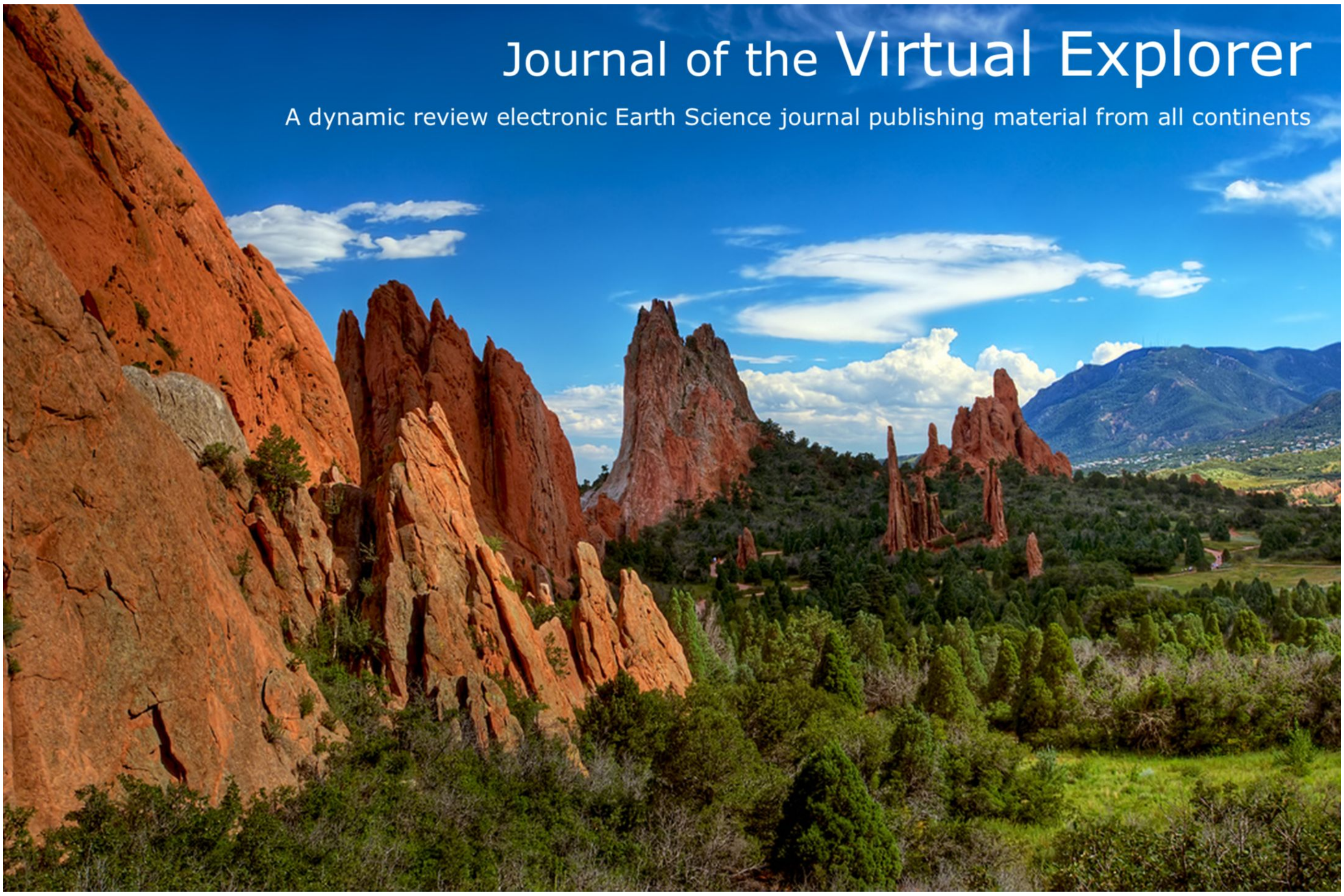

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Formation of Oroclines in the New England Orogen, Eastern Australia

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Abstract: Most of the New England Orogen comprises a convergent margin, in which Middle Devonian to latest Carboniferous continental margin arcs, forearc basin and subduction complexes were developed above a west-dipping subduction zone. The subsequent history is marked by an early and middle Permian hiatus in arc magmatism, followed by a resumption of west-dipping subduction from the late Permian to Triassic. The geometry of the southern New England Orogen is dominated by a northern, well-established oroclinal fold pair, developed in a subduction complex and overlying Permian rocks, and by a southern oroclinal fold pair, more controversial in acceptance. Our data sustain the presence of the two southern oroclines or megafolds, and suggest that they formed by anticlockwise fold rotation over a possible time span of ~40 million years, beginning in the latest Carboniferous and continuing into the middle Permian. By generating an oroclinal model that takes into account the fold-thrust deformation style of the forearc basin, along with multiple deformation, variations in directions and amounts of shortening, as well as vergence variations, we suggest that the Manning and Hastings oroclinal folds in forearc basin and subduction complex rocks developed as amplified buckle folds of large amplitude, the hinges of which can be tracked south-southwest along their axial traces into smaller amplitude folds along the old arc/forearc boundary. Rather than forming in response to either sinistral or dextral simple shear slip of hundred of kilometres on an inferred N-trending onshore or offshore master fault, these oroclines are reflections of changes in directions and amounts of shortening that occurred along the western margin of the New England Orogen during a lull in convergent margin tectonism.

N.B. May 2013. In response to feedback from readers, the authors have updated several image captions and improved the resolution of some of the figures to enable viewing at higher magnification. Earlier printed copies of the paper should be replaced by the current version.

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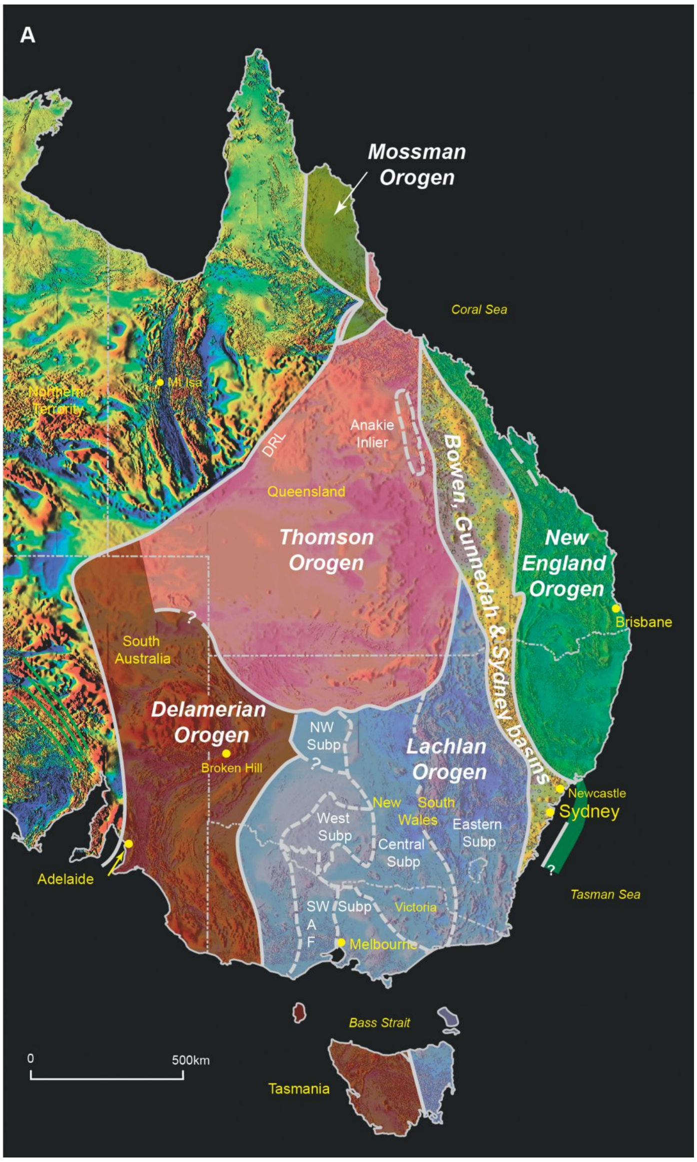
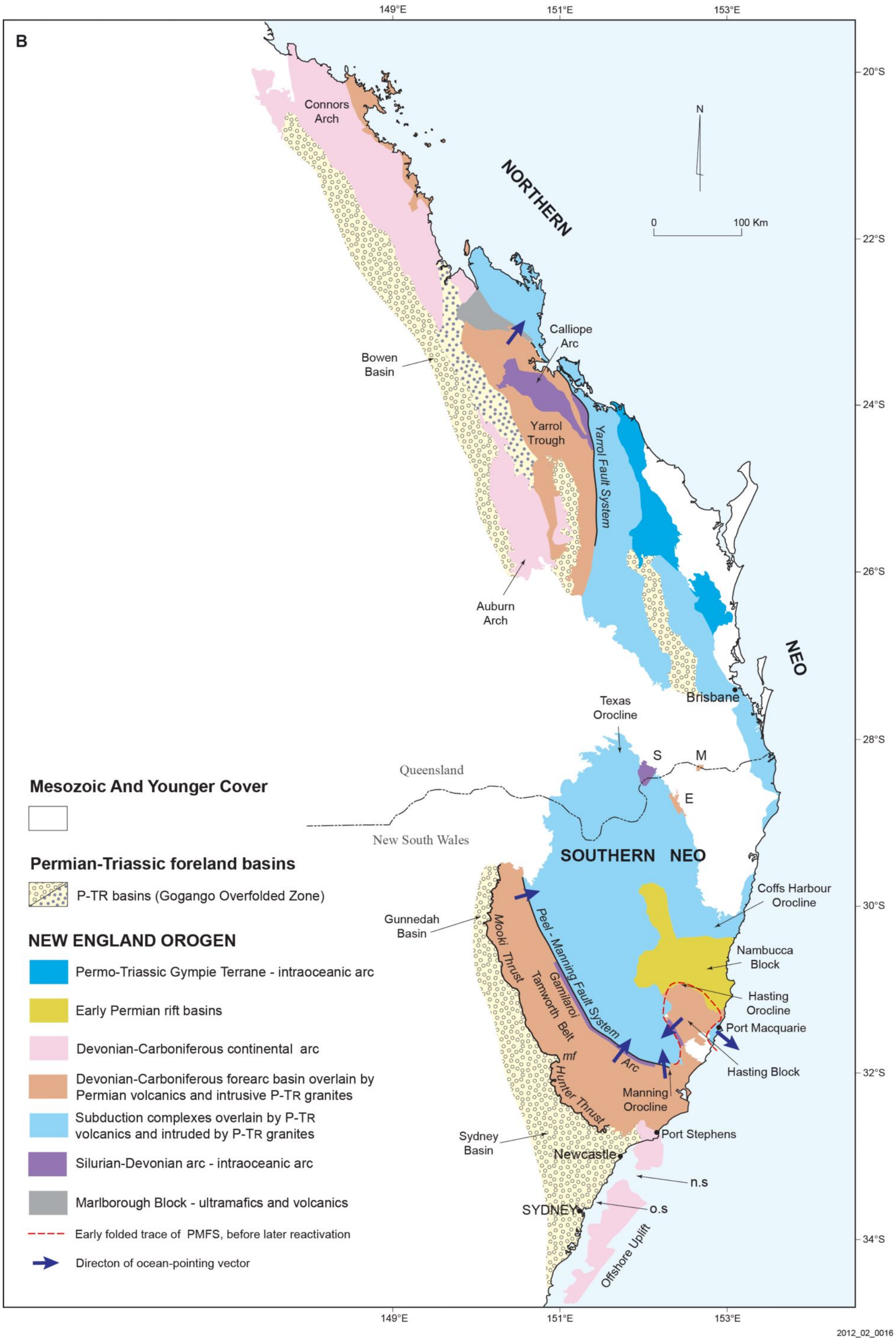
Introduction

The most obvious feature of the southern part of the New England Orogen of eastern Australia (Fig. 1a) is the presence of a double orocline pair outlined most simply by the boundary between the forearc basin and the coeval subduction complex (Figs. 1b, c). These oroclines, with wavelengths and amplitudes of tens of kilometres, explain the great width of subduction complexes in the centre of the orogen, and the presence of forearc basin lithologies on the east as well as the west of these duplicated subduction complexes (Fig. 1b). All four oroclinal hinges are clearly outlined by grey scale 1VD aeromagnetic imagery that highlights folding of ultramafic rocks in the major Peel-Manning Fault System (and extensions under cover to the north) that separates the forearc basin from the subduction complex (Fig. 1c).

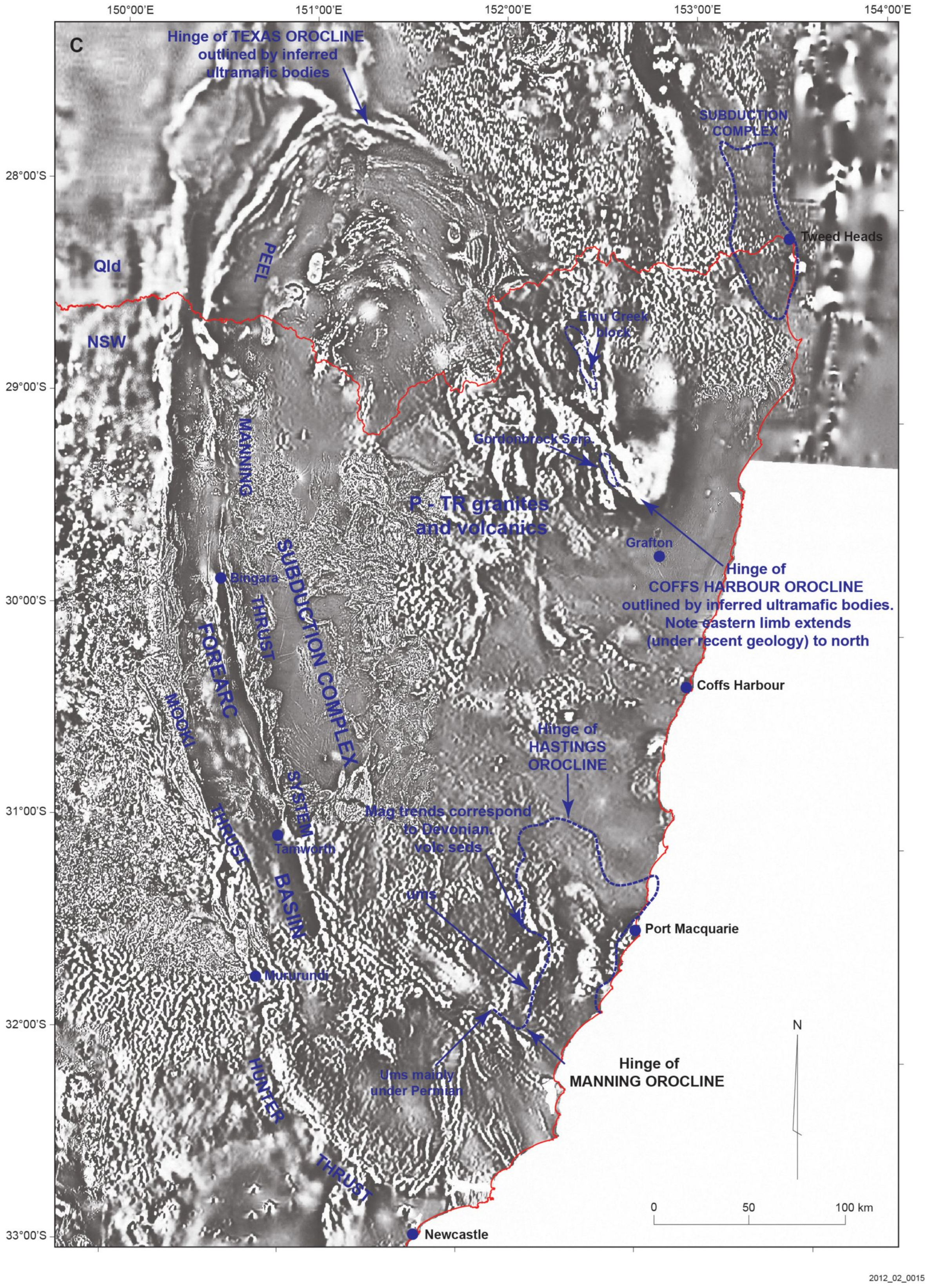
Figure 1. Location of the New England Orogen



A. Geology of eastern Australia showing location of New England Orogen as the most outboard element of the Tasmanides. AF=Avoca fault; DRL=Diamantina river lineament.



B. Simplified geology of the New England Orogen. The frontal thrusts of the southern New England Orogen, the Mooki Thrust in the north and the Hunter Thrust in the south are separated by the Murrurundi fault (mf). Note: i) linear geometry in the northern part of the orogen compared to oroclinal folding in the southern part; ii) the presence of inferred arc rocks offshore (Offshore Uplift) separated from onland Sydney basin by offshore syncline (os), and from expanded volcanic centre at Port Stephens by Newcastle syncline (ns); iii) outcrops of forearc basin rocks east of subduction complex at E (Emu Creek block) and M (Mt Barney); iv) presence of subduction complex rocks east of forearc basin rocks at E and M above, and at Port Macquarie, east of forearc basin rocks in the Hastings Block; v) presence of Calliope arc rocks on eastern side of Texas orocline at S (Silverwood block); vi) thin sliver of Silurian-Devonian Gamilaroi arc along Peel-Manning Fault System; v) the Gogango Overfolded Zone only occurs in the Queensland part of the New England Orogen. The onland part of the figure is from Champion *et al.* (2009).



C. Greyscale total magnetic intensity first vertical derivative (1VD) map over the southern New England Orogen. Ultramafic rocks along the forearc basin/subduction complex boundary clearly highlight the northern oroclinal folds, and less clearly the southern Manning Orocline. Abbreviations: mag = magnetic; volc = volcanic; ums = ultramafic rocks.

The northern oroclinal pair comprises the Texas orocline in the northwest and the Coffs Harbour orocline in the southeast (Flood and Fergusson 1982; Korsch and Harrington 1987) (Figs. 1b, c). The pair has a clockwise sense of rotation. The Coffs Harbour orocline is outlined by subvertically folded strata in Devonian–Carboniferous subduction complexes (Korsch 1993); the Texas orocline by steeply (70-80º) plunging folded strata in subduction complexes and by moderately (~30º) plunging folds in early Permian strata (Lennox and Flood 1997; Li *et al.* 2012). The southern orocline pair, comprising the Manning orocline in the west and the Hastings orocline in the east, is more controversial and several workers (eg. Lennox and Roberts, 1988; Offler and Foster 2008; Lennox and Offler 2009; Lennox and Offler 2010) have questioned its existence. However, both megafolds are also visible, albeit not so clearly, in aeromagnetic data, with the greyscale 1VD image highlighting discontinuous rotation of ultramafic and volcanic rocks around the southern Manning Orocline (Fig. 1c).These data suggest the southern oroclines have an anticlockwise sense of rotation. As will be discussed below, these fold hinges are more complex than in the northern pair.

The aim of this paper is to present evidence for this southern oroclinal pair, consisting of the southwestern Manning orocline and the northern Hastings orocline, to analyse their significance in a New England Orogen tectonic context, and then to propose a new model for oroclinal formation that does not involve strike-slip movement on any inferred master fault. The first part of the paper presents map-scale evidence for the rotation of stratigraphy around these two folds. Their geometry is then discussed, with an emphasis on a new interpretation of the Hastings Block presented in Appendix A.

New England Oroclines

Orocline formation in the southern New England Orogen is generally agreed as having occurred during a Permian hiatus in continental arc magmatism during west-(continent) dipping subduction along the Gondwana palaeo-Pacific boundary. The evolution of ideas culminating in the formation of present day models of oroclines in the New England Orogen has been presented by Murray (1997). Despite consensus on the age of oroclinal folding, there is little agreement on the dynamics of their formation, especially since the southern pair has an opposite movement sense to the northern pair.

Models may be grouped into 2 types: i) formation as megafolds inboard of a major N to NNW-trending shear zone with either a sinistral (Cawood 1982, Cawood and Leitch 1985; Cawood *et al.* 2011a; Collins *et al.* 1993) or dextral sense of shear (Murray *et al.* 1987; Offler and Foster 2008); and ii) formation in a composite model, whereby an original irregular plate margin or variation in plate boundary rollback velocities was accentuated by a dextral movement sense on an offshore megashear followed by east-west contraction (Li *et al.* 2011; Rosenbaum *et al.* 2012).

Geological background

The New England Orogen is the most easterly of the five orogenic belts and an internal foreland basin system that constitute the Tasmanides of eastern Australia (eg. Cawood 2005; Glen 2005) (Fig. 1a). Late Devonian to end Carboniferous rocks of the New England Orogen of eastern Australian accumulated in a convergent margin orogen that comprises a western continental margin arc, a central forearc basin and an eastern subduction complex (eg. Scheibner 1973; Leitch 1975; Cawood 2005; Glen 2005) (Fig. 1b). These elements can be followed for ~2000 km from Townsville in north Queensland southwards to Newcastle in NSW. This paper only discusses the NSW part. In NSW, these elements were built upon older Cambrian to Ordovician supra-subduction zone elements in the south, older continental crust in the west and older Silurian-Middle Devonian accreted arcs (Cawood and Leitch 1985; Aitchison and Flood 1995; Glen 2005). Indirect evidence suggests the southern New England Orogen is also partly built on Neoproterozoic continental crust (Glen 2005; Glen submitted) that is the source for some zircons in granites (Shaw *et al.* 2011). Cambrian and Ordovician supra-subduction zone elements are preserved largely as blocks in a serpentinite matrix melange within the major Peel-Manning Fault System (see Fig. 1b, c), in fault blocks to the west, and in coastal outcrops at Port Macquarie (Fig. 1b) (eg. Glen 2005).

Western arc

The presence of the western Late Devonian intermediate (andesitic) Baldwin arc and the overlying Carboniferous largely felsic arc Currububula arc (Veevers *et al.* 1982; McPhie 1987) is inferred from the nature of detritus in the forearc basin to the east (eg. Korsch 1984). Interpretation of seismic data (see below) suggests the arc might lie at depths between 3 and 7 km, beneath overthrust rocks of the forearc basin. The eastern fringe of the Late Devonian arc is approximated by large olistoliths of andesitic volcanics in the north of the Tamworth belt (Brown 1987). The eastern fringe of the Carboniferous arc is approximated by Carboniferous rhyolite to rhyodacitic, rarely andesitic, ignimbrites, with rare intrusive dacites, along the curvilinear western and southern margins of the Tamworth belt (eg. Roberts *et al.* 2003). Up to 1200 m of the felsic (rarely intermediate) Nerong Volcanics at Port Stephens (located in Fig.1b) reflect a volcanic centre (Buck 1986; 1988; Roberts *et al.* 1991). No arc is recorded from the southern New England Orogen in the early Permian, but subduction-related magmatism in the Gympie arc in Queensland is early Permian in age (Sivell and Mcculloch 2001). Late Permian–Triassic, granites of the Clarence River Supersuite represent the roots of a continental margin arc (Bryant *et al.* 1997) that intruded older subduction complex rocks, reflecting either steepening or rollback of the subduction zone plate boundary (Jenkins *et al.* 2002) or by upper crustal transport (Cawood *et al.* 2011b).

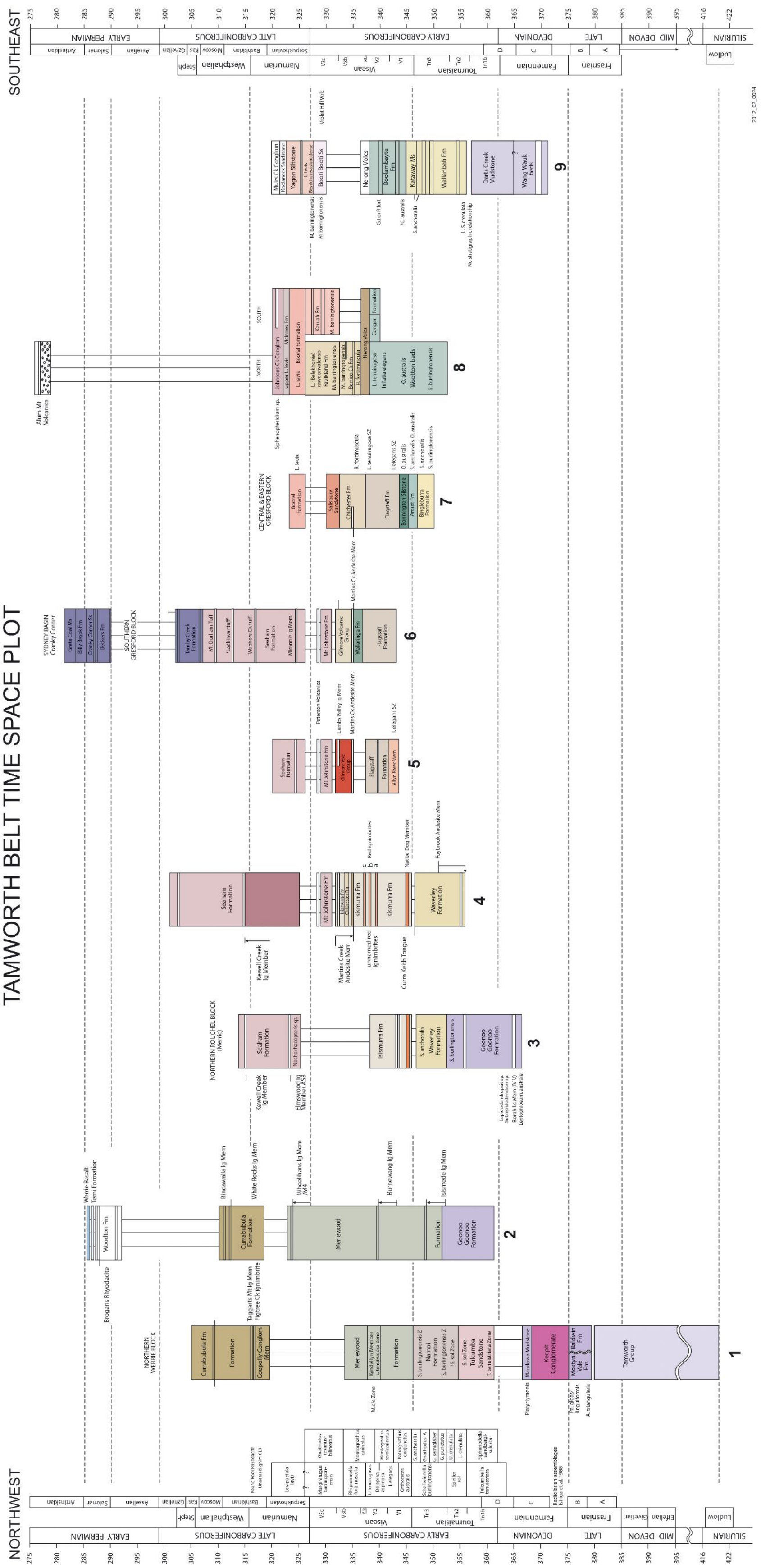
Petroleum exploration east of Sydney has identified undated volcanic and volcaniclastic rocks that define the Offshore Uplift (Grybowski 1992; Bradley 1993; Alder *et al.* 1998; Bounty Oil and Gas NL 2002; Breeze 2009) (Figs. 1b) (see later). Breeze (2009) suggested these volcanic rocks are progressively overlain by Permian to Cainozoic strata, and aeromagnetic data indicate continuity and similarity with the Carboniferous arc (Nerong Volcanics) at Port Stephens (Fig. 1b).

The forearc basin

The forearc basin is called the Yarrol trough in Queensland and the Tamworth trough in the southern New England Orogen, in NSW, where it is better known as a fold-thrust belt called the Tamworth belt (Fig. 1b). The Tamworth belt swings in strike from NNW in the north to E in the south, and outlines a broad, south-closing fold (Fig. 1b). The western and southern boundaries of the forearc basin are separated from the Permian Gunnedah-Sydney foreland basin system to the west by the Mooki Thrust in the north and the Hunter Thrust in the south, separated by the latitudinal Murrurundi Fault (Fig. 1b). The Mooki Thrust disappears under Mesozoic cover at its northern end, passing northwards into a series of meridional thrusts (Goondiwindi, Kelvin, Tingan and Moonie) that can be recognised in seismic data as the thrusted western margin of the Tamworth belt (Korsch *et al.* 2009).

The eastern and northern parts of the forearc basin comprise Late Devonian volcaniclastic strata built upon the accreted Silurian-Devonian Gamilaroi arc (Tamworth Group, Aitchison and Flood 1995), and Cambrian and Ordovician blocks (Cawood and Leitch 1985) that flank the western side of Peel-Manning Fault System. The western and southern parts of the forearc basin consist of Carboniferous strata interrupted by Devonian rocks in a major hangingwall anticline in the northwest, and overlain by early Permian strata in a few key synclines. Major facies changes along the length of the basin have produced a proliferation of stratigraphic names that complicate correlations. Our time-space plot (Fig. 2) shows correlations based on palaeontology and SHRIMP dating of ignimbrites (Roberts *et al.* 1991, 2003, 2004, 2006) and is used as a basis for later discussions.

Figure 2. Time-space plot showing stratigraphic correlations in the southern part of the Tamworth Belt.



From Roberts and Glen (2010), based on Roberts *et al.* (2003, 2004, 2006). Numbered sections are located in Figure 3.

Repetitions of the forearc basin and its basement around the Texas orocline occur near the NSW/Queensland border as the Emu Creek Formation (Scheibner 1976), Mount Barney Beds (Olgers *et al.* 1974) and the Silverwood Group (van Noord 1999) respectively (Fig. 1b). Several early workers (Scheibner 1976; Leitch 1980; Cawood 1982) suggested that the Hastings Block formed as part of the forearc basin, and was structurally out of place. Its origin, as a fold repeat of the forearc basin (Fig. 1b) is discussed further below.

Subduction complex rocks

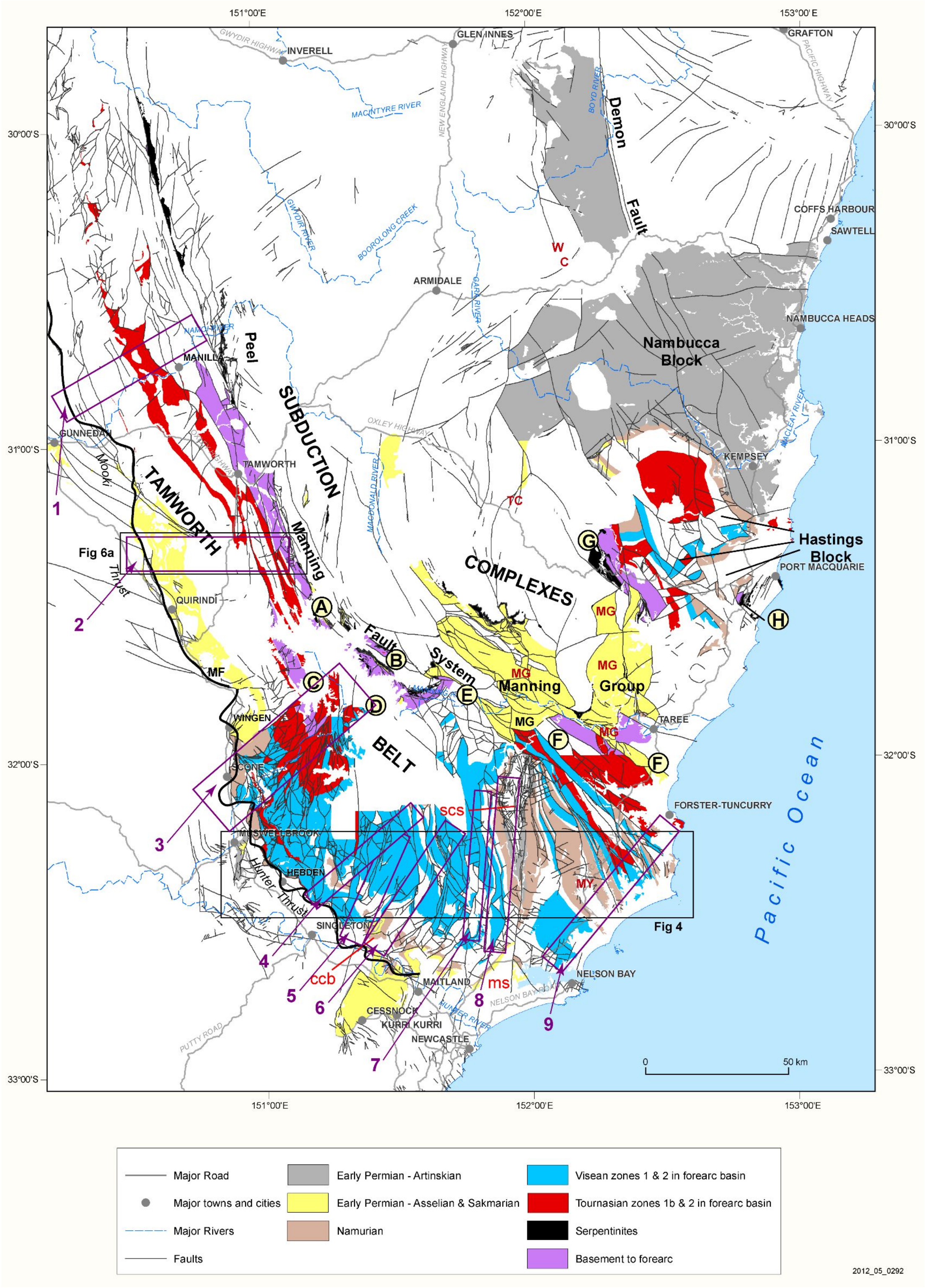
Subduction complex rocks are separated from the forearc basin by the Peel-Manning Fault System (Leitch 1974) (Figs. 1b, 1c), which contains Cambrian and Ordovician igneous and meta-igneous blocks in a serpentinite matrix melange that was only emplaced by the early Permian (Allan and Leitch 1990). Ages range from Silurian in west to Carboniferous in the east and south. Descriptions have been given by Cawood and Leitch (1985), Aitchison *et al.* (1992), and have been summarised by Glen (2005) and Cawood (2005).

Permian units

Permian rocks of the southern New England Orogen occur in four different settings (Fig. 3): i) early and middle Permian volcanic and sedimentary units in synclines above forearc basin rocks, such as in the Stroud-Gloucester, Myall and Medowie synclines, the cranky Corner Basin and above the Mooki Thrust north of Wingen (Figs 3, 4). Early Permian volcanic rocks (Alum Mountain Volcanics) are mafic to felsic with enriched-MORB-type chemistry (Jenkins *et al.* 2002) and are dated as Asselian in age (Roberts *et al.* 1991); ii) the early Permian Manning Group southwest of the Hastings Block (Figs. 3, 5). These clastic strata, commonly with chert clasts derived from uplift of the subduction complex, are in fault contact with the subduction complex; and iii) shallow water early Permian (Asselian and Sakmarian) rocks around the northern margin of the Hastings Block (Figs. 1b, 3, 5) that deepen northwards (across faults) into iv), mainly Artinskian turbiditic strata of the Nambucca Block and region to the east (Fig. 3). Volcanic rocks in the Nambucca Block include the felsic, Sakmarian Halls Peak Volcanics (SHRIMP age of 292.6 ± 2 Ma, Cawood *et al.* 2011a), and early Permian basalts – the alkali within-plate-Petroi Metabasalt (Asthana and Leitch 1985) and the ocean floor tholeiitic MORB-type (McGraths Hump Metabasalt, Scheibner and Pearce 1978; Leitch and Asthana 1985). It is still uncertain whether ii) and iv) are relics of a single large basin (Leitch 1988) or formed as separate basins, either of rift or transtensional origin (eg. Atchison and Flood, 1992).

West of the New England Orogen, early to late Permian strata occur in the Sydney and Gunnedah basins (Fig. 1b). Although mainly yoked to the New England Orogen, they were initiated as rift basins with mafic and felsic volcanics (eg. Rylstone, Werrie, Boggabri volcanics and in the Dalwood Group) that still show some relic supra-subduction zone component in the melt (Jenkins *et al.* 2002).

Figure 3. Chronostratigraphic elements of the forearc basin



Geology of forearc basin showing the distribution of key chronostratigraphic horizons, together with its basement and Early Permian cover. Note that the Tournasian zones are over-emphasised in the Hastings Block, as are the Visean zones just north of Nelson Bay. Abbreviations: ccb=Cranky Corner Basin; MG=Manning Group; ms=Medowie Syncline; my=Myall Syncline; scs=Stroud-Gloucester Syncline; tc=Tia complex; wc=Wongwibinda complex. Letters refer to localities mentioned in text. Boxes refer to approximate locations of stratigraphic sections 1-9 in Figure 2.

Granites

Much of the area occupied by subduction complex rocks has been intruded by granites. The oldest event (300 to 285 or 280 Ma, Cawood *et al.* 2011b; Rosenbaum *et al.* 2012) comprises plutons of the S-type, undeformed Bundarra Supersuite (~292-288 Ma) and of the S-type deformed Hillgrove Supersuite (~296-288 Ma). The oldest granite of the I-type Clarence River Supersuite, the Kaloe Granodiorite, was also emplaced in this intervaal at 291.9 ± 2 Ma (Cawood *et al.* 2011b). These granites provide a minimum age for early deformation of the subduction complex and were deformed by oroclinal folding (Cawood *et al.* 2011a; Rosenbaum *et al.* 2012). Younger granites range in age from late Permian to Early Triassic (255-244 Ma, Bryant and Chappell 2010). They are I-types, constitute the New England Batholith that cuts across oroclinal folds (eg. Cawood *et al.* 2011b figure 2) and are coeval with large volumes of latest Permian I-type volcanic rocks (eg. Brownlow and Cross 2010). The youngest granites, which occur near the coast, are 235-212 Ma in age and are I and A-type in composition (Shaw and Flood 1991; Bryant and Chappell 2010; Blevin 2010). They intrude and mask the southeastern parts of the Hastings Block (see later). The main hiatus in granite magmatism lasted from ~280 to ~260 Ma (except for the 267 Ma Barrington Tops Granite, Rosenbaum *et al.* 2012; Cawood *et al.* 2011b).

Rotation of units around the Manning and Hastings oroclines

Curvature of the western arc

Despite the absence of the western arc due to inferred underthrusting, the distribution of “proximal” Carboniferous volcanic fields in the Tamworth belt outlines a curvilinear shape to the present, largely faulted inner margin of the forearc basin between Muswellbrook in the north and Port Stephens in the southeast (Fig. 1b). Offshore extensions of Carboniferous volcanic rocks extend south of Sydney, indicating that the approximate arc/forearc basin boundary outlines an open, anticlockwise fold pair (Fig. 1b). Proximal Carboniferous volcanic rocks are absent from the Hastings Block (Roberts *et al.* 1995).

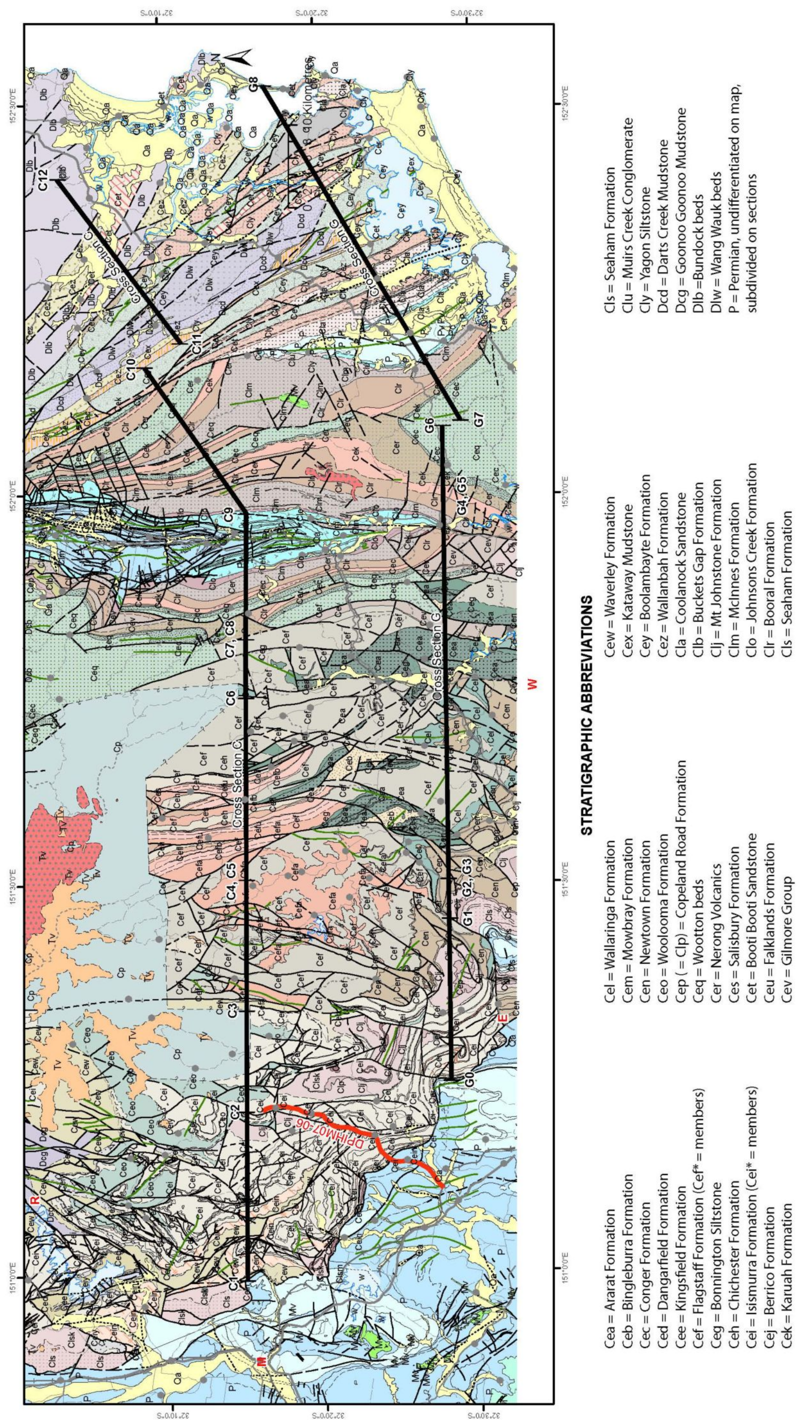
Rotation of the boundary between forearc basin and its basement and the subduction complex.

Figure 1b shows that over most of the southern New England Orogen, subduction complex rocks lie east of forearc basin sediments. That means that the vector towards the trench points east. In the hinge of the Manning orocline, however, subduction complex rocks lie north of forearc basin sediments and the vector points north. In this hinge region, the subduction complex/forearc boundary truncates stratigraphy in the forearc basin that is controlled by NNW trending folds and faults (see below). On the western side of the Hasting block, subduction complex rocks lie west of forearc basin sediments and the vector points west or southwest, despite being largely obscured by overlying early Permian strata (see below). In the southeastern part of the Hastings Block a fault slice of Devonian strata (Touchwood Formation) is separated from the main part of Hastings Block by an early Permian overlap assemblage and lies in fault contact with subduction complex rocks to the east (Och *et al.* 2007). There, the vector points southeast again, having been folded around two major oroclinal hinges (Fig. 1b).

Devonian-Carboniferous units in the forearc basin around the Manning and Hastings oroclines

Major facies changes occur within the southern Tamworth belt and the Hastings Block, complicating correlation of geological units (Roberts *et al.* 1991; Roberts *et al.* 1995). Relations between strata of the Tamworth belt and the Hastings Block are also obscured by widespread development of both early Permian sedimentary rocks, and by Early Triassic sedimentary units that cover the southeastern part of the Hastings Block (Fig. 3). A key feature of the north Hastings Block is that in the Namurian, shallower water conditions existed in the east with deeper water in the west (Lennox and Roberts 1988). While this is the opposite of the Tamworth belt (Lennox and Roberts 1988), it is consistent with the rotation of stratigraphy around the Manning orocline and consistent also with above-mentioned rotation in direction of the trench-facing vector.

Figure 4. Simplified map of southern part of the Tamworth belt



Simplified map of southern part of the Tamworth belt. In the left corner, the folded Hunter Thrust separates blue-coloured Permian units in the southwest from coloured Carboniferous units in the northeast. The meridional Stroud-Gloucester Syncline runs though locality C9 in cross section C. The red line is seismic section DPIHM07-06; the two black lines are cross sections C and G. Short green lines are fold axial traces. Abbreviations: M=Muswellbrook; R= Rouchel; E=Elderslie; W=Woodville.

Using the time-space plot of figure 2, we have produced a map of the forearc basin (and its basement) that ignores detailed stratigraphic names, and focuses instead on time slices (Fig. 3). These are now discussed.

i. Basement to the forearc basin, comprising the Tamworth Group (Gamilaroi arc) and correlative units to the east. North of A (Fig. 3), the Tamworth Group occupies a SSE-trending zone in the eastern part of the forearc basin. At B, fault repetition is present (eg. Offler and Gamble 2002). A second line of Tamworth Group to the west, at C, occurs in two windows beneath Tertiary basalts and mainly represents fold repetition. From D to E, the Tamworth Group trends ENE. Possible extensions of the Tamworth Group lie south and southwest of Taree (locality F, Fig. 3). The Bitter Ground Volcanics and Birdwood Formation/Elenborough Volcanics on the western side of the Hastings Block (G Fig. 3, and Fig. 5) are also included in this time slice, with their Frasnian age indicating an age correlation with the upper part of the Tamworth Group (Roberts *et al.* 1995) (Fig. 5b). Aitchison *et al.* (1994) and Aitchison and Ireland (1995) suggested that these rocks and the underlying disrupted Yarras ophiolite (Leitch 1980) represent another fragment of the Gamilaroi arc. The Emsian Touchwood Formation and the Givetian Mile Road beds (now Formation, Pickett *et al.* 2009) (H) are other fragments of the forearc basement, this time on the southeastern side off the Hastings Block (Figs. 3, 5).

ii. The lower part of the forearc basin occupies Tournasian zones 1b and 2. In the north, this time slice is broadened to include the Mandowa Mudstone, (outcropping on both limbs of a regional anticline, from west of Manilla to northeast of Wingen), and the Goonoo Goonoo Formation east and southeast of Wingen (Fig. 3). No strata of this time slice occur in the forearc basin between the Hebden area and the Stroud-Gloucester Syncline. East of the Stroud-Gloucester Syncline, this zone comprises the Darts Creek and Bundook beds that occur in N to NNW-trending fault slices (Fig. 4), interpreted to be part of an east-verging imbricate thrust stack in cross section C (Fig. 8b, c). In the Hastings Block, it includes the Pappinbarra Formation, the lower part of the Hyndmans Creek Formation and the lower half of the Boonanghi beds (Fig. 5).

iii. The middle part of the forearc basin, occupying Visean zones 1 and 2, contains the lower part of the Merlewood Formation (in the north) and the lower part of the Isismurra Formation, which can be tracked as dipping and repeated ignimbritic strata from just north of Muswellbrook to just west of the Cranky Corner Basin (Fig. 4). Farther east, this time slice includes the Flagstaff Formation, Bonnington Siltstone, and upper Wootton beds on the west side of the Stroud-Gloucester Syncline and the Boolambayte Formation on the east (Fig. 4). In the Hastings block, it is represented by the upper part of the Hyndmans Creek Formation and the upper half of the Boonanghi beds (Fig. 5).

iv. the upper part of the forearc basin occupies the Namurian stage. It includes the lower half of the Seaham Formation (Figs. 3, 4), that can be tracked in synclines from Wingen to Muswellbrook, as dipping strata in the immediate hangingwall of the Hunter Thrust south to Hebden, and as isolated doubly plunging synclines south to Woodville (Fig. 4). Its easternmost extent is a linear zone on the western side of the Myall Syncline. To the east and north, it is replaced stratigraphically mainly by the Booral Formation on the western side of the Stroud-Gloucester Syncline, and then by the Yagon Siltstone farther east: both occur in fanning fault slices that lie at high angles to the forearc basin/subduction complex boundary (Fig. 3). In the Hastings Block, it is represented by the Mingaletta, Majors Creek and most of the Kullatine and Youdale C formations that clearly outline the Parrabel Anticline (Fig. 5).

Curvature of early Permian units

Early Permian units with SSE-oriented outcrop boundaries overlie subduction complex rocks just east of the Peel-Manning Fault System, north and northwest of locality E (Fig. 3). Between E and G, the trends of these outliers change from SSE to NNE, outlining a north-plunging synform in the east that overlies the forearc basin/subduction complex boundary. Between G and H (Fig. 3), shallow-water early Permian strata have been folded around the Hastings Block, separated from underlying Late Carboniferous strata by a disconformity or unconformity (Roberts *et al.* 1995).

Crustal Architecture

Hastings Block

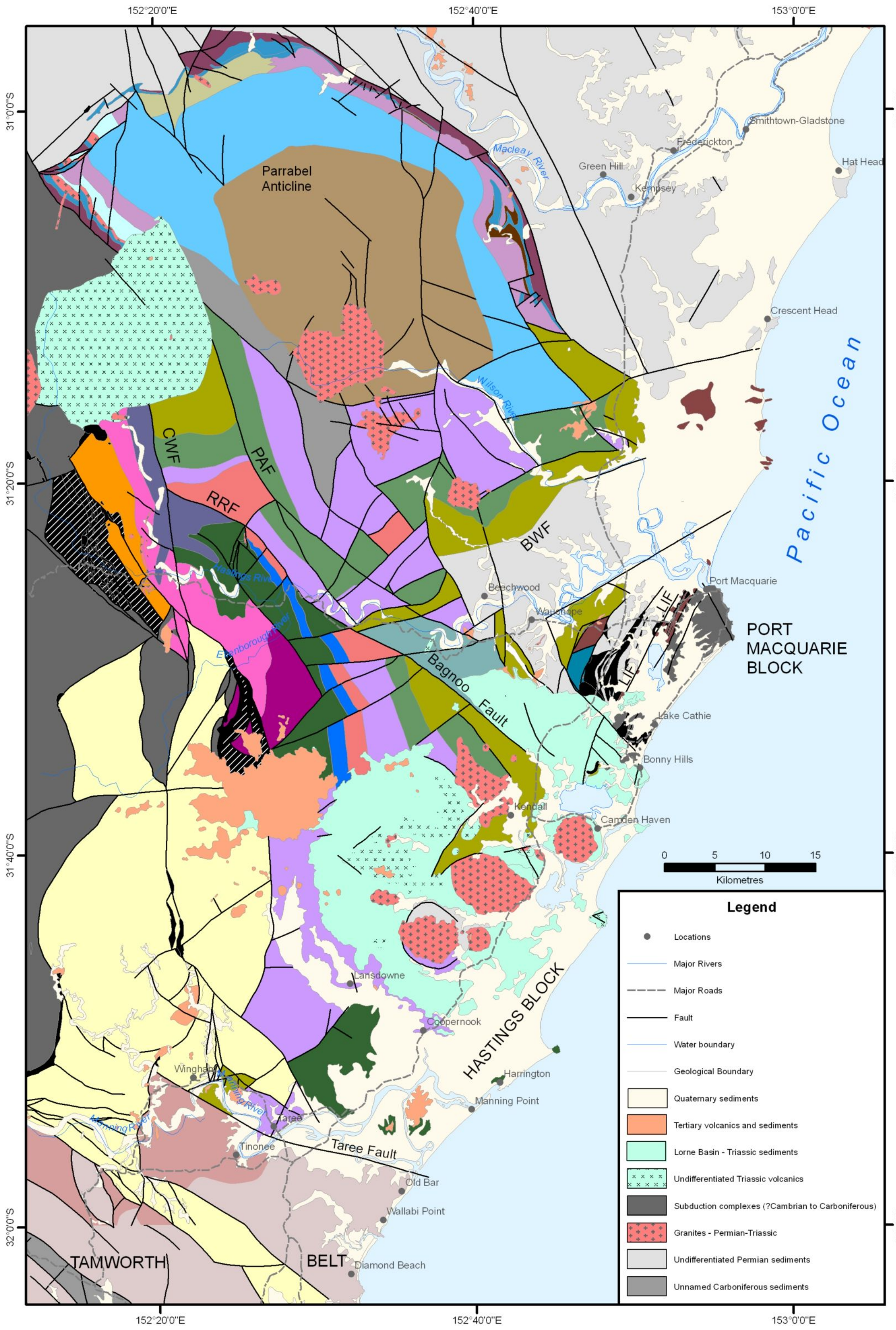
Our view of the architecture of the Hastings Block is discussed in some detail in Appendix A, building on earlier work of Lennox and Roberts (1988), Roberts *et al.* (1995) and Lennox *et al.* (1999). In summary (Fig. 5), Devonian-Carboniferous strata in this block are mainly flanked by Permian strata. Locally, there is a contact to the west between volcanic rocks (and associated ultramafic rocks of the Yarrol ophiolite, eg. Aitchison *et al.* 1994) and subduction complex strata. In the east, a narrow zone of faulted Permian strata separates the block from subduction complex rocks of the Port Macquarie block. Triassic strata obscure the southeastern part (Fig. 5).

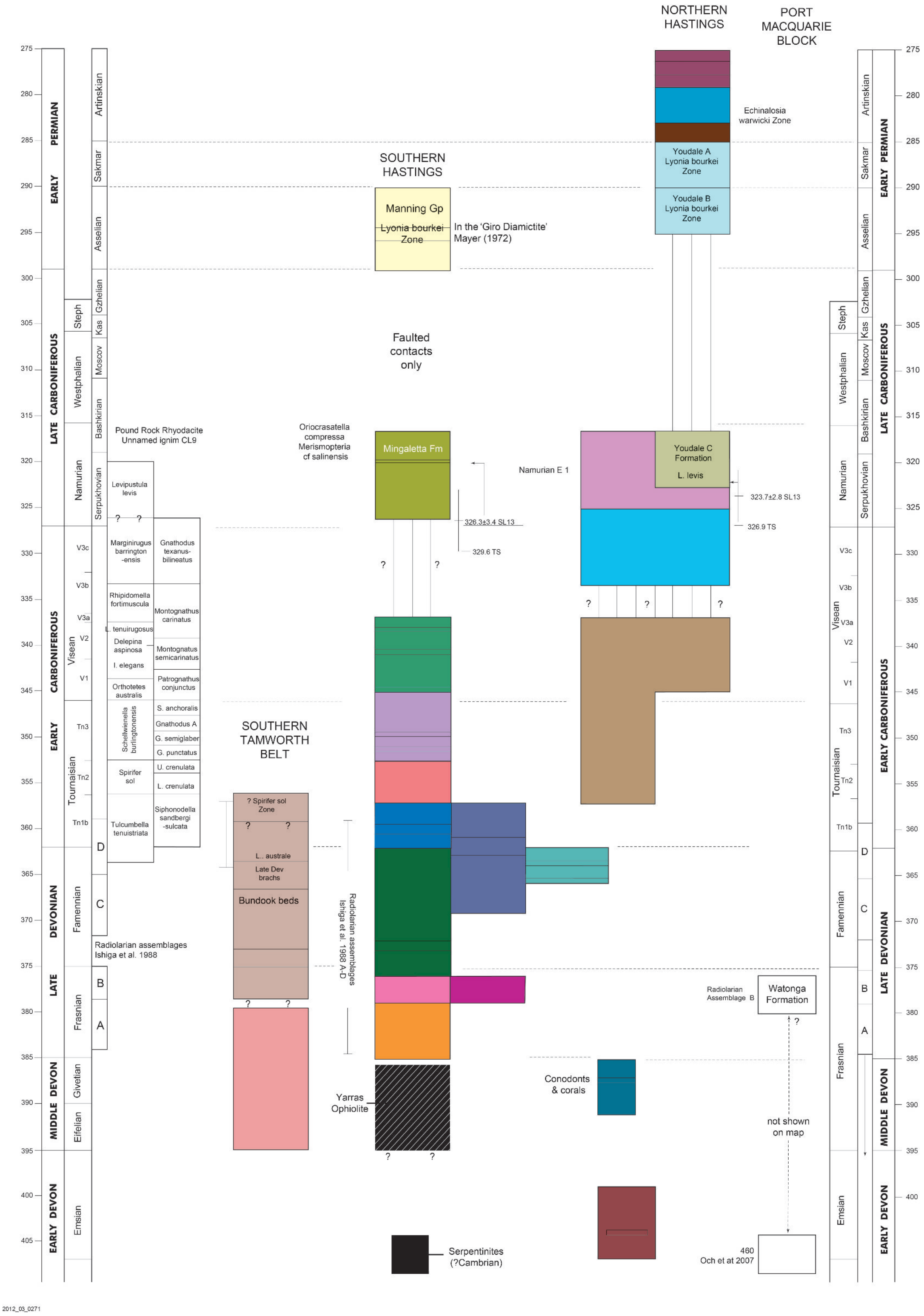
A key feature is the doubly plunging Parrabel anticline that occupies the northern part of the block (Lennox and Roberts 1988). This D2 fold deforms older (S1) cleavage and folds and is locally overprinted by D3 folds (Lennox and Roberts 1988). In the northern broad hinge, dips in Late Carboniferous strata range from 50 to 35° and in early Permian sequences from 60 to 28° (unpublished data, Roberts *et al.*). Early Permian shallow-water strata in the hinge of the Parrabel anticline pass northeastwards (across faults) into undifferentiated deeper water strata that comprise the multiply deformed and metamorphosed fill of the early Permian Nambucca rift basin (Lennox *et al.* 1999). The western part of the Hastings Block consists of an east-younging Devonian-Carboniferous sequence that passes from the Devonian Bitter Ground Volcanics, and associated ultramafic units, up into the Carboniferous Mingaletta Formation (Fig. 5).

In Appendix 1 we present our reinterpretation of the Hastings Block that is based on figure 2 of Roberts *et al.* (1995). We suggest that the Parrabel anticline is a hangingwall anticline above an east-dipping thrust sytem; that an east-younging sequence lies in the footwall of this thrust stytem; and that the whole packet has been probably thrust west over rocks of the subduction complex (Figs. 11a, b).

This sequence lies in the footwall of a major east-dipping major thrust represented by the Bagnoo Fault and its inferred extensions to the north. This thrust and the folded D1 thrust above flank a relict steeply north-plunging syncline that may be complementary to the Parrabel Anticline (Fig. 10a,b and Appendix A.).

Figure 5. Geology of the Hastings Block





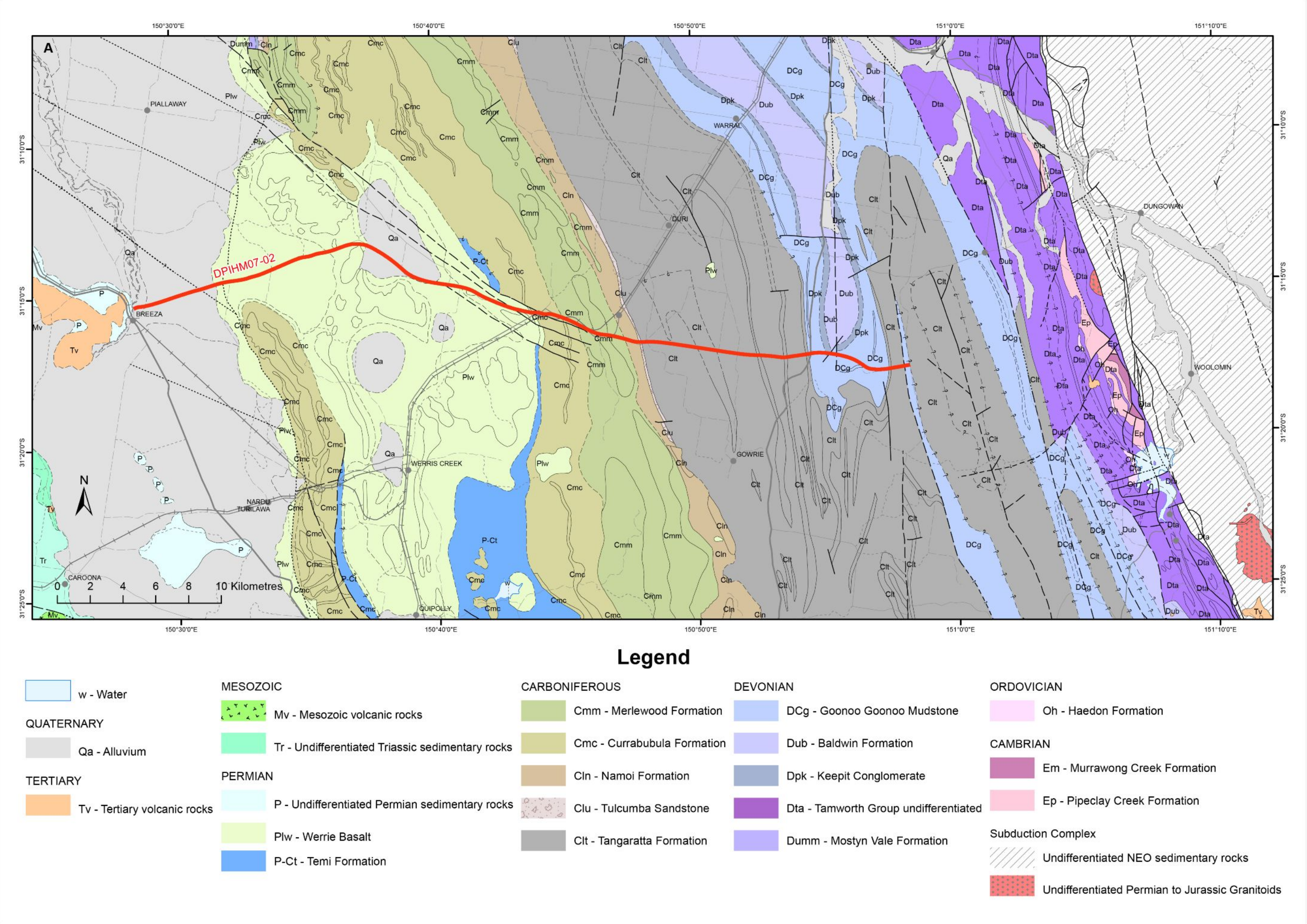
A. Geology of the Hastings Block, after figure 2 of Roberts et al. (1995). Abbreviations: BWF=Beechwood fault; CWF=Cowarral fault; LIF=Lake Innes fault; PAF=Pappinbarra fault; RRF=Rollans Road fault. B. Legend.

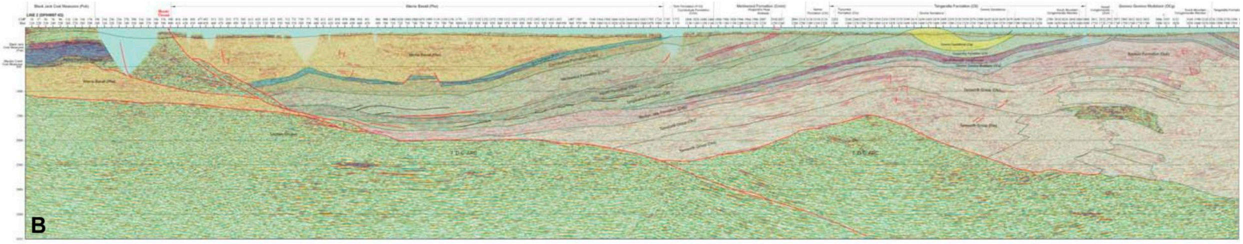
Northern Tamworth belt

The northern part of the Tamworth belt has a relatively simple geometry east of the leading, N to NNW-trending, 170 km long Mooki Thrust (Fig. 3). Traces of major thrusts and folds lie parallel to the eastern boundary of the forearc basin (except for possible local duplex formation, Woodward 1995), and are thus inferred to lie subparallel to the old continental margin. They reflect shortening at high angles to this margin.

An example of the structure of this region is shown in Fig. 6a in map view and 6b in section view. In section, the upper crustal architecture is controlled by an east-dipping detachment fault that has transported the forearc basin, over inferred basement of accreted Silurian–Devonian arc in the east and over a footwall in the west that is inferred to represent the missing and underthrust Devonian-Carboniferous arc. The detachment rises from a depth of ~3.5 seconds two-way travel time (~12 km) to become subhorizontal or shallowly dipping under the the lower coal measures or the underlying early Permian volcanics of the Gunnedah Basin (Fig. 6b). A stair-tread geometry produces regional folds in the hangingwall. The frontal Mooki Thrust splays off the detachment where it truncates the leading limb of frontal hangingwall syncline that is cored by Permian strata. An additional deeper detachment is inferred at the base of the accreted Silurian–Devonian arc of the Tamworth Group.

Figure 6. Representative part of the northern Tamworth belt





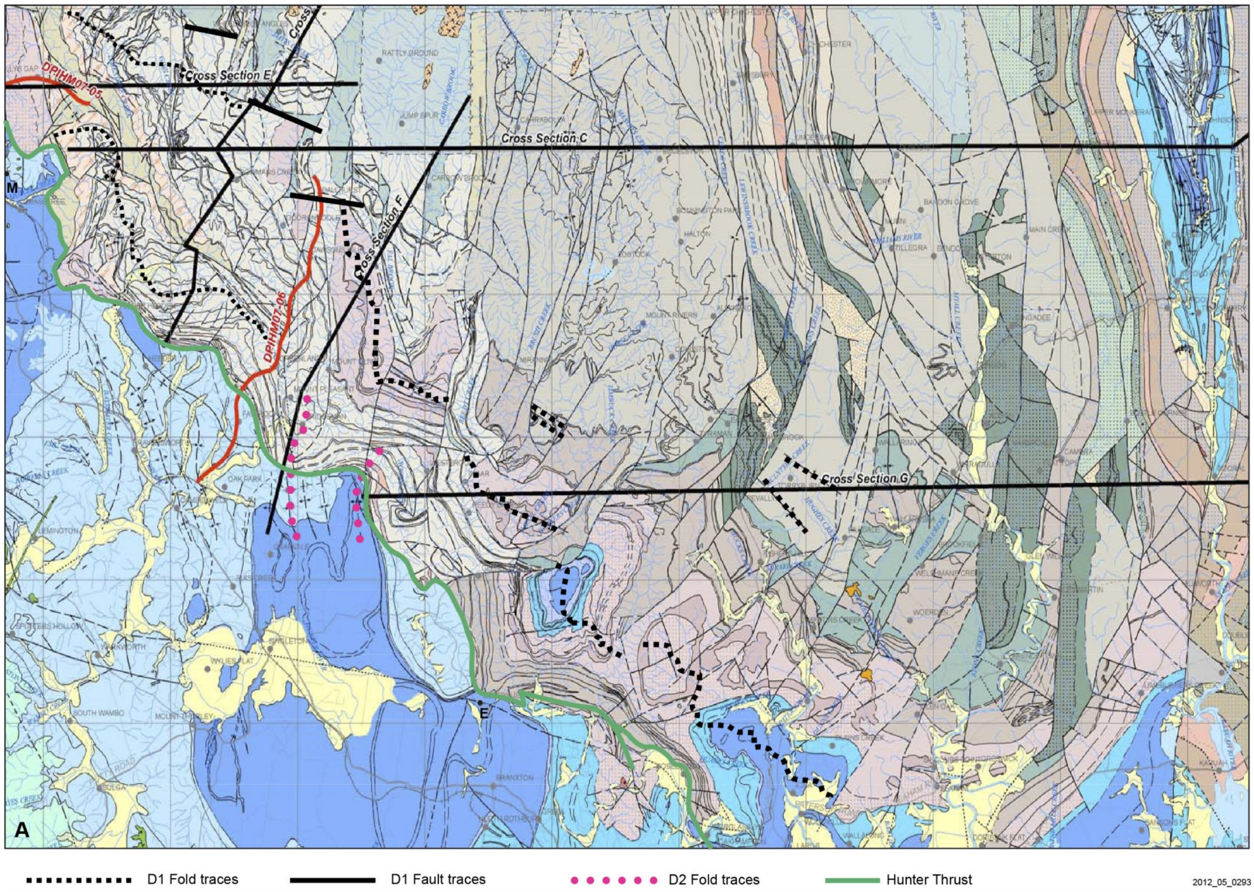
Representative part of the northern Tamworth belt showing A. simplified geology, and B preliminary interpretation of seismic section DPIHM07-02. Vertical scale is in seconds of two way travel time, with 1 sec approx = 3 km. Ratio is approximately 1:1.

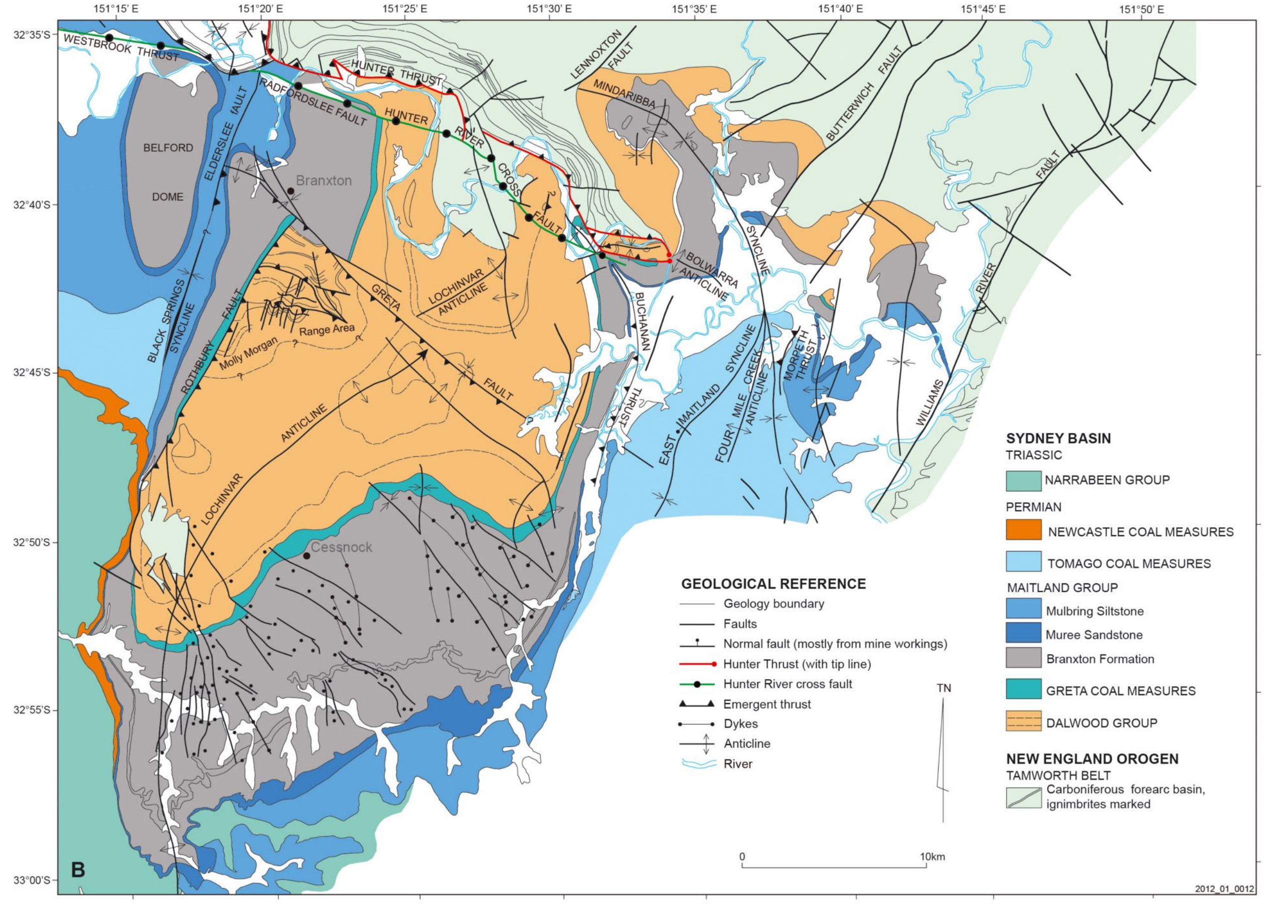
Southern Tamworth belt

Structures in the southern Tamworth belt are much more complex, reflecting multiple deformation in which structures parallel to the continental margin have been overprinted by younger structures that lie at high angles to the plate boundary.

The Hunter Thrust separates the Tamworth belt from the Sydney Basin. It trends south for 65 km from the Murrurundi Fault to Muswellbrook (Fig. 3), comprising individual segments cut by latitudinal cross structures (Glen and Roberts work in progress). South of Muswellbrook, the Hunter Thrust swings to the SE and ESE for ~70 km, and is not only folded (Glen and Beckett 1997) (Fig. 7a), but loses stratigraphic separation to the southeast before dying out in the Bolwarra Anticline, 3 km NNE of Maitland and 35 km WNW of Newcastle (Glen 1993) (Fig. 7b). As a result, Permian strata of the Dalwood Group to the northeast lie unconformably above forearc basin rocks (Fig. 7b). The greater complexity of deformation in this southern region reflects the overprinting of early orogen–parallel D1 structures by D2 folds and faults that have N and NE-trends in the west and N- to NNW trends farther east (Fig. 7a). D2 intensity increases from west to east. From the town of Muswellbrook eastwards to the town of Elderslie, D1 folds and thrusts can be can be easily recognised at map scale, despite being overprinted by D2 structures (Figs. 4, 7a). However, from Elderslie eastwards, mapscale D1 continuity is not so obvious. While present in between D2 faults close to the southern margin of the New England Orogen, continuity is lost in the northern part where more intense strain has produced panels of stratigraphy swinging from NNE to NNW (Figs. 4, 7a). Greater D2 strain occurs from the Stroud-Gloucester syncline eastwards to the coast where all the forearc basin units lie parallel to D2 thrust slices that fan in strike from N to NNW (Fig. 4). Since these D2 structures reflect approximately east-west contraction, cross sections drawn NE-SW lie parallel to D1 transport directions, whereas E-W sections reflect the D2 geometry and transport.

Figure 7. Southern Tamworth belt



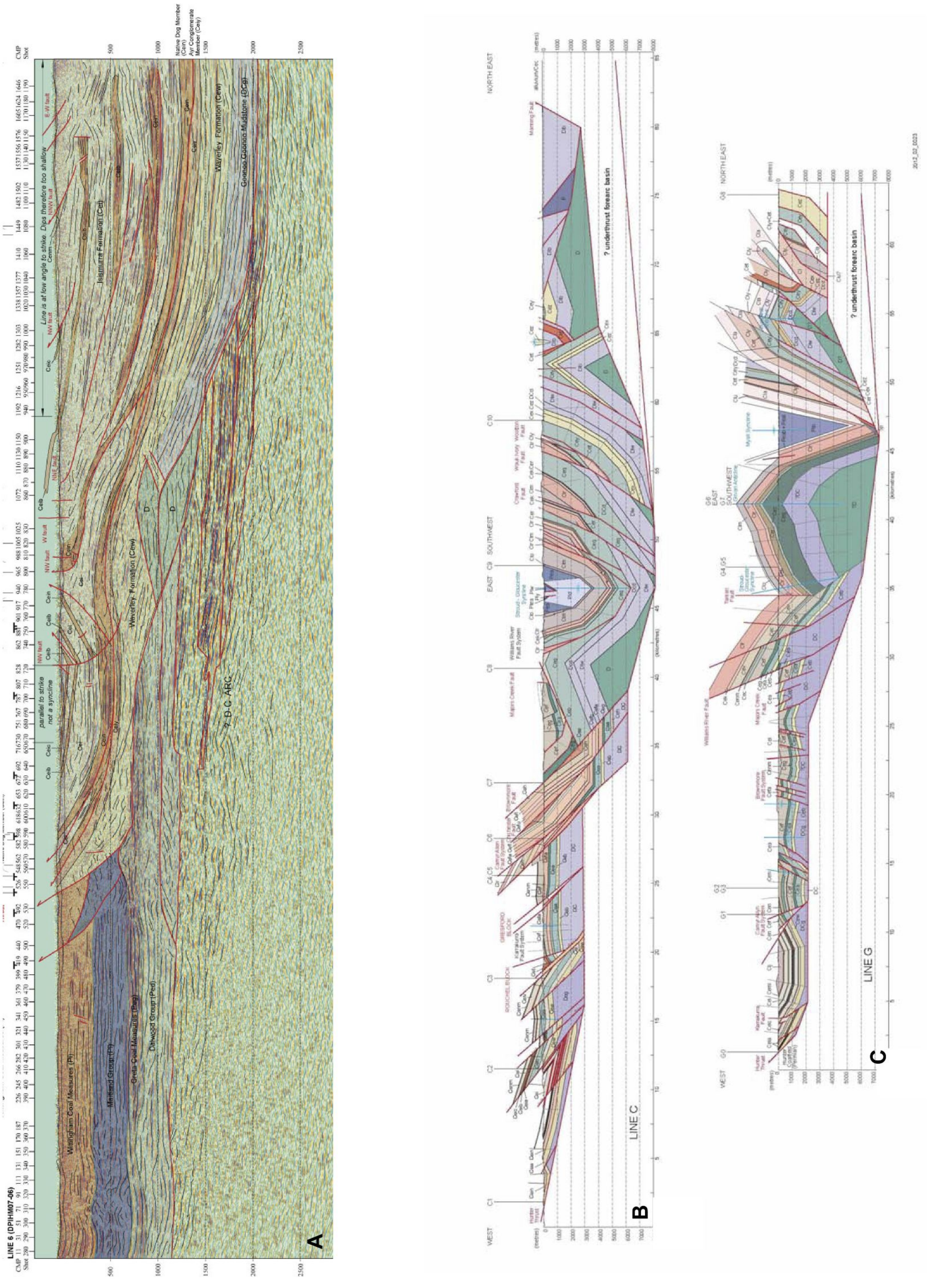


A. Simplified map of southern part of the Tamworth belt showing folded Hunter Thrust, separating blue Permian units to the south and coloured Carboniferous units to the north, and D1 structures folded by D2 structures. Blue-coloured units on easterm margin are the Stroud-Gloucester Syncline in the north and the Medowie faulted syncline in the south. Map faces north, with grid squares 10 km across. B. map showing southern termination of Hunter Thrust, and resultant conformable contacts between Carboniferous and Permian strata to the northeast (from Glen 1993).

Seismic section DPIHM07-06 (Fig. 7a) lies perpendicular to the Hunter Thrust and extends from the Sydney basin in the southwest into the forearc basin. The geometry of Fig. 8a shows that the upper 1 sec twt (~3 km) of the eastern part of the line is distorted by lying subparallel to regional strike. The lower part shows a regional NE-dipping detachment, with stair-tread geometry, that has transported the forearc basin over inferred reflective Devonian-Carboniferous arc volcanic rocks in the footwall.

Sections C and G (located in Fig. 7a) run west-east, approximately normal to D2 structures (Figs. 8b, c). In summary, they show a tripartite subdivision: a western, west-verging part, in which forearc strata, cut mainly by west-dipping thrusts, lie above a regional detachment; a central zone marked by a western anticline and eastern syncline, the latter cored by Permian strata, and shown as extending in depth to 7-8 km; and an eastern zone marked by east-verging thrusts inferred to overlie a west-dipping detachment with stair-tread geometry.

Figure 8. Cross sections through southern Tamworth belt



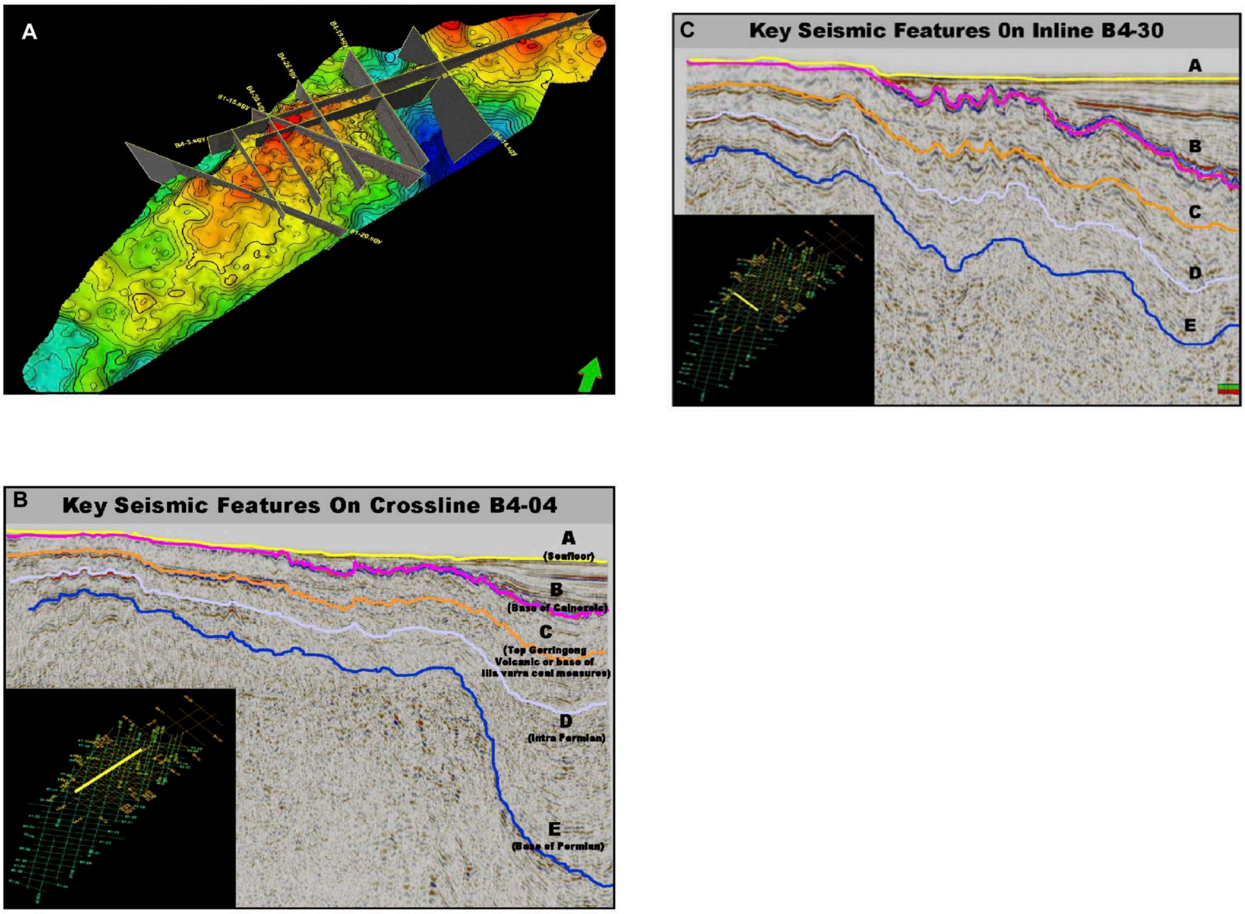
A. SW-NE preliminary cross section along seismic line DPHM07-06 and drawn perpendicular to D1 thrusts. B. Preliminary cross sections C and G drawn from west to east, perpendicular to D2 structures overprinting D1 thrusts in the southern part of the Tamworth belt. Geology of the Stroud-Gloucester Syncline has been simplified. For locations and key to letter symbols, see figures 4 and 7a.

Offshore Uplift

Diessel (1980) reported an easterly (offshore) source for late Permian sediments at Newcastle and Jones *et al.* (1984) suggested that this source was the offshore continuation of the New England Orogen (called the Currarong

Orogen) which had wrapped around the Newcastle recess. Petroleum exploration has provided more information. Offshore from the Sydney basin there are three main structures: the Offshore Syncline in the west, the Offshore Uplift in the east, and to its north, the Newcastle Syncline (Grybowski 1992; Bradley 1993; Alder *et al.* 1998; Bounty 2002; Breeze 2009) (Fig.1 b). Aeromagnetic data (Fig. 9a) suggest that the core of the Offshore Uplift has similar properties to, and is continuous (across the Newcastle Syncline), with the Carboniferous continental margin arc volcanic rocks at Port Stephens and the inferred volcanic centre that lay just to the south (Buck 1998) (Fig. 1b). Above these rocks are inferred Permian to Cainozoic strata (Breeze 2009) (Fig. 9b). Seismic interpretations (Alder *et al.* 1998; Breeze 2009) suggest that the Offshore Uplift has been thrust NNE over Permian strata in the Newcastle Syncline (Fig. 9b) in Permian times, with a similar overthrust relationship along the margin between the Offshore Uplift and the Offshore Syncline (Fig. 9c).

Figure 9. The Offhore Uplift



A. Aeromagnetic map of Offshore Uplift (see Fig. 1b for location and shape) passing NNE into Newcastle Syncline (blue colours) and then into volcanic centre south and at Port Stephens (Bounty Oil and Gas 2002). B and C interpreted seismic sections showing picks of key stratigraphic horizons, from Breeze (2009) with permission. B. Section oriented SW-NE from left to right, from Offshore Uplift into Newcastle Syncline. C. Section oriented WNW from left to right from Offhore Uplift into Offshore Syncline. Structural elevation in both sections is inferred to reflect the presence of dipping thrusts

Discussion

Manning and Hastings oroclines

The four separate datasets, described above, provide persuasive arguments for the presence of a southern Manning oroclinal hinge and a northern Hastings oroclinal hinge. Together these hinges define an orogen-scale, west-verging, sinistral fold pair with a wavelength of ~150 km. In summary, the four datasets are: i) rotation of the fault boundary between subduction complex rocks and the basement to the forearc basin, the Tamworth Group; ii) key Devonian-Carboniferous stratigraphic units, correlated on the basis of fossil and in situ zircon U-Pb SHRIMP ages, which can be tracked around the Hastings orocline and which extend south along the western limb that is shared with the Manning orocline. iii) The change in outcrop shapes of the early Permian overlap assemblage lying above subduction zone rocks and above the boundary between forearc basin and subduction zone rocks; and iv) the curvature of arc proximal rocks and their inferred offshore location.

Six points require further elaboration. Firstly, the forearc basin/subduction complex boundary outlines a southern, south-closing Manning orocline and is inferred to link outcrops of the boundary on opposite limbs of the Hastings orocline around the north-closing hinge before deposition of the early Permian overlap strata. Folding of this boundary around the Manning orocline is most clearly seen in greyscale 1VD image where it is outlined by ultramafic rocks emplaced within the intervening Peel-Manning Fault System (Fig. 1c). The vector pointing oceanward swings from easterly to westerly around the Manning Orocline and then back to easterly on the eastern side of the Hastings Orocline.

Secondly, there is a lack of continuity of forearc basin rocks around the Manning orocline. This reflects the break along the Taree Fault in the eastern part of the hinge zone (Figs. 3, 5), coupled with the strong D2 deformation in the hinge, where stratigraphy is broken up into a series of N to NNW-trending fault slices that fan around the hinge and which lie at high angles to the contact between the forearc basin and the subduction complex (Fig. 3). Map scale and cross section repetition of stratigraphy across these faults (Figs 4, 8b-c) rules out previous ideas wherein they were regarded as extensional faults on the outer arc of a regional fold. Many of these faults may have a strike-slip component to them that is not apparent from construction of cross sections and is not clear from degraded, sporadic outcrop.

Thirdly, amplitudes of the two oroclinal folds vary markedly along the traces of their hinge lines. At the arc/forearc datum line, these folds have smaller amplitudes and are much more open, involving much less limb rotation, than the at the forearc basin/subduction complex datum line (Fig. 1b). These relations suggest that: i) the involvement of the arc/forearc boundary in the oroclines means that emplacement of the Hastings Block in its current location was not simply due to translation and rotation of isolated blocks of the forearc along major faults (see later); and that ii) most of the folding strain was taken up in the more outboard strata, necessarily involving formation of decoupling horizons (see below).

Fourthly, our data do not extend into the subduction complex itself, which has undergone up to seven deformations (Dirks *et al.* 1992). As a result, we have no independent information from these rocks to indicate whether there is stratal rotation mirroring that suggested by the four datasets above. However, Cawood (1982) suggested that the dominant cleavage also rotated around the orocline, from a 190-200° trend in the west into a 140-150° trend in the east. Rosenbaum *et al.* (2012) briefly discussed the rotation of foliations in these subduction complex rocks, and noted general dips of 70 to 80º indicative of hinge areas. The faulted contact between forearc basin strata and subduction complex rocks in the hinge region of the Manning orocline implies there must have been mechanical decoupling between the two rock packages.

Fifthly, Rosenbaum (2010) and Rosenbaum *et al.* (2012) also suggested that the Manning orocline and the Hastings orocline (equivalent to his Nambucca orocline) are also outlined by rotation of granite bodies, linking the Bundarra suite (granite age 294-284 Ma) in the west with the Hillgrove suite (299 Ma to 287 Ma) in the east.

Sixthly, the presence of the Manning and Hastings oroclines implies that the Peel-Manning Fault System has been folded around both hinges. Although largely obscured by early Permian strata, Lennox and Offler (2009) showed discontinuous serpentinites wrapping around the Hastings orocline, although some of these are Devonian in age rather than Cambrian as occurs farther north along the Peel-Manning Fault System. In this interpretation, serpentinites in the Port Macquarie block and between that block and the eastern part of the Hastings Block are parts of the folded fault system, overprinted now in the east by WNW-trending faults.

We thus argue that there are two megafolds in the southern part of the south New England Orogen. The Hastings orocline is outlined only by strata in forearc basin: subduction complex rocks are obscured by early Permian rift basins. Folds in the hinge of this fold plunge both north and south (see Appendix A.), possibly a result of an earlier fold event. The Manning orocline is outlined by the curvature of serpentinites and Permian strata. The western limb of this orocline is outlined by folded stratigraphy, bedding surfaces, D1 faults and D1 fold axial traces. In the hinge and eastern limb of this orocline, D2 NNW-NNE structuring has destroyed map-scale evidence of bedding rotation, although outcrop scale D1 structures can still be identified.

These structural complications mean that neither the Manning nor the Hastings megafold fit the strict definition of Weil and Sussman (2004) that an orocline must have undergone vertical axis rotation. However, they fulfil another criterion, in that these folds developed from a linear orogenic belt. We thus follow Rosenbaum *et al.* (2012) in suggesting that the tem orocline can be broadened, in this case to cover structurally complex hinges involving multiple deformations.

Where did the Hastings block come from?

Most models of the New England Orogen agree that the original location of the Hastings block was south of its present location, and somehow connected to the southeastern part of the Tamworth belt. A critical question is whether the Tamworth belt and the Hastings block were ever physically connected, with continuity of strata before covering by early Permian overlap sequence, or whether they were they separated by major strike-slip and/or contractional faults. Roberts *et al.* (1995) used stratigraphic and facies differences to suggest there was similarity, but no continuity of strata between the Tamworth belt between the two. They concluded that the two regions, although not directly contiguous, formed in a sedimentary basin close to a major long-lived arc at or near the western margin of the New England Orogen. Thus, the Hastings Block is not an exotic terrane.

This conclusion precludes a palaeogeography wherein the Hastings Block was a simple along-strike extension of the most easterly part of the outcropping Tamworth belt, and that there was simple folding of continuous stratigraphy around both oroclines. Either a now-missing part of the forearc basin lay between them, or the Hastings Block formed farther from the arc, again with intervening strata missing. Where could these missing strata be? One possibility is in the footwall of the Taree fault that separates the Tamworth belt from the Hastings Block (Figs. 3, 5). Stratigraphic separation across the fault suggests reverse south-block up displacement of Famennian strata on the south against Carboniferous strata on the north, and Lennox and Offler (2009) presented evidence for left-lateral strike-slip. If the fault had a moderate to shallow southerly dip, the missing strata could lie in its immediate footwall.

Our preferred possibility, however, is that the missing part of the forearc basin has been overthrust from southwest to northeast (in the present reference frame) by the eastern part of the Tamworth belt, producing the east vergent structures and the west-dipping detachment in the cross sections C and G (Figs. 4, 8b, c). In this interpretation, the amount of missing forearc basin is ~40 km in section C and ~60 km in section G. These are minima assuming no imbrication or folding of the underthrust plate.

Timing of deformation

In the Hastings Block (Fig. 5), the earliest signs of uplift of the subduction complex and redeposition of detritus into Late Carboniferous (Namurian) strata of the forearc basin are recorded by clasts of high-level granite, slate, phyllite, minor quartzose sandstone and especially radiolarian chert, in the Majors Creek, Kullatine and Youdale (c) formations, although they are subordinate to dominant dacitic and andesitic material from the arc (Roberts *et al.* 1995). More direct constraints on this Namurian deformation of the subduction complex is provided by the ~311 Ma early metamorphism of sedimentary rocks in the Wongwibinda complex, west of the Nambucca Block (Fig. 3) up to 18 myr before emplacement of the ~293 Ma Abroi pluton (Craven 2010). Similarly, the Tia Granodiorite was emplaced at ~296 Ma, during the peak D5 deformation in the Tia complex (Fig. 3) (Dirks *et al.* 1992; Cawood *et al.* 2011b) and after ~318 and ~312 K-Ar white mica ages (Watanabe *et al.* 1988) that approximate D2 deformation (Dirks *et al.* 1992).

In the northern Hastings Block, deformation at the Carboniferous-Permian boundary is reflected by erosional unconformities between latest Carboniferous (Namurian strata, extending up to ~312 Ma) and Asselian strata

(300-295 Ma) and below Artinskian strata (~280 Ma) that are chert-bearing. At Cranky Corner in the southern Tamworth belt (Fig. 3), this Carboniferous-Permian deformation is recorded by a probable 13 m.yr. time gap between latest Carboniferous volcanogenic sedimentary strata (303.7 to 300.3 ± 2.4 Ma), and the oldest U-Pb SHRIMP age, 287.1 ± 2.4 Ma, in overlying late Asselian to early Sakmarian strata (Stevenson 2003; Claoué-Long and Korsch 2003). The widespread presence of chert detritus in the early Permian (Asselian to Artinskian, Briggs 1998) Manning Group, deposited across the boundary between the forearc basin and subduction complex in the core of the Manning orocline, attests to widespread continuous or intermittent deformation of the subduction complex during early Permian deposition.

Younger Permian deformation is well-defined at Cranky Corner in the southern Tamworth belt. Conglomerate in coal measures dated as upper Artinskian (approximately ~277 Ma) has eroded down into older Permian strata with SHRIMP ages of 285.4 ± 2.2 and 285.8 ± 3.0 Ma, suggesting a hiatus of ~7 million years (Balme and Foster 2003; Claoué-Long and Korsch 2003). Clasts of green chert and red jasper occur in this conglomerate, derived from uplift of the subduction complex (Stevenson 2003).

A minimum age for deformation of the southern part of the Tamworth belt is constrained by middle Permian strata in the D2 Stroud-Gloucester and Myall synclines located in Fig 3. In the Stroud-Gloucester Syncline, the youngest unit is a conglomerate with inferred palynology late stage 5, Kazanian to Tatarian flora. While Briggs (1998) suggested this boundary lay at ~257 Ma, Gradstein *et al.* (2004) showed it to be at 267 Ma and middle Permian. Middle Permian strata lie with an angular unconformity to disconformity on early Permian volcanics, with a time gap corresponding to the Artinskian and Kungurian stages (Roberts *et al.* 1991). Deformation is thus no older than 267 Ma. The Crowthers Road Conglomerate, the top unit in the Myall Syncline, contains detritus of chert as well as volcanic rocks from underlying units (Roberts *et al.* 1991), suggesting that regional deformation at this time affected the arc, the forearc basin and the subduction complex. This minimum age of deformation of the southern Tamworth belt is tightly constrained by the emplacement of the stitching Barrington Tops Granite SHRIMP dated at 267.2 ± 1.4 Ma (Cawood *et al.* 2011b).

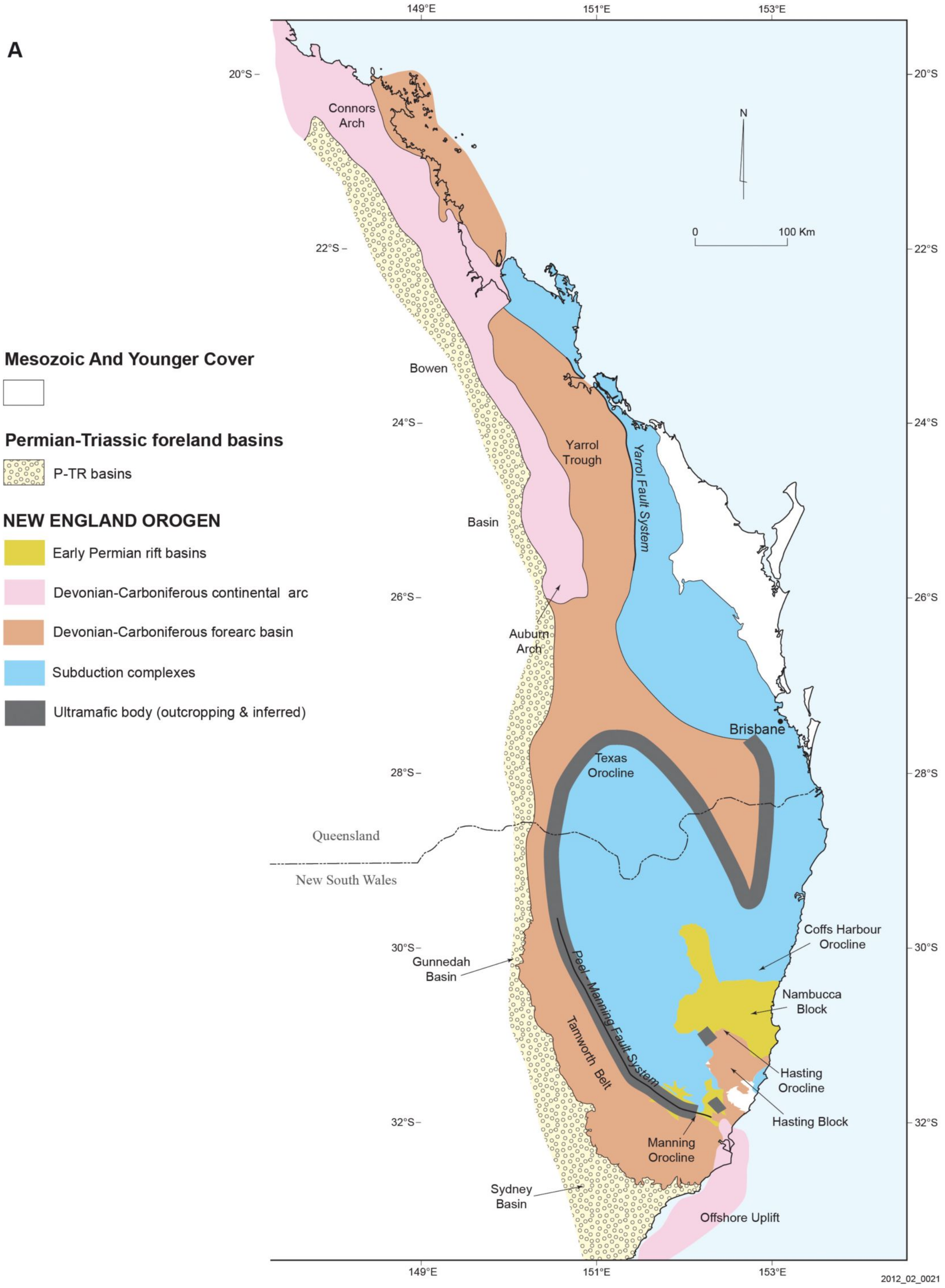
Other age constraints on oroclinal folding include; i) the folding of inliers of early Permian Manning Group around the Manning orocline. Briggs (1993) estimated an upper age on these units as Late Artinskian (~280-275 Ma); ii) onlap of Permian turbidites of the southern Nambucca Block onto the early Permian strata in the northern Hasting block; iii) formation of an S1, east-west cleavage in early Permian strata in the northern part of the Hasting block, correlated by Lennox *et al.* (1999) in age and orientation with east-west trending cleavages in the adjacent Nambucca block to the north and northeast. These cleavages have 260 Ma Ar-Ar cooling ages, following a deformation inferred at 264-260 Ma (Offler and Foster 2008); and v) folding of the early Permian (~280 Ma, Artinskian) Yessabah Limestone around the northern hinge of the D2 Parrabel anticline in the Hastings Block.

The last major ductile deformation recorded in the forearc basin occurs in the southeastern part of the Hastings Block where open folding occurred between deposition of late Early Triassic fluviatile strata and Late Triassic to Early Jurassic intrusions has also deformed the underlying Carboniferous strata (Pratt 2010).

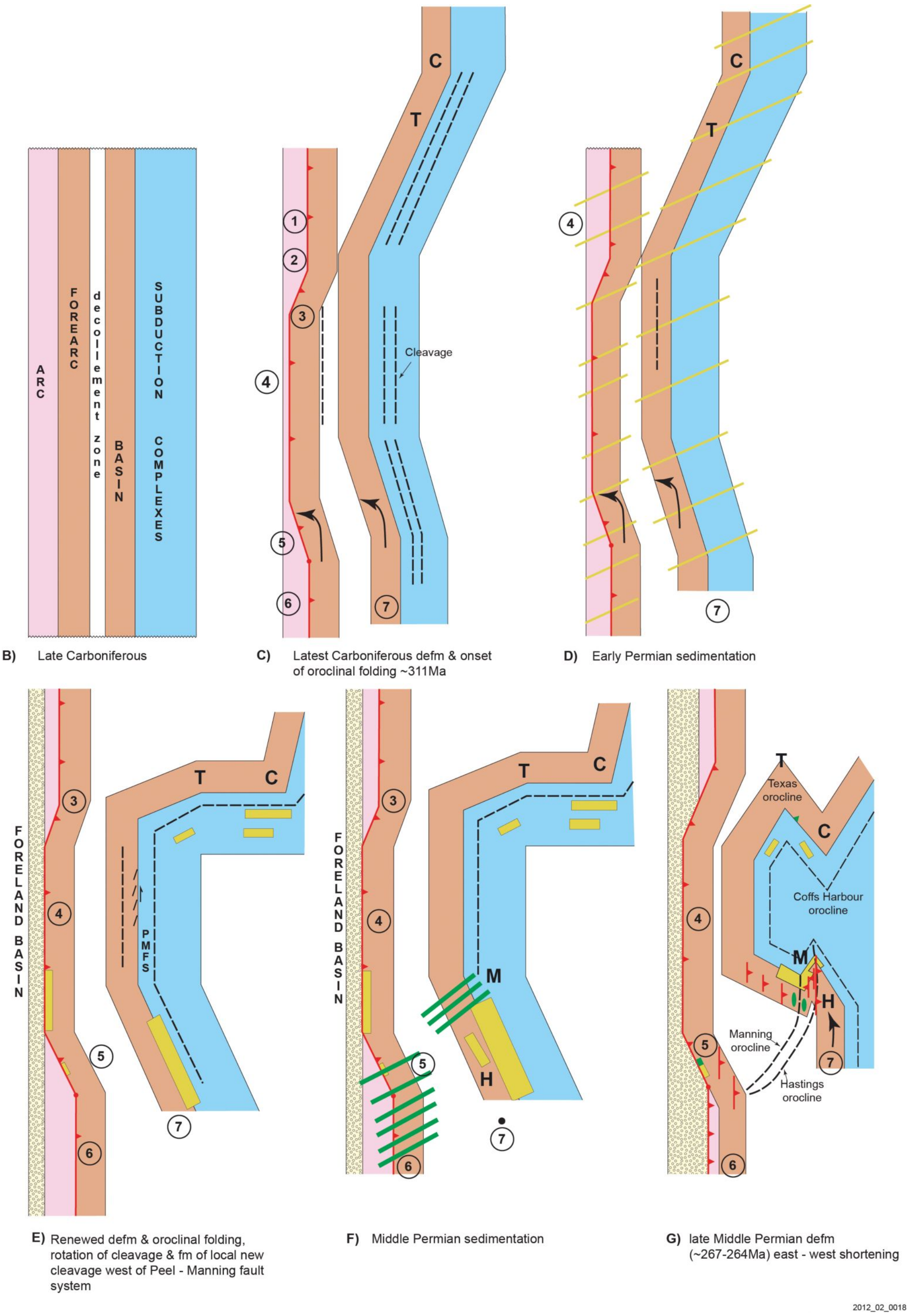
A new model of oroclinal folding

Our new model of oroclinal folding is based on coupling new structural datasets (the recognition of thrust geometry, the recognition of two deformation phases in the core of the Manning orocline, and the new interpretation of the Hastings Block) with previous ideas on sedimentary facies distributions in the forearc basin, and also taking the Offshore Uplift into account. Our model suggests that oroclinal folding not only affected the subduction complex and forearc basin, but also the interface between the arc and the forearc basin. We use the variations in shortenings along the inboard edge of the New England Orogen as indicators of more general variations in shortening in the New England Orogen, but we admit that this point needs to be more thoroughly tested. Finally, interpretations of our datasets, which suggest fold–dominated rotation of blocks and minimal translations, differ from models invoking strike-slip fault displacements of hundreds of kilometres, guided in many cases by interpretation of palaeomagnetic data.

Figure 10. Cartoon showing preferred model for the evolution of oroclines in the New England Orogen.



A. Simplified regional map of the whole New England Orogen, based on figure 1b, but showing tectonic elements interpreted beneath Mesozoic and younger cover that obscures join between northern and southern parts of the orogen. Western margin of forearc basin based on Korsch et al. (2009); eastern margin based on interpretation of figure 1c.



B) Late Carboniferous

C) Latest Carboniferous defm & onset of oroclinal folding ~311Ma

D) Early Permian sedimentation

E) Renewed defm & oroclinal folding, rotation of cleavage & fm of local new cleavage west of Peel - Manning fault system

F) Middle Permian sedimentation

G) late Middle Permian defm (~267-264Ma) east - west shortening

B-G. Outline model for orocline formation. See text for descriptions. Yellow stripes in D indicate approximate area of early Permian sedimentation; preserved areas are shown in yellow polygons. Green stripes in F indicate approximate area of middle Permian sedimentation; preserved areas are shown in green polygons in G. Note that in G, green middle Permian strata on the eastern side of the Texas orocline represents the Gilgurry Mudstone that postdates megafolding. Other schematic green outcrops in G predate east-west shortening. Abbreviations: C=Coffs Harbour orocline; H=Hastings orocline; M=Manning orocline; T=Texas orocline.

Our model of the Manning and Hastings oroclines suggests that the stratigraphy in both hinges formed in nearby, but not contiguous, parts of forearc basin. The simplest configuration is one in which the two sequences were along strike from each other but separated by an unknown distance. We suggest this minimum distance was

40-60 km. Imposed on this stratigraphic architecture is a structural one, in which the forearc basin was converted to a largely west-vergent fold thrust belt, developed above one or more crustal detachments. Largely north to northeast-dipping bedding panels in D1 thrust sheets were increasingly overprinted towards the hinge of the Manning orocline by D2 NNW to NE-trending, west-dipping structures (Glen and Roberts 2010).

The model begins with a ~2000 km largely linear Carboniferous convergent margin now deformed as sshown in Fig. 10a. We develop it, somewhat simplistically, in subsequent figures 10b to 10g, with discrete deformation pulses, but are aware that these might have been continuous. We focus on the southern segments of this margin as possessing a simple linear meridional configuration (western arc, central forearc arc basin and eastern subduction complexes) (Figs. 10a, b). Because the major mismatch in orocline geometry between two datum lines referred to above requires the development of internal discontinuities in the forearc basin during deformation, we have shown the forearc basin in two parts, separated by this ‘future’ decollement zone.

Early shortening in the forearc basin and subduction complex, which we suggest was associated with the first stages of orocline formation, occurred in the latest Carboniferous, below regional Permian unconformities and during waning subduction or after cessation of subduction at ~305 Ma (Fig. 10c). We attribute the subvertical dips of bedding and (sub) parallel cleavage in the Texas and Coffs Harbour oroclines (Lennox and Flood 1997; Korsch 1993) to this deformation (Fig. 10c), although fabric and steepening could have formed during earlier accretion. Similarly, we suggest that the sporadically developed regional cleavage in the Tamworth belt might be of this age. As part of this deformation, we show the first stages of westward thrusting of the forearc basin over arc rocks (Fig. 10c). Different amounts of shortening must have been a feature of the system and this is shown somewhat simplistically in Fig. 10 by how much of the arc has been overthrust by the forearc basin. Thus the NE-tending segment 3 links lesser amounts of shortening in segment 2 to the north with more shortening in segment 4 to the south. Similarly, segment 5, represented by the frontal Hunter Thrust, is pinned to the south in a structural recess, but increases in displacement as it sweeps to the north, to link with more shortening in segment 4. This event was followed by deposition of early Permian sedimentary and volcanic rocks in rifts or transtensional basins above this deformed package (Fig 10d), the latter increasingly characterised by backarc and MORB-type signatures, as the plate boundary retreated eastwards.

The second phase of shortening occurred in the late early Permian, around 284-277 Ma, constrained by Permian strata folded around the Texas orocline (Lennox and Flood, 1997; Li *et al.* 2012) and by the unconformity in the southern Tamworth belt. We suggest that this deformation involved renewed westward thrusting of the forearc basin over the arc, in segment 4 especially, the beginning of major folding in the Texas and Coffs Harbour oroclines, and the deformation of Permian overlap strata to form outliers along or near the forearc basin/subduction complex boundary (Fig. 10e). Formation of the Peel-Manning Fault System, containing early Palaeozoic lithologies in a serpentinite matrix, occurred then, with limited left-lateral kinematics reflected by a NE-trending cleavage along some eastern parts of the forearc basin (eg. Cao and Durney, 1993). This was followed by deposition of middle Permian strata (Fig. 10f).

Tightening of the Texas and Coffs Harbour oroclines, and final formation of the Manning and Hastings oroclines, is attributed to the middle Permian (Fig. 10g). In the Manning orocline, this deformation postdates 267-264 Ma sedimentation that is stitched by a 267.2 ± 1.4 Ma granite. The Hastings orocline may be a few million years younger, folding an early cleavage correlated with the 264-260 Ma cleavage in the Nambucca block to the north. In segment 5, this shortening is reflected by formation of D2 folds and thrusts, overprinting D1 structures, the tightness and displacement of which increase towards the hinge of the Manning orocline, increasing the outcrop width of the forearc basin (Fig. 10g). Thrusting of southern Tamworth belt a minimum of ~60 km northeast over the ‘southwestern part’ of Hastings Block is a late part of this D2 deformation, and is responsible for juxtaposition of different forearc basin packages against each other.

The amplitude of the Texas and Coffs Harbour oroclines is magnified by post-granite dextral slip on the N-trending Demon Fault, although this is estimated to be only ~ 17 km (Korsch *et al.* , 1978) or ~23 km (McPhie and Fergusson, 1983). The amplitude of the Hastings orocline is magnified by plunge changes in the Hastings Block, where variable and low plunges (Lennox and

Roberts 1988) contrast with subvertical dips in subduction complex rocks in the Coffs Harbour and Texas oroclines, though in the latter Lennox and Flood (1997) showed low plunges in folded Permian outliers.

As this stage we cannot be certain about the causes of the variations in shortening directions and amounts outlined in Fig. 10. We cannot tell whether they reflect changes in the direction of push from the plate boundary, or were caused by irregularities in the underlying basement (Devonian–Carboniferous arcs or older Lachlan orogen crust). Because we think the bulk of orocline bending occurred during a lull in continental arc magmatism, coeval with the formation of rift basins and changes in volcanic geochemistry from subduction to rift to MORB-like, we suggest it occurred during rollback of the plate boundary. Such an environment, with less coupling between plates, would have allowed the spatial freedom for orocline formation to occur (see for example a modern example, in Rosenbaum and Lister 2004). Our working model is thus that the variations in shortening reflect an irregular continental margin, with embayments and promontories in the continental margin, corresponding to salients and recesses in the thrust belt, which influence the amounts and directions of maximum shortening. These irregularities must underlie shape variations in the foreland basins, implying that at deeper levels, soft or hard-linked weak zones of flowage occur below the basal detachments that propagated west of the forearc basin into the foreland basins.

This shortening model for the formation of New England Orogen oroclines differs from most previous models in which the megafolds were inferred to have developed in response to sinistral or dextral simple shear on a major N to NE to NNW-trending master fault located either onshore or offshore. These models are now discussed and commented upon.

Previous orocline models for the New England Orogen

Murray (1997) summarised the evolution of ideas that led from the concept of simple cross faulting to the recognition of oroclinal bending in the southern parts of the New England Orogen. Korsch and Harrington (1987), Harrington and Korsch (1987), Cawood and co-workers and Collins *et al.* (1993) recognised only three oroclines: Texas, Coffs Harbour and Manning. Lennox and coworkers and Offler and Foster (1998) argued that Manning orocline did not exist, but accepted that the Hasting Block was most likely allochthonous in its current position. Rosenbaum *et al.* (2012) supported the presence of the Texas, Coffs Harbour and Manning oroclines, and recognised the northern expression of the Hastings orocline (Nambucca orocline).

Dextral strike-slip models

Murray *et al.* (1987) suggested the Texas and Coffs Harbour oroclines formed by dextral slip on an inferred Gogango-Baryulgil Fault At the same time Harrington and Korsch (1987) proposed that oroclinal bending occurred in response to dextral strike-slip faulting, but they argued that the Mooki Thrust was the master fault. Lennox and Flood (1997) suggested dextral transpression in eastern Australia occurred in a broad shear zone oriented SE-NW. Offler and Foster (2008) inferred oblique subduction on the plate boundary. Instead of partitioning deformation with formation of a dextral fault onland, these authors invoked pinning in the south, which led to buckling of the subduction complex about a vertical axis. Vertical axis rotation is consistent with subvertical dips measured in subduction complex rocks in the hinge of the Coffs Harbour orocline (Korsch 1993) and with subvertical folds and intersection lineations in the hinge of the Texas orocline (Lennox and Flood 1997; Li *et al.* 2012). There, Lennox and Flood (1997) showed that bedding in the subduction complex had been folded about an axis plunging at 76°-164°, with cleavage folded about an axis plunging 82°- 316°. More recently, Li *et al.* (2011) recorded a fold axis in S1 cleavage plunging 80° - 255°. Lennox and Flood (1997) also reported that the intersection (=fold) lineation in Permian outliers around Texas orocline plunged at 28° - 315°, implying steepening of bedding dips in subduction complexes before the Permian. Lennox and Flood (1997) also reported a weak fanning S2 cleavage and an overprinting E-W S3, but Li *et al.* (2011) did not record any penetrative S2 cleavage. The dextral model for the Texas and Coffs Harbour oroclines of Li *et al.* (2011) suggested that oroclinal folding at 280-265 Ma occurred in response to dextral strike-slip on an offshore meridional fault. This folding was followed by <265 Ma E-W shortening and was imposed upon a non-linear margin, either acquired during early Permian rollback of the subduction zone or to an older palaeogeography.

Sinistral strike-slip models

In contrast to the views above, several authors suggested that the New England oroclines formed by strike-slip movement on sinistral faults in response to a change in the nature of the plate boundary from convergent to transform. Cawood (1982) and Cawood and Leitch (1985) suggested that the Hastings Block originally formed immediately south of the southern Tamworth belt. Cawood (1982) invoked sinistral strike-slip movement on a series of rotating N-NNW-trending faults to produce the Parrabel anticline in the Hastings Block and the broad curvature of the southern Tamworth belt. Collins *et al.* (1993) extended the reconstruction of Cawood and Leitch (1985), suggesting that the Hastings Block originated ~500 km south of the southern Tamworth belt, and underwent ~1000 km of northward translation, accompanied by anticlockwise rotation. Collins *et al.* (1993) also suggested that the Nambucca block had been translated northwards along with the Hastings Block, in contrast to previous ideas that the block formed in situ and that the E-W structural fabric (Leitch 1978) formed by squeezing it between the northward-moving Hastings Block and the southward-moving Coffs Harbour block (eg. Scheibner 1976) (see Offler and Foster (2008) for a counter argument). Based on palaeomagnetic measurements, Schmidt *et al.* (1994) favoured a clockwise 130°rotation of the Hastings Block as part of any displacement.

The reconstruction of Cawood al. (2011b) was guided by existing palaeomagnetic data, which they pointed out were limited in nature and thus incapable of producing an unequivocal tectonic model. However, they noted that these data suggested that dextral strike-slip models were not permissible, whereas sinistral translation was permissible. Their model was able to generate all four of the oroclines by buckling in response to sinistral movement along an offshore NNW-trending fault, the tip point of which lay in the core of the Coffs Harbour orocline. Figure 5 of their paper envisages large scale displacements, with the Hastings Block forming 1600 km south of present location, the southern Tamworth belt 1080-830 km to south, and the northern Tamworth belt and Texas block 470-400 km to the south of their present locations. In addition to this northward movement, their figure 5 suggests that there were hundreds of kilometres of westwards movement: the hinge of Texas orocline was translated 340 km; the north Tamworth belt 440 km and the hinge of Manning orocline 400km.

Timing of oroclinal bending

Murray *et al.* (1987) suggested that the New England oroclines formed in the latest Carboniferous (310-300 Ma). However, more recent papers favoured formation in the Permian, before emplacement of the large, latest Permian–Triassic granites of the New England Batholith. Offler and Foster (2008) suggested that the Texas and Coffs Harbour oroclines formed between 273 and 260 Ma. Rosenbaum *et al.* (2012) suggested formation between 295-285 Ma and a second phase prior to ~260 Ma. Cawood *et al.* (2011b) suggested that oroclinal bending occurred between 270 and 265 Ma. In contrast, Aubourg *et al.* (2004) argued that in the Texas orocline, ~40° of rotation had occurred before extrusion of volcanics in one of the deformed early Permian outliers, with a further ~80° rotation afterwards. They further showed that this rotation had been overprinted by the ‘Kiaman’ reversal dated at ~265 Ma, and predating deposition of flat-lying late Permian strata in the Emu Creek Block. However, the age of these strata is controversial. Briggs (1998) suggested that these sedimentary rocks had a maximum age of ~252 Ma, whereas Waterhouse (1967) suggested a late Kungurian or early Kazanian age, i.e. around 270 Ma (Gradstein *et al.* 2004).

Comparison with previous models

Our fold model above considers that the Hastings block arrived at its (near) present position due to oroclinal folding coupled with underthrusting. This is not compatible with models in which the Hastings block is inferred to be a separate terrane that drifted in along faults (eg. Cawood 1982; Collins *et al.* 1993; Schmidt *et al.* 1994) and underwent rotation as a separate microplate. The rotation model of Schmidt *et al.* (1994) favoured a clockwise 130° rotation of the block to restore it to the Carboniferous part of the Gondwana Apparent Polar Wander path (APWP), but they indicated that a 230° anticlockwise rotation was also possible. This was placed in a context wherein the southern Tamworth belt was subdivided by facies into three structural blocks separated by N to NE-trending faults ~ 40 km apart (Roberts et al. 1991). Geeve et al. (2002) used palaeomagnetic data to infer these blocks had undergone anticlockwise rotations of 80°, 80° and 120°. However, the continuity of stratigraphy coupled with two generations of thrusting (see above) allow the possibility that the vertical axis rotations are the result of D2 overprinting D1 thrusts with variable displacements in segment 5 of Fig. 11. As a result, we suggest the limb rotation of our model is ~90-120° anticlockwise. This amount is closer to the anticlockwise rotation of ~150° suggested by Klootwijk (2009) if the block is rotated back to the Klootwijk-Giddings (KG) variant of the Gondwana APWP rather than the Schmidt-Li-Powell (SLP) variant used by Schmidt *et al.* (1994).

Although it did not discuss the Manning or Hastings oroclines, the model of Li *et al.* (2011) has two similarities with our model. Firstly, it envisages multiphase orocline formation, beginning before the Permian. Secondly, it discusses the possibility that the early phase may have involved a non-linear margin of Gondwana. The model by Rosenbaum *et al.* (2012) also has some similarities. It envisages enhancement of a primary curvature during variable early Permian roll back of the plate boundary to the northeast, accompanied by dextral strike-slip faulting offshore followed by fold tightening during E-W shortening and re-establishment of subduction.

Our model of minimal displacements is an alternative to the large displacement model of Cawood *et al.* (2011b). They suggested that the arc, forearc and subduction complexes in the northern (Queensland) part of the orogen were autochthonous, whereas those in the southern (NSW) part of the New England Orogen were allochthonous. Beginning at ~275 Ma, their model involved translations of 1600-~500 km northwards and ~400 km westwards, with convergent margin elements presumably thrust onto the pre- or early Permian Gondwana margin. These north-to-south differences, however, do not appear to be reflected in the evolution of the Permian-Triassic Bowen-Gunnedah-Sydney basin system to the west. The >1200 km long, latest Carboniferous-early Permian volcanic-filled, mid-crustal rift (Meandarra gravity ridge) that marks the beginning of this basin system extends from the beneath the Sydney basin to beneath the central part of the Bowen basin without deflection (Krassay *et al.* 2009). And foreland basin loading phases of the Bowen Basin (in Queensland in the north) and the Gunnedah Basin (in NSW in the south) show parallel and similar sedimentary development (Brakel *et al.* 2009; Totterdell *et al.* 2009). Movement of elements of the southern New England Orogen 400 km to the west would thrust them above crust of the Lachlan Orogen that lies west of the New England Orogen, thereby leading to possible Lachlan sources for granites in the western parts of the New England Orogen. Both Chappell (1994) and Shaw *et al.* (2011) have emphasised the differences between Lachlan and New England Orogen granites, although the Bathurst granites in the Lachlan Orogen have some similarity to the Mooki granite in the New England Orogen.

Finally, although we are unable to differentiate between deformation and uplift of subduction complex rocks and oroclinal bending at ~311 Ma, our suggestion for latest Carboniferous onset of oroclinal folding is similar to the suggestion of Aubourg *et al.* (2004) that formation of the Texas orocline began before early Permian sedimentation at ~299 Ma. Li *et al.* (2012) have also suggested prolonged formation of the Texas and Coffs Harbour oroclines, with the first phase inferred to be synchronous with, or older than, Carboniferous subduction.

Conclusions

1. Late Devonian to Late Carboniferous volcanism in the forearc basin of the southern New England Orogen involved a diachronous change in the nature of volcanism from intermediate to felsic in different volcanic centres: at the ~Devonian-Carboniferous boundary (~360 Ma) in the Tamworth belt, but Visean to Namurian (~325 Ma) in the Hastings Block. This change was associated with uplift in the forearc basin in both regions, recorded by a change to shallow and non-marine deposition, above an unconformity and short time break in the Hastings Block. The youngest arc rocks are 305 Ma in the Tamworth belt.

2. The complex Manning and Hastings oroclines exist. Together with the simpler Texas and Coffs Harbour oroclines to the north, they form four oroclinal hinges that may have begun forming in the latest Carboniferous, and which had completed, either intermittent or continuous, oroclinal bending, except for minor local deformation in the latest early Triassic, by 267-264 Ma. Deformation in the earliest Permian was synchronous with deposition of sedimentary rocks containing Late Devonian cherts from the subduction complex, mixed with /recycled volcanic + granite detritus.

3. If the early Permian turbidites of the Nambucca block are largely in situ and continuous (across ?rift margin faults) with shallow- water sediments in the hinge of the Parrabel anticline (Hastings Block), then the unconformity above latest Carboniferous strata indicates that the Hastings Block had already begun rotating, and was largely coupled to the Nambucca block, by the earliest Permian.

4. Final formation/modification of the Manning orocline occurred in the middle Permian by 267-264 Ma, and was accompanied by strong D2 faulting, that produced NNE to NNW-trending thrusts fanning around hinge (forming discontinuities in outcrop patterns) and overprinting older D1 orogen-parallel structures. The resultant NNW-trending structurally repeated strips of forearc stratigraphy in the hinge of the orocline lie at high angles to the fault between the forearc basin and the subduction complex, implying mechanical separation between the two units. This D2 event is similar in age to final formation of the Texas orocline, that is overprinted by the ~265 Ma Kiaman palaeomagnetic reversal.

5. East-west shortening, completed by ~267 Ma, predates resumption of subduction magmatism as measured by emplacement of I-type granites of the New England batholith, beginning at ~ 255 Ma. Unless there was a ~10 myr lag time in melt generation and emplacement, D2 east-west shortening does not appear to be linked to the resumption of subduction and thus to development of stronger coupling across the plate boundary.

6. The Hastings orocline was formed by 90-120° anticlockwise fold rotation of the Hastings Block within the deforming forearc basin. Stratigraphy and facies changes suggest that the Hastings Block was not exotic but formed in the Devonian to Carboniferous forearc basin, close to, but not in contact with, the Tamworth belt. Changes in regional vergence in two cross sections suggest that the missing connections may have been overthrust by the eastern part of the Tamworth belt by ~60 km.

7. The opposite senses of rotation vergence for the two pairs of oroclines, anticlockwise for the Manning and Hastings and clockwise for the Texas and Coffs Harbour, have led to published models in which they formed due to dextral or sinistral displacement on a major fault located either onshore or offshore. However, we suggest that the oroclines reflect buckle folds responding to variable shortening within the forearc basin and subduction complex. These variations are continuous along axial traces with smaller amplitude changes in amounts and directions of shortening on the inboard margin of the forearc basin.

8. Changes in shortening occur in an otherwise linear belt some 2000 km long that became the site of renewed subduction magmatism in the late Permian, with arc and backarc granite roots cutting across oroclines and emplaced into subduction complex rocks.

9. The timing of the bulk of orocline formation, during inferred rollback of the plate boundary, leads us to suspect that the changes in amounts and directions of maximum shortenings developed in response to recesses and/prominences in the continental margin, rather that just to plate boundary-induced variations.

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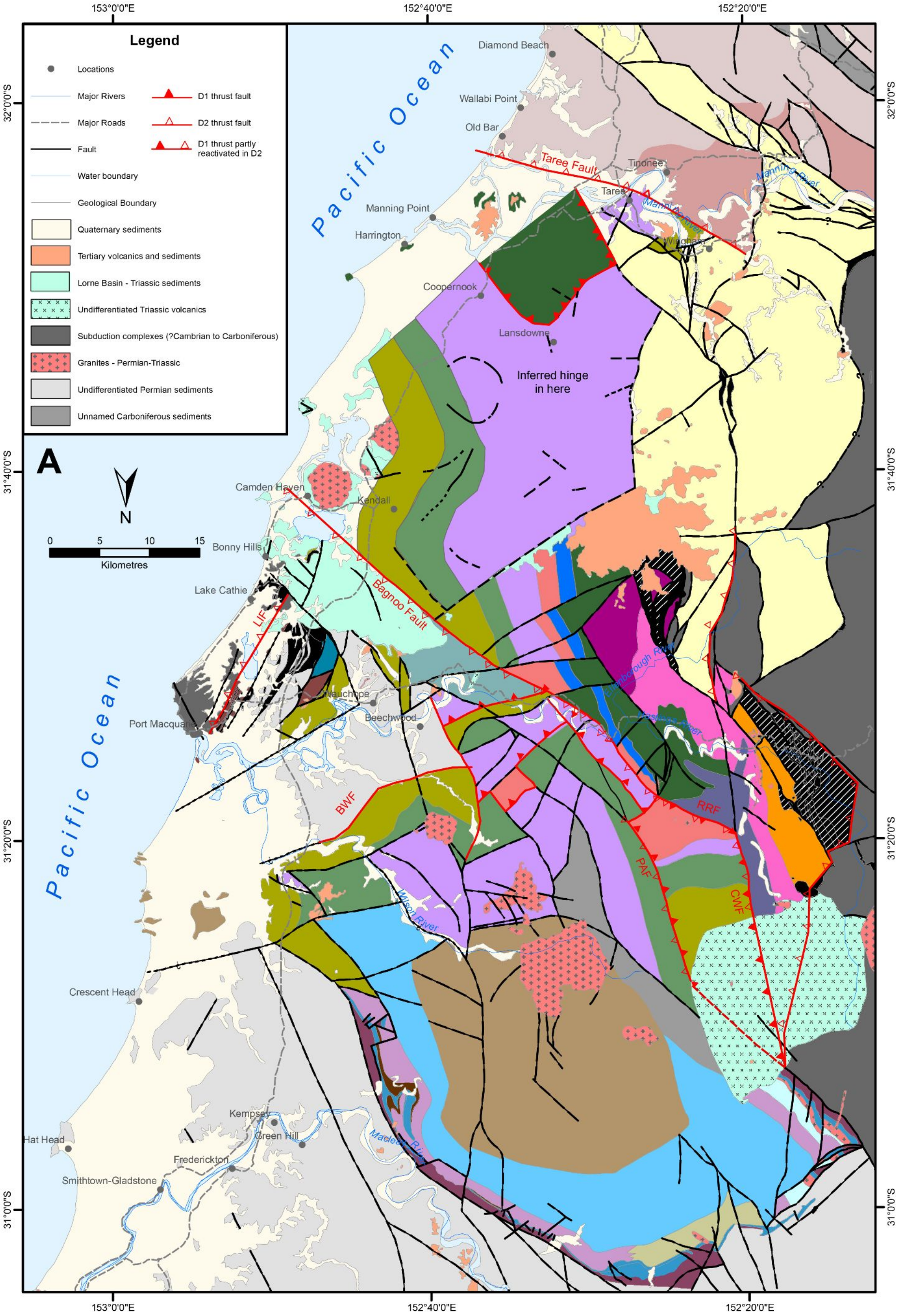
A. Geology of the Hastings Block

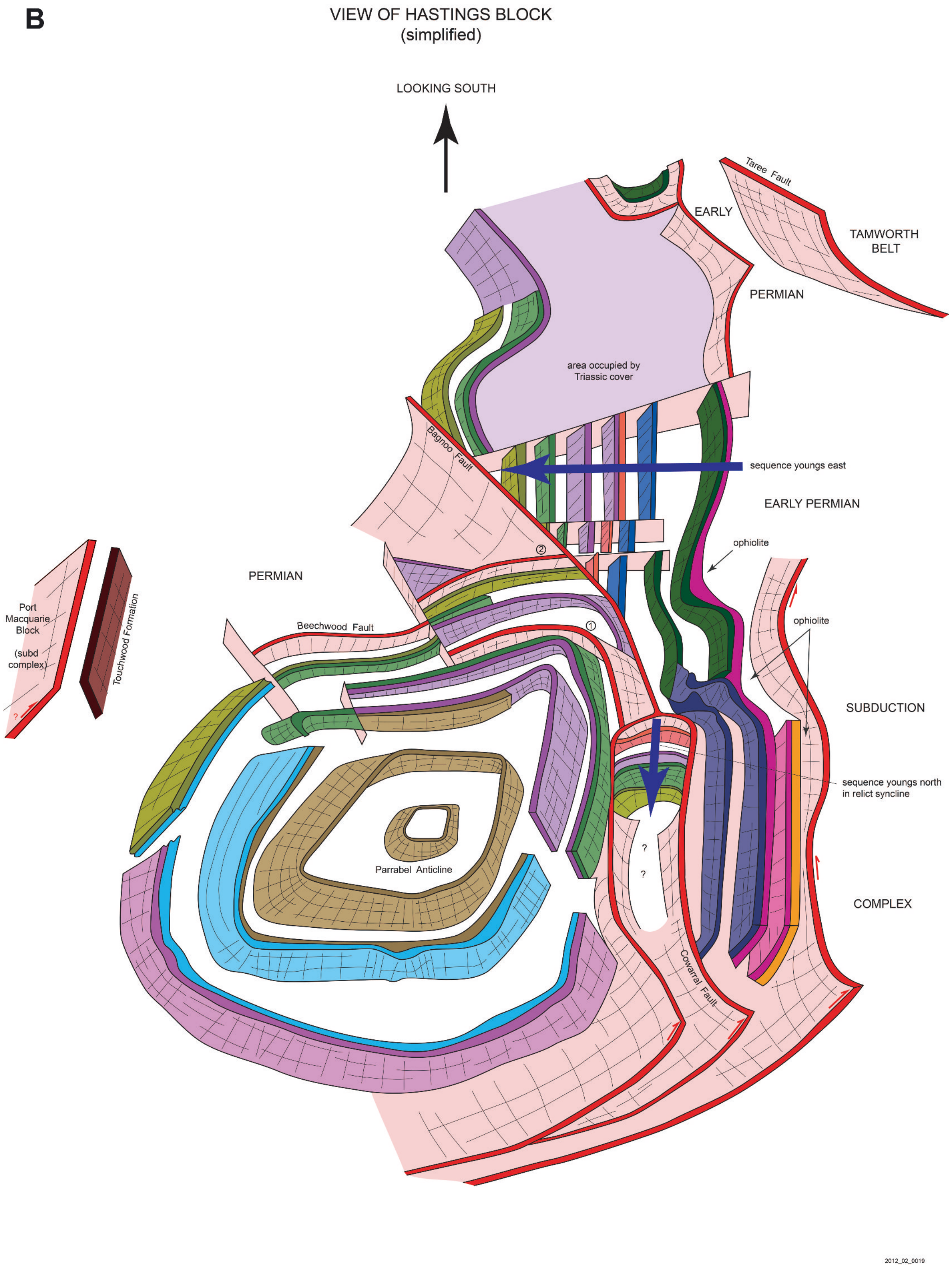
The Devonian-Carboniferous stratigraphy of the Hastings Block (Fig. 5) is based on Roberts *et al.* (1995), with the latest Carboniferous-early Permian stratigraphy of Roberts *et al.* (1993) updated in Schmidt *et al.* (1994). These data show that the Hastings Block (Fig. 5a), which represents the core of the Hastings orocline, contains major facies changes, prompting the division into a northern and southern part that differ in pre-Permian stratigraphy (Roberts *et al.* 1995). The southern part has a mid-Devonian to Late Carboniferous stratigraphy similar to that of the Tamworth belt to the southwest. In contrast, the northern Hastings Block only contains Carboniferous and Permian units. Differences in Carboniferous Visean–Namurian stratigraphy reflect true facies changes as well as changes in outcrop nature from good in the south to poor in the north due to impenetrable tree cover. However, there are also many similarities between the two parts: for example, both parts show a changeover from mafic/intermediate to felsic volcanism at the base of the Namurian, above a regional unconformity or disconformity.

The Hastings Block is separated from Devonian strata of the Tamworth belt by the ENE-trending Taree fault (Figs. 3, 5a). Northeast of that fault, the Hastings Block is surrounded by subduction complex rocks to the west and to the east at Port Macquarie, but elsewhere by Permian strata to the north and southwest, and by Triassic strata to the southeast (Fig. 5a). The Hastings Block possesses a complex internal structural geometry that has been divided into several domains (Lennox and Roberts 1988; Roberts *et al.* 1995; Lennox *et al.* 1999). Lennox and Roberts described the complex geometry in terms of formation of east-west S1 cleavage (best seen in the Nambucca Block to the north) that has been folded round the D2 Parrabel Anticline which has then been overprinted by D3 folds. The crestal area in the Boonanghi beds contains open and upright folds with half wavelengths of ~2 km that may represent refolded D1 folds (Lennox and Roberts 1988).

Figure 11 presents our structural re-interpretation of Figure 5. The variably plunging Parrabel anticline (Lennox and Roberts 1988) that dominates the northern part of the Hastings Block, appears to fold earlier thrust and folds, and contrasts with a NNW-trending, east younging sequence to the west and southwest. Our preferred interpretation is that the anticline has thrust over this sequence from the east (Fig. 11a, b) and lies in the hangingwall of an east-dipping thrust that has partially reactivated older thrusts. In this interpretation, the Parrabel anticline is a D2 hangingwall fold that may have nucleated on an earlier D1 structure. The north-plunging hinge of the Parrabel anticline is defined by a north-younging stratigraphy passing up from Boonanghi beds through Majors Creek Formation into the Kullatine Formation and Youdale (C) Formation, and locally into the Warbro Formation, that have been folded around several angular hinges that plunge to the north, west and east. Dips in the Late Carboniferous strata range from 50-35° and in the early Permian 60 to 28° (unpublished data, Roberts *et al.* . The south-plunging, southern hinge of the Parrabel anticline is outlined by the south-younging sequence of Pappinbarra Formation, Hyndmans Creek Formation, and in the southeast, the Mingaletta Formation. Individual dips occur to both north and south (and to the east and west in the limbs) and are interpreted as reflecting the presence of east-west D1 km scale folds (figure 2 of Roberts *et al.* 1995).

Figure 11. Hastings Block interpretation





A. South-looking interpretation map of the Hastings Block, highlighting major thrusts, and based on Roberts et al. (1995, figure 2) and on Fig. 5a of this paper. Southward-looking orientation is designed to simplify comparison with the block diagram in B. B. Three-dimensional sketch of the Hastings Block, looking south, showing the Parrabel anticline as an asymmetrical hangingwall D2 anticline above an east-dipping D2 thrust, with older D1 thrusts folded around the anticlinal hinge. Left-lateral strike-slip on thrust faults separating the western part of the Hastings Block from subduction complex rocks to the west based on Lennox and Offler (2009). Inferred east-block up displacement is inferred on the LIF fault separating subduction complex rocks of the Port Macquarie block from the eastern part of the Hastings Block. Abbreviations: BWF=Beechwood fault; CWF= Cowarral fault; LIF=Lake Innes fault; PAF=Pappinbarra fault; RRF=Rollans Road fault. For units and abbreviations, see Figure 5.

Our view of the Parrabel anticline is based on the interpretative map (Fig. 11a) and the block diagram (Fig. 11b), both looking southward. Figure 10b shows that the D2 Parrabel anticline is asymmetrical, with a steeply dipping western limb and a more shallowly dipping eastern limb. Based on our interpretation of stratigraphy, the D2 anticline also folds two south-dipping thrusts that root down into Devonian strata, and are thus also of D1 age (Fig. 11a, b). The northernmost thrust (labelled 1 in Fig. 11b) has a footwall of folded Hyndmans Creek Formation passing around the hinge of the Parrabel anticline, although in the eastern limb it cuts down section across a lateral ramp so the footwall is only the Pappinbarra Formation. The hangingwall mainly comprises the Pappinbarra Formation, probably containing a hangingwall anticline (J. Roberts unpublished mapping), but locally the older Nevann Siltstone. The thrust is shown as folded around the hinge of the Parrabel Anticline and cut off on the east by a west-dipping thrust, partly against early Permian strata. In the west, this fault is called the Pappinbarra fault (PAF). Its footwall contains a north-younging, steeply (~70°) north-dipping sequence that passes up-section from the Nevann Siltstone into Mingaletta Formation. This fault–bounded north-dipping sequence occupies a relict (D1) synclinal hinge (Fig. 11b). It is possible that the eastern margin of this hinge originally dipped to the west and has been partially reactivated as an east-dipping thrust in D2 times. The southern most D1 thrust (labelled 2 in Fig. 11b) lies south of the first and is shorter. It is cut off to the east by a NNW-trending, west-dipping post-early Permian thrust, and on the west by an east-younging, west-dipping sequence. This folded thrust juxtaposes Mingaletta Formation against a hangingwall ramp of folded strata that pass down section from Pappinbarra Formation in the east into Wallibree Formation in the west.

The western part of the Hastings Block consists of an east-younging Devonian-Carboniferous sequence that passes from the Yarras ophiolite and the Devonian Bitter Ground Volcanics up into the Carboniferous Mingaletta Formation (Figs. 5, 11a). The bounding fault against subduction complex rocks to the west is shown as an east-dipping thrust (Fig. 11b), with a component of left-lateral movement based on data of Lennox and Offler (2009). (These authors suggested that kinematic histories of serpentinites along major faults on the margins of the Hastings Block postdated emplacement of the block itself.) This sequence lies west of and below the east-dipping major Bagnoo fault and its inferred extensions, the Rollans Road fault (RRF) and the Cowarral Fault (CWF), both of which are inferred to be reactivated D1 thrusts, and is structurally bound to the west by the Taree fault and by subduction complex rocks (Figs, 5, 11a, b). Both figures suggest that south-vergent fold pairs in the Cowangara and Birdwood formations accommodate the fault-bounded relict synclinal hinge referred to above. Stratigraphic separation on the Bagnoo fault dies out southward, so that in the southern part, the Late Carboniferous Mingaletta Formation is juxtaposed against Triassic strata (Roberts *et al.* 1995 Fig. 2; Pratt 2010, map 1) (Fig. 11a). This east-younging package is truncated at its southern margin by the ENE-trending unnamed fault partly overlapped by Triassic strata. South of this fault and northeast of the Taree fault (Fig. 5a), Triassic strata, which have been intruded by Late Triassic-Early Jurassic intrusions, outline an open an east-younging syncline-anticline pair plunging to the southeast (Roberts *et al.* 1995; Pratt 2010). Joining small scattered outcrops of Palaeozoic strata (Fig. 11a) suggests this part of the Hastings Block is occupied by the very wide Pappinbarra Formation that passes up section through the Hyndmans Creek Formation into the Mingaletta Formation. While stratigraphic repetition suggests the presence of a possible fold or imbrication in this area, available dips suggest a faulted contact with south-dipping Devonian Cowangara Formation bounded to east and west by younger strata (Fig. 11a).

On the eastern edge of the Hastings Block, the Mingaletta Formation passes eastwards into the Givetian Mile Road Formation and the Emsian Touchwood Formation, one slice of which is separated from the main part of the block by the early Permian overlap assemblage (Figs. 5, 11a). This slice is in fault contact to the east with subduction complex rocks of the Port Macquarie Block that include high-level, volcaniclastic broken formation, containing Ordovician cherts (Watonga Formation, Och *et al.* 2007a) and serpentinite matrix melange, enclosing various blocks including high grade metamorphic schists, (Och *et al.* 2007b). Permian-Late Triassic gabbro and dykes stitch the two blocks and the Permian overlap assemblage (Och *et al.* 2007b). Note that this description differs from that of Roberts *et al.* (1995) and Leitch *et al.*

(1990) both of which include the Touchwood Formation in the Port Macquarie block.

In the hinge and northeastern limb of the Parrabel anticline, early Permian shallow water strata pass north-eastwards across faults into deeper water strata that comprise the multiply deformed and metamorphosed fill of the early Permian Nambucca rift basin (Lennox *et al.* 1999).