and drillhole evidence indicate that the exposed Mount Wright Volcanics represent only a small fraction of the arc and back-arc igneous material that is now buried beneath the Bancannia Trough.

Large magnetic bodies below the Bancannia Trough form a continuous chain that extends the length of the trough, and which stretches 15–20 km west from its eastern boundary: this represents about half the width of the southern part of the trough, and the entire width of the northern quarter of the trough. Additional large magnetic sources occur at intervals along the western half of the trough. This structure resembles the distribution of large magnetic bodies below the TVZ of New Zealand (Fig. 8). Magnetic anomalies in the TVZ, continued upwards by 5 km to simulate deep burial, closely resemble the basement-sourced anomalies in the Bancannia Trough. Magnetic modelling of the TVZ (Soengkono, 1995) invoked deep magnetic sources similar to those modelled below the Bancannia Trough, with comparable dimensions, net magnetisation, and spacing. Back-arc volcanism in the TVZ is expressed as a bimodal assemblage of rhyolite and high-Al basalt occupying caldera structures; drilling has encountered diorite as the intrusive equivalent (Browne et al., 1992). At the northern and southern ends of the TVZ, and in a narrow belt along the eastern margin of the zone, a series of volcanic centres with a basaltic andesite–andesite–dacite assemblage represents the active volcanic arc (Cole et al., 1995).

Very extreme extension in the Bancannia Trough, and the injection of very voluminous and extensive intrusives to the point of lateral crustal growth, is suggested by analogy to the TVZ. In this case, it is reasonable to treat the two sides of the trough (the Curnamona Province and the Wonnaminta Zone) as separate plates, and to reconstruct one against the other. Extension on low-angle normal faults, and hence overlap in the reconstruction, can be expected in the southern part of the trough, where crustal growth appears to be restricted to the eastern half of the trough, but there should be little overlap in the northern half of the trough. A clockwise rotation of 20° around an Euler pole at 140.60°E, 30.35°S not only reconstructs the northern flanks of the trough (with a degree of strike-slip movement involved), it also aligns significant gravity and magnetic features on the two sides (Fig. 9). These structures include early Delamerian folds in the Mount Arrowsmith Volcanics and their equivalents in the Farnell Group, indicating that rifting post-dated the earliest Delamerian stage, although later Delamerian deformation did deform the Mount Wright Volcanics.

This reconstruction assumes that rifting in the Bancannia Trough reached the point where intrusion essentially constituted growth of new crust, begging the question of whether the same applies in the modern TVZ. Extremely high heat flow (700-800 mW/m^2) in the TVZ, and the alignment of the Central Volcanic Region as the onshore continuation of the Havre Trough back-arc basin, led Stern (1985) to infer active extension, involving complete separation of rifted margins and generation of new crust through intrusion of very voluminous igneous bodies under a few kilometres of Quaternary volcanics. Extension involving dyke injection is certainly occurring in the TVZ (Seebeck and Nicol, 2009), but many geologists have contended that extensive crustal growth within the TVZ is unlikely, preferring that the TVZ (and the rest of the Central Volcanic Region) is underlain by extended, but continuous, Mesozoic greywacke (e.g., Wilson et al., 1995). Greywacke basement to the TVZ has been recovered in deep boreholes (Stern, 1986) and as lithic fragments in ignimbrites (Krippner et al., 1998), but in both cases these are restricted to the downfaulted edges of the TVZ. P-wave velocity below most of the TVZ is 5.4–5.5 km/s, a range typical of either andesite or greywacke (Robinson et al., 1981; Stern, 1986); higher velocity ($Vp = 6–8$ km/s) below the easternmost 10–15 km of the TVZ corresponds to the position of the large magnetic sources in the Soengkono (1995) model, and the basement here has been interpreted as a large andesitic intrusion (Sherburn et al., 2003). Marine seismic reflection over the offshore extension of the TVZ (Davey et al., 1995) indicates a continuous greywacke basement, albeit that this is highly extended (80% extension) on nearly horizontal listric normal faults (dips about 10°); however, the TVZ is wider (maximum width about 70 km) onshore than it is offshore (about 35-40 km wide), and this may allow lateral crustal growth in at least part of the TVZ. Regardless of the details of the mechanism, it is clear that very extreme extension, perhaps reaching the point of actual crustal growth, characterises the Taupo arc system.

Extension within the TVZ, and the CVR more generally, has divided Mesozoic greywacke basement of the North Island Axial Ranges from its equivalent in western North Island, in a similar geometry to the Grey Range and Farnell groups on either side of the Bancannia Trough. The active volcanic arc of the Taupo system sits on the eastern edge of the TVZ, and is built on greywacke basement. A fore-arc basin, the East Coast Basin, extends east of the Axial Ranges. Together, the features of the east coast of the North Island comprise an analogous assemblage to the Wonnaminta Zone of the Koonenberry

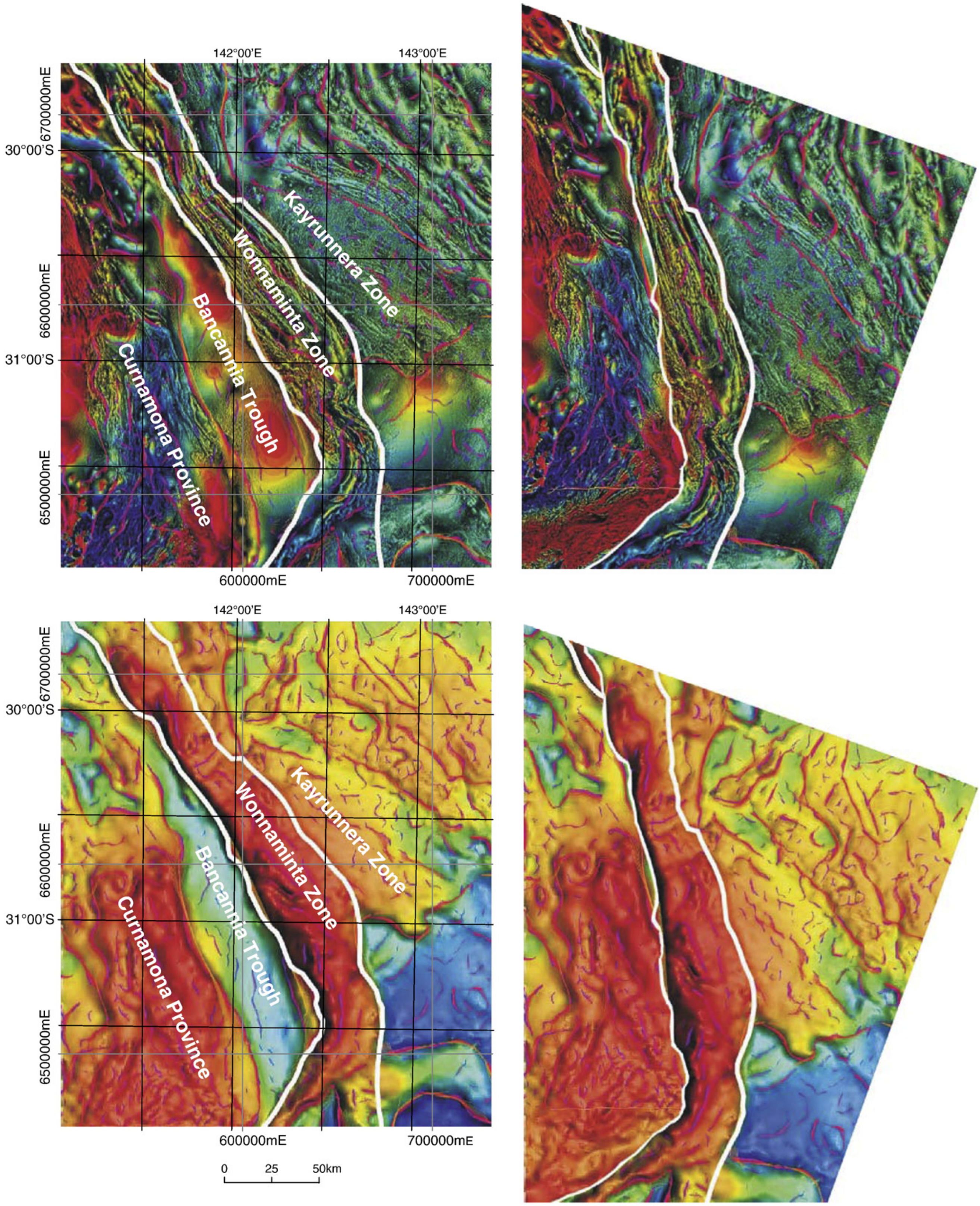


Fig. 9. Euler reconstruction of the Wonnaminta Zone against the Curnamona Block, assuming complete Cambrian rifting under the Bancannia Trough. Upper panels show an image generated by draping a pseudocolour TMI layer over a magnetic tilt-filter intensity layer (Cooper and Cowan, 2006). Lower panels are isostatically reduced Bouguer gravity. Boundaries of the Wonnaminta Zone, shown as white lines, follow prominent gravity edges. Right-hand panels show reconstruction by 20° clockwise around an Euler pole at 140.60°E, 30.35°S.

Belt, differing mainly from the New Zealand example in the absence of passive margin volcanics. Extension of the TVZ is accompanied by rotation of the east coast of New Zealand, seen in the GPS velocity field (Wallace et al., 2004; Stern et al., 2006); this rotation closely resembles the rotation of the Wonnaminta Zone implicit in the reconstruction to close the two sides of the Bancannia Trough.

Subsidence of the Bancannia Trough, commencing in the Devonian, occurred substantially after the end of activity of the Mount Wright Arc, and is not a part of the phase of back-arc rifting. Rather, it is presumably a response to cooling of the large volume of igneous bodies within the trough, and of the anomalous mantle that would have underlain the back-arc, to which was added the tensional environment that resulted in rifting throughout western New South Wales during the Devonian (Scheibner and Basden, 1998); pre-existing bounding faults imposed the geometry of the subsequent graben.

Another interpretation from this study is that the Ponto Group was deposited in a supra-subduction setting, probably in the fore-arc environment. Whilst classic boninites are absent from the suite (e.g. Crawford and Berry, 1992), the chemistry of the Bittles Tank Volcanics, which exist as dykes and lavas mainly within the Ponto Group, is still consistent with deposition in a fore-arc environment. The volcanics are characterised by a mix of oceanic island tholeiite and depleted N-MORB source affinities, with probable interaction with subduction zone fluids. Basalts with similar chemistry have been observed in the Izu-Bonin and Mariana fore-arcs (Ishizuka et al., 2008), and in the Boring Volcanics of the Cascadia fore-arc (Leeman et al., 2005).

Felsic tuffs are also characteristic of the Ponto Group and have chemistry and age (~511 Ma) that is indistinguishable from the Mount Wright Volcanics, placing the Ponto Group within range of air fall ejecta from Mount Wright Arc volcanism. The host rocks to these tuffs and Bittles Tank Volcanics are fine-grained pelagic sediments, typical of an oceanic environment. Also, the Ponto Group is the most strongly deformed and metamorphosed of the Cambrian units, contained within a set of east-dipping thrust faults, including faulted contacts with all underlying units. It lies within the same structural position, along the western edge of the Koonenberry Shear Zone, for the entire strike length of the Koonenberry Belt—at least 300 km, not including the strike extensions of the Ponto Group into the Loch Lilly–Kars Belt. These structural observations are consistent with our interpretation that the Ponto Group was deposited in an oceanic setting relatively close to the Mount Wright Arc but later thrust onto the continental margin (i.e. the Koonenberry Belt) during the Delamerian Orogeny (Fig. 10).

The location of the west-dipping subduction zone outboard of the Ponto Group fore-arc is uncertain. If, as we suggest, the Kayrunnera Zone represents an accretionary prism to the Mount Wright Arc, its northeastern limit should have marked the position of the frontal thrust of the subduction zone. However, this feature is not preserved, having been overthrust by the Olepoloko Fault, which marked the boundary to the Thomson Orogen during the Lachlan Orogenic Cycle. This sets a minimum width of about 100 km for the putative accretionary prism as it is currently deformed, and an undeformed width, very approximately, of about 200 km prior to orogenic shortening (Mills and David, 2004). The accretionary prism to the Taupo volcanic arc, the Hikurangi margin, extends for a similar distance (Davey et al., 1986). Accreted sediment thickness in the Hikurangi margin amounts to a maximum of about 14 km, and thickness over the inner 100 km of the prism exceeds 4 km. Gravity modelling indicates that the Teltawongee Group in the Kayrunnera Zone has a present-day preserved vertical extent of about 10 km, indicating a comparable sediment accumulation, allowing for tectonic thickening of 50% or so during the Delamerian and later orogenies.

The long-wavelength magnetic anomalies in the northern part of the Kayrunnera Zone may represent thrust blocks of oceanic basement that could be part of an accretionary prism, but these are absent in the southern part of the Kayrunnera Zone, and magnetic imagery instead suggests relatively broad packages of folded rocks, without clear evidence for repetitively stacked fault slices characteristic of a conventional prism accreted as a Coulomb wedge. This may merely reflect relatively gentle thrust stacking and the accumulation of Teltawongee Group sediments in slope basins, masking the underlying thrusts, and making them difficult to discriminate after later deformation; similar structures are recognised on the Hilurangi prism.

Inflow of the sediment that comprises the Teltawongee Group from the Gondwanan continent over both the Wonnaminta and Kayrunnera zones represents a different depositional regime to that of the Hikurangi margin, and some differences would be expected between the style of an accretionary prism in the Kayrunnera Zone and that of the Hikurangi margin. Incoming sediment thickness to the modern Indo-Burmese wedge (Maurin and Rangin, 2009) is around 10 km, and this, together with a transpressional environment similar to the late Delamerian orogenic stage in the Koonenberry Belt, prompted overprinting of thick-skinned deformation on initial thin-skinned deformation, accompanied by rapid outstepping of the frontal thrust. If this analogy holds true for the Kayrunnera Zone, then the west-dipping Koonenberry Shear Zone represents the boundary between the inner fore-arc thrust wedge and the outer, thick-skinned wedge, equivalent to the Kaladan Fault in the modern Indo-Burnese Wedge (Maurin and Rangin, 2009).

When the late Delamerian oroclinal folding of the Ponto Group is restored, the fore-arc accretionary system extends out from the continental margin into the paleo-Pacific Ocean along the same northwest–southeast trend as the Koonenberry Fault and parallel to the axis of extension that was active during the Neoproterozoic break-up of Rodinia (Fig. 10a). Similarly, Cambrian calc-alkaline volcanic rocks in the Loch Lilly–Kars Belt are interpreted to represent the (now oroclinally rotated) continuation of the Mount Wright Arc (Direen, 1999; Sharp et al., 2006; this study). Our geophysical interpretation suggests that, once restored, the volcanic arc would also have extended along the same northwest–southeast trend, and thus to the southwest of the fore-arc. How far southeast the arc extended outboard from the continental margin is unknown, but presumably the subduction system would have had to swing to the south to tie into the broader convergent margin extending to Tasmania and East Antarctica (Foden et al., 2006; Musgrave and Rawlinson, 2010). Our interpretation also implies that during oroclinal folding, the fore-arc rocks were thrust over the volcanic arc in the Loch Lilly–Kars Belt (Fig. 10d).

The concept of the Mount Wright Arc originally extending into the palaeo-Pacific Ocean was first conceived by Scheibner and Basden (1998) and later developed by Scheibner and Veevers (2000). They postulated that the arrival of a microcontinent block (shown as the Hay–Booligal Zone in Fig. 10d) at the trench provided the main impetus for oroclinal folding and the thrusting of the arc system against the Curnamona Province during the Delamerian Orogeny.

We have presented evidence of sinistral transpression along the Koonenberry Shear Zone in the late Delamerian, coincident with the oroclinal folding of the arc system. Dating and mapping of shear zone fabrics in the northeast sector Curnamona Province by Williams et al. (2009) also provides evidence of sinistral movement along north-northwest trending major shear zones during the late Delamerian Orogeny, caused by oblique west-northwest convergence against the Curnamona Province hinterland. Fundamental to their fold-arc model is that the central to western Curnamona Province acted as a rigid backstop during Delamerian convergence. Our observations are consistent with this model, with the folded Cambrian arc elements in the Loch Lilly–Kars Belt being thrust against the southeastern margin of the Curnamona Province.

5. Conclusions

The principal conclusions of this study are: (i) confirmation that the Mount Wright Volcanics represent a volcanic arc in a subduction setting; (ii) the association of this arc with a continental back-arc, developed immediately behind the volcanic arc in a close analogy to the modern Taupo Volcanic Zone; and (iii) the implication in the setting of the arc and back-arc on and within the passive margin sequence on the Gondwana margin that the Delamerian subduction system, at least

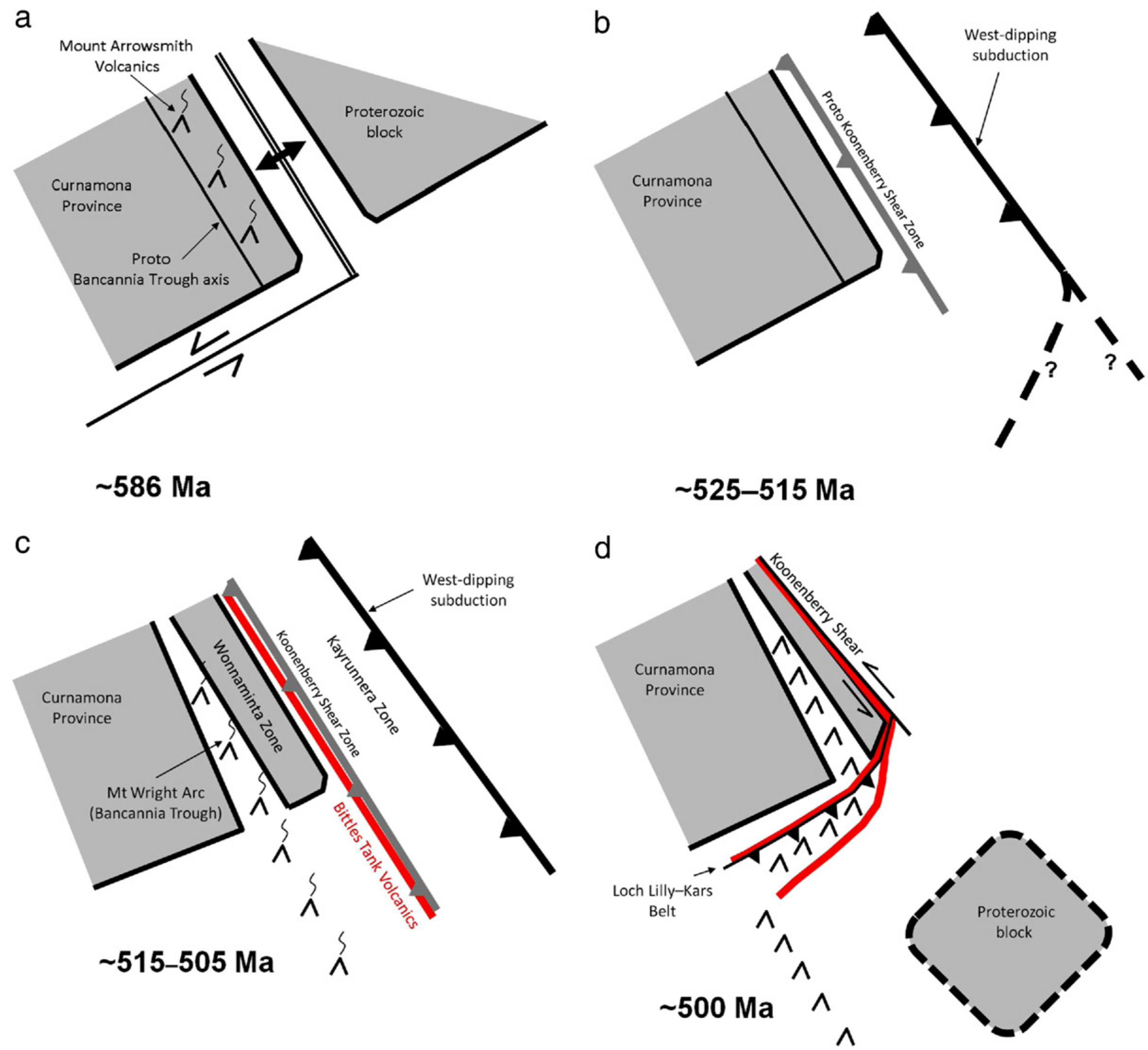


Fig. 10. Palaeotectonic cartoon reconstructions of the east Gondwana Margin adjacent to the Curnamona Province from the Late Neoproterozoic to the Late Cambrian. (a) Final break-up of Rodinia during the Late Neoproterozoic and development of a passive margin. Crustal weakness along the axis of the future Bancannia Trough possibly developed at this time. (b) Transition to convergent margin in the Early Cambrian. Initiation of the west-dipping Koonenberry Shear Zone and subduction trench outboard of the Kayrunnera Zone. The trench extended into the proto-Pacific Ocean, although the original trend is unknown. (c) Development of the Mt Wright Arc within the Bancannia Trough and extrusion of the Bittles Tank Volcanics (red line). (d) Cessation of arc volcanism and onset of the Delamerian Orogeny. Possible influence of a rigid crustal block now represented by the Hay–Booligal Zone. Oroclinal folding and thrusting of part of the Bittles Tank Volcanics over arc volcanics to form the Loch Lilly–Kars Belt.

locally, faced northeast over a southwest-dipping subduction zone, and that the Mount Wright Arc developed in situ on the Gondwana Margin, and was not emplaced as a result of arc-continent collision.

Corollaries to the principal conclusions are inferences about the nature and history of other structural elements of the Koonenberry Belt. The Cambrian Ponto Group is interpreted to represent fore-arc material thrust onto the continental back-stop represented by the Wonnaminta Zone, while the Koonenberry Shear Zone may preserve the boundary between the inner thin-skinned fore-arc thrust wedge and the outer, thick-skinned accretionary prism. The arc system extended into the palaeo-Pacific Ocean along strike from the continental margin, but was deformed during the Delamerian Orogeny, which resulted in part of the arc being thrust against the southern margin of the Curnamona Province. The Late Cambrian Delamerian Orogeny caused cessation of subduction and volcanism associated with the Mount Wright Volcanic Arc.

Supplementary datasets and table associated with this article can be found in the online version, at www.gondwanaresearchonline.com. Supplementary materials related to this article can be found online at doi:10.1016/j.gr.2010.11.017.

Acknowledgements

Informal reviews by Richard Glen and Wolfgang Preiss have greatly improved the manuscript, as have formal peer reviews of the manuscript by Nick Direen and John Foden. We thank Supri Soengkono and Glass Earth Gold Limited for access to, and permission to use, a low-pass subset of their aeromagnetic data from the Taupo Volcanic Zone. SHRIMP II U-Pb zircon analyses were conducted at Geoscience Australia, by Lance Black between 2004 and 2007, and Simon Bodorkos in 2010, and were co-funded by Industry and Investment NSW and Geoscience Australia under the National Geoscience Agreement. This paper is published with the permission of the Acting Director, Geological Survey of New South Wales, Industry and Investment NSW.

References

Baarda F. D. 1968. Planet Bancannia South No 1. Completion report for Planet Exploration Company Pty. Ltd. Geological Survey of New South Wales, File WCR129 (unpubl.).

Black, L.P., 2005. SHRIMP U–Pb zircon ages obtained during 2004/05 for the NSW Geological Survey. Geological Survey of New South Wales, Report GS2005/745 (unpubl.).

Black, L.P., 2006. SHRIMP U–Pb zircon ages obtained during 2005/06 for NSW Geological Survey projects. Geological Survey of New South Wales, Report GS2006/821 (unpubl.).

Black, L.P., 2007. SHRIMP U–Pb zircon ages obtained during 2006/07 for NSW Geological Survey projects. Geological Survey of New South Wales, Report GS2007/298 (unpubl.).

Boger, S.D., 2011. Antarctica—before and after Gondwana. Gondwana Research 19, 335–371.

Boger, S.D., Miller, J. McL, 2004. Terminal suturing of Gondwana and the onset of the Ross–Delamerian Orogeny: the cause and effect of an Early Cambrian reconfiguration of plate motions. Earth and Planetary Science Letters 219, 35–48.

Browne, P.R.L., Graham, I.J., Parker, R.J., Wood, C.P., 1992. Subsurface andesite lavas and plutonic rocks in the Rotokawa and Ngatamariki geothermal systems, Taupo Volcanic Zone, New Zealand. Journal of Volcanology and Geothermal Research 51, 199–215.

Bruce, M.C., 2010. Geochemistry. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 370–388.

Burton, G.R., 2010. New structural model to explain geophysical features in northwestern New South Wales: implications for the tectonic framework of the Tasmanides. Australian Journal of Earth Sciences 57 (1), 23–49.

Cabanis, B., Lecolle, M., 1989. Le diagramme La/10–Y/15–Nb/8: an outil pour la discrimination des series volcaniques et la mise en evidence des processus de melange et/ou de contamination crustale. Comptes Rendus de l'Academie des Sciences Series II 309, 2023–2029.

Cole, J.W., Darby, D.J., Stern, T.A., 1995. Taupo Volcanic Zone and Central Volcanic Region: Backarc structures of North Island, New Zealand. In: Taylor, B. (Ed.), Backarc Basins: Tectonics and Magmatism. Plenum Press, New York, pp. 1–28.

Cooper, G.R.J., Cowan, D.R., 2006. Enhancing potential field data using filters based on the local phase. Computers and Geosciences 32, 1585–1591.

Cooper, P.F., Tuckwell, K.D., Gilligan, L.B., Meares, R.M.D., 1978. Geology of the Torrowangee and Fowlers Gap 1:100 000 sheets 7135, 7235. Explanatory notes. Geological Survey of New South Wales, Sydney. .

Corbett, W.L., 2000. Annual report for exploration licences 4659, 5478, 5515 and 5528 'Broken Hill Porphyry Project' for the period 27 April 1999 to 26 April 2000. Report GS2001/463 (unpubl.).

Cox, K.G., Hawkesworth, C.J., 1985. Geochemical stratigraphy of the Deccan Traps, at Mahabaleshwar, western Ghats, India, with implications for open system magmatic processes. Journal of Petrology 26, 355–377.

Crawford, A.J., Berry, R.F., 1992. Tectonic implications of Late Proterozoic–Early Palaeozoic igneous rock associations, western Tasmania. Tectonophysics 214, 37–56.

Crawford, A.J., Donaghy, A.G., Black, L., Stuart-Smith, P., 1996. Mt Read Volcanics correlates in Western Victoria: a new exploration opportunity. Australian Institute of Geoscientists Bulletin 20, 97–102.

Crawford, A.J., Keays, R.R., 1978. Cambrian greenstone belts in Victoria: marginal sea-crust slices in the Lachlan Fold Belt of southeastern Australia. Earth and Planetary Science Letters 41, 197–208.

Crawford, A.J., Stevens, B.P.J., Fanning, M., 1997. Geochemistry and tectonic setting of some Neoproterozoic and Early Cambrian volcanics in western New South Wales. Australian Journal of Earth Sciences 44 (6), 831–852.

Davidson, G., 1981. A contribution to the geology of the Mt. Wright area. B.Sc. (Hons) thesis, Australian National University. (unpubl.).

Davey, F.J., Hampton, M., Childs, J., Fisher, M.A., Lewis, K., Pettinga, J.J., 1986. Structure of a growing accretionary prism, Hikurangi margin, New Zealand. Geology 14, 663–666.

Davey, F.J., Henrys, S.A., Lodolo, E., 1995. Asymmetric rifting in a continental back-arc environment, North Island, New Zealand. Journal of Volcanology and Geothermal Research 68, 209–238.

Davies, S.W., 1985. The geology and structure of the Ponto – Little Koonenberry Mountain area, north-western New South Wales. B. App. Sc. (Hons) thesis, University of Technology, Sydney (unpubl.).

Direen, N.G., 1998. The Palaeozoic Koonenberry Fold and Thrust Belt, Western NSW: a case study in applied gravity and magnetic modelling. Exploration Geophysics 29, 330–339.

Direen, N.G., 1999. Geology and geophysics of the Koonenberry Belt, far western New South Wales, and eastern Australian correlates: timing, development and prospectivity of a sector of the late Neoproterozoic–Palaeozoic Gondwana margin. PhD thesis, University of Tasmania. (unpubl.).

Direen, N.G., Jago, J.B., Meffre, S., 2009. New perspectives on the tectonostratigraphic setting of the, Grassy Group, King Island, Australia: "Snowball Earth" or rift related deposit? Geological Society of Australia (Tasmania Division), King Island Field Symposium, March 2009. Geological Society of Australia Field Guide and Abstracts 29–34 (Tas8), ISBN 978 0 9806264 0 7.

Direen, N.G., Crawford, A.J., 2003a. Tasman Line: where is it, and is it Australia's Rodinian break-up boundary? Australian Journal of Earth Sciences 50 (4), 491–502.

Direen, N.G., Crawford, A.J., 2003b. Fossil seaward dipping reflector sequences preserved in southeastern Australia—a 600 Ma volcanic passive margin in eastern Gondwanaland. Journal of the Geological Society, Geological Society of London 160, 985–990.

Edwards, A. C., 1980. The geology and petrology of the igneous rocks of Mt Arrowsmith and related areas of northwestern New South Wales. PhD thesis, University of New South Wales, Sydney (unpubl.).

Evarts, R.C., Conrey, R.M., Fleck, R.J., Hagstrum, J.T., 2009. The Boring Volcanic Field of the Portland-Vancouver area, Oregon and Washington: tectonically anomalous forearc volcanism in an urban setting. In: O'Connor, J.E., Madin, I.P. (Eds.), Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide, vol. 15, pp. 253–270. doi:10.1130/2009.fld015(13).

Finn, C., Moore, D., Damaske, D., Mackey, T., 1999. Aeromagnetic legacy of early Paleozoic subduction along the Pacific margin of Gondwana. Geology 27, 1087–1090.

Flöttmann, T., Gibson, G.M., Kleinschmidt, G., 1993. Structural continuity of the Ross and Delamerian orogens of Antarctica and Australia along the margin of the paleo-Pacific. Geology 21, 319–322.

Foden, J., Barovich, K., Jane, M., O'Halloran, G., 2001. Sr-isotopic evidence for Late Neoproterozoic rifting in the Adelaide Geosyncline at 586 Ma: implications for a Cu ore forming fluid flux. Precambrian Research 106, 291–308.

Foden, J., Song, S.H., Turner, S., Elburg, M., Smith, P., Van der Steldt, B., Van Penglis, D., 2002. Geochemical evolution of lithospheric mantle beneath S.E. South Australia. Chemical Geology 182, 663–695.

Foden, J., Elburg, M., Dougherty-Page, J., Burtt, A., 2006. The timing and duration of the Delamerian Orogeny: correlation with the Ross Orogen and implications for Gondwana assembly. Journal of Geology 114, 189–210.

Foster, D.A., Gray, D.R., Spaggiari, C., 2005. Timing of subduction and exhumation along the Cambrian East Gondwana margin, and the formation of Paleozoic backarc basins. Geological Society of America Bulletin 117, 105–116.

Gatehouse, C.G., 1986. The geology of the Warburton Basin in South Australia. Australian Journal of Earth Sciences 33, 161–180.

Gilmore, P.J., 2010. SHRIMP 1 age dating by PRISE of the Wahratta prospect, near Broken Hill. Unpublished Geological Survey report no GS2010/0807, Geological Survey of NSW.

Gilmore, P.J., Greenfield, J.E., Mills, Musgrave, R.M. and Reid, W.J. in press. Koonenberry Belt 1:250 000 Solid Geology (southern sheet). Geological Survey of New South Wales, Sydney (map).

Gilmore, P.J., Greenfield, J.E., Reid, W.J., Mills, K.J., 2007. Metallogenesis of the Koonenberry Belt. In: Lewis, P.C. (Ed.), SMEDG Mines and Wines Conference, September 2007, Orange NSW: Australian Institute of Geoscientists Bulletin, vol. 46, pp. 49–64.

Glen, R.A., 2005. The Tasmanides of eastern Australia. In: Vaughan, A.P.M., Leat, P.T., Pankhurst, R.J. (Eds.), Terrane Processes at the margins of Gondwana: Geological Society, London, Special Publications, 246, pp. 23–96.

Greenfield, J.E., 2010a. Structural Geology. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 340–369.

Greenfield, J.E., 2010b. Metamorphism. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 389–398.

Greenfield, J.E., 2010c. Warratta Group. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 98–109.

Greenfield, J.E., Mills, K.J., 2010. Grey Range Group. In: Greenfield, J.E., Gilmore, P.J. and Mills, K.J. (compilers). Explanatory notes for the Koonenberry Belt geological maps. Geological Survey of New South Wales, Bulletin 35, 12–29.

Greenfield, J.E., Mills, K.J., Percival, I.G., 2010a. Kayrunnera Group. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 110–133.

Greenfield, J.E., Mills, K.J., Percival, I.G., 2010b. Mutawintji Group. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 134–151.

Hart, S.R., 1988. Heterogeneous mantle domains: Signatures, genesis and mixing chronologies. Earth and Planetary Science Letters 90, 273–296.

Hornby, P., Bochetti, F., Horowitz, F.G., 1999. Analysis of potential field data in the wavelet domain. Geophysical Journal International 137, 175–196.

Hunt, T.M., Smith, E.G.C., 1982. Magnetisation of some New Zealand igneous rocks. Journal of Royal Society of New Zealand 12, 159–180.

Ishizuka, O., Yuasa, M., Sakamoto, I., Kanayama, K., Taylor, R.N., Umino, S., Tani, K., Ohara, Y., 2008. Earliest Izu-Bonin arc volcanism found on the submarine Bonin Ridge. American Geophysical Union. Fall Meeting 2008, abstract #V31A-2106.

Jagodzinski, L., 2007. Cymbric Vale SHRIMP II dating. Written communication between L. Jagodzinski of Department of Primary Industries and Resources, South Australia (PIRSA) and K.J. Mills, former senior geologist, Geological Survey of New South Wales.

Krippner, S.J.P., Briggs, R.M., Wilson, C.J.N., Cole, J.W., 1998. Petrography and geochemistry of lithic fragments in ignimbrites from the Mangakino Volcanic Centre: implications for the composition of the subvolcanic crust in western Taupo Volcanic Zone, New Zealand. New Zealand Journal of Geology and Geophysics 41, 187–199.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27, 745–750.

Leeman, W.P., Lewis, J.F., Evarts, R.C., Conrey, R.M., Streck, M.J., 2005. Petrologic constrains on the thermal structure of the Cascades arc. Journal of Volcanology and Geothermal Research 140, 67–105.

Leitch, E.C., Webby, B.D., Mills, K.J., Kolbe, P., 1987. Terranes of the Wonominta Block, far western New South Wales. In: Leitch, E.C., Scheibner, E. (Eds.), Terrane Accretion and Orogenic Belts: American Geophysical Union, Geodynamics Series, vol. 19, pp. 31–37.

Li, Z.X., Powell, C.Mc.A., 2001. An outline of the palaeogeographic evolution of the Australasian region since the beginning of the Neoproterozoic. Earth Science Reviews 53, 237–277.

Malavieille, J., Trullenque, G., 2009. Consequences of continental subduction on forearc basin and accretionary wedge deformation in SE Taiwan: insights from analogue modeling. Tectonophysics 466, 377–394.

Maurin, T., Rangin, C., 2009. Structure and kinematics of the Indo-Burmese Wedge: recent and fast growth of the outer wedge. Tectonics 28, TC2010. doi:10.1029/2008TC002276.

Middlemost, E.A.K., 1994. Naming materials in the magma, igneous rock system. Earth Science Reviews 37, 215–224.

Miller, J. McL, Phillips, D., Wilson, C.J.L., Dugdale, L.J., 2005. Evolution of a reworked orogenic zone: the boundary between the Delamerian and Lachlan fold belts, southeastern Australia. Australian Journal of Earth Sciences 52, 921–940.

Mills, K.J., 1992. Geological evolution of the Wonominta Block. Tectonophysics 214, 57–68.

Mills, K.J., 2010a. Teltawongee Group. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 31–50.

Mills, K.J., 2010b. Nundora Formation. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 39–40.

Mills, K.J., 2010c. Geological History. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 425–442.

Mills, K.J., 2010d. Ponto Group. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 75–98.

Mills, K.J., David, V., 2004. The Koonenberry Deep Seismic Reflection Line and Geological Modelling of the Koonenberry Region. Western New South Wales. Geological Survey of New South Wales, Report GS2004/185. .

Miyashiro, A., 1974. Volcanic rock series in island arcs and active continental margins. American Journal of Science 274, 321–355.

Mizow, D., 2006. Geochemical, tectonic and economic relationships of mafic bodies in the Wonominta Block, Western N.S.W. BSc (Hons) Thesis, University of Adelaide. (unpubl.).

Münker, C., Crawford, A.J., 2000. Cambrian arc evolution along the SE Gondwana active margin: a synthesis from Tasmania–New Zealand–Australia–Antarctica correlations. Tectonics 19, 415–432.

Musgrave, R.J., 2010. Geophysics. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 297–340.

Musgrave, R., Rawlinson, N., 2010. Linking the upper crust to the upper mantle: comparison of teleseismic tomography with long-wavelength features of the gravity and magnetic fields of southeastern Australia. Exploration Geophysics 41, 155–162.

Nagler, T.F., Kramer, J.D., 1998. Nd isotopic characteristics of S-type and I-type granites. Earth and Planetary Science Letters 58, 51–64.

Nakamura, H., Iwamori, H., 2009. Contribution of slab-fluid in arc-magmas beneath the Japan arcs. Gondwana Research 16, 431–445.

Ogg, J.G., Ogg, G., Gradstein, F.M., 2008. The concise geologic time scale. Cambridge University Press, Cambridge, United Kingdom.

Oldenburg, D.W., Pratt, D.A., 2007. Geophysical inversion for mineral exploration: a decade of progress in theory and practice. In: Milkereit, B. (Ed.), Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, pp. 61–95.

Pearce, J.A., 1982. Trace element characteristics of lavas from destructive plate boundaries. Andesites: Orogenic Andesites and Related Rocks. John Wiley and Sons, London, pp. 525–548.

Pearce, J.A., 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins. In: Hawkesworth, C.J., Norry, M.J. (Eds.), Continental basalts and mantle xenoliths, pp. 230–249.

Percival, I.G., 2010a. Cymbric Vale Formation. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 62–63.

Percival, I.G., 2010b. Palaeontology Appendix. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35, 443–456.

Planke, S., Eldholm, O., 1994. Seismic response and construction of seaward dipping wedges of flood basalts: Vøring volcanic margin. Journal of Geophysical Research 99, 9263–9278.

Planke, S., Alvestad, E., 1999. Seismic volcanostratigraphy of the extrusive breakup complexes in the northeast Atlantic: implications from ODP/DSDP drilling. In: Larsen, H.C., Duncan, R.A., Allan, J.F., Brooks, K. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 163, pp. 3–16.

Preiss, W.V., 1995. Delamerian Orogeny. In: Drexel, J.F., Preiss, W.V. (Eds.), The Geology of South Australia. Vol. 2, The Phanerozoic: South Australian Geol. Survey Bull., vol. 54 (2), pp. 45–57.

Preiss, W.V., 2000. The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental reconstruction. Precambrian Research 100, 21–63.

Richardson, B., 1998. Potential for porphyry copper mineralisation in the Broken Hill region, NSW. Gibson, G.M. (compiler). Broken Hill Exploration Initiative: Abstracts of papers presented at fourth annual meeting in Broken Hill, October 10-21, 1998. AGSO Record 1998/25.

Robinson, R., Smith, E.G.C., Latter, J.H., 1981. Seismic studies of the crust under the hydrothermal areas of the Taupo Volcanic Zone, New Zealand. Journal of Volcanological and Geothermal Research 9, 253–267.

Rose, G., Brunker, R.L., 1969. The upper Proterozoic and Phanerozoic geology of north-western New South Wales. Proceedings Australasian Institute of Mining and Metallurgy 229, 105–120.

Scheibner, E., 1972. The Kanmantoo Pre-Cratonic Province in New South Wales. Quarterly Notes Geological Survey of N.S.W. 7, 1–8.

Scheibner, E., 1974. A plate tectonic model of the Palaeozoic tectonic history of New South Wales. Journal of the Geological Society of Australia 20 (1), 405–426.

Scheibner, E., 1992. Influence of detachment-related passive margin geometry on subsequent active margin dynamics: Applied to the Tasman Fold Belt System. Tectonophysics 214, 401–416.

Geology of New South Wales — Synthesis. Volume 1 Structural framework. In: Scheibner, E., Basden, H. (Eds.), Geological Survey of New South Wales Memoir Geology, vol. 13 (1).

Geology of New South Wales — Synthesis. Volume 2 Geological Evolution. In: Scheibner, E., Basden, H. (Eds.), Geological Survey of New South Wales, Memoir Geology, vol. 13 (2).

Scheibner, E., Veevers, J.J., 2000. Tasman Fold Belt System. In: Veevers, J.J. (Ed.), Billion-Year Earth History of Australia and Neighbours in Gondwanaland. GEMOC Press, Sydney, pp. 154–234.

Seebeck, H., Nicol, A., 2009. Dike intrusion and displacement accumulation at the intersection of the Okataina Volcanic Centre and Paeroa Fault zone, Taupo Rift, New Zealand. Tectonophysics 475, 575–585.

Sharp, T.R., Buckley, P.M., 2003. Palaeozoic history of the Bancannia Trough and resurrection of the Mt Wright Volcanic Arc. *In* Broken Hill Exploration Initiative: Abstracts from the July 2003 Conference, compiled by Matt Peljo. Geoscience Australia Record 2003 (13), 154–157.

Sharp, T.R., and Buckley, P.M., in press. Nuchea 1:100 000 Geological Sheet 7335, second edition. Geological Survey of New South Wales (map).

Sharp, T.R., Robson, D.R., Hallett, M.S., Mills, K.J., Stevens, B.P.J., 2006. Loch Lilly–Kars Belt 1:250 000 geological–geophysical interpretation map. Geological Survey of NSW, Maitland.

Sherburn, S., Bannister, S., Bibby, H., 2003. Seismic velocity structure of the central Taupo Volcanic Zone, New Zealand, from local earthquake tomography. Journal of Volcanology and Geothermal Research 122, 69–88.

Soengkono, S., 1995. A magnetic model for deep plutonic bodies beneath the central Taupo Volcanic Zone, North Island, New Zealand. Journal of Volcanology and Geothermal Research 68, 193–207.

Spaggiari, C.V., Gray, D.R., Foster, D.A., 2003. Tethyan- and Cordilleran-type ophiolites of eastern Australia: implications for the evolution of the Tasmanides. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in Earth History, Geological Society of London Special Publication, vol. 218, pp. 517–539.

Spinks, K.D., Acocella, V., Cole, J.W., Bassett, K.N., 2005. Structural control of volcanism and caldera development in the transtensional Taupo Volcanic Zone, New Zealand. Journal of Volcanology and Geothermal Research 144, 7–22.

Stern, T.A., 1985. A back-arc basin formed within continental lithosphere: the Central Volcanic Region of New Zealand. Tectonophysics 112, 385–409.

Stern, T.A., 1986. Geophysical studies of the upper crust within the Central Volcanic Region, New Zealand. In: Smith, I.E.M. (Ed.), Late Cenozoic Volcanism in New Zealand, Royal Society of New Zealand Bulletin, vol. 23, pp. 92–111.

Stern, T.A., Stratford, W.R., Salmon, M.L., 2006. Subduction evolution and mantle dynamics at a continental margin: central North Island. New Zealand. Reviews of Geophysics 44, RG4002. doi:10.1029/2005RG000171.

Stevens, B.P.J., Mills, K.J., Direen, N.J., Buckley, P.M., Cooper, I., 2000. Koonenberry Pre-Permian Interpretation Map. Geological Survey of New South Wales (map).

Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in ocean basins: Geological Society of London Special Publication, vol. 42, pp. 313–345.

Taylor, S.R., McLennan, S.M., 1995. The geochemical evolution of the continental crust. Reviews of Geophysics 33, 241–265.

Thompson, R.N., Morrison, M.A., Hendry, G.L., Parry, S.J., 1984. An assessment of the relative roles of a crust and mantle in magma genesis: an elemental approach. Philosophical Transactions of the Royal Society of London A310, 549–590.

VandenBerg, A.H.M., Willman, C.E., Maher, S., Simons, B.A., Cayley, R.A., Taylor, D.H., Morand, V.J., Moore, D.H., Radojkovic, A., 2000. The Tasman Fold Belt System in Victoria. Geological Survey of Victoria Special Publication, 374–379.

Veevers, J.J., Walter, M.R., Scheibner, E., 1997. Neoproterozoic tectonics of Australia–Antarctica and Laurentia and the 560 Ma birth of the Pacific Ocean reflect the 400 million year Pangean supercycle. Journal of Geology 105, 225–242.

Veevers, J.J., 2000. Antarctic Beardmore–Ross and Mirny provenances saturate Paleozoic–Mesozoic East Gondwanaland with 0.6–0.5 Ga zircons. In: Veevers, J.J. (Ed.), Billion-Year Earth History of Australia and Neighbours in Gondwanaland. GEMOC Press, Sydney, pp. 110–130.

Veevers, J.J., 2009. Edge Tectonics (Trench Rollback, Terrane Export) of Gondwanaland-Pangea Synchronized by Supercontinental Heat. Gondwana Research 8 (4), 449–456.

Vickery, N.M., Greenfield, J.E., 2010. Bittles Tank Volcanics. In: Greenfield J.E., Gilmore P.J. and Mills K.J. (compilers) 2010. Explanatory notes for the Koonenberry Belt maps. Geological Survey of New South Wales, Bulletin 35.

Wallace, L.M., Beavan, J., McCaffrey, R., Darby, D., 2004. Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. Journal of Geophysical Research 109, B12406. doi:10.1029/2004JB003241.

Warris, B.J., 1967. The Palaeozoic stratigraphy and palaeontology of north-western New South Wales. PhD Thesis. University of Sydney (unpubl.).

Willcox, J.B., Leven, J.H., Yeates, A.N., Johnstone, D., Wake-Dyster, K., Mills K.J., and Shaw R.D. 2000. A deep-crustal seismic image through the Bancannia Trough and Koonenberry Zone, NSW. (unpublished manuscript).

Williams, H.A., Stewart, J.R., Betts, P.G., 2009. Imposition of a Proterozoic salient on a Palaeozoic orogen at the eastern margin of Gondwana. Gondwana Research 16, 669–686.

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M., 1995. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. Journal of Volcanology and Geothermal Research 68, 1–28.

Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology 20, 325–343.

Wopfner, H., 1967. [imprint 1966]. Cambro-Ordovician sediments from the northeastern margin of the Frome Embayment (Mt Arrowsmith, N.S.W.). Journal and Proceedings Royal Society of New South Wales 100, 163–177.

Zhou, B., 1992. Petrological, geochemical and Sr–Nd isotopic studies of metamorphosed mafic rocks in the Wonominta Block, north-western New South Wales, Ph.D. Thesis University of Sydney (unpubl.).

Zhou, B., Whitford, D.J., 1994. Geochemistry of the Mt Wright Volcanics from the Wonominta Block, northwestern New South Wales. Australian Journal of Earth Sciences 41, 331–340.