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Australian Palaeozoic palaeomagnetism and tectonics—I. Tectonostratigraphic terrane constraints from the Tasman Fold Belt

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Abstract—The Tasman Fold Belt (TFB) of Eastern Australia can be divided into three meridional orogenic realms: the Kanmantoo, Lachlan–Thomson and New England Orogens. The geological histories of the orogens overlap, but each is distinctive. The Kanmantoo Orogen was provenance-linked to the Australian craton in the Early Cambrian, and accreted to Australia by Late Cambrian. There are many possible tectonostratigraphic terranes in the Lachlan Fold Belt (LFB) but these can be simplified to two major amalgamated terranes by the Middle Silurian. All the LFB terranes appear provenance-linked in the Ordovician, and were progressively covered, from the west, during the Late Silurian to Late Devonian, by a quartzose overlap assemblage. The New England Orogen has a fragmentary Early Palaeozoic history, but from the Devonian onwards its geology is related to a series of volcanic island and continental margin magmatic arcs. There is some evidence of provenance-linking between the Lachlan and New England Orogens in the Devono-Carboniferous but docking is not demonstrated until the mid-Carboniferous. The few reliable pre-Late Carboniferous palaeomagnetic poles available from the TFB come from the eastern LFB. The poles post-date accretion of the LFB to the Australian craton. Thus, the possibility that parts of the Lachlan–Thomson and New England Orogens contain exotic elements is yet to be tested palaeomagnetically.

INTRODUCTION

Ideas about the origin of the Tasman Fold Belt (TFB) have evolved rapidly in the past two decades. The synthesis of facies and faunal distributions by Brown *et al.* (1968) was followed by the first plate-tectonic models in the early 1970s (e.g. Oversby 1971, Solomon & Griffiths 1972, Scheibner 1974). Many important aspects of the tectonic framework, however, remained controversial (Packham & Leitch 1974). The early generalized models were followed by attempts to make more detailed comparisons with modern tectonic settings of palaeogeography during particular geological intervals (e.g. Cas & Jones 1979, Cas *et al.* 1980, Jones & McDonnell 1981, Powell 1983a). These palaeogeographic reconstructions formed the basis for conclusions about tectonic evolution (e.g. Powell 1984, Murray *et al.* 1987). In the past 5 years, there have been various attempts to subdivide the TFB into tectonostratigraphic terranes (e.g. Scheibner 1985, Fergusson *et al.* 1986, Stump *et al.* 1986, Leitch & Scheibner 1987), but the views about the nature, or even existence, of some of the purported terrane boundaries differ.

Terrane analysis of the TFB has focused on both the internal integrity of each segment of the fold belt, and the nature of the segment boundaries. Are the terranes parts of much larger entities that have later been faulted and jostled during consolidation of the fold belt? Are some truly exotic (i.e. travellers from distant places)? Solutions to these problems require careful study of the palaeo-fauna and the sedimentary facies, as well as the structural, metamorphic and igneous signatures. In many cases, however, the question of whether a particular terrane has moved a few kilometres, or a few thousand kilometres, cannot be resolved simply by comparison of geological attributes.

Palaeomagnetic investigations are useful to test whether a terrane has always been in its current position and orientation in a fold belt. Palaeomagnetic data provide important constraints on latitudinal displacement and azimuthal rotation of a terrane. Alternatively, when geological evidence demonstrates that a portion of a fold belt has not been displaced since a particular time, palaeomagnetic results can contribute to the apparent polar wander path (APWP) for the main continental craton.

Early palaeomagnetic data have been used to support both allochthonous (Embleton *et al.* 1974, McElhinny & Embleton 1974) and autochthonous (Schmidt & Morris 1977) models of parts of the TFB. More recent palaeo-

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magnetic data (Goleby 1980a,b, Schmidt *et al.* 1986, 1987) tend to favour a modified autochthonous model for the southeastern LFB. Those models are reviewed in a companion paper (Li *et al.* 1990), where a revised Palaeozoic APWP is presented, and its tectonic implications for Australia are discussed. In this paper we discuss the nature and age of likely terrane boundaries in the TFB. In addition, we review the palaeomagnetic poles derived from the TFB. The palaeomagnetic data are then addressed in the context of the terrane analysis to determine whether they have any bearing on the displacement and rotation of terranes in the TFB, or whether they can be used to enhance the Palaeozoic APWP of cratonic Australia.

TECTONIC FRAMEWORK

The Tasman Fold Belt is traditionally divided into three meridional tectonic realms. The geological histories overlap but each has a distinctive history (Figs. 1 and 2). The westernmost realm, the Kanmantoo Orogen, is represented by rocks exposed in eastern South Australia, western Victoria and New South Wales (NSW). It had a tectonically active history from the Late Precambrian (~650–600 Ma) until the Early Ordovician (~500 Ma). The central realm, the Lachlan–Thomson Orogen, is the widest, and was tectonically active from some time in the Cambrian (~550 Ma) until the mid-Carboniferous (~330 Ma). The eastern realm, the New England Orogen, has an uncertain Early Palaeozoic beginning, but was known to exist by the Silurian (~430 Ma) and continued to be tectonically active until the mid-Cretaceous (~95 Ma).

The Kanmantoo Orogen comprises Late Precambrian to mid-Cambrian quartzose clastics deposited mainly in turbiditic facies (Parkin 1969). It was uplifted, deformed and intruded by granites in the Middle Cambrian to Early Ordovician (530–490 Ma) (data summarized in Veevers & Powell 1984). It could well have been a marginal sea formed adjacent to the Australian craton during the Late Precambrian continental breakup. The Delamerian Orogeny (Thomson 1969), which terminated the orogenic history of the Kanmantoo realm (Preiss 1987), affected many parts of the extension of the TFB in Antarctica and South America.

The Lachlan–Thomson Orogen was a deep-water oceanic realm in the Cambrian. Its history is imperfectly known from the few, scattered outcrops available. Mafic volcanics, cherts and distal turbidites suggest marginal seas or back-arc basins of the west Pacific type (Crawford & Keays 1978, Crawford *et al.* 1984). The Ordovician history is far better known (Cas *et al.* 1980, Powell 1983a, 1984, Fergusson *et al.* 1987). Widespread quartzose clastics of turbidite facies have remarkably consistent palaeocurrents indicating provenance to the west and south. The Early to Middle Ordovician history is dominated by a turbidite apron marginal to the uplifted Delamerian Highlands to the west. By the Late Ordovician, a mafic volcanic arc had formed to the east.

The onset of widespread silicic magmatism in the mid-Silurian (~430 Ma) followed deformation known locally as the Benambran and Quidong Orogenies. The magmatic activity accompanied a change to an extensional, horst-and-graben tectonic phase (Powell 1983a). Late Silurian and Early Devonian volcanics occur throughout the Lachlan–Thomson Orogen. The end of the silicic interval is marked by deformation that is intense in central and eastern Victoria and in the Anakie Inlier of Queensland, but mild in central New South Wales. The mineralogically mature, quartzose clastics of continental facies (the Lambie Facies) then prograded eastwards. The entire orogen, as well as the cratonic basins of Central Australia, was deformed in the mid-Carboniferous (~330 Ma) by a compressive event that terminated the orogenic history of Eastern Australia west of the New England realm (for more detail see Powell 1984).

The New England Orogen has a long and complex history (Leitch 1974, Day *et al.* 1978, 1983, Korsch & Harrington 1987, Murray *et al.* 1987). Calc-alkaline volcanics and marine sediments as old as Silurian–Devonian are known from limited outcrop extent in Queensland, but beginning in the Late Devonian extensive volcanics, and sediments with a volcanic provenance, were deposited in shallow- to deep-marine settings (Day *et al.* 1983, Cross *et al.* 1987). The inferred palaeographic elements are diverse and fragmentary; some of the terranes could be exotic, or severely disrupted and displaced. There is growing geological evidence for important dextral translational movement, with formation of an orocline in northeastern NSW (Fig. 1) during the Late Carboniferous–Early Permian (Korsch & Harrington 1987, Murray *et al.* 1987). The orogenic history of the New England Fold Belt (NEFB) continued long after the mid-Carboniferous stabilization of the Lachlan–Thomson Orogen. The NEFB did not stabilize until the mid-Cretaceous (~95 Ma) when activity of the continental magmatic arc, which lay alongside Eastern Queensland, ceased as the Tasman Sea began to open (Veevers 1984).

A fourth, smaller tectonic realm is the Hodgkinson–Broken River Orogen, which lies north of the E–W-trending Lolworth–Ravenswood block (Fig. 1). This Hodgkinson Fold Belt (HFB) (Murray & Kirkegaard 1978) contains Lower Palaeozoic rocks of deep-marine turbidite facies, which pass upward, in the west, into shallow-marine mid-Palaeozoic carbonates (Henderson 1980). In the east, deep-water facies, with andesitic volcanics, persisted. During the Devonian, shallow-marine to terrestrial clastics prograded across the western part of the belt, all of which was deformed at the end of the Devonian (Henderson 1980). Transcurrent fault movement, with associated igneous activity, continued episodically along the eastern exposures of the fold belt throughout the rest of the Palaeozoic. In many ways, the HFB reflects, in one narrow fold belt, many of the elements of the geological history which, further south, are spread out over 1000 km in the three adjacent major fold belts.

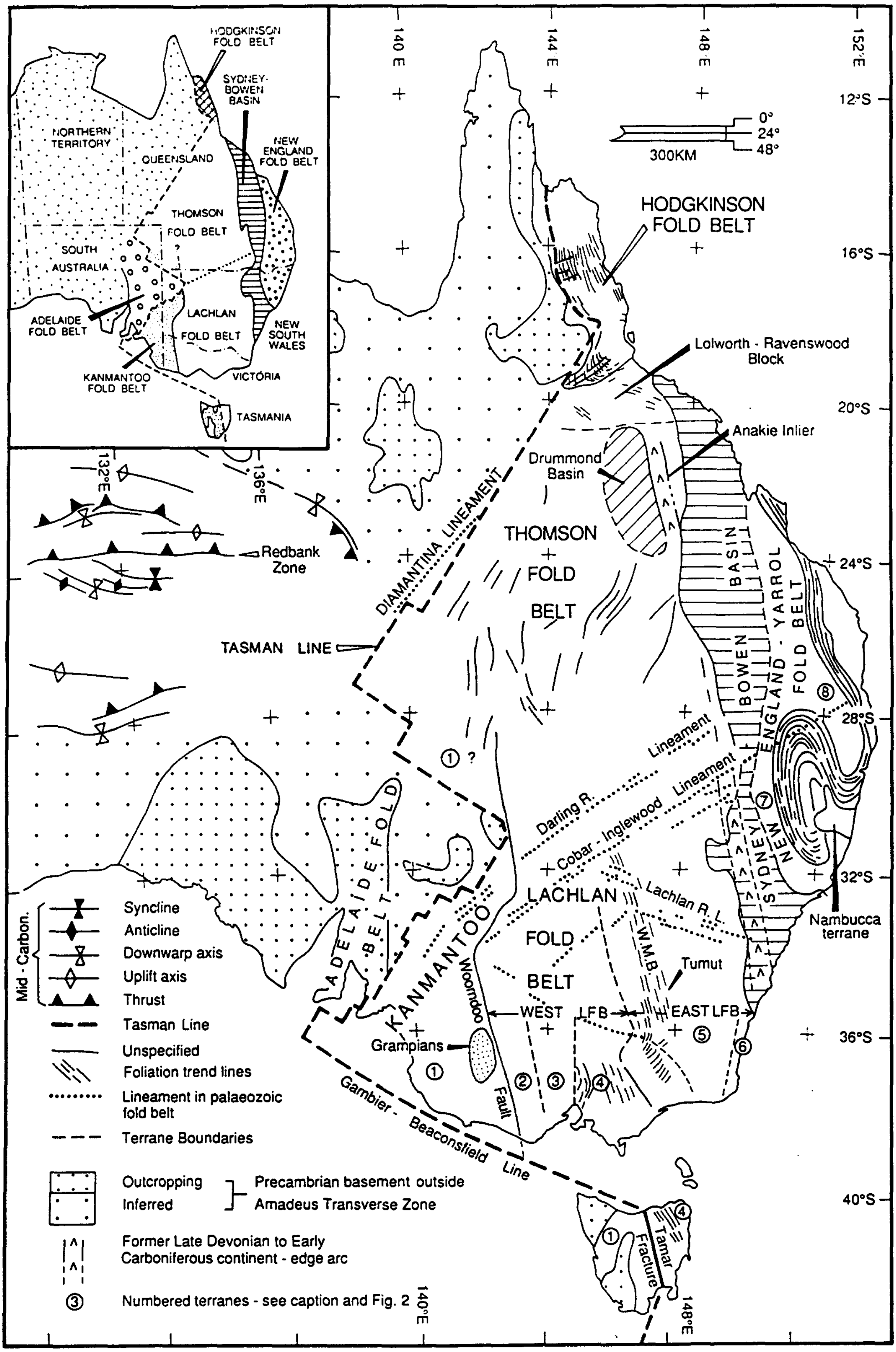

Fig. 1. Selected tectonic elements of the Tasman Fold Belt.

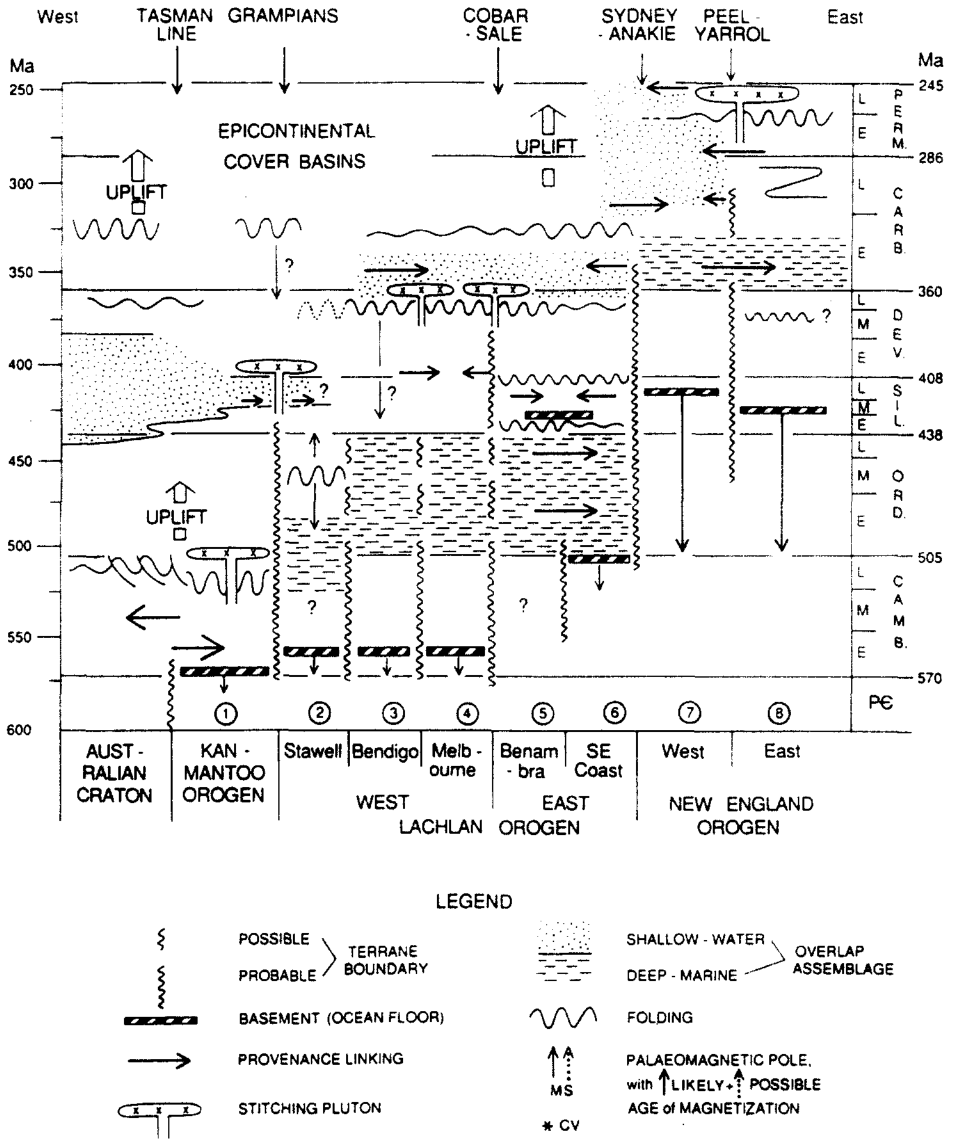

Fig. 2. Schematic time–space chart through the southern Tasman Fold Belt.

Terrane boundaries

The three main fold belts are superterranes; their boundaries are shown in Figs. 1 and 2. The superterranes are discussed below in terms of the age of the oldest known basement, and their boundaries are considered in terms of provenance-linking, pluton-stitching and overlap assemblages with adjacent terranes. More detailed analyses of individual terranes, which might constitute each of the superterranes, can be found in the papers edited by Leitch & Scheibner (1987) and papers in this issue. In this summary, we consider only those aspects which are germane to the implications of the TFB palaeomagnetic data.

Kanmantoo Orogenic realm

The westernmost boundary is the Tasman Line (Veevers 1984) which separates the western two-thirds of Australia, where a long Precambrian history is known and the Phanerozoic was a time of platform or cratonic behaviour, from the TFB to the east. No Precambrian rocks are exposed east of the Tasman Line, despite geochemical inferences about their presence in the subsurface (e.g. Compston & Chappell 1979, McCulloch & Chappell 1982). In Queensland, the Tasman Line is inferred to lie along the Diamantina River Lineament (Leitch & Scheibner 1987) beneath successor basins as old as latest Carboniferous. In western New South Wales and South Australia, the Tasman Line separates the Kanmantoo Fold Belt (KFB), on the east, from the Adelaide Fold Belt, on the west. Because of the similarity of latest Precambrian–Early Cambrian facies in these two belts, as well as evidence that much of the Kanmantoo flyschoid sediment was derived from a mature, subdued, continental source to the west, we are reasonably confident that the two fold belts were linked by provenance and dispersal systems in the Early Cambrian (E-directed arrow in Fig. 2). Moreover, by the end of the Middle Cambrian, the palaeoslope had reversed, with clastics being shed to the northwest (Moore 1979) and north (Powell *et al.* 1982) from the rising Delamerian Highlands in the KFB. Both the Adelaide and Kanmantoo fold belts were deformed in the Cambro-

Ordovician, with the KFB being intruded extensively by granitoids (data summarized in Veevers & Powell 1984, Preiss 1987).

In Tasmania, rocks equivalent in age to the Kanmantoo succession lie within, and on, Precambrian rocks, though the nature of the contacts is not clear. The Late Proterozoic–Cambrian successions of Tasmania have been interpreted as deposits in a volcano-sedimentary graben, or half-graben, faulted into the Precambrian basement (Solomon & Griffiths 1972, Williams 1978, Corbett & Lees 1987). Recently, however, Berry & Crawford (1988) have addressed evidence that contacts between the Cambro-Ordovician successions and the Precambrian are thrust-faulted, and that the whole succession has been emplaced tectonically by westward transport. This new interpretation, which is in keeping with permissible relationships between the Kanmantoo and Adelaide fold belts, postulates a Middle Cambrian age for nappe emplacement concomitant with the rise of the Delamerian Highlands. If this revised interpretation is correct, then Early Cambrian and older sedimentary rocks in parts of Tasmania are part of suspect terranes, but from Late Cambrian onwards the terranes have been linked by deformation and provenance to the Australian craton.

Thus, there is reasonable geological evidence that the KFB was provenance-linked to the Australian craton by the Early Cambrian, and good evidence that it was amalgamated to the craton in the late Middle Cambrian. The early Late Cambrian Cupala Creek Formation in the northern KFB (Powell *et al.* 1982) can be regarded as an overlap assemblage for the three terranes recognized there (Leitch *et al.* 1987). Moreover, by relating this overlap assemblage to the rise of the Delamerian Highlands (Veevers & Powell 1984), the KFB can be tied to the Australian craton.

The eastern boundary of the superterrane is far less well defined. Kanmantoo-like rocks, metamorphosed to varying grades, crop out as far east as the Grampians Mountains in western Victoria. Exposure of Lower Palaeozoic rocks there is poor, and the boundary between the KFB and the LFB to the east is variably placed either along the Woorndoo Fault to the east of the Grampians (Scheibner 1985), or as a concealed boundary beneath the Grampians (Ramsay & VandenBerg 1986). If the latter is correct, then the quartzose sandstone and conglomerate of the Grampians, which were deposited in terrestrial to paralic environments, are an overlap assemblage. Its age is not well-defined from internal evidence, but, because it is intruded by ~400 Ma granitoids (Richards & Singleton 1981) and overlies the flyschoid rocks of Cambro-Ordovician age, the Grampians succession is likely to be Silurian to earliest Devonian. The similarity of palaeo-windflow directions in an aoelian unit in the upper part of eastern Grampians Ranges, with palaeo-windflow directions in aoelian units recently mapped (by Owen and Powell) in the lower part of the Mereenie Sandstone of Central Australia, suggests that both could have been deposited in the Silurian, possibly early in the period.

The Grampians sandstone succession contains palaeocurrents in fluvial units indicating derivation from the south and west, and is thus the oldest known occurrence of the quartzose 'Lambie Facies' that prograded northeastward across all the LFB terranes. Determination from geological grounds as to whether the Grampians succession is an overlap assemblage between the Kanmantoo and Lachlan fold belts is important for the interpretation of palaeomagnetic poles that might be determined within the LFB. Attempts to derive a palaeomagentic pole from the Grampians succession, have so far been inconclusive (Thrupp 1988).

Lachlan–Thomson orogenic realm

The LFB has been divided into four terranes by Fergusson *et al.* (1986) and up to 14 terranes by Leitch & Scheibner (1987). In Figs. 1 and 2, we have shown some of the more important discontinuities in the LFB, along each of which there might have been sufficient offset (tens of kilometres or more) to warrant classifying some of the blocks as allochthonous terranes. However, after consideration of the geological history of the 14 terranes proposed by Leitch & Scheibner (1987), we consider it more appropriate to regard the LFB since the Cambrian as one large disrupted superterrane, with the only substantial internal boundary lying approximately along the "Cobar–Sale line" of Powell (1983a). This boundary, which corresponds to the suture between the Benambra and Melbourne terranes of Fergusson *et al.* (1986), also corresponds in part with the southern half of Scheibner's (1985) Gilmore suture. We use this boundary to divide the LFB into East and West sections; the geological history of each is considered separately (see Fig. 2).

The most important feature of all the proposed terranes in the LFB is the occurrence of a mineralogically and texturally mature Ordovician quartzose flysch. In many places, the quartzose flysch is so uniform that asssignment to a terrane on the basis of outcrop appearance alone is impossible. Moreover, sedimentary dispersal patterns (Cas *et al.* 1980, Powell 1983b, 1984, Fergusson *et al.* 1987, Powell & Conaghan unpublished work) all conform to a simple consistent pattern of flow to the north and the east. There is some variation with stratigraphic level, and there are some palaeogeographic anomalies in the present location of portions of the quartzose turbidites (as noted, for example, by Fergusson *et al.* 1986), but these do not change substantively the inference that the Ordovician quartzose flysch was derived from a mature continental area somewhere to the south and west. Displacement of several hundred kilometres by disruption after, or even during, deposition of the turbidite apron is possible, and explicitly indicated in palaeogeographic reconstructions such as those in Powell (1983a, 1984) and Fergusson (1987). If these inferences are correct, the Ordovician quartzose turbidite succession is an overlap assemblage covering fragmentary Cambrian outcrops belonging to an unknown number of possible terranes.

The differences in post-Ordovician geological history between the East and West LFB is quite marked (see Powell 1983a, 1984). In the West LFB, there was no further sedimentation in the Stawell and Bendigo terranes (Leitch & Scheibner's 1987 terminology; also Fig. 2), but continuous sedimentation of a gradually shallowing-upward succession occurred in the Melbourne Terrane (VandenBerg 1978). The Stawell Terrane, and perhaps also the Bendigo Terrane, could have been deformed any time between the end of the Cambrian and the early Silurian. At the end of the Silurian, deposition along the western margin of the Melbourne Terrane of the quartose, shallow-marine Mt Ida Sandstone could have been associated with transgression of the regional overlap assemblage, the Lambie Facies. Today, however, no outcrops of Lambie Facies are preserved between the western margin of the Melbourne Terrane and the Grampians some 200 km to the west. The entire West LFB was deformed in the Middle Devonian, or possibly earlier in the west (Fergusson *et al.* 1986). Intrusion of plutons stitched together the tectonic elements of the West LFB Terrane in Devono-Carboniferous time.

The possible Ordovician overlap or provenance-linked turbidite apron indicates that all the terranes in the west have lain alongside the Gondwana continental margin since the Cambrian. Rotations and lateral displacements are possible, but any post-Cambrian exotic terranes are unlikely. Provenance-linking in the Siluro-Devonian, a common deformation in the mid-Devonian, and suture-stitching by plutons of Late Devonian age show that the West LFB was firmly fixed to the Australian craton by the end of the Devonian, and in close contact by the end of the Silurian, if not earlier.

In the East LFB, the divergence in geological history begins in the Early Silurian, and concludes in the Middle Devonian, when the widespread Tabberabberan deformation affected all the terranes. A more detailed account of this history is given elsewhere (Powell 1983a, 1984, Scheibner 1985, Fergusson *et al.* 1986); below, we mention only those points which are particularly germane to terrane constraints on the implications of LFB palaeomagnetic poles.

In Fig. 2 we have shown the East LFB as one terrane (albeit composite) since the beginning of the Ordovician. This interpretation is based on the presence of the widespread quartzose turbidite apron, as discussed above. Prior to the Ordovician, there is the possibility of some allochthonous material, which may comprise an exotic terrane, in the Wagonga Beds of the south coast of New South Wales (SE Coast in Fig. 2). Recent work in this terrane has led to the discovery of Middle and Late Cambrian fossils (Bischoff & Prendergast 1987) associated with mafic volcanics. Bischoff & Prendergast (1987) followed Powell (1983b) in interpreting these deposits as possible fragments of seamounts subducted along the eastern margin of Australia during the Ordovician. Work in progress (Conaghan *et al.*) suggests other interpretations of the palaeogeography are possible.

The Upper Ordovician turbidite apron is partially intercalated with, and overlain by, shoshonitic mafic volcanics that have been interpreted as the remnants of an Ordovician volcanic island arc (Packham 1973, 1987, Scheibner 1974, 1985, Cas *et al.* 1980, Powell 1983a). The evidence for an arc is best preserved in the Late Ordovician; an earlier existence is quite speculative. Furthermore, whether the arc was E-facing (Packham 1973, 1987, Cas *et al.* 1980, Powell 1983a) or W-facing (Scheibner 1985), is still an open question. The possibility that the Ordovician volcanic island arc has been tectonically emplaced into, and on, the Early to Middle Ordovician quartzose turbidite apron cannot be discounted.

The Silurian to mid-Devonian geological history of East LFB is complex in detail, yet there is a similarity that enables the various tectonic blocks (terranes of Basden *et al.* 1987, Leitch & Scheibner 1987) to be related in a reasonably compatible and coherent fashion (Powell 1984). The most significant feature from a palaeomagnetic point of view is the presence of a dismembered ophiolite suite in the Tumut Area (summary in Basden *et al.* 1987). These authors recognized five suspect terranes, three of which are overlapped by the mid-Silurian turbiditic sediments of the Tumut Trough. All three terranes were amalgamated and stitched by plutons prior to the Early Devonian when they were overlapped by terrestrial silicic volcanics.

Conventional interpretations of the region (summarized in Basden *et al.* 1987) have favoured intra-arc development of a sedimentary trough (the Tumut Trough), in which locally ocean floor was formed (the now-dismembered Coolac ophiolite). As Basden *et al.* (1987) pointed out, implicit to the rift models is the notion that, with the exception of the ophiolite slivers, the relative positions of most of the surrounding rock bodies have remained essentially as seen today. Powell (1983a) viewed formation of the Tumut Trough as a transtensional pull-apart basin formed by dextral shear on a NNW-trending fault along the eastern margin of the Wagga Metamorphic Belt. This model implies several hundred kilometres of right-lateral displacement, but does not change the relative positions of the surrounding terranes. Crook (1980) favoured a much larger amount of closure across the Tumut Trough, with the ophiolite slivers being the remnants of a potentially large ocean. Basden *et al.* (1987) argued for a thrust-tectonic allochthonous model for the amalgamation and accretion of the five terranes in the Tumut district.

The differences between these models are important from a palaeomagnetic viewpoint. If Crook's (1980) large-ocean model is correct, then the entire East LFB, and hence the TFB to the east of the Gilmore suture, could have been exotic to Australia until the mid-Silurian. The thrust-tectonic model of Basden *et al.* (1987) relates mainly to the amalgamation phase of the region, and leaves open the question of the amount of ocean floor subducted. We have mentioned earlier various possibilities about the nature of the Ordovician volcanic island arc, including the possibility that it was tectonically emplaced on the Early and Middle Ordovician continental margin and turbidite apron. The death of this arc at the end of the Ordovician could also have been related to the Early Silurian amalgamation and accretion of the five terranes in the Tumut district. On the other hand, the widespread quartzose turbidite apron derived from the Gondwana craton to the south and west, extends well eastward of the Tumut region, and suggests that, apart from possible discrete exotic accretions (e.g. parts of the Wagonga Beds), most of the surrounding terranes were overlapped by Gondwanan sediments, and were thus marginal to Gondwanaland in the Ordovician. Despite the uncertainties about the Ordovician palaeogeography, the terranes of the Tumut district, and thus terranes further east, were amalgamated by the Devonian. Thus, Early Devonian and younger palaeomagnetic data from East LFB can be treated as belonging to a single terrane.

Evidence for provenance-linking between the East and West LFB (apart from the Ordovician) is tenuous until the Devonian. In the Cobar region (Figs. 1 and 2). there is evidence in the Early Devonian that fold-belt detritus (including volcanogenic material) was shed westwards from the uplifted former Wagga Metamorphic Belt to interfinger with craton-derived material (Glen 1982, Powell 1984, Glen *et al.* 1987, Powell *et al.* 1987). The fluvial sediments of the Mulga Downs Group, the local representative of the regional Lambie Facies overlap assemblage, prograded eastward in this region during the Middle and Late Devonian.

The Lambie Facies overlap assemblage did not reach the easternmost LFB until the Late Devonian, when it infilled a brief-lived volcano-tectonic zone, the so-called Eden–Comerong–Yalwal Rift Zone (McIlveen 1974, Fergusson *et al.* 1979, Powell 1983b). This zone, of bimodal volcanic character, existed for probably less than 5 million years after the widespread late Middle Devonian Tabberabberan deformation. It is important palaeomagnetically because it contains the Comerong Volcanics, from which a reliable palaeomagnetic pole has been derived (CV, Schmidt *et al.* 1986). All terranes of the LFB are overlapped by the Lambie Facies overlap assemblage, or stitched by plutons which pre-date the overlap. From the consistency of the palaeodrainage network inferred from detailed palaeocurrent studies in many, widely spaced areas (summarized in Powell 1984, with later unpublished work by Powell & Conaghan, and Killick 1987), we are confident that there have been no significant displacements of any part of the LFB since deposition of the Lambie Facies overlap assemblages. Mega-kinking, however, could have produced local rotations about steep axes (Powell *et al.* 1985, Schmidt *et al.* 1986).

In the Thomson Orogen, only one terrane (the Anakie–Nebine–Cooper) has been identified (Leitch & Scheibner 1987), largely because of the lack of exposure other than in the northeastern margin. The rest of the Thomson Fold Belt is known only from penetration in western Queensland of 'basement' by drilling for hydrocarbons. The Drummond Basin, a Late Devonian–Early Carboniferous foreland basin just west of the Anakie Inlier (Powell 1984, fig. 224), is attractive for future palaeomagnetic studies to calibrate further the Australian APWP.

The relationship between the Tasmanian portion of the LFB (Fig. 1) and the Precambrian-cored western two-thirds of the island is not clear prior to the Devonian. The terrane boundary lies along the Tamar Fracture (Baillie 1985), which is also taken as the Tasman Line (Fig. 1). There is a limited area of Early Ordovician distal flysch east of the Tamar Fracture, but no evidence of palaeocurrent- or provenance-linking to the Precambrian-floored, terrestrial to shallow-marine terrane, lying immediately to the west. The Siluro-Devonian part of the East Tasmania Terrane has a cratonic, quartzose sediment source to the southwest (Powell *et al.* work in progress), and is arguably the on-strike continuation of the Melbourne Terrane, especially if the 120 km of continental extension along a NNE trend between Tasmania and Victoria is removed (Etheridge *et al.* 1985, Powell *et al.* 1988). Amalgamation of the East Tasmania Terrane with the rest of Tasmania occurred during the Middle Devonian Tabberabberan deformation.

The entire LFB was folded in the mid-Carboniferous by the Kanimblan deformation, which was probably the most extensive compressive deformation of Palaeozoic Australia. The Kanimblan deformation is estimated to have occurred in late Early Carboniferous in the LFB (Crook & Powell 1976, Powell 1984), and in the mid-Carboniferous in central Australia (data summarized in Powell & Veevers 1987). This deformation was most intense in the northeastern LFB, but extended westward to the Tasman Line in western NSW (Powell *et al.* 1982). From a palaeomagnetic point of view, the Kanimblan deformation is very important, because it provides fold tests against which the time of acquisition of magnetization can be tested. Thus, pre-deformational magnetization in the Lambie Facies can be limited to the time between the age of deposition (commonly Late Devonian or earliest Carboniferous in the northwestern Lachlan Fold Belt), and the age of deformation (340–320 Ma), to give a tight time constraint in many areas.

New England Orogenic realm

The New England Fold Belt (NEFB) has a two-fold subdivision: (a) the western, Tamworth–Yarrol Terrane (Figs. 1 and 2) (Scheibner & Leitch 1987), which corresponds to Zone A of Leitch (1974); and (b) an eastern collage of terranes (six identified by Leitch & Scheibner 1987, in New South Wales, and at least a further three possible in Queensland, Korsch & Harrington 1987). The western terrane has an uncertain, fragmentary Early Palaeozoic history, but, from the Devonian through the Carboniferous, was a fore-arc basin to a magmatic arc which lay just to the west. The arc was basaltic and andesitic in the Devonian, and became increasingly silicic during the Carboniferous (Leitch 1974).

Time-equivalent terranes to the east comprise fault-bounded slivers and blocks of turbidite, argillite, chert and mafic volcanics, and contain extensive units of mélange (Cross *et al.* 1987). The terranes are disrupted, and inferred to have been deposited on oceanic floor and accreted to the Tamworth–Yarrol Terrane by westward subduction, as well as transcurrent movement. Amalgamation of the eastern collage in New South Wales to the western NEFB was completed by the end of the Carboniferous, when the first of the extensive batholithic suites was emplaced. The only younger terrane in New South Wales is the Nambucca Terrane, inferred to have been a Permian rift or pull-apart basin (Leitch & Scheibner 1987) possibly associated with transcurrent orogen-parallel movement.

A major structural feature of the eastern part of the NEFB is a Z-shaped orocline (Fig. 1) (Cross *et al.* 1987, Korsch & Harrington 1987, Murray *et al.* 1987), around which sediments and structures are folded about a near-vertical axis. The orocline developed sometime in the Late Carboniferous–Early Permian interval, with a Carboniferous age favoured by Murray *et al.* (1987), and an Early Permian age by Cross *et al.* (1987) and Korsch & Harrington (1987).

The boundary between the western Tamworth-Yarrol Terrane and the eastern collage is a major serpentinite belt, the Yarrol-Peel Fault. Early Carboniferous provenance-linking across this boundary can be inferred from the presence of ooliths in the eastern turbidite succession (Fleming *et al.* 1974, 1975, Roberts 1987). The Yarrol–Peel Fault was stitched by the mid-Permian plutons. The only likely exotic terrane in the eastern collage is the ?Silurian–Devonian Silverwood Group, inferred to have been accreted to the NEFB in the Middle or Late Devonian (Day *et al.* 1978, Cross *et al.* 1987, see also Powell 1984, fig. 218).

The time of docking of the NEFB with the LFB appears to be in the mid-Carboniferous. Provenance-linking of the two fold belts in the latest Devonian–Early Carboniferous is indicated by the otherwise anomalous presence of immature volcanogenic detritus at the eastern margin of the Lambian Foreland Basin (Powell 1984, figs. 220B and 224). Docking could have occurred in the mid-Carboniferous during the Kanimblan deformation (~330 ± 10 Ma), which was a time of regression in the Tamworth Terrane (Roberts 1987). Detritus derived from the uplifted LFB and deposited in the Late Carboniferous conglomerates of the Tamworth Belt (McPhie 1983, Cross *et al.* 1987) also provides a provenance-link. From these two-way provenance-linkages, we have little doubt that the LFB and NEFB were amalgamated by the Late Carboniferous.

There are several tectonic relationships that can be tested palaeomagnetically. The Tamworth Terrane offers the possibility of testing whether the NEFB was substantially displaced or rotated with respect to the LFB prior to the Late Carboniferous. Preliminary results (Klootwijk 1985), have been interpreted to indicate possible latitudinal displacement since the Early Carboniferous. However, the data are yet to be published: the full impact of the associated palaeopole must await further scrutiny. Likewise, Schmidt (1988) presented preliminary palaeomagnetic results comparable to those of Klootwijk (1985), but interpreted them in terms of a 30° counterclockwise rotation of the Tamworth Terrane some time after the Early Carboniferous. Further work is underway to test this hypothesis. A second feature that has attracted attention is the latest Carboniferous–Early Permian orocline (Klootwijk 1985). A palaeomagnetic test of the proposed oroclinal rotation, however, is difficult because during the latest Carboniferous–Early Permian this region of Australia was close to the South Pole, so the magnetic field was nearly vertical. Nonetheless, palaeomagnetic study of rocks older than Carboniferous could provide a test of the orocline hypothesis. A third feature worthy of investigation is the possible exotic terrane in the eastern collage of terranes (Silverwood Group, Cross *et al.* 1987), and its northern equivalent, the "Calliope Arc" of Day *et al.* (1978). Palaeomagnetic data younger than mid-Carboniferous in the Tamworth–Yarrol Terrane can be regarded as belonging to the Australian craton, for by then the NEFB was accreted to the LFB, which at that time was the eastern edge of the Gondwanan continental craton.

PALAEOMAGNETIC DATA FROM THE TASMAN FOLD BELT

Palaeomagnetic data from the Tasman Fold Belt are summarized in Table 1, which includes a ranking for each pole and a brief commentary on the quality of each palaeopole. Class A palaeomagnetic poles are the most reliable, D the least. We consider that class A poles can be used to calibrate the APWP; their positions are reliable and the age of magnetization is known to within an epoch. The position of a Class B pole can be just as reliable as a class A pole, but the age of magnetization is not as well constrained. Because they lie on the APWP, class B poles can be used to define its trend. Class C poles are less reliable than class B poles for various reasons, and should be used with great caution in defining an APWP. Generally, more work is required before class C poles can be used to constrain a tectonic model. The reliability of class D poles is doubtful and they are not recommended for use in defining the APWP. The details of the criteria used to rank the palaeomagnetic studies are given in Table 1 of Li *et al.* (1990).

There is only one class A pole in the TFB (Table 1 and Fig. 3): pole SRV of Early Devonian age. This pole is a reference point for any APWP of the eastern LFB, and, as we have argued above, also likely to be representative of the Australian cratonic APWP.

Of the 10 class B poles, five come from the LFB (poles CV, HG, MM, SO and BO) and five from the NEFB (poles MG, RC, DDR, DI and UM). The age of the magnetization used to define all of these poles post-dates the accretion of the terranes to the Australian craton (Fig. 3). Thus, these poles can be used to define the Devonian and younger part of the Palaeozoic APWP (Li *et al.* 1990). Of the 11 reliable poles, two are Devonian, one Devono-Carboniferous, four Late Carboniferous

Table 1. Palaeozoic palaeomagnetic data from the Tasman Fold Belt

Rating*	Mnemonic	Rocks Reference	Age of rocks	Location Elong/Slat	S pole Elong/Slat	A_{95}	N†	Comments
D	G1	compilation Goleby (1980a,b) selected data from five formations; no adequate presentation of the data; both polarities; improved grouping with tilt corrections	M–L Ord.	~148.8/33.7	019/06	8	11 S	?FT
C	G2	compilation Goleby (1980a,b) selected data from four formations; no adequate presentation of the data; both polarities; improved grouping with tilt corrections	E–M Sil.	~148.8/33.0	036/38	8	?	+?FT; +?RT
C	G3	compilation Goleby (1980a,b) selected data from four formations; no adequate presentation of the data; both polarities; improved grouping with tilt corrections	M–L Sil.	~148.8/33.0	358/47	8	?	+?FT; +?RT
C	SV	Silurian volcanics Luck (1973) poor to no attitude control; no thermal demagnetization; probably insufficient SV average	M–L Sil.	148.8/34.8	271/54	7	13 S	~+RT, no FT
D	MP	Mugga Mugga Porphyry Briden (1966) no attitude control; probably insufficient SV average. Goleby (1980b) applied tilt correction: adjusted pole is 8.0E/63.0S	L Sil.–E Dev.	149.4/35.1	340/80	7	17 s all N	
A	SRV	Snowy River Volcanics Schmidt *et al.* (1987) perhaps slight error due to insufficient SV average	E Dev. (~400 Ma)	148.3/37.5	223/74	12	10 S	+FT, ~+RT folding mid-Dev.
D	AV	Ainslie Volcanics Luck (1973) no attitude control; probably insufficient SV average; no thermal demagnetization. Goleby (1980b) applied tilt correction giving pole of 341.0E/72.0S or 285.0E/68S	E Dev.	149.0/35.5	353/71	10	7 S	all N, no FT
D	BG	Bowning Group volcanics Luck (1973) poor to no attitude control; probably insufficient SV average; + cgl. test does not justify pole; no thermal demagnetization	E Dev.	149.8/34.8	045/64	9	7 S	all N, no FT
C	G4	compilation Goleby (1980a,b) selected data from four formations; no adequate presentation of the data	E–M Dev.	~149.0/32.6	253/44	25	4 S	?FT; both polarities
C	G5	compilation Goleby (1980a,b) no adequate presentation of the data	Ord.–Sil. (E–M Dev. OP)	~148.8/33.0	273/50	8	? S	?FT; ?RT
B	CV	Comerong Volcanics Schmidt *et al.* (1986)	M–L Dev. ~375 Ma	150.0/35.5	331/77	7	10 S	+FT, +RT, folding E Carb.
C	MD	Mulga Downs Gp redbeds Embleton (1977) Schmidt *et al.* (1986) suggest E–M Carb. OP; uncertain attitude if overprinted; attitude is ~30 dip to 335; if OP post-dates tilt, pole is 134.0E/62.0S	mid-Dev.	143.5/32.8	096/54	11	14 s	~+RT, no FT
C	DR	Dotswood redbeds Chamalaun (1968) thermal demagnetization at 250°C; magnetization believed by Chamalaun to be L Carb.; McElhinny & Embleton (1974) suggest that magnetization may be primary	L Dev.	146.4/19.8	136/46	15	19 s	no FT all R
C	LF	Lochiel Fm lavas Luck (1973); Green (1961) advanced epidotization of flows; AF demagnetization	L Dev.	149.8/37.2	320/58	7	48 s	?FT; ~+RT
B	HG	Hervey Group SS Li *et al.* (1988) positive fabric test for pre-deformational remanence in non-cleaved samples	L Dev.–E Carb.	148.5/33.3	024/54	12	8 S	folding mid-Carb.
C	VV	Visean volcanics Luck (1973), Irving (1966) poor attitude control; only AF cleaning; perhaps L Carb. OP; folding Permian?	E Carb.	151.5/32.7 151.4/32.2	214/73	21	~11 S	?+FT; ~+RT
D	PT	Patterson Toscanite Irving (1966) just beneath Kiaman R superchron; no thermal demagnetization; attitudes from adjacent sediments; only one 100 m thick lava flow, insufficient SV average; A VGP not a pmag. pole	L Carb. (~300 Ma)	~151.6/32.6	147/73	5	4 S	no FT
B	MG	Main Glacial Stage Irving (1966) Hunter Valley sediments; Kiaman reversed superchron; 108 specimens; thermal demagnetization	L Carb. (~290 Ma)	~151.6/32.6	148/53	11	5 S	+FT Perm-folding
C	CF	Currabubula Fm Irving (1966) Kiaman reversed superchron; 60 specimens; thermal demagnetization; streaked data set (incompletely cleaned)	L Carb. (~290 Ma)	~151.0/31.2	135/43	24	5 S	no FT

Continued overleaf

Table 1. *Continued*

Rating*	Mnemonic Rocks Reference	Age of rocks	Location Elong/Slat	S pole Elong/Slat	A_{95}	N†	Comments
B⁻	RC Rocky Creek Conglomerate Irving (1966) Kiaman R superchron 96 specimens; thermal demagnetization; little variation in attitude	L Carb. (~290 Ma)	~150.3/29.9	138/52	17	8 S	?FT, Perm. folding
D	PCV Perm–Carb. volcanics McElhinny & Embleton (1974) compilation pole; crude attitude control; insufficient average of SV	L Carb.–E Perm.		132/44	26	4 S	??
B⁻	DDR Dundee Rhyodacite Lackie (1989) all R polarity; possible CRM associated with devitrification	L Perm. (~247 Ma— magnetization probably slightly younger, earliest Tr?)	~151.76/29.5	136/25	11	14 S	no FT
B	DI Dundee Ignimbrite Lackie (1989) possible CRM associated with devitrification of the welded tuff	L Perm. (247 Ma— magnetization probably slightly younger, earliest Tr?)	~152.01/29.16	154/36	6	19 S	no FT, +RT
B⁻	UM Upper Marine latites Irving & Parry (1963) all reverse polarities; mostly AF cleaning; thermal and AF on one site ~ equal; crude attitudes; probably insufficient SV average	L Perm. (~250 Ma)	~150.78/34.63	132/44	7	~5 S	no FT
B⁻	MM Milton Monzonite all reversed; thermal demagnetization resolution of magnetic components	L Perm. (~245 Ma K–Ar, but pole position suggests L Jr.–E K. age)	~150.42/35.32	171/22	7	6 S	no FT or RT
B	SO Snowy River Volcanics Schmidt *et al.* (1987) all N polarity	E Dev. (mid-Carb.? OP)	148.3/37.5	133/69	5.5	77 s	−FT folding mid-Dev.
B	BO Buchan Caves Limestone Schmidt *et al.* 1987 all N polarity	E Dev. (mid-Carb.? OP)	148.3/37.5	128/65	4.5	64 s	−FT folding mid-Dev.

* Rating: see Table 1 in companion paper by Li *et al.* (1990):
A = most reliable and can be used to calibrate the age of the APWP;
B = sufficiently reliable to define trend of APWP;
C = reliability is questionable;
D = reliability is doubtful.

† N: S number of sites;
s number of samples.

Abbreviations:
Elong = longitude (°E);
Slat = latitude (°S);
A_{95} = radius of 95% confidence;
OP = overprint;
N = normal polarity;
R = reverse polarity;
SV = secular variation of the geomagnetic field;
FT = fold test (+FT means magnetization pre-dates folding);
RT = reversal test (+RT means N and R polarities are nearly antipodal, which indicates that SV is averaged adequately and a single component is isolated).

and the remaining four are Late Permian or Early Triassic, apart from pole MM which is likely to be Late Jurassic–Early Cretaceous (Schmidt & Embleton 1981). These poles are very important in calibrating (pole SRV) and defining the Australian cratonic APWP (Li *et al.* 1990), but they do not provide any palaeomagnetic test of whether parts of the LFB and NEFB are displaced, rotated or exotic.

DISCUSSION AND CONCLUSIONS

This brief critique of tectonostratigraphic terranes in the TFB focuses on the nature of the terrane boundaries, and the evidence for docking and amalgamation. The data indicate that the westernmost belt, the KFB, was accreted to the Australian craton by the Late Cambrian, and was linked by provenance in the Early Cambrian. The LFB appears to have been provenance-linked to the Gondwanan craton in the Ordovician by the widespread quartzose flysch. Later dispersion events, however, partly disrupted the LFB before it accreted to the Australian craton in the Middle Devonian. The quartzose, terrestrial, Lambie Facies overlap assemblage prograded from the southwest, and began to tie the western part of the LFB to the Australian craton in the Silurian, reaching the eastern part in the Late Devonian.

Both the KFB and LFB have some similarity in tectonic history in that they are interpreted to have formed in continental-margin, back-arc or marginal-sea tectonic settings. The NEFB is different in that its pre-Permian history is mainly related to tectonic elements that developed oceanward of volcanic island or continental margin magmatic arcs. The NEFB could have begun to dock with the LFB in the earliest Carboniferous, but accretion was not completed until the Late

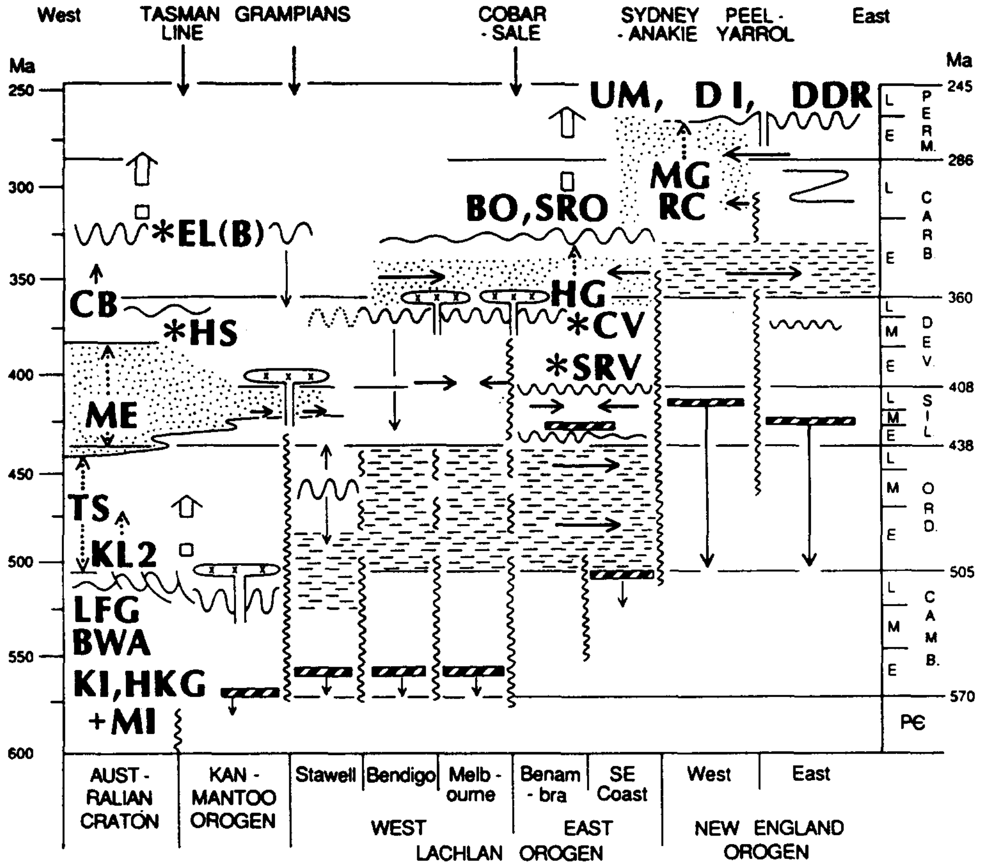

Fig. 3. Position in time and space of reliable palaeomagnetic poles from the Tasman Fold Belt.

Carboniferous. The accretion of the NEFB is associated with widespread mid-Carboniferous deformation that extended throughout the LFB and across the continent in the Amadeus Transverse Zone. The associated mid-Carboniferous lacuna marks the end of the 250 Ma-long Uluru regime, and the beginning of the succeeding 230 Ma-long Innamincka regime (Veevers 1984, Veevers & Powell 1990).

On a global scale, the TFB is distinctive in its history and tectonic style. The TFB lacks a well-developed miogeocline or craton-directed fold-and-thrust belt (cf. Rocky Mts and Appalachian Valley and Ridge) until the mid-Permian (~275 Ma), when the Sydney–Bowen Basin first developed its foreland basin character cratonward of the uplifted NEFB (Conaghan *et al.* 1982). The fold-and-thrust belt at the eastern edge of the Sydney Basin is craton-directed, though displacement on faults is measured in a few tens rather than hundreds of kilometres.

A final point to note is the distinction made by Chappel *et al.* (1988) in the LFB between 'basement terranes' and those recognized by surface geology. There is a long-continuing debate about the nature of the basement to the LFB, with some workers arguing that the LFB was formed on a substrate of foundered Precambrian continental crust (e.g. Rutland 1976, Compston & Chappell 1979, McCulloch & Chappell 1982). Arguments supporting these conclusions are mainly geochemical and petrological. Other workers dealing mainly with the facies, composition and distribution of sedimentary rocks (e.g. Cas *et al.* 1980, Crook 1980, Powell 1983a, 1984) have favoured an Early Palaeozoic ensimatic floor to the LFB. In the LFB, Chappell *et al.* (1988) recognized eight basement terranes, but the boundaries do not necessarily coincide with terrane boundaries identified from surface geology. Moreover, for some of their basement terranes (e.g. their Bega and Kosciusko basement terranes) there is no marked difference in surface structure and stratigraphy across the terrane boundary.

The resolution of these apparently conflicting conclusions could lie in a careful re-examination of the limits that each line of argument provides. Powell (1984, pp. 302–305) commented briefly on the nature of the dilemma, viz. was the LFB formed in an ensimatic setting up to the end of the Ordovician, and did it then become underplated (underthrust?) by continental crust, including some Precambrian material? We think this is possible.

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