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Early Cretaceous volcano-sedimentary successions along the eastern Australian continental margin: Implications for the break-up of eastern Gondwana

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Abstract

We report on three large volume Early Cretaceous volcanic and sedimentary provinces: the Whitsunday Volcanic Province and Great Artesian Basin system, both of northeastern Australia, and the Otway/Gippsland basin system along the southeastern margin of Australia. The Whitsunday Volcanic Province is part of a mafic to silicic, high-K calc-alkaline pyroclastic volcanic belt that extends for more than 900 km along the central and southern Queensland coast. Estimated extrusive volumes are $> 10^5$ km^3. Volcanic and intrusive activity shows a broad range of ages from 132 to 95 Ma, but ages are dominated by an event between ~ 120 and 105 Ma. Contemporaneous with volcanism in the Whitsunday Volcanic Province, sedimentary basins in interior and eastern Queensland were receiving large volumes ($> 10^6$ km^3) of volcanogenic sediment. The Otway and Gippsland basins 1500 km to the south, were initiated by the break-up of Antarctica and Australia. These basins contain $> 4 \times 10^5$ km^3 of Aptian–Albian extrabasinal volcanogenic sediment supplied from the east. This volcanogenic sedimentation post-dates rift-related volcanism within the basin system. These three provinces are each significant for: (1) the accumulation of large volumes of volcanic and/or coeval volcanic-derived material; (2) the compositional similarity between phenocryst and detrital plagioclase, augite and hornblende; and (3) age data recording a major volcanic episode between 125 and 105 Ma. A causal relationship between volcanism in the Whitsunday Volcanic Province and volcaniclastic sedimentation in the Otway/Gippsland and Great Artesian basin systems is therefore suggested. We propose these provinces record volcanism related to the break-up of eastern continental Gondwana and the formation of the modern eastern Australian passive margin. The scale and volume of volcanic products, coupled temporally with

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emplacements of oceanic plateaux in the Southwest Pacific, demonstrate that this volcanic event along the present eastern Australian plate margin should be considered as another Early Cretaceous large igneous province.

Keywords: Gondwana; Lower Cretaceous; intraplate processes; plate boundaries; volcanism; volcanic processes

1. Introduction

The Early Cretaceous is recognised as a time of Gondwana break-up and the emplacement of large igneous provinces. These provinces are manifest as continental flood basalts, oceanic plateaux and volcanic-dominated passive margins, and represent the voluminous emplacement of predominantly mafic intrusive and extrusive rocks. Emplacement typically occurs over a relatively short period of time (10^5–10^6 yr), and is often related to continental break-up [1]. Documented large igneous provinces of Early Cretaceous age include the Paraná–Etendeka continental flood bimodal volcanic province that was emplaced at ~ 132 Ma, just prior to seafloor spreading in the South Atlantic (e.g., [2,3]); Kerguelen (114–109.5 Ma, [1] and references therein); and a number of oceanic plateaux that formed in the Southwest Pacific between 130 and 115 Ma (e.g., the Manihiki, Ontong–Java and Hikurangi plateaux [4,5]).

For eastern Gondwana in the Early Cretaceous, however, two aspects have remained enigmatic: (1) the nature of the eastern Gondwanan plate margin, whether it was undergoing rifting and plate break-up, or convergence; and (2) the source of large volumes of volcanogenic sediment now preserved in the Otway/Gippsland basins and Great Artesian Basin system of southeastern and northeastern Australia, respectively (Fig. 1). The lack of early Mesozoic structural and geologic information in southeastern Australia, and the widespread coverage of northeastern Australia by the poorly studied Great Artesian Basin system, have limited our understanding of the Cretaceous tectonic setting of eastern Australia.

It is widely held that an Early Cretaceous convergent margin and an andesitic magmatic arc existed along eastern Gondwana, roughly coincident with the modern Queensland coastline (e.g., [6,8–10]), on the following grounds: (1) the calc-alkaline geochemical affinities of volcanic rocks exposed in eastern Queensland (e.g., Whitsunday Volcanic Province, and Grahams Creek Formation [11] of the Maryborough Basin; Fig. 1) have been interpreted as indicating subduction; (2) the Aptian–Albian volcanogenic detritus in continental basins was petrographically determined to be of 'andesitic' derivation [12–14]; and (3) as a continuation (e.g., [8–10]) of the preceding history of plate subduction, magmatism and tectonism during the Palaeozoic and early Mesozoic

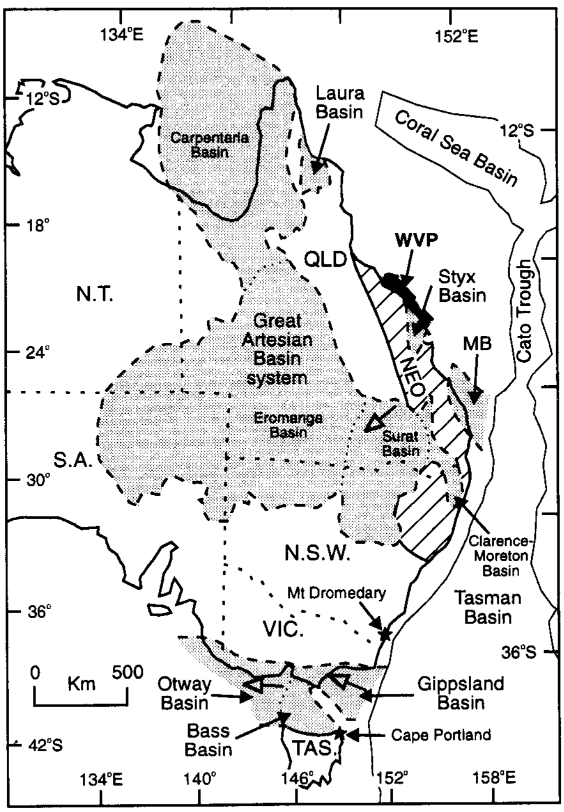


Fig. 1. Map showing locations of the Whitsunday Volcanic Province (*WVP*) and Cretaceous sedimentary basins (shaded) in eastern Australia. *MB* = Maryborough Basin; *NEO* = New England Orogen. Hollow arrows represent generalised palaeocurrent directions for the Surat Basin [6] and Otway/Gippsland basins (this study). The Tasman Basin–Cato Trough–Coral Sea Basin system was formed by seafloor spreading over the period 84–56 Ma [7,8].

recorded by the New England Orogen (Fig. 1) in eastern Australia (e.g., [15]).

In contrast, offshore seismic reflection profiling across the eastern margin of Australia (e.g., [7,16,17]) identified marginal plateaux and complex rift-basin systems adjacent to the continental shelf. These rift-basins, interpreted to contain Cretaceous rift-fill, indicated that rifting and development of the eastern Australian passive margin began in the Cretaceous, prior to seafloor spreading in the Tasman Basin (Fig. 1). Detachment models have been used to explain the rift geometry of the eastern Australian passive margin (e.g., [17,18]), but more importantly, these models imply no prior convergence in the Jurassic–Cretaceous. Taylor and Falvey [19] suggested that any continental arc would probably have become inactive during the Early Cretaceous when the Pacific Plate motion changed to northwest with respect to Australia along a predominantly transform plate boundary.

Contemporaneously with volcanism in eastern Queensland, large volumes of feldspar and volcanic lithic-dominated sediment were being shed into the Great Artesian Basin system of interior Queensland and the Otway and Gippsland basins in southeastern Australia (Fig. 1). A major problem has been to identify the source of this volcaniclastic sediment as there are no interbedded volcanic rocks within the Aptian–Albian sedimentary successions. For the Otway/Gippsland basins, two models have been proposed: (1) a continental 'andesitic' volcanic arc source located to the east of the Gippsland Basin [20]; and (2) an intra-rift volcanic source located in the Otway Basin, with sediment transported eastwards into the Gippsland Basin [21–23]. For the Great Artesian Basin system, volcanogenic sedimentation has been related to an andesitic volcanic arc situated off the eastern coast of Queensland (e.g., [6,8,10]).

The aim of this paper is to provide comparative data for these Early Cretaceous provinces along the eastern Australian margin. A substantial geochronological, geochemical and petrological database for the Whitsunday Volcanic Province [24,25] is compared with fission track age data of detrital minerals [21], and petrologic studies [22,23,26] from the Otway/Gippsland basins. The Great Artesian Basin system has not been studied to the same extent, but an extensive petrographic study of the Cretaceous sedimentary rocks from the Surat Basin [6] forms the basis of comparison with the other provinces. This paper presents new data on the detrital mineralogy for the Aptian–Albian volcanogenic sediments of the Otway/Gippsland basins, and previously unpublished feldspar mineral data from the Whitsunday Volcanic Province. Some K/Ar ages from the Whitsunday Volcanic Province presented in previous studies [25,27] were incorrect due to a laboratory calculation error; the corrected age data is presented in Appendix A.

The mineral chemistry, which provides the only available control on volcanic source characteristics for the Otway/Gippsland and Great Artesian basin systems, is compared with the mineral chemistry from the temporally equivalent Whitsunday Volcanic Province. A number of similarities exist between these provinces that, collectively, place important constraints on the nature of the Early Cretaceous eastern Gondwana margin. Although the provinces are spatially isolated, we argue that the Whitsunday Volcanic Province and the contemporaneous inundation of volcanogenic sediment into the Otway/Gippsland and Great Artesian basin systems record the same, margin-wide event. We suggest that volcanism and volcanogenic sedimentation was associated with a ~ N–S oriented rift system > 2,500 km in length that developed along the present eastern Australian margin at approximately 125 Ma. Large volumes ($> 1.5 \times 10^6$ km^3) of volcanic and volcanically derived material characterised the early stages of dispersal of continental fragments of the eastern (Australian) margin of Gondwana.

2. Whitsunday Volcanic Province

Ewart et al. [25] and Parianos [27] have provided detailed accounts of the petrology, geochemistry, and volcanic lithologies of the Whitsunday Volcanic Province. The province comprises volcanic rocks and related granites exposed in the Whitsunday, Cumberland, and Northumberland Island groups, and onshore exposures (Proserpine Volcanics of Clarke et al. [28]) along the central Queensland coast (Fig. 2). Early Cretaceous volcanic rocks crop out further south in the Shoalwater Bay area near Rockhampton, and in the Maryborough Basin (Fig. 1), defining an Early Cretaceous silicic pyroclastic volcanic belt (Fig. 2) more than 900 km long, ~ 100 km wide, and locally more than 2 km thick. Volume estimates for the extrusive component of the Whitsunday Volcanic Province are $> 3 \times 10^4$ km^3, but exceed 10^5 km^3 when the full extent of this volcanic belt is taken into consideration.

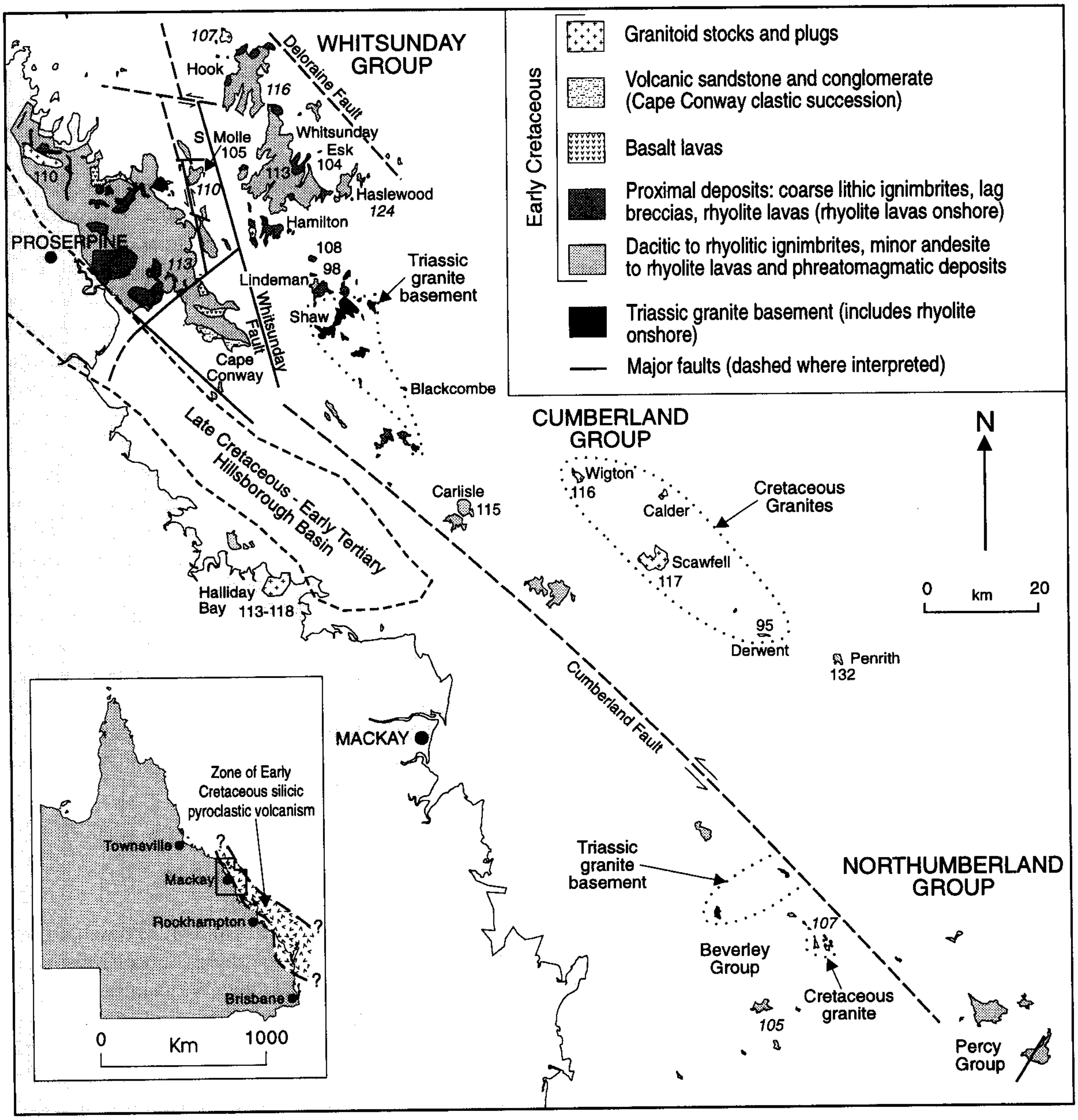


Fig. 2. Extent and generalised volcanic geology of the Whitsunday Volcanic Province. Numbers are corrected K–Ar and Rb–Sr (italicised) dates from Ewart et al. [25] and Parianos [27]. Locations of islands referred to in text are shown. The inset map shows the inferred distribution of Early Cretaceous volcanism along the eastern coast of Queensland [25,28].

Volcanic lithologies are dominated by dacitic to rhyolitic lithic ignimbrite, with intercalated lithic lag breccia, surge, fallout, and phreatomagmatic deposits. Rhyolitic and dacitic domes and andesite lavas are subordinate. Basalt lavas (uncommon on the islands) are volumetrically more abundant in younger mainland exposures. Ignimbrite depositional units are commonly 10–100 m thick, and ignimbrite sequences exceed 1 km in thickness on the Hook and Whitsunday islands. Associated with the volcanics are locally significant thicknesses of coarse volcanogenic conglomerate and sandstone exposed at Cape Conway (~ 550 m) and South Molle Island (75 m). The sedimentary rocks are texturally and compositionally immature, reflecting local provenance, and sedimentation appears to have been in a poorly confined alluvial environment in which upper flow regime conditions dominated.

The volcanic sequences are interpreted as subaerially deposited, with localised water–magma interaction (cf. [28]). The Hook, Whitsunday, Hamilton, and Lindeman island sequences (Fig. 2) are interpreted by Ewart et al. [25] as 'intracaldera' facies, based on: (1) the > 1 km thickness of ignimbrite-dominated sequences on these islands; (2) a pervasive low grade alteration; (3) the abundance of intermediate to silicic dyke swarms; and (4) the occurrence of very coarse lithic lag breccias with clasts up to 6 m in diameter. The paucity of debris-flow deposits, and the burial of near-vent deposits, such as basaltic agglomerate, by ignimbrites are interpreted as indicating an overall low-relief depositional environment. The interstratification of proximal/near-vent lithofacies, such as rhyolite domes and lavas, basaltic agglomerate and agglutinate, and medial to distal lithofacies including ignimbrite and surge deposits suggests a multiple vent volcanic environment. We conclude volcanism occurred in a low-relief extensional environment, dominated by several caldera centres, with no evidence from the facies architecture to support a high-standing, stratovolcano-type andesitic magmatic arc.

Age data (Fig. 3) show a broad duration of volcanic and intrusive activity from 132 to 95 Ma, predating seafloor spreading in the Tasman Basin to the south (> 84 Ma [8]). More importantly, the dates confine the main period of activity between ~ 120 and 105 Ma. Intrusive activity was largely coeval

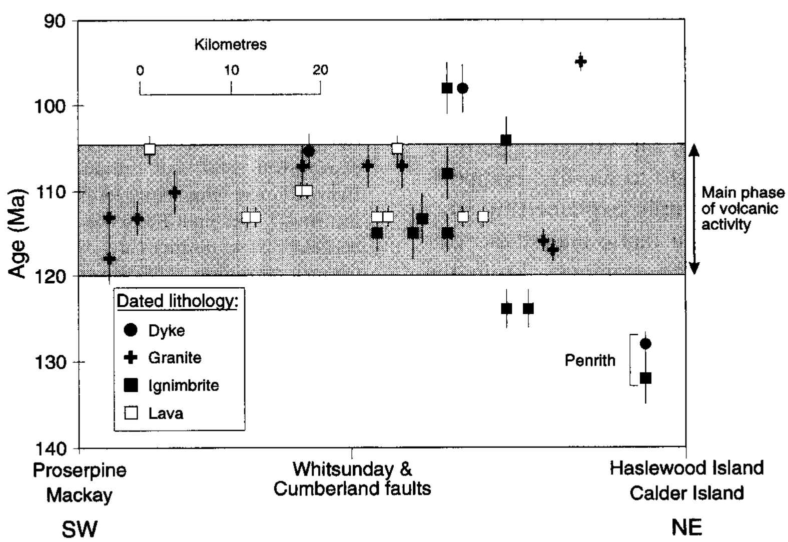


Fig. 3. Space–time presentation of isotopic (Rb/Sr and corrected K/Ar) age data with error bars from the Whitsunday Volcanic Province [24,25,27,28]. Ages have been projected onto a cross-section, oriented SW–NE from the mainland to the outer islands. Illustrated is the main phase of activity for the Whitsunday Volcanic Province, identified by Ewart et al. [25].

with volcanism and, combined with field relationships, the major period of explosive volcanism is interpreted to have occurred ~ 120–110 Ma.

The phenocryst mineralogy comprises plagioclase, augite, Fe–Ti oxides, with lesser hypersthene (altered), hornblende, biotite, quartz, and sanidine. Plagioclase is the primary phenocryst phase in all volcanic compositions. Although plagioclase is altered to albite, sufficient remnant primary compositions are generally preserved to determine compositional ranges (Fig. 4). In coherent volcanic rocks, plagioclase phenocryst compositions extend from labradorite (An_{80}) and bytownite (An_{54}) in the dolerites and andesites, through to andesine (An_{30}) in the rhyolite lavas and dykes (Fig. 4). In the volumetrically dominant dacitic and rhyolitic ignimbrites, compositions are primarily andesine to oligoclase (An_{48}–An_{24}), tending towards more sodic compositions than in the coherent volcanic lithologies. Both calcic pyroxene and amphibole are relatively magnesian (Figs. 5 and 6), while augite shows little variation in Fe–Mg–Ca ratios amongst the dolerite to low-silica rhyolite compositional range. Bimodal to divergent phenocryst compositions, and the occurrence of normal and reverse compositionally zoned phenocrysts in dolerites through to rhyolites are indicative of magma mixing.

The volcanic suite exhibits a continuous spectrum of compositions from basalt to high-silica rhyolite (Fig. 7), with high-K calc-alkaline affinities and geochemical signatures that are comparable to Southwest Pacific island arc regions [25]. On Ba/Nb versus La/Nb plots (Fig. 8), the volcanics show a complete range from intraplate to arc-like compositions. The data cannot be simply explained by fractional crystallisation since the mafic and silicic volcanic fields almost completely coincide. From the Hf–Th–Ta relationships, the data plot as a linear array that is most readily explained as a mixing array (Fig. 8), with the mafic end of the spectrum projecting into the E-MORB or within-plate field, whereas the silicic volcanics and granites plot within the calc-alkaline or destructive plate margin field.

Trace element and isotopic studies [25,27] have argued that the broad spectrum of compositions was generated by two-component magma mixing, with superimposed fractional crystallisation in the high-silica rhyolites. The two magma sources are defined as: (1) a large volume, partial melt of relatively young crust with a non-radiogenic, calc-alkaline character; and (2) a within-plate tholeiitic basalt (near E-MORB) with a geochemical character similar to the Tertiary within-plate basalts of eastern Australia [25,35]. Three important conclusions that can be drawn from the geochemical studies are: (1)

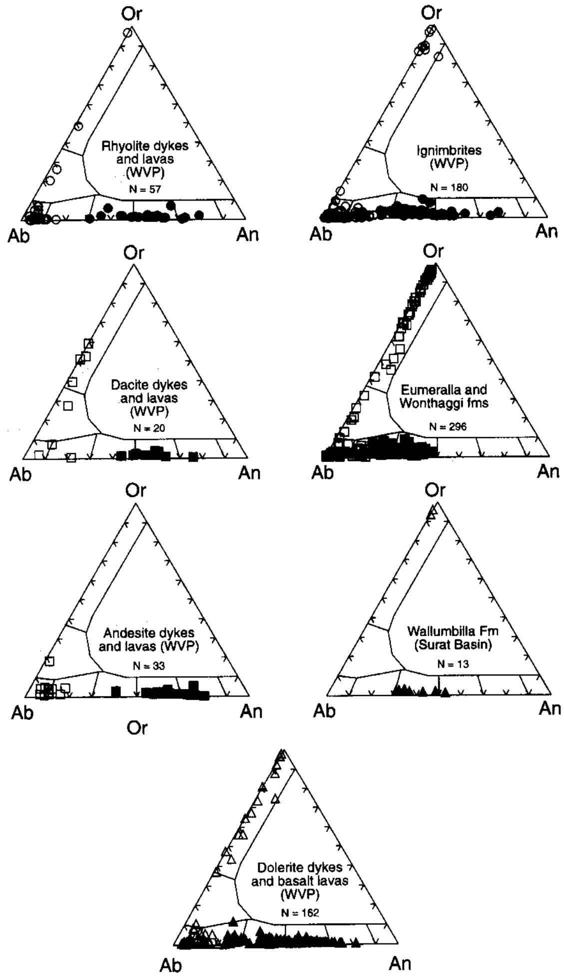


Fig. 4. Feldspar phenocryst compositions from coherent and pyroclastic volcanic rocks of the Whitsunday Volcanic Province (WVP, unpublished data), and detrital feldspar compositions from the Eumeralla and Wonthaggi formations (Otway/Gippsland basins, this study), and Surat Basin (Great Artesian Basin [6]). End-member feldspar compositions are: An = Anorthite; Ab = Albite; Or = Orthoclase. Hollow symbols represent altered compositions. N = number of analyses.

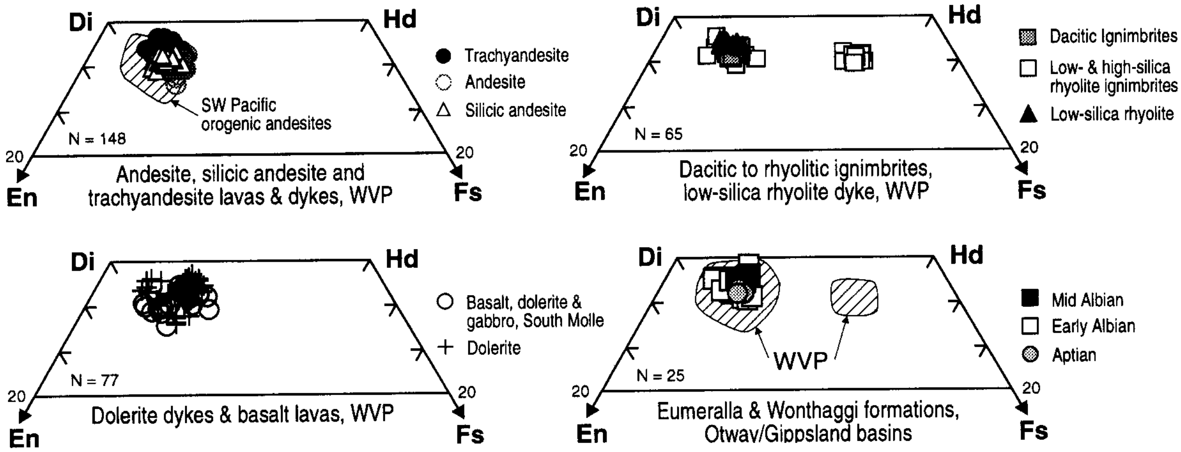


Fig. 5. Pyroxene phenocryst compositions from coherent and pyroclastic volcanic rocks of the Whitsunday Volcanic Province (WVP [25]; South Molle, unpublished data), and detrital pyroxene grains from the Eumeralla and Wonthaggi formations of the Otway/Gippsland basins (this study). Clinopyroxene compositional variation is projected in terms of the four-component system: Diopside (Di); Enstatite (En); Ferrosilite (Fs); and Hedenbergite (Hd). Note: (1) the overlap of phenocryst and detrital calcic pyroxenes with modern Southwest Pacific orogenic andesites; (2) Fe-enriched compositions are only observed in the fractionated high-silica rhyolites of the WVP; and (3) detrital calcic pyroxene chemistry shows little to no variation from the Aptian through to the mid-Albian in the Otway/Gippsland basins. N = number of analyses. Field for Southwest Pacific orogenic andesites after Ewart [29].

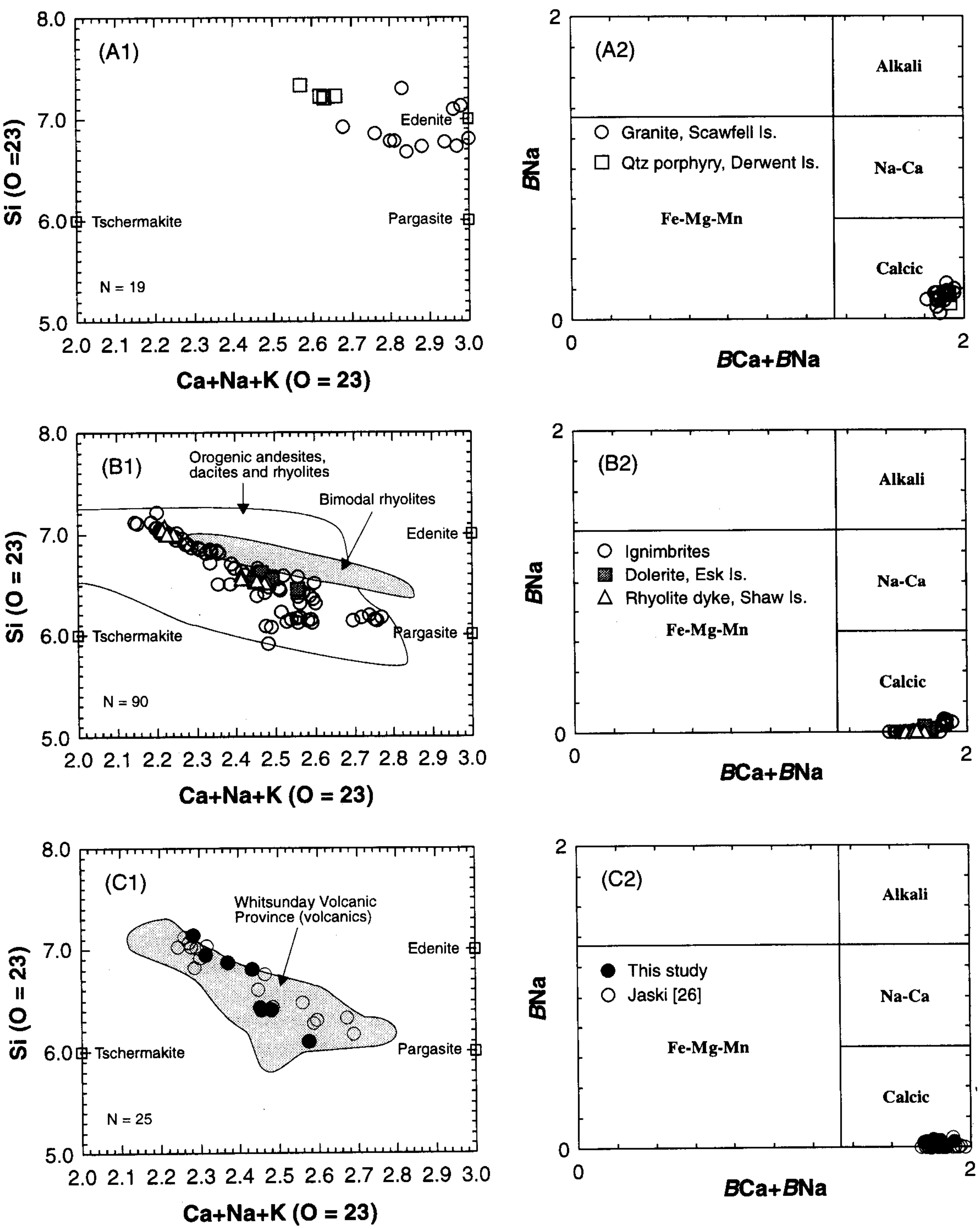
the calc-alkaline signature is inherited from the crustal source; (2) the inferred basaltic end-member is distinct from basalts occurring in arc and back-arc environments that are transitional between N-MORB and island arc or calc-alkaline basalts [36]; and (3) that a large thermal flux into the crust is required to maintain volcanism [35]. We support the conclusions of Roberts and Clemens [37] that, for crust-derived partial melts, the trace element and isotope data reflects the nature of the magma source(s), rather than the tectonic setting in which the magmas were produced.

3. Otway and Gippsland basins

The Otway and Gippsland basins (Figs. 1 and 9) represent two of three WNW-trending, transtensional rift basins which form the eastern extremity of a complex rift system (Southern Rift System of Willcox and Stagg [38]) that extended along the length of the southern margin of Australia during the Late Jurassic–Early Cretaceous. Their formation represents a precursor stage to the post-Middle Cretaceous break-up of Australia and Antarctica [7,8].

The Late Jurassic–Early Cretaceous sequences in the Otway and Gippsland basins comprise the Otway and Strzelecki groups, respectively (Fig. 9). The sequences in each basin are divided into three tectonolithostratigraphic units representing: pre-, syn-, and post-rift (sag) phases of deposition. Of specific interest are the post-rift (sag) phase, fluvial-lacustrine Eumeralla and Wonthaggi formations (Fig. 9). Both units are > 2,500 m thick and dominated by sandstone and mudstone. The sediments were deposited by a series of multistorey sheetflood to braided river-like channel complexes, up to 200 m thick, separated by overbank sequences ranging between 5 and 100 m in thickness. Internally, the channel complexes are characterised by thick packages of planar cross-stratified, trough cross-stratified, horizontally stratified, massive, and low-angle cross-stratified sandstone. The range of lithofacies, coupled with the remarkable uniformity in sand grain size, suggests the sediments were deposited by a fluvial system subject to high energy discharge events.

Petrographic studies show that sandstones of the Eumeralla and Wonthaggi formations are lithic-rich (Fig. 10) with an average quartz:feldspar:lithic frag-


(A1)
Edenite
Tschermakite
Pargasite
N = 19
Si (O =23)
Ca+Na+K (O = 23)
(A2)
Alkali
Na-Ca
Calcic
Fe-Mg-Mn
Granite, Scawfell Is.
Qtz porphyry, Derwent Is.
BNa
BCa+BNa
(B1)
Orogenic andesites, dacites and rhyolites
Bimodal rhyolites
Edenite
Tschermakite
Pargasite
N = 90
Si (O = 23)
Ca+Na+K (O = 23)
(B2)
Alkali
Na-Ca
Calcic
Fe-Mg-Mn
Ignimbrites
Dolerite, Esk Is.
Rhyolite dyke, Shaw Is.
BNa
BCa+BNa
(C1)
Whitsunday Volcanic Province (volcanics)
Edenite
Tschermakite
Pargasite
N = 25
Si (O = 23)
Ca+Na+K (O = 23)
(C2)
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This study
Jaski [26]
BNa
BCa+BNa

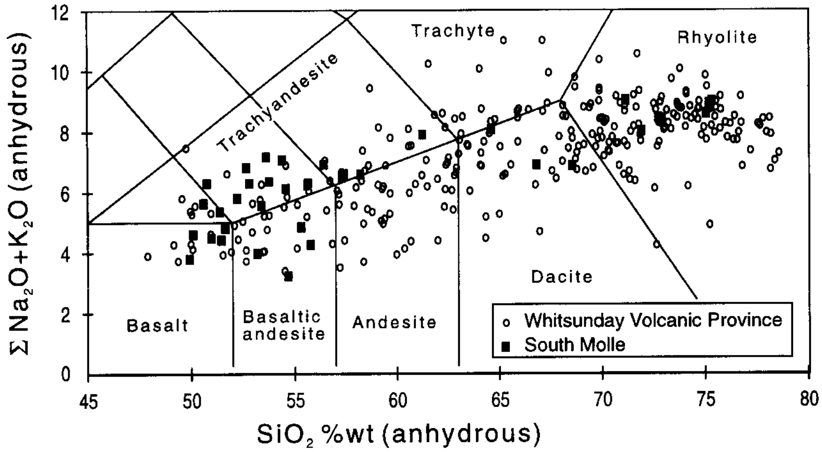

Fig. 7. Total alkalis versus silica diagram (boundaries after Le Maitre [31]) showing the range and continuity of volcanic and intrusive compositions of the Whitsunday Volcanic Province [25], which is represented at the small scale by individual island sequences (South Molle, unpublished data). The diagram contains 315 X-ray fluorescence analyses.

ments (Q:F:L) ratio of 15:10:75 (Eumeralla Formation) and 8:26:66 (Wonthaggi Formation). A major change in sediment provenance is indicated from the underlying Crayfish Subgroup (> 4,500 m thick) and Tyers Subgroup (> 425 m thick) that consist predominantly of basement-derived quartz sandstones with an average Q:F:L ratio of 84:10:6 (Crayfish Subgroup [42]) and 95:1:4 (Tyers Subgroup). The Eumeralla and Wonthaggi sandstones comprise volcanic lithic grains of andesitic, dacitic and rhyolitic composition, and average 78% (Eumeralla Formation) and 83% (Wonthaggi Formation) of the total lithic component. Detrital minerals are predominantly plagioclase, with lesser quartz, hornblende, pyroxene (augite), apatite, titanite (sphene), and zircon. Fission track dating of apatite, titanite, and zircon (Fig. 9) supports a contemporaneous volcanic source for the sediment [21], and is further supported by palynological dating indicating the Eumeralla and Wonthaggi formations to be Aptian–Albian in age. The fresh nature of the detrital grains also implies the sediment sources were contemporaneous volcanoes. Unaltered, detrital plagioclase grains are primarily andesine to oligoclase (An_{46}–An_{20}) in composition (Fig. 4), whereas calcic pyroxenes and amphiboles are relatively magnesian (Figs. 5 and 6), as commonly found in (high-K) calc-alkaline volcanic suites [22,29,30].

Palaeocurrent measurements from both the exposed Aptian section of the Wonthaggi Formation in the Gippsland Basin, and the exposed Albian section of the Eumeralla Formation in the Otway Basin, indicate the source of the volcaniclastic sediment lay to the east of the Gippsland Basin (Fig. 9). This palaeocurrent data precludes an Otway Basin (intra-rift) volcanic source for the sediment that has been proposed by previous workers (e.g., [22,23]). In addition, the complete absence of interbedded volcanic rocks within the succession also argues against an intra-basinal volcanic source. Furthermore, these vol-

Fig. 6. Compilation of calcic amphibole data from the Whitsunday Volcanic Province (phenocryst) and Otway/Gippsland basins (detrital grains): (A1) and (A2) granites, and (B1) and (B2) volcanics from the Whitsunday Volcanic Province [25]; (C1) and (C2) Wonthaggi Formation, Gippsland Basin. Amphibole analyses are plotted in terms of number of cations per structural formula unit, on the basis of 23 oxygens (A1, B1, and C1), and expressed as numbers of Ca + Na and Na atoms in the *B* structural site (A2, B2, and C2). Note the complete overlap of hornblende compositions between these two regions, and with the field of 'orogenic' intermediate to silicic volcanics. Fields for orogenic andesites, dacites and rhyolites, and bimodal rhyolites after Ewart [30]. All hornblende analyses were recalculated on the basis of all Fe as Fe^{2+}. N = number of analyses.

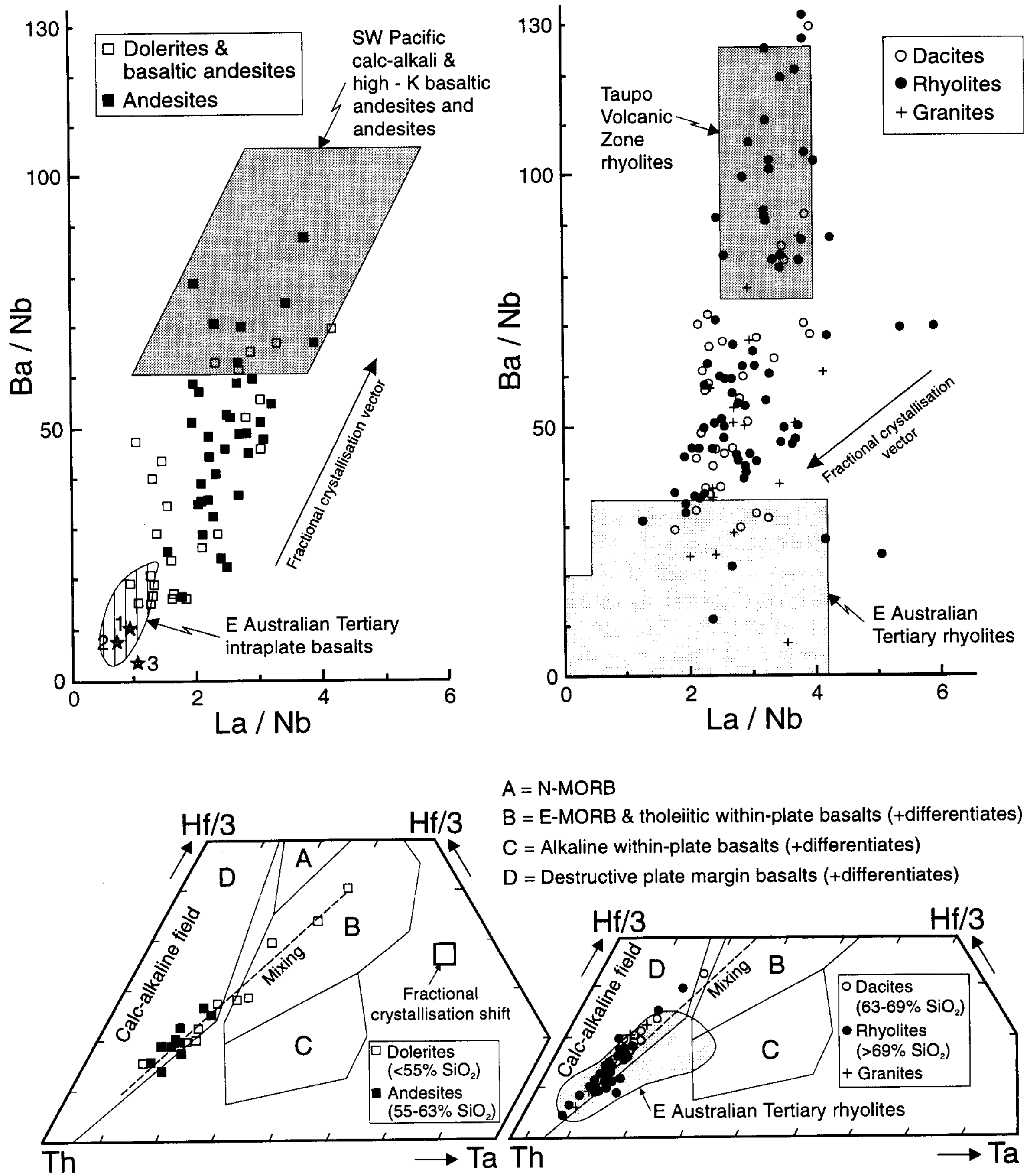

Fig. 8. Above: Ba/Nb vs. La/Nb plots of Ewart et al. [25] for the Whitsunday Volcanic Province, divided into dolerite–andesite; and dacite, rhyolite and granite groupings. Intraplate fields after Ewart and Chappell [32]; the averaged southwestern Pacific andesites after Ewart [29]; the Taupo Volcanic Zone after G. Corlett (unpublished data); the stars labelled 1, 2, and 3 are the average primitive mantle, E-MORB and N-MORB compositions respectively, after Sun and McDonough [33]. Below: Hf–Ta–Th relationships for the Whitsunday Volcanic Province from Ewart et al. [25]. Field boundaries after Wood [34].

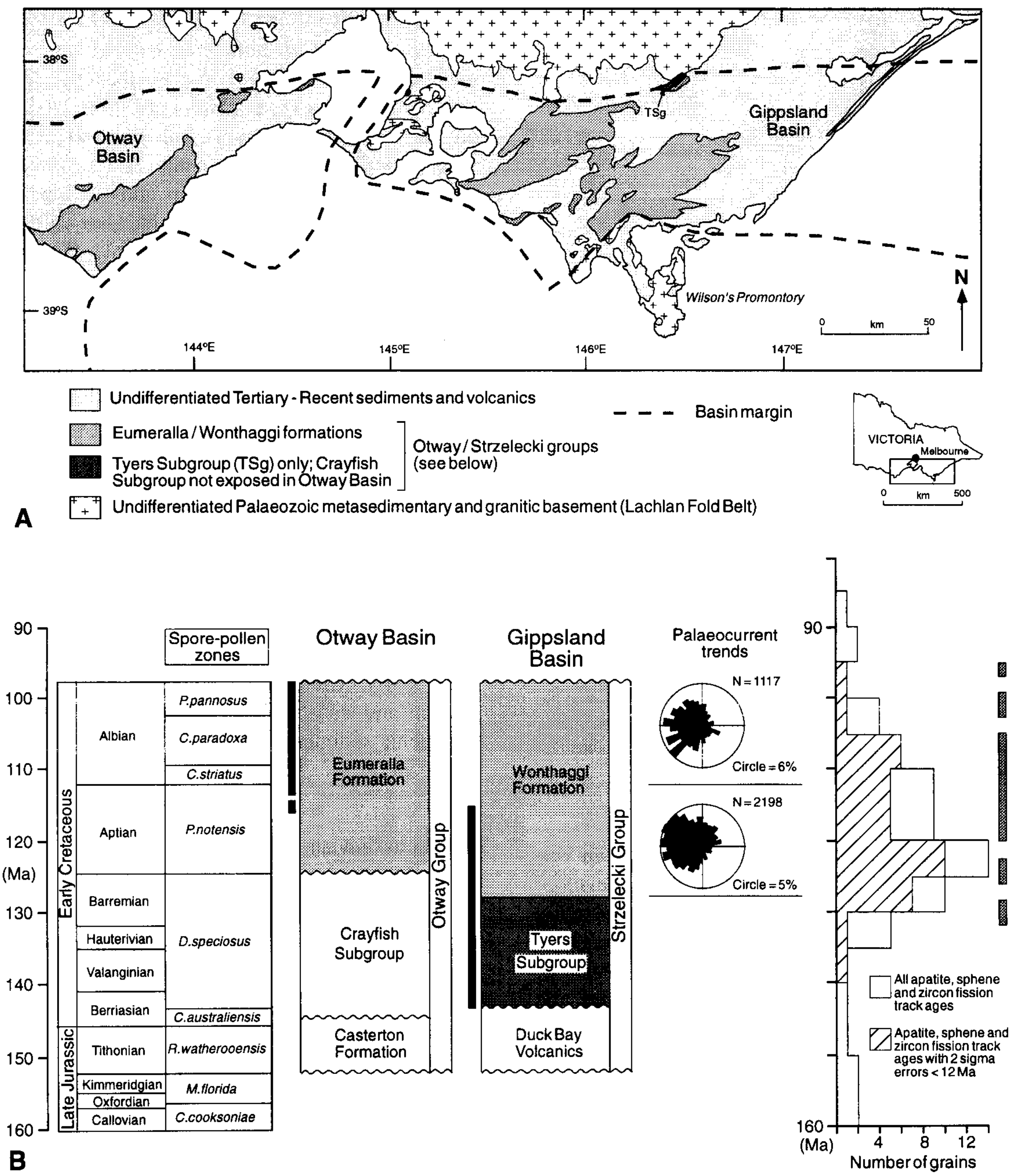

Fig. 9. (A) Outcrop and subsurface extent of the Otway Group (Otway Basin) and Strzelecki Group (Gippsland Basin). (B) Stratigraphic subdivision of the Otway [39] and Strzelecki groups (this study). Outcrop age ranges are illustrated by vertical black bars beside stratigraphic columns, and age range of volcanism in the Whitsunday Volcanic Province is illustrated by the vertical grey bar beside fission track age data. Palaeocurrent measurements are from channel facies for the *P. notensis* zone (Wonthaggi Formation) and *C. striatus–P. pannosus* zones (Eumeralla Formation); N = number of measurements. Palaeocurrent measurements for the Eumeralla Formation also includes data from [23,40]. Fission track data from Gleadow and Duddy [21]. Time scale after Harland et al. [41].

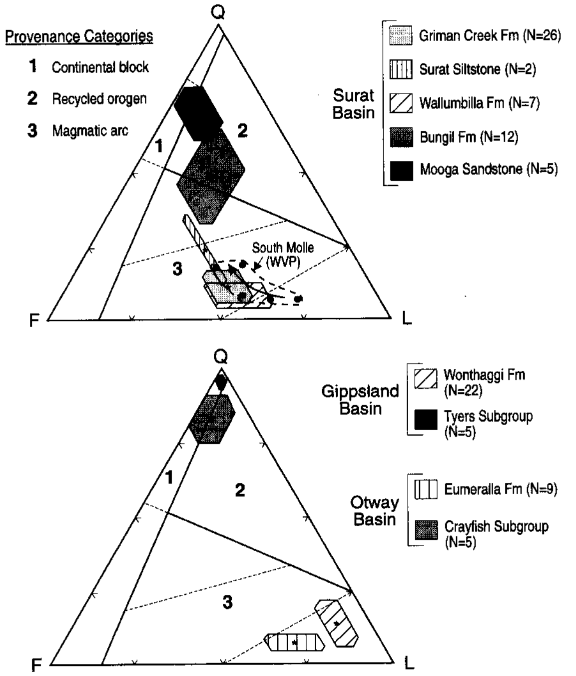

Fig. 10. Sandstone petrology of the Surat [14] and Otway/Gippsland (this study) basins, and Whitsunday Volcanic Province (WVP, this study). Sandstone detrital compositions from South Molle (WVP) show an up-sequence trend towards more quartz-rich compositions (arrow). Dots = individual samples; stars = average compositions; N = number of samples. The three apices or poles are: total quartzose grains (Q), including polycrystalline quartz; monocrystalline feldspar grains (F); and total lithic fragments (L). QFL provenance boundaries after Dickenson et al. [43].

caniclastic units cannot have been sourced from volcanics associated with the onset of basin development; that is, the early to middle Tithonian Casterton Formation and Duck Bay Volcanics (Fig. 9). These units consist of olivine basalt, vitric tuff, volcanic breccia, conglomerate, dark red–brown shale and sandy siltstone [44], and are considerably older than the fission track ages obtained from detrital minerals in the Eumeralla Formation [21].

4. Great Artesian Basin system

The Great Artesian Basin system (Fig. 1), comprising the Eromanga, Surat, Clarence–Moreton and Carpentaria basins, is a large intracratonic sag that developed initially in latest Triassic times, and was active during much of the Mesozoic era [45]. In the context of this paper, the Great Artesian Basin system is significant for containing Early Cretaceous (Aptian–Albian), volcanogenic sedimentary rocks of the Rolling Downs Group (Fig. 11) that cover 2×10^6 km^2 with an average thickness of 500 m [13]. These are dominated by mudstone, siltstone and sandstone, with depositional environments ranging from fluvial/lacustrine to coastal plain and shallow marine [14,45]. Sandstones are feldspathic–lithic (Fig. 10), with an average Q:F:L ratio of 15:41:44, and volcanic lithic grains represent more than 90% of the total lithic component [6,14]. Limited mineral chemistry data is supported by an extensive petrographic study [6] that indicates the abundant, relatively fresh feldspar grains are predominantly andesine (An_{52}–An_{31}) in composition (Fig. 4). The Rolling Downs Group records a major change in sedimentary provenance from the underlying (Neocomian), basement-derived quartzose sandstones (Fig. 10) that have an average Q:F:L ratio of 49:28:23 (Bungil Formation) and 70:21:9 (Mooga Sandstone [6,14]). Limited palaeocurrent data from the Surat Basin [6] indicate an easterly source for the sediment (Fig. 1), and Smart and Senior [13] have speculated that the coeval Early Cretaceous volcanic belt along the Queensland coast (Fig. 2) was the source of volcanogenic sediment.

5. Discussion and comparison

The previous discussion emphasises the existence of a major volcanic province along the present eastern Australian margin during the Early Cretaceous. The volcanic architecture of the Whitsunday Volcanic Province argues against a high-standing, stratovolcano-dominated, andesitic magmatic arc. Deltaic/coastal plain to shallow marine facies associations from the adjacent Styx Basin (Fig. 1) and Maryborough Basin [45] further indicate widespread low relief depositional environments in eastern Queensland during the Early Cretaceous. Several points argue against volcanism being related to continental back-arc extension. Basalts from the Whitsunday Volcanic Province show E-MORB affinities that are distinct from the N-MORB and calc-alkali geochemical signatures of basalts that are erupted in back-arc basins. If volcanism was related to back-arc extension, then this would imply that the Tasman Basin system (including the Cato Trough and Coral Sea Basin, Fig. 1) is a marginal/back-arc basin. This contradicts a substantial body of work that considers the Tasman Basin system to be formed by normal seafloor spreading, and bordered by a passive continental margin (e.g., [7,16–18]). A characteristic feature of back-arc extensional environments is the migration of the locus of extension and volcanism as extension and roll-back proceeds (e.g., Early Pliocene of Lau Basin [46]). The Whitsunday Volcanic Province is notable for its prolonged magmatic history, spanning 37 m.y., and elongate, narrow geometry.

The Otway/Gippsland basins, and Whitsunday Volcanic Province show a number of marked similarities, including: (1) the similarity between phenocryst and detrital mineral compositions (Figs. 4–6), that is also consistent with the limited data from the Rolling Downs Group of the Great Artesian Basin system; (2) both regions having similar periods of volcanic activity (Figs. 3 and 9); and (3) the production and accumulation of large volumes of volcanic and volcanically derived material.

Previous studies have related the calc-alkaline geochemical character of both volcanic and volcanogenic sedimentary rocks to modern 'orogenic' destructive plate margin volcanics (e.g., [6,9,14,26]). The main feature of the mineral chemistry (Figs. 4–6) is the overlapping phenocryst compositions between the dacitic to rhyolitic pyroclastic rocks of the Whitsunday Volcanic Province and detrital grains from the volcanogenic sedimentary rocks of the Otway/Gippsland and Surat basins. This overlap implies a remarkable consistency in mineral composition, and consequently, whole-rock chemistry, for Early Cretaceous volcanism. Duddy [22] noted the plagioclase compositions from the Otway Basin sediments are distinctly more sodic than a range of Tertiary to Recent low-K to high-K calc-alkaline basalts and andesites [29]. From our studies, only the phenocryst compositions from the temporally equivalent and volumetrically dominant dacitic to rhyolitic ignimbrites of the Whitsunday Volcanic Province approaches the detrital mineral chemistry, and we suggest that silicic pyroclastic volcanism dominated this volcanic event.

Age data from both regions are consistent in showing a broad range in volcanic activity (Figs. 3 and 9). There does appear to be precursory activity > 130 Ma in eastern Queensland, consisting mainly of small stocks and intrusions, the significance of which is presently poorly understood [47]. Importantly though, the compiled fission track and radiometric age data record a major volcanic event between ~ 125 and 105 Ma along the present eastern Australian margin. The onset of volcanogenic sedimentation in the Great Artesian Basin (Rolling

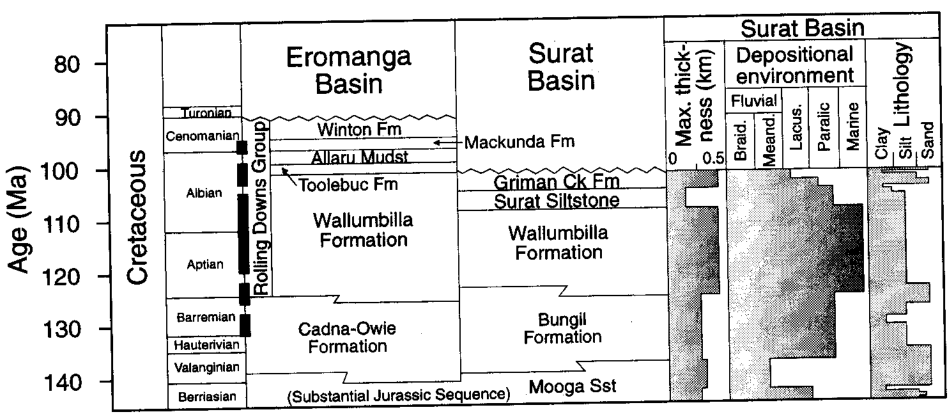

Fig. 11. Simplified Cretaceous stratigraphy of the Eromanga and Surat Basins, components of the Great Artesian Basin system, with rock types, formation thickness, and depositional environments for the Surat Basin. Age range of volcanism in the Whitsunday Volcanic Province is illustrated by the vertical black bar. Modified from Fielding [45] and Hawlader [14]. Time scale after Harland et al. [41].

Downs Group) near the beginning of the Aptian (Fig. 11), provides further evidence of a major volcanic event beginning 125–120 Ma.

The onset of this volcanic event near the beginning of the Aptian is better illustrated by the sandstone detrital compositions (Fig. 10). The Aptian–Albian Wallumbilla Formation, Surat Siltstone and Griman Creek Formation of the Surat Basin (Great Artesian Basin system) are feldspatholithic and distinct from the underlying basement-derived sandstones of the Bungil Formation and Mooga Sandstone. Volcanic sandstone compositions from the Whitsunday Volcanic Province have also been plotted and are similar to sandstones of the same age in the Surat Basin. This change in sedimentary provenance at the beginning of the Aptian is even more dramatically illustrated in the Otway/Gippsland basins (Fig. 10). The volcanic-lithic-rich Eumeralla and Wonthaggi formations are clearly distinct from the underlying basement-derived quartz sandstones of the Tyers and Crayfish subgroups.

The third important factor regarding these Early Cretaceous provinces is the large volume of volcanic-derived sediment: $> 4 \times 10^5$ km^3 in the Otway/Gippsland basins and $> 10^6$ km^3 in the Great Artesian Basin system [13]. More than 10^5 km^3 of probable volcanic source rocks are preserved along the central and southern Queensland coast. Of particular note is the rapid influx of such large volumes of volcanogenic sediment into the basin systems, where volcanogenic sediment was present almost to the exclusion of basement-derived material [21]. The fission track age data, fresh nature of the detrital mineral grains and the sheer volume of volcanogenic sediment in both the Otway/Gippsland and Great Artesian Basin systems preclude a basement-derived source for the sediment (e.g., Lachlan and New England fold belts).

6. Conclusions

From the above discussion and comparison, we draw several conclusions:

1. A major volcanic episode was initiated approximately 125 ± 5 Ma, and continued for another 25–30 m.y.
2. Volcanism occurred along the length of the present eastern Australian margin (Fig. 12), a distance of $> 2{,}500$ km, with the Whitsunday Volcanic Province interpreted as representing the northern extension of this volcanic belt.
3. Although the Otway/Gippsland basins formed in response to Antarctic–Australia rifting, volcanogenic sediment of the Eumeralla/Wonthaggi formations was derived from a contemporaneous volcanic source further to the east, outside of the basins.
4. Phenocryst compositions from volcanics (Whitsunday Volcanic Province) and detrital grains from volcanogenic sedimentary rocks (Otway/Gippsland and Great Artesian Basin systems) overlap, and closely approximate the volumetrically dominant (dacitic-) rhyolitic ignimbrites of the Whitsunday Volcanic Province. This suggests that silicic pyroclastic volcanism characterised the Early Cretaceous volcanic event. Furthermore, the pyroclastic mode of fragmentation and dispersal was an important factor in the availability of large volumes of fine-grained sediment which could be rapidly delivered into these basin systems.
5. Despite the volcanic architecture showing similarities to volcanic arc complexes in extensional environments (e.g., Taupo Volcanic Zone), the within-plate geochemical signature to mafic volcanics of the Whitsunday Volcanic Province precludes the volcanism being related to back-arc extension.

The critical point is that a major volcanic event occurred along the length of the present margin of eastern Australia, and was sudden in its initiation, and voluminous in its products. We suggest that volcanism was related to a ~N–S oriented rift system, extending for more than 2,500 km that was initiated approximately 125–120 Ma. This rift-related volcanic event led to the fragmentation of eastern Gondwana, now dispersed as segments of continental crust in the Southwest Pacific. The intersection of the Antarctic–Australian rift and this ~N–S oriented rift system to the east of the Gippsland Basin, allowed the shedding of volcanic material towards the west into the Otway/Gippsland basin system. Only minor, isolated exposures of Early Cretaceous volcanic and intrusive rocks are exposed along the southeast margin of Australia (e.g., Cape Portland, 95–99 Ma [50,21]; Mount Dromedary

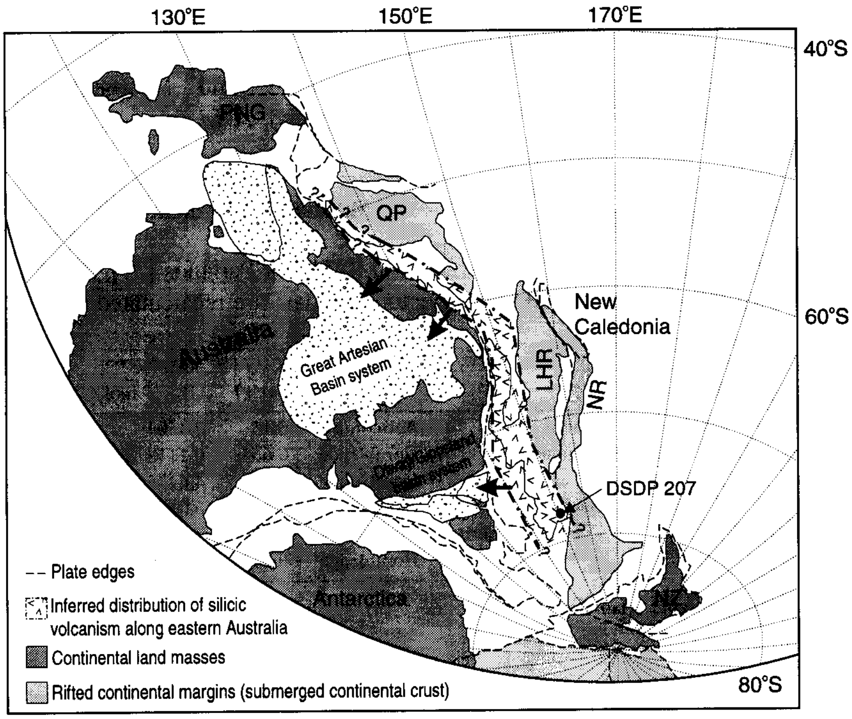

Fig. 12. Map of the Southwest Pacific reconstructed at 100 Ma [48], showing the inferred distribution of the Early Cretaceous silicic pyroclastic volcanic belt along the eastern Australian plate margin: the proposed source of Aptian–Albian volcanogenic sedimentary rocks in the Great Artesian and Otway/Gippsland basin systems. Volcanogenic sediment was shed westwards (arrows) into the basin systems. The location of site 207, DSDP Leg 21 is shown, which bottomed in 96 Ma rhyolites on the Lord Howe Rise [49]. *PNG* = Papua New Guinea; *QP* = Queensland Plateau; *LHR* = Lord Howe Rise; *NR* = Norfolk Ridge; *NZ* = New Zealand.

complex, 98.6 Ma [51], see Fig. 1; and references in Jones and Veevers [9]), but more volumetrically significant volcanic rocks may be present on the Lord Howe Rise (Fig. 12). The ~ 96 Ma rhyolites recovered from deep sea drilling on the Lord Howe Rise [49] may be the youngest expression of this volcanism.

This volcanic event, now preserved mainly in the sedimentary basins of eastern Australia, is similar to many large volcanic provinces in its large volume of products, scale, and association with a regional extensional regime. The temporal association of large volume silicic magmatism in eastern Australia (this study), oceanic plateau formation in the Southwest Pacific (e.g., [4,5]), and flood bimodal volcanism of the Paraná–Etendeka province (e.g., [2,3]) with the break-up of Gondwana, supports the view [52] that the Early Cretaceous was a period of widespread rifting, global magmatism and continental break-up.

These conclusions argue for the interpretation of the eastern Australian margin as a passive margin that evolved from intraplate extension, leading to continental break-up, and our observations add weight to the notion that break-up of eastern Gondwana began in the Early Cretaceous. Finally, we believe that the recognition of voluminous volcanism marking the break-up of eastern Gondwana indicates that the eastern Australian plate margin should be considered as a volcanic-dominated passive margin.

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Appendix A. New and corrected K/Ar age data for the Whitsunday Volcanic Province

Note that some of these ages were quoted in Ewart et al. [25] and Parianos [27], but the recognition of an error in the laboratory calculation has required their revision. All data are recalculated with reference to Steiger and Jäger [53].

Sample	Location	Grid Reference[a]	Lithology	Mineral	K_2O (wt%)	40Ar* (10^{-11} mol/g)	40Ar* (%)	Age (m.y.)
323A	Dryander	661 760	Diorite	Actinolite	0.15	2.4503	43.41	110.1 ± 5
636D	Ben Lomond	651 777	Granodiorite	Hornblende	0.665	0.111813	51.0	113.2 ± 4
PD73	Lindeman Island	714 738	Dacite dyke	Hornblende	0.32	4.64358	51.91	98.1 ± 3
SMB112	South Molle Island	693 759	Gabbro dyke	Plagioclase	0.385	6.01791	75.46	105.4 ± 1.7
WH6	Whitsunday Island	703 762	Crystal ignimbrite	Hornblende	0.43	7.24136	64.71	113.3 ± 2.5
ES3/1	Esk Island	713 761	Ignimbrite	Hornblende	0.57	8.80109	57.91	104.2 ± 2.9

[a]Grid references are from the Australian Map Grid, zone 55.

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