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Unraveling the New England orocline, east Gondwana accretionary margin

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[1] The New England orocline lies within the Eastern Australian segment of the Terra Australis accretionary orogen and developed during the late Paleozoic to early Mesozoic Gondwanide Orogeny (310–230 Ma) that extended along the Pacific margin of the Gondwana supercontinent. The orocline deformed a pre-Permian arc assemblage consisting of a western magmatic arc, an adjoining forearc basin and an eastern subduction complex. The orocline is doubly vergent with the southern and northern segments displaying counter-clockwise and clockwise rotation, respectively, and this has led to contrasting models of formation. We resolve these conflicting models with one that involves buckling of the arc system about a vertical axis during progressive northward translation of the southern segment of the arc system against the northern segment, which is pinned relative to cratonic Gondwana. Paleomagnetic data are consistent with this model and show that an alternative model involving southward motion of the northern segment relative to the southern segment and cratonic Gondwana is not permissible. The timing of the final stage of orocline formation (~270–265 Ma) overlaps with a major gap in magmatic activity along this segment of the Gondwana margin, suggesting that northward motion and orocline formation were driven by a change from orthogonal to oblique convergence and coupling between the Gondwana and Pacific plates.

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1. Introduction

[2] Oroclines are map-view bends of originally quasi-linear lithospheric elements [*Carey*, 1955, 1958; *Marshak*, 1988; *Weil and Sussman*, 2004] and are the outcome of “an orogenic system that has been flexed in plan to a horseshoe or elbow shape” [*Carey*, 1955, p. 256]. Such bending is a significant element in the history of many orogens (e.g., Alaska Orocline, Bolivian Orocline, Rif-Betic Belt, and Himalayan syntaxes). In eastern Australia, the continental-scale doubly vergent New England orocline [*Korsch and Harrington*, 1987] lies within the eastern Australian segment of the Terra Australis Orogen along the margin of Gondwana (Figure 1) [*Cawood*, 2005]. The orocline has an along strike extent of some 600 km and a width of around 350 km. It is defined by the folding of a convergent plate margin assemblage, and developed during the late Paleozoic to early Mesozoic Gondwanide orogeny [*Korsch and Harrington*, 1987; *Cawood et al.*, 2011]. This paper outlines the formation and age of the orocline based on geological and paleomagnetic data and discusses implications for unraveling lithospheric-scale structural and tectonic processes within an evolving accretionary orogen along the eastern Australian segment of Gondwana.

2. Regional Setting

[3] The Terra Australis Orogen is an accretionary orogen [*Cawood*, 2005; *Cawood et al.*, 2009] that preserves a latest Neoproterozoic to early Mesozoic convergent plate margin assemblage, which developed along the paleo-Pacific and Iapetan margins of Gondwana (Figure 1). The easternmost segment extends 1600 km from north of Sydney to Townsville and is referred to as the New England Fold Belt [*Leitch*, 1974]. It is bounded to the west, and in part overthrusts, the late Paleozoic to Mesozoic Sydney, Gunnedah and Bowen basins, and is divisible into northern and southern portions by Mesozoic and younger strata of the Clarence-Moreton Basin (Figure 2).

[4] Subduction along the paleo-Pacific margin of Gondwana began at the end of the Neoproterozoic and continued throughout the Paleozoic [*Cawood*, 2005; *Cawood and Buchan*, 2007; *Cawood et al.*, 2009]. In New England, convergent plate margin activity is expressed in the development of a tripartite association comprising the western Keepit-Connors magmatic arc, the central Tamworth-Yarrol forearc basin, and the eastern Tablelands-Wandilla subduction

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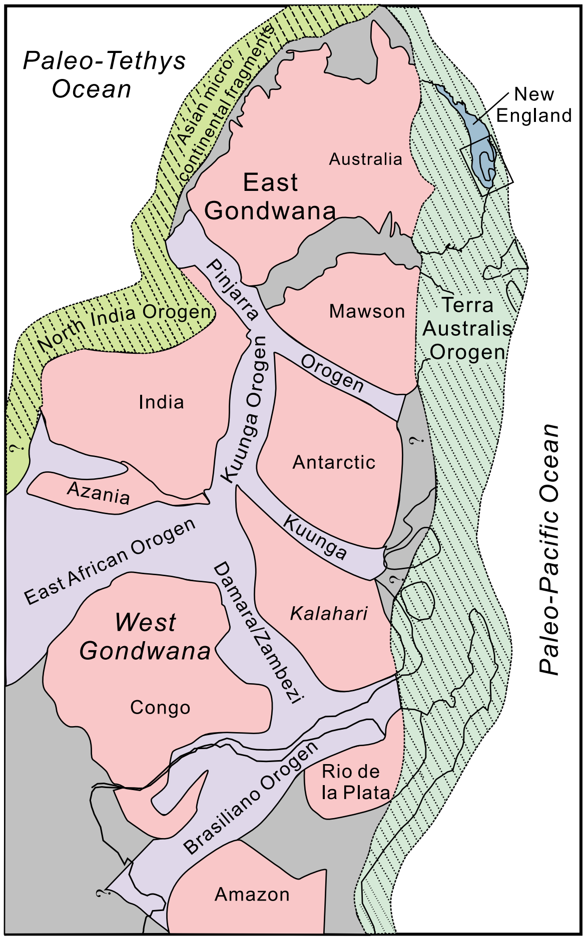

Figure 1. Simplified lithotectonic map of Gondwana showing distribution of the Terra Australis Orogen along the margin of East and West Gondwana. Areas shaded blue show Neoproterozoic collisional belts associated with assembly of cratonic blocks of Gondwana (shaded pink). Areas delineated by various shades of green with diagonal lines highlight Gondwana margin origins. Dark blue region in eastern Australia outlines the New England Fold Belt, and the rectangle highlights the position of Figure 2. The schematic outline of the New England orocline is shown within the rectangle.

complex (Figure 2) [*Leitch*, 1974; *Korsch*, 1977; *Cawood and Leitch*, 1985]. The arc, particularly in the south, is largely buried under the Sydney, Gunnedah and Bowen basins. The forearc and subduction complex are separated by a major fault, the Peel-Manning-Yarrol Fault System, which is marked by serpentinite bodies [*Benson*, 1913] that represent a disrupted early Cambrian ophiolite succession [*Aitchison et al.*, 1992]. This succession likely formed part of the forearc basin basement [*Cawood*, 1982a, 1983].

[5] Orogenesis and stabilization of the convergent plate margin assemblage commenced at around 310–305 Ma with termination of activity along the western magmatic arc (Figure 3) [*Roberts et al.*, 2006; *Cawood et al.*, 2011]. Over the next 70 Ma, the region underwent pulses of compression, oroclinal bending, metamorphism, extension and basin formation. Overlapping with this orogenic activity, a new magmatic arc was established, commencing around 300 Ma [*Cawood*, 1984; *Chappell*, 1994; *Bryant et al.*, 1997a; *Cawood et al.*, 2011]. The arc is characterized by widespread pluton emplacement (New England Batholith) and associated volcanic rocks [*Shaw and Flood*, 1981; *Shaw et al.*, 2011]. This young arc was located largely to the east of the old magmatic arc, and in the southern portion of New England was principally emplaced into the old subduction complex (Figure 2) [*Cawood*, 1984]. The arc was active until around 230–220 Ma [*Shaw and Flood*, 1993; *Bryant et al.*, 1997b; *Shaw et al.*, 2011] and overlaps in space and time with continuing deformation and metamorphism of the Gondwanide Orogeny (Figure 3) [*Collins*, 1991; *Korsch et al.*, 2009; *Cawood et al.*, 2011]. The initial phases of igneous activity overlap with extension, subsidence and basin formation (300–270 Ma) [*Leitch*, 1988].

[6] The New England orocline occurs within the southern portion of the New England segment of the Terra Australis Orogen, south of the Clarence-Moreton Basin (Figure 2). The orocline is doubly vergent consisting of the northern Texas-Coffs Harbour segment and the southern Manning-Hastings segment (Figure 2). The doubly vergent character of the orocline has led to competing models of formation involving dextral motion that formed the Texas-Coffs Harbour segment [*Korsch and Harrington*, 1987; *Murray et al.*, 1987; *Offler and Foster*, 2008] and sinistral motion that formed the southern Manning-Hastings segment [*Cawood*, 1982b]. In this paper we show that these opposite senses of relative motion can be produced during overall sinistral strike-slip movement along the Gondwana margin. Furthermore, only a sinistral sense of motion with respect to cratonic Gondwana is consistent with available paleomagnetic data.

3. New England Orocline

[7] The geometry of the New England orocline is outlined by regional folding of rock units within the Paleozoic (pre-Permian) convergent margin succession, particularly the subduction complex succession (Figure 2), and is also manifest on gravity and aeromagnetic maps (Figure 4). The Texas-Coffs Harbour segment of the orocline has a wavelength of ~250 km and amplitude of ~150 km forming a large-scale Z-fold. The Manning-Hastings segment is more disrupted, in part due to subsequent faulting, and delineates an S-fold with a wavelength and amplitude on the order of 200 km and 100 km, respectively (Figure 2).

[8] In eastern Australia regional trends are predominantly north northwest, but in the New England region near the New South Wales–Queensland border, in the Texas–Warwick region, *Ball* [1923] noted anomalous east-west trends that he related to large-scale folding. *Lucas* [1960] confirmed that geological units in the Texas region were folded into a regional arc concave to the south. *Runnegar* [1974] suggested that the Peel-Manning Fault system (PMFS, Figure 2) was involved in the regional folding and that serpentinites at Baryulgil (B, Figure 2) were a continuation of those found along the Peel Fault. Anomalous east-west regional trends were also recognized in the Coffs Harbour region by *Voisey* [1934] and *Kenny* [1937] and documented in detail by *Korsch* [1973, 1981]. *Flood and Fergusson* [1982] proposed that folding in the Texas and Coffs Harbour regions was linked and involved equivalent rock units, forming a Z-shaped

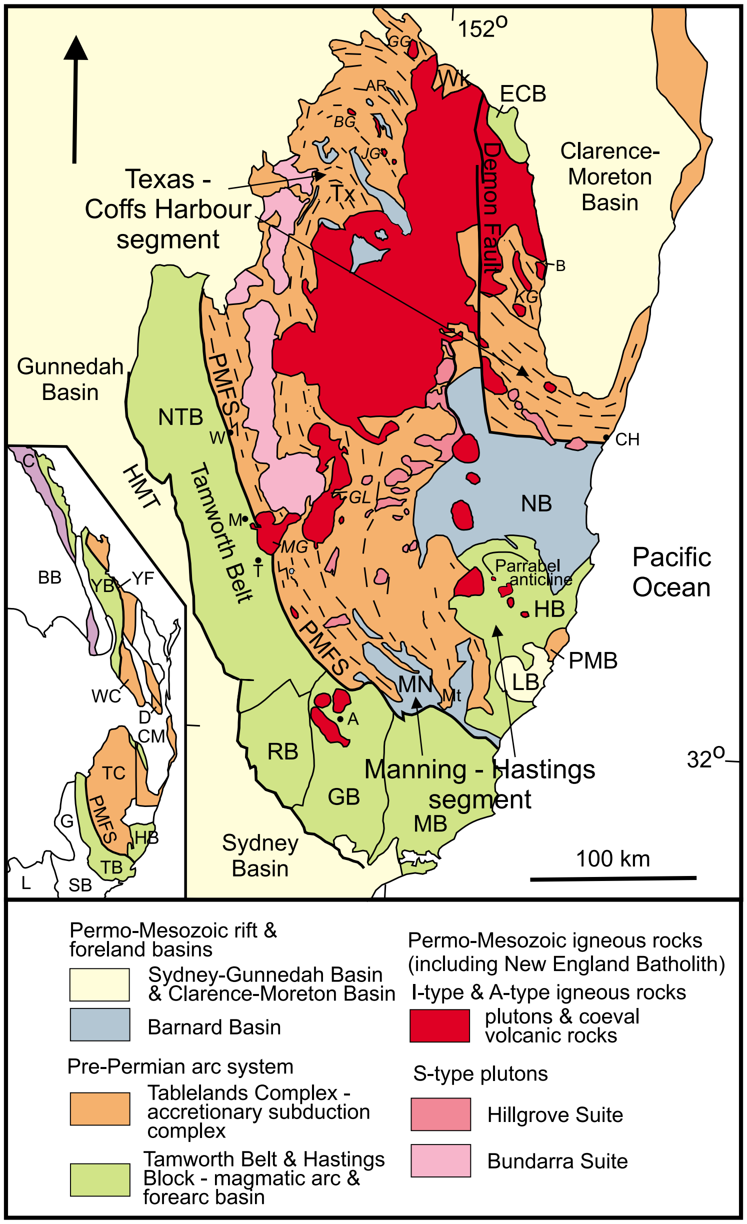

Figure 2. Geological map of the southern New England region of the Terra Australis Orogen showing the position of the Texas–Coffs Harbour and Manning–Hastings segments of the New England orocline with respect to the distribution of pre-Permian arc system elements, Permo-Mesozoic igneous rocks, and Permo-Mesozoic rift and foreland basins. Dashed lines in Tablelands Complex are the trend of bedding and subduction-related bedding parallel foliation. Inset shows location of New England with respect to surrounding tectonic units. Abbreviations (geologic terms): AR, Alum Rock; BG, Bullaganang Granite; ECB, Emu Creek Block; GB, Gresford Block; GG, Greymare Granodiorite; GL, Glenburnie Leucoadamellite; HB, Hastings Block; HMT, Hunter Mooki Thrust; JG, Jibbinbar Granite; KG, Kaloe Granite; LB, Lorne Basin; MB, Myall Block; MG, Moonbi Granite; MN, Manning Block; NB, Nambucca Block; NTB, Northern Tamworth Block; PMB, Port Macquarie Block; PMFS, Peel Manning Fault System; RB, Rouchel Block; TB, Tamworth Belt; Tx, Texas; Wk, Warwick; Abbreviations (geographic terms): A, Alyn River; B, Baryulgil; CH, Coffs Harbour; M, Manila; T, Tamworth; W, Woodsreef; Abbreviations (inset): BB, Bowen Basin; C, Connors Arc; CM, Clarence Moreton Basin; D, D'Aguilar Block; HB, Hastings Block; G, Gunnedah Basin; L, Lachlan Fold Belt; Mt, Mt. George; SB, Sydney Basin; TB, Tamworth Belt; TC, Tablelands Complex; WC, Wandilla Complex; YB, Yarrol Belt; YF, Yarrol Fault.

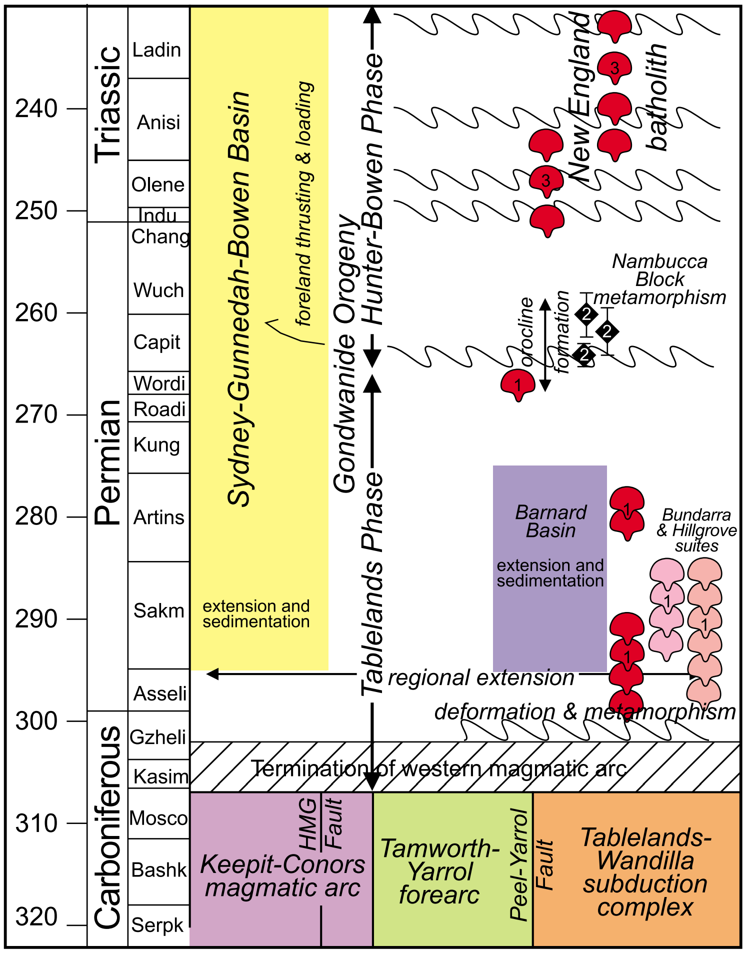

Figure 3. Schematic time-space diagram for the New England segment of the Terra Australis Orogen and adjoining Sydney-Gunnedah Basin. Color scheme for tectonostratigraphic assemblages based on Figure 2. Abbreviations: Serpk, Serpukhovian; Bashk, Bashkirian; Musco, Muscovian; Kasim, Kasimovian; Gzheli, Gzhelian; Asseli, Asselian; Sakm, Sakmarian; Artins, Artinskian; Kung, Kungurian; Roadi, Roadian; Wordi, Wordian; Capit, Capitanian; Wuch, Wuchiapingian; Chang, Changhsingian; Indu, Induan; Olene, Olenekian; Anisi, Anisian; Ladin, Ladinian. Sources of data: 1, *Cawood et al.* [2011]; 2, *Offler and Foster* [2008]; 3, *Bryant et al.* [1997b], *Cawood et al.* [2011], *Shaw and Flood* [2009] and *Shaw et al.* [2011].

megafold or orocline [see also *Korsch and Harrington*, 1987; *Murray et al.*, 1987; *Offler and Foster*, 2008]. The orocline is outlined by the trend of bedding and early, bedding-parallel, cleavage within the subduction complex that defines a regional fold sequence that is steeply plunging with a subvertical north northwest trending axial surface [*Lennox and Flood*, 1997]. No axial planar foliation is associated with the regional oroclinal folds.

[9] Forearc units to the subduction complex lithologies within the Texas-Coffs Harbour orocline, along with intervening ophiolitic lithologies are represented by the Emu Creek Block and Baryulgil Serpentinite, respectively (ECB, B, Figure 2). These units now lie to the east of the subduction complex assemblages, within the central limb of the double orocline, but formed a linear belt during west-facing subduction prior to formation of the orocline [*Korsch and Harrington*, 1987].

[10] The Manning-Hastings segment of the New England orocline is defined by a swing in the trend of subduction complex lithologies into a concave to the north regional arc. Forearc and disrupted ophiolitic units mimic this trend with a swing in regional orientation from north northwest-south southeast to more east-west trends toward the south (Figure 2) The Hasting Block (HB, Figure 2) represents a component of the Paleozoic forearc succession that now lies east of the subduction complex [*Leitch*, 1980; *Cawood*, 1982b]. The northern margin of the block is folded into the Parrabel Anticline. Serpentinite along the western margin of the block displays kinematic features indicating late sinistral movement consistent with displacement of the Hastings Block from an original location farther to the south [*Leitch*, 1980; *Cawood*, 1982b; *Lennox and Offler*, 2009]. The half wavelength and amplitude of the Manning-Hastings segment of the orocline are of the order of 100 km with a north northwest trending axial surface and a generally steeply plunging fold axis. Early Permian strata in the region of the Manning Block (MN, Figure 2 [*Gilligan et al.*, 1987]) form an overall south-plunging anticlinal structure, the hinge

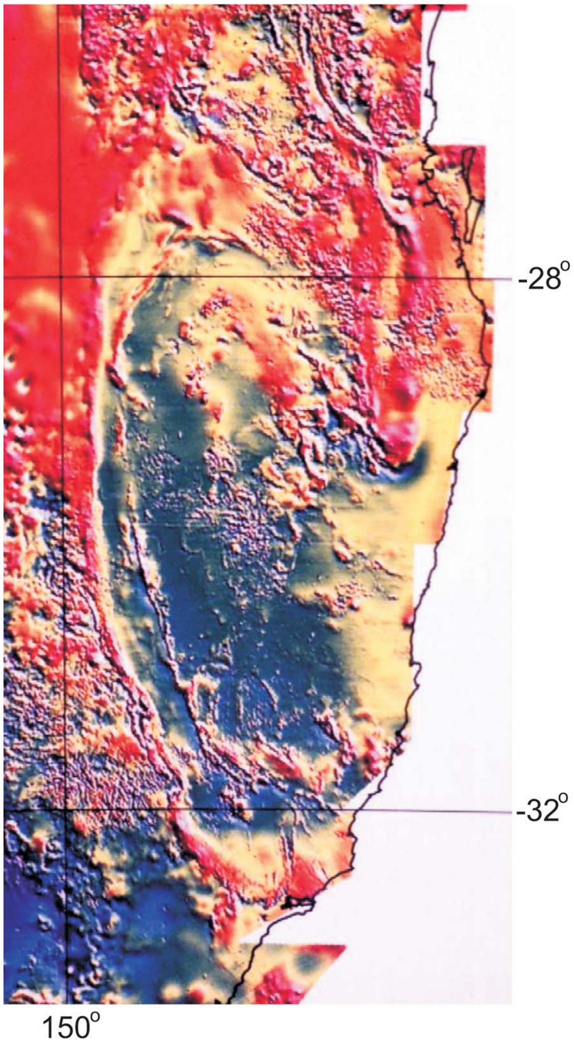

Figure 4. Aeromagnetic anomaly map for eastern Australia covering the southern New England fold Belt showing Texas-Coffs Harbour and Manning-Hastings segments of the New England orocline.

area of which is disrupted by the piercement-like mass of subduction complex rocks that form a block extending north from Mt. George (Mt, Figure 2). Further northeast the Early Permian succession is cut-off by, and caught along, faults near the western margin of the northern Hastings Block but it reappears again around the nose of the Parrabel Anticline where it seems to change strike from north northwest to north to north northwest around the anticline going from west to east. Overall, however, this segment of the New England orocline is much less coherent than the Texas-Coffs Harbour segment and was extensively disrupted by sinistral strike-slip and thrust faulting, after orocline formation, during the late Permian to Triassic Hunter-Bowen Phase of the Gondwanide Orogeny [*Roberts and Engel*, 1987; *Collins*, 1991; *Dirks et al.*, 1992; *Landenberger et al.*, 1995].

4. Pre-orocline Configuration

[11] The present configuration of Paleozoic convergent plate margin elements in the New England segment of the Terra Australis Orogen is the result of orocline development and does not correspond to a pre-Permian syn-subduction disposition. The forearc and ophiolitic elements are repeated across both the Texas-Coffs Harbour and Manning-Hasting segments of the orocline. In the Texas-Coffs Harbour segment, lithotectonic units within the subduction complex young away from the Gondwana margin forearc elements, such that at Texas they young toward the core of the geometric arc within the orocline and at Coffs Harbour young toward the rim of the arc. Within individual thrust slices however, younging is generally toward the magmatic arc [*Flood and Fergusson*, 1982; *Fergusson*, 1984, 1985]. In the Manning-Hastings segment, and immediately to the north, similar age relations have been recognized in the subduction complex [*Cawood*, 1982a; *Cross et al.*, 1987; *Collins et al.*, 1993]. These age relationships are consistent with a model of progressive imbricate thrusting of ocean floor and trench fill along an originally linear convergent plate margin [*Cawood and Leitch*, 1985]. In the Texas and Coffs Harbour regions, oroclinal folding resulted in some 180° of rotation of bedding and thrust imbricates in the subduction complex. In the region of the Manning Block however, the amount of regional folding of the subduction complex is probably less than 90° and the east facing limb of the Manning orocline, if ever present, has been lost during later Permian faulting.

[12] On the basis of the relationships within the Paleozoic convergent plate margin assemblage, we have assumed an original linear configuration of tectonic elements along the New England segment of the Terra Australis Orogen [*Cawood and Leitch*, 1985; *Collins et al.*, 1993]. Figure 5 shows the inferred original linear disposition of arc, forearc and subduction complex. The northern New England segment of the Terra Australis Orogen is largely unaffected by orocline formation and the southern segment has been unwound from a pinning point located near the Queensland–New South Wales state border (Figure 5). Reference points (1–6) are distributed along the outboard margin of the forearc basin in both the orocline and its inferred original linear configuration. Points 1 and 6 have a current separation of some 250 km but an original along strike separation of at least 1000 km. The exact position of the Hastings Block to the south of the Tamworth Belt cannot be constrained by geological data alone (see section on paleomagnetics). The position of point 5 before and after orocline formation requires some 350 km of movement westward onto the Gondwana craton, relative to the northern segment.

[13] The present distribution of temporally equivalent S-type granite suites is in divergent belts with the Bundarra Suite having an overall northerly trend and the Hillgrove Suite trending north northeast (Figure 2). *Flood and Shaw* [1977] suggested that prior to deformation the Hillgrove Suite lay south and slightly east of the Bundarra Suite [cf. *Collins et al.*, 1993].

5. Age of Orocline Formation

[14] Geological relations constrain the timing of orocline formation to around 270–265 Ma. These constraints include the youngest ages for originally linear elements that predate and are folded by the orocline, and the oldest ages for units unaffected by orocline formation or that transgress deformation associated with the orocline.

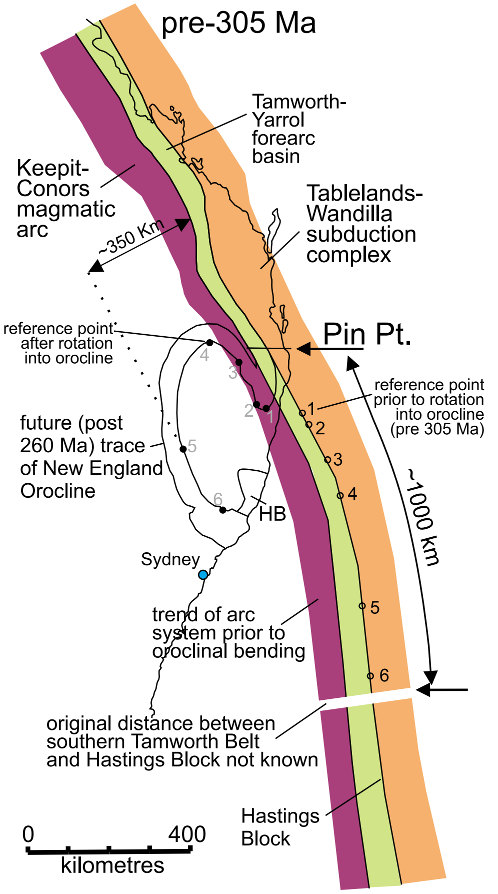

Figure 5. Schematic model showing simple unwinding of the New England orocline by straightening the pre-Permian convergent plate margin assemblages (Keepit-Connors magmatic arc, Tamworth-Yarrol forearc basin and Tablelands-Wandilla subduction complex). Colors of pre-Permian arc elements are the same as those in Figure 2; 305 Ma is chosen as the time for original linear orientation of the arc system as this corresponds with the age of the youngest arc magmatism along the Keepit-Connors arc. Points 1–6 are series of reference points along the boundary between the forearc arc and subduction complex elements and are shown in both their inferred pre-orocline and current locations.

[15] The orocline deformed the pre-existing, pre-Permian arc-forearc-subduction complex assemblage, resulting in across strike repetition of these lithotectonic units (Figures 2 and 5). The youngest arc magmatism associated with this convergent plate margin activity is 310–305 Ma [*Roberts et al.*, 2006; *Cawood et al.*, 2011]. A younger ~290 Ma belt of igneous activity within the western subduction complex is also folded by the Texas-Coffs Harbour segment of the orocline (Figure 6). This belt includes the Bundarra Suite of S-type granites and the I-type Glenburnie, Greymare, Jibbinbar, Bullaganang and Kaloe bodies (abbreviations GL, GG, JG, BG and KG, respectively, Figures 2 and 6). These bodies form a belt close to the boundary of the Tablelands subduction complex with the forearc basin units in the Tamworth Belt and Emu Creek Block. Early Permian basinal deposits are also involved in oroclinal bending [*Lennox and Flood*, 1997]. The youngest rocks identified within the basin are Late Artinskian, probably around 280–275 Ma [*Briggs*, 1993, 1998].

[16] The greatest intensity of deformation associated with oroclinal deformation appears to lie within the Nambucca Block where large-scale mostly steeply plunging folds have affected previously deformed Early Permian strata (D5 of *Leitch* [1978]). Multiply deformed slate within the block lie in the pincer between the northern and southern segments of the orocline (Figure 2). Metamorphism at 265–260 Ma [*Offler and Foster*, 2008], based on Ar/Ar mica dating of slate and phyllite within the block, provides a likely minimum age for orocline formation. The major pulse of I-type magmatism that produced the New England Batholith is ~250 Ma and younger [*Flood and Shaw*, 1977; *Shaw and Flood*, 1981; *Bryant et al.*, 1997a; *Shaw and Flood*, 2009; *Shaw et al.*, 2011]. This pulse forms an overall northeast trending belt extending from the Moonbi region in the southwest to Warwick in the northeast, which cuts across

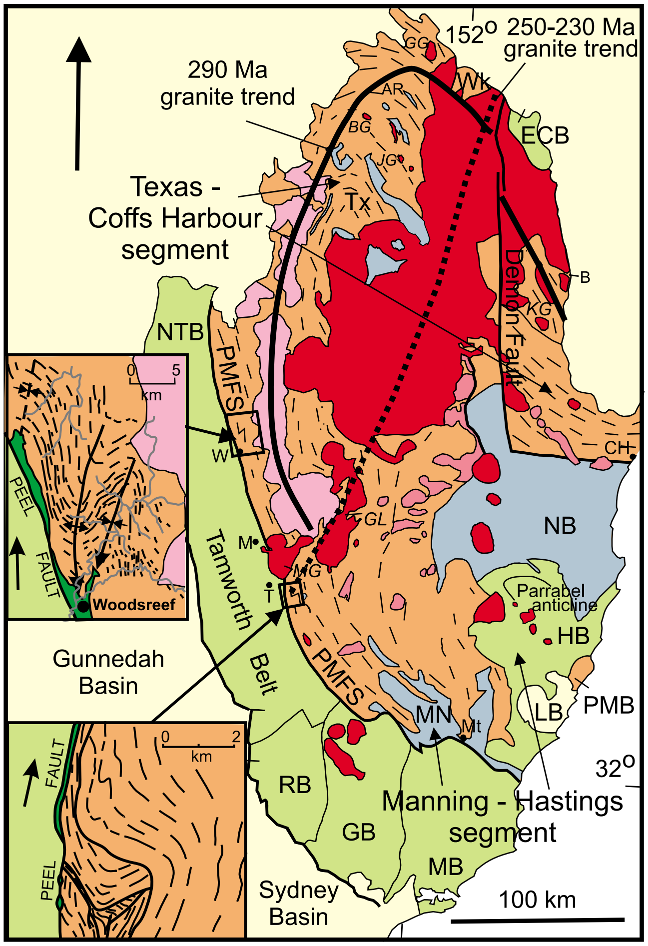

Figure 6. Map of the southern New England region showing the general trend of pre-orocline formation plutons (290 Ma, solid line) and post-oroclne formation plutons (250–230 Ma, dashed line). The 290 Ma trend is offset by the Triassic Demon Fault. Insets show north-verging folds with subduction complex at Woodsreef and south of the Moonbi Granite after *Corbett* [1976] and *Cawood et al.* [2011], respectively. Legend and abbreviations are as for Figure 2, except that insets also show serpentinite (dark green) along Peel Fault.

Table 1. Paleomagnetic Poles From Blocks of the New England Region[a]

			Paleopole							
Pole	Terrane	Object	°N	°E	dp/dm (deg)	Plat (deg)	Age (Ma)	Q	Reference	GPMDB
1	Hastings	Kullatine Fm	14.3	139.3	13.4/13.4	−43	327–315	6	*Schmidt et al.* [1994]	7561
2	Myall	L.Visean Ignimbrite	35.7	53.2	9.1/14.7	−25	336–326	5	*Geeve et al.* [2002]	9018
3	Gresford	M-L.Visean Ignimbrite	72.8	48.4	13.4/19.2	−35	335–328	6	*Geeve et al.* [2002]	9017
4	Gresford	Hunter Valley Volcanics	73.0	34.0	21.0/21.0	−35	340–328	4	*Luck* [1973]	1906
5	Rouchel	E-M.Visean Ignimbrite	64.9	78.1	5.5/9.2	−22	332 ± 2; 342 ± 3	6	*Geeve et al.* [2002]	9016
6	N. Tamworth	Mean pole	54.5	313.6	8.3/8.3	−62	322–302	4–7	This study	8591, 8819, 8821, 8589, 8590, 8592, 8822, 9203–9205
7	N. Tamworth	Mean pole	50.0	349.1	13.6/13.6	−66	300–260	4–5	This study	6682, 7739, 9206
8	N. Queensland	Connors Volcanics	46.0	280.0	13.0/16.0	−45	298–292	5	*Clark* [1994] and *Withnall et al.* [2009]	8406
9	N. Queensland	Rockwood Volcanics	55.0	312.0	22.0/25.0	−55	280–275	4	*Clark* [1994], *Briggs* [1998], and *O'Connell* [1995]	8585
10	Texas Orocline	Alum Rock (unrotated[b])	5.3	301.7	17.3/17.3	−53	295–284	5	*Aubourg et al.* [1994]	8414

[a] Plat, paleolatitude; Q, quality factor after *Van der Voo* [1990], which ranges from 0 to 7 with the latter representing the highest quality data; GPMDB, pole number in the IAGA Global Paleomagnetic Database [*Pisarevsky*, 2005].

[b] *Aubourg et al.* [1994] corrected their data due to suggested oroclinal bedding.

the orocline (Figures 2 and 6). The western margin of the southern New England segment of the Terra Australis Orogen is delineated by the Hunter-Mooki Thrust (HMT, Figure 2). It forms the southernmost of a series of faults (Mooki-Burunga faults), which can be traced over some 700 km to the north, and form a linear trend that roughly lies along the 150° meridian [*Korsch et al.*, 2009]. The faults displace Early Middle Triassic or younger strata and their linear trend is unaffected by the Texas-Coffs Harbour segment of the orocline, providing another upper age limit on rotation. The trend of the Hunter segment of the Hunter-Mooki Thrust in part mimics the swing attributable to oroclinal folding in the Manning region, suggesting part of its history may be older [*Glen and Beckett*, 1997].

[17] Although the bulk of the data support a late Permian age for orocline formation, local evidence suggests some deformation, possibly related to an early phase of oroclinal bending, may have occurred in the Early Permian. The western Tablelands Complex, east of Woodsreef and east of Tamworth (Figure 6, insets), is deformed into a series of large-scale asymmetric, north-verging folds, indicative of large scale sinistral movement in the region [*Corbett*, 1976; *Cawood*, 1982a; *Cawood et al.*, 2011]. The folds post-date subduction-related thrust imbrication associated with the pre-Permian convergent plate margin and are cut by the ~290 Ma Bundarra Suite plutons, suggesting a latest Carboniferous or Early Permian age (305–290 Ma). In the Texas region, *Aubourg et al.* [1994] argued on the basis of paleomagnetic data that the Alum Rock Formation (AR, Figures 2 and 6), which has yielded U-Pb zircon ages of ~292 Ma [*Roberts et al.*, 1996], underwent some 40° of rotation prior to extrusion of interstratified volcanic rocks and a further 80° of rotation subsequently. This data however, conflicts with geological relations that folding post-dated the end of Early Permian deposition [*Lennox and Flood*, 1997], and more work is needed to resolve this conflict.

6. Paleomagnetic Data

[18] Paleomagnetic studies of the Paleozoic rocks of the New England segment of the Terra Australis Orogen began in the 1950s [*Irving and Green*, 1958]. Since then 39 paleomagnetic poles with ages ranging from 340 Ma to 260 Ma, broadly overlapping the time of orocline formation, have been published [*Pisarevsky*, 2005]. Using the Q criteria of *Van der Voo* [1990], we selected the 19 most reliable poles from across the New England region. The data are largely from the pre-Permian, forearc basin succession in the Tamworth Belt, which on the basis of geological relations and the paleomagnetic data can be divided into the Northern Tamworth, Rouchel, Gresford, and Myall blocks, and the Hastings Block (abbreviations NTB, RB, GB, MB, HB respectively, Figure 2 [*Roberts et al.*, 2006]). Poles from the Northern Tamworth Block are divided into two age groups, for which poles are calculated, reducing the number of poles to 10 (Table 1). Ages assigned to poles incorporated the recent stratigraphic review by *Fielding et al.* [2008]. Only two areas of the northern part of the New England segment have been studied paleomagnetically; the Texas region at Alum Rock by *Aubourg et al.* [1994] and the northernmost tip in North Queensland [*Clark*, 1994].

[19] The available paleomagnetic data is limited and the paleopoles from the various blocks are generally not coeval (Table 1); for example, the pole for the Kullatine Formation of the Hastings Block [*Schmidt et al.*, 1994] only just overlaps in age with the poles from Myall, Gresford and Rouchel blocks [*Geeve et al.*, 2002]. In addition, all poles younger than 300 Ma are from the northern part of New England orocline (Table 1), so the history of the southern part for this time interval is unconstrained paleomagnetically. It is thus impossible to produce an unequivocal tectonic model for the New England orocline based purely on paleomagnetic data. However, the data are sufficient to test some existing models with the available reliable paleopoles by comparing them with the Gondwanan Apparent Polar Wander Path (APWP). Gondwana's APWP is debated [*Klootwijk*, 2003; *McElhinny et al.*, 2003; *Klootwijk*, 2009]. Using the terminology of *Klootwijk* [2009], we prefer the SLP (Schmidt-Li-Powell)-type clockwise path of the Gondwana APWP [*Li et al.*, 1990; *Schmidt et al.*, 1990], because unlike the alternative KG (Klootwijk-Giddings) anticlockwise path [*Klootwijk and Giddings*, 1988], the SLP

Table 2. Paleozoic APWP for Gondwana in NW Africa Coordinates[a]

Geological Age	Age (Ma)	Mean (Ma)	m	N	k	Mean Pole Lat °N	Mean Pole Lon °E	A_{95} (deg)
Mid- to Late Permian	250–270	260	12	80	5.096	45.6	246.5	7.8
Early Permian	270–290	280	19	196	9.401	35.4	244.4	3.5
Late Carboniferous 2	290–310	300	12	96	11.551	30.7	240	4.4
Late Carboniferous 1	310–330	320	15	124	6.297	25.8	236.2	5.5
Early Carboniferous	330–350	340	5	65	3.507	3.8	218.2	11.1
Late Devonian/Early Carboniferous	350–370	360	7	63	8.992	13.3	189	6.3

[a] Means are recalculated from *McElhinny et al.* [2003] using the method of *McFadden and McElhinny* [1995] for combining groups of poles by including recently published poles of *Anderson et al.* [2003], *Bachtadse et al.* [2002], *Derder et al.* [2001a, 2001b, 2001c, 2006, 2009]], *Gilder et al.* [2003], *Merabet et al.* [2005], *Rakotosolofo et al.* [2006]; m is the number of poles; N is total number of sites; k is the estimate of *Fisher* [1953] precision; A95 is the radius of circle of 95% confidence about the mean pole position. Ages are based on the Geologic Timescale 2004 [*Gradstein et al.*, 2004].

path is based on primary remanences of rocks from the Gondwana Craton. One of the most recent versions of the SLP-type APWP was published by *McElhinny et al.* [2003]. We have slightly modified their compilation by adding more recently published poles (Table 2).

[20] We tested two end-member models for the New England orocline. The first involves progressive northward (sinistral) translation of the southern segment (New South Wales) of the pre-Permian arc system against the northern segment (Queensland), which is pinned relative to cratonic Gondwana [cf. *Cawood and Leitch*, 1985; *Collins et al.*, 1993]. Figure 7 shows that this model is paleomagnetically permissive: all available New England paleopoles are close to the geographic pole and to coeval Gondwanan poles at the corresponding time slices. The key elements of this model are that the various forearc elements of the pre-Permian arc (northern Tamworth, Rouchel, Gresford, Myall and Hastings) form a linear to slightly curvilinear sequence prior to orocline formation (Figure 7a), and that these blocks, along with the Texas Block, originate significantly south of their current locations with respect to both cratonic Gondwana and the north Queensland segment. The Rouchel, Gresford and Myall blocks are displaced with respect to the northern Tamworth Block, and the Hastings Block originated significantly further south than the other blocks. Animation S1 in the auxiliary material contains an animation model that outlines a possible movement history of the blocks from their pre-oroclinal positions (Figure 7a) to their present relative positions (Figure 7f) and is consistent with the available paleomagnetic data (Table 1).[1] The animation is in present-day Australian coordinates.

[21] The alternative model for formation of the orocline, involving southward movement of the northern elements of the pre-Permian arc with respect to the southern elements and with respect to cratonic Gondwana [cf. *Korsch and Harrington*, 1987; *Murray et al.*, 1987; *Murray*, 1997; *Offler and Foster*, 2008] can also be tested paleomagnetically (Figure 8). The key features of this model as portrayed by *Offler and Foster* [2008], are that the southern part of the New England orogen is not an orocline–Hastings, Myall, Gresford, Rouchel and north Tamworth blocks were originally in their present-day mutual orientations and belonged to cratonic Australia, and the North Queensland part of the orogen was originally outboard of the craton as depicted in Offler and Foster's Figure 6. Available paleomagnetic data shows that this model is not permissible. In particular, the paleopoles from the Hastings, Myall, Gresford, Rouchel and North Tamworth blocks fall well away from the geographic poles on the reconstructions if the blocks were attached to cratonic Australia in their present-day configuration (Figure 8). It is not possible to adequately test the hypothesis about detachment of North Queensland from cratonic Australia, because the scale of this displacement is not indicated in those models purporting dextral motion. Our best estimate [from *Offler and Foster*, 2008, Figure 6] is demonstrated in Figure 8 and shows that this detachment is paleomagnetically not permissible (compare the position of the North Queensland pole with that in Figure 7 at 295 Ma).

7. Discussion

[22] Integration of geological and paleomagnetic data suggest that the New England orocline involved buckling of a pre-Permian convergent plate margin assemblage about a vertical axis due to northward translation of the southern (New South Wales) elements of the arc-trench assemblage against the northern (Queensland) segment, which was pinned relative to cratonic Gondwana. For the southern elements to reach their current configuration (Figure 2) significant northward displacement is required, as well as significant differential displacement of the Hastings, Myall, Gresford, Rouchel, and Northern Tamworth blocks with respect to each other, North Queensland and cratonic Gondwana. The southern elements have also moved laterally onto the cratonic Gondwana foreland relative to the northern elements (Figure 5). At 340 Ma (Figure 7a), the Hastings Block lay 1600 km south of its current location, the Rouchel, Gresford and Myall blocks some 1080–830 km, and the Northern Tamworth Block and Texas region were around 470 and 400 km to the south respectively. Differential displacement requires that major sinistral faults separate the Hastings Block from the Myall, Gresford and Rouchel blocks, with a further fault separating these from the Northern Tamworth Block (Figure 8). These faults probably formed a linked system that developed in response to kinematic changes between the Gondwana margin and the paleo-Pacific plate during Gondwanide orogenesis [*Cawood et al.*, 2011]. The estimated timing of orocline formation at ~270–265 Ma corresponds with a gap in igneous activity along the margin separating the older 300–280 Ma and younger 250–230 Ma pulses of magmatism (Figure 3). These pulses of igneous activity have been interpreted to represent a Cordilleran-style magmatic arc [*Cawood*, 1984;

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011TC002864.

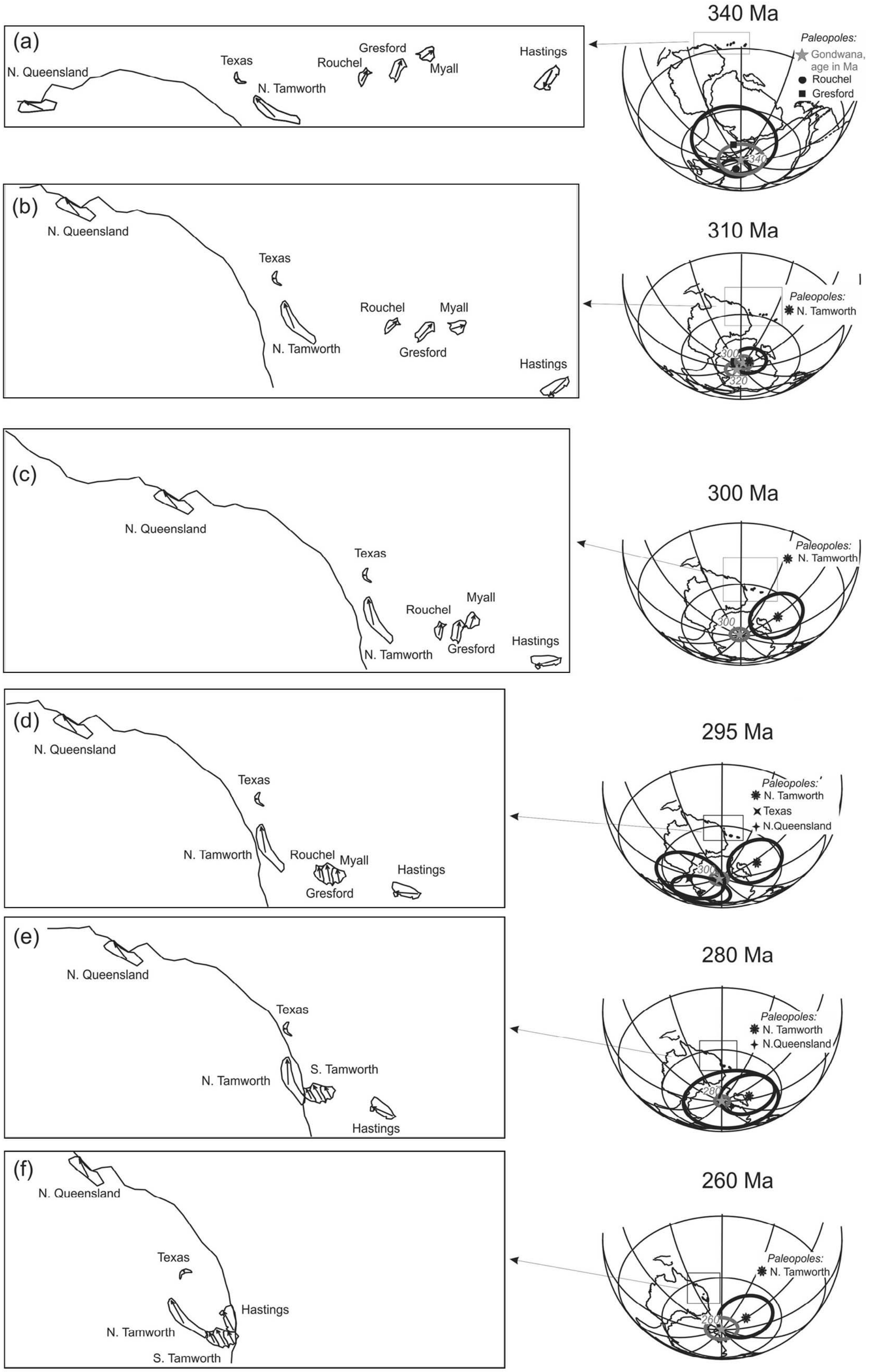

Figure 7. Paleogeographic reconstruction of Gondwana and blocks of the New England orogen at (a) 340, (b) 310, (c) 300, (d) 295, (e) 280 and (f) 260 Ma with relevant paleopoles. Rotation parameters provided in the Appendix.

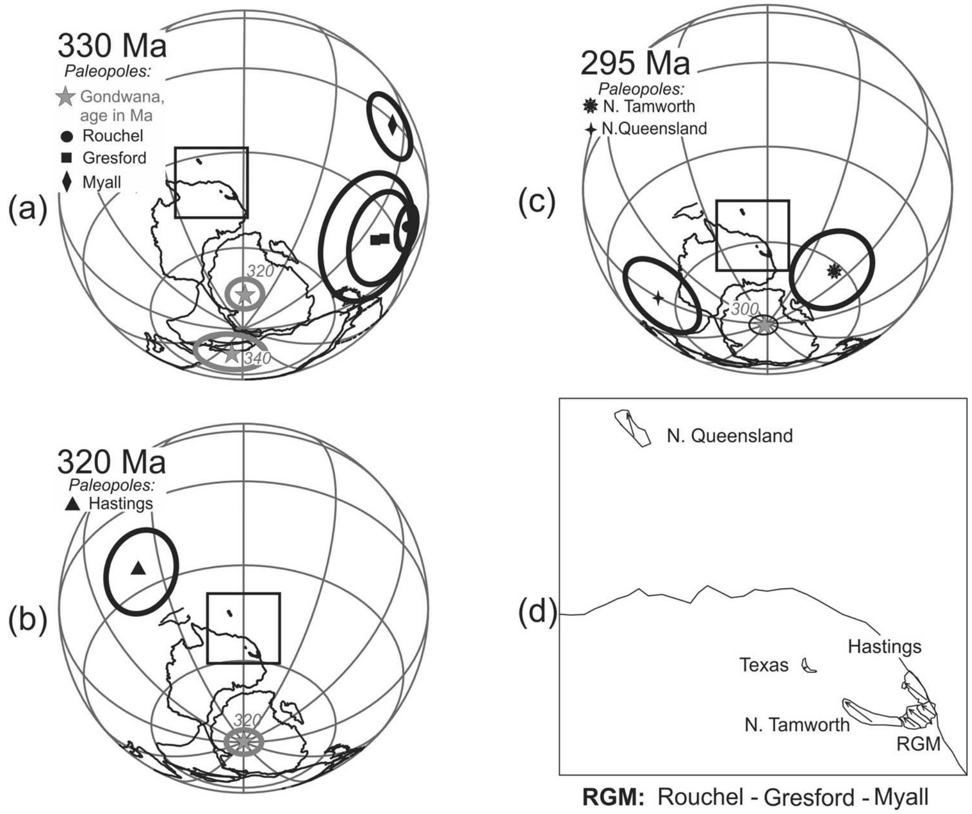

Figure 8. Paleogeographic reconstruction of Gondwana and blocks of the New England orogen at (a) 330, (b) 320 and (c) 295 Ma based on model in which the southern segment of the New England Fold Belt is fixed and the northern segment is moved southward to form the Texas-Coffs Harbour segment of the orocline [cf. *Offler and Foster*, 2008]. (d) Box outlined in Figures 8a, 8b and 8c.

Chappell, 1994; *Bryant et al.*, 1997a]. The age gap between the two magmatic pulses may represent a change from more orthogonal to sinistral strike-slip interaction between the Gondwana and Pacific plates [cf. *Mortimer et al.*, 1999], which then drove orocline formation. In addition to differential shortening between blocks, the overall northward movement of the blocks relative to North Queensland and cratonic Gondwana requires a major fault to lie between the craton and the displaced blocks. The displacement along this structure, however, must decrease to zero toward the north so that the northern segment (in Queensland) stays fixed with respect to the craton. The exact position of the fault is not well constrained. The present boundaries between the blocks within southern New England are largely a consequence of post-oroclinal deformation [e.g., *Lennox and Offler*, 2009], although the Waverley Fault, which separates the Northern Tamworth and Rouchel blocks shows evidence for deformation prior to orocline formation [*Roberts et al.*, 2006].

[23] Geometric considerations that require the pre-Permian convergent plate margin north of the orocline to be fixed with respect to cratonic Gondwana suggest that the major fault strands accommodating northward translation should terminate within the core of the Coffs Harbour segment of the orocline. This position marks the change from the

Figure 9. (a) Paleomagnetically constrained reconstruction of blocks within New England Fold Belt (based on Figure 6a) prior to orocline formation showing potential position of faults that are needed to accommodate differential movement between blocks as they are emplaced onto the Gondwana margin to form the New England orocline. The trace of the orocline is shown for reference. (b and c) Schematic reconstructions showing formation of the New England Orocline at approximately 275 Ma and 265–260 Ma through northward translation of the southern elements of an originally linear pre-Permian arc system, as depicted in Figure 9a, relative to both the northern elements (fixed at the pin point) and the Gondwana craton (compare with Figure 6). A-B and C-D are schematic cross sections through the arc system at approximately 275 Ma and 265–260 Ma, respectively. The position of the sections is shown on reconstructions in Figures 9b and 9c. Section A-B represents crustal architecture prior to, or during early stages of, orocline formation and section C-D represents post-orocline formation; section A-B shows the disposition of units after regional extension (see Figure 3) but prior to major phase of oroclinal bucking, and section C-D shows inferred disposition of units across the Texas-Coffs Harbour segment of the orocline after its formation. Colors are as for Figure 2. Abbreviations: HB, Hastings Block; T, Texas; TB, Tamworth Belt, including Tamworth, Rouchel, Gresford and Myall blocks and inferred extensions north of Texas and now covered by younger basin strata.

Carboniferous and older convergent plate margin assemblage to the north that maintains an overall linear trend, to oroclinally deformed equivalents to the south. This fault would have extended south southeast from a tip point within the core of the Coffs Harbour segment of the orocline along or inboard of the forearc basin strata (Figure 9). A second fault must have transgressed across the forearc basin strata, between the southern Tamworth Belt (Myall Block) and the

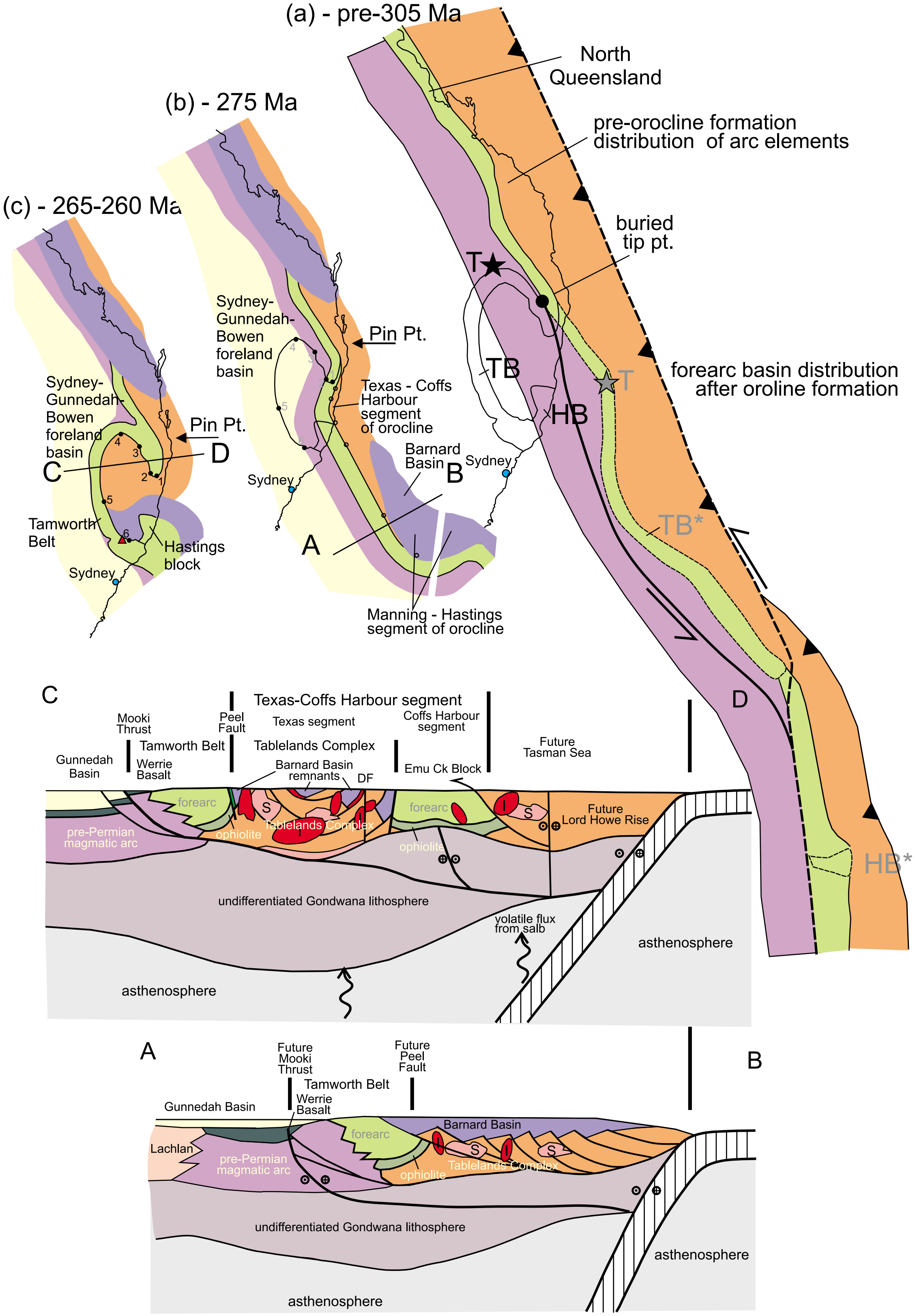

Figure 9

Hastings Block to account for the foreshortening between these blocks required by the paleomagnetic reconstructions (Figure 7). Additional faults may have developed between the blocks of the Tamworth Belt to accommodate their differential movement. Buckling of the forearc and subduction complex units is accommodated by westward displacement toward the orogenic foreland relative to their along strike equivalents to the north, and is a requirement of the decreasing displacement on the western bounding sinistral fault (e.g., compare pre- and post-orocline position of arc elements in Figure 5).

[24] The apparent eastward displacement of the magmatic arc from its pre-310 Ma position along the western margin of the Tamworth Belt to its post-260 Ma position within the subduction complex probably reflects foreshortening and westward displacement of the upper crustal lithosphere of the arc system during orocline formation rather than a dramatic shift in the position of the subduction zone within an asthenospheric reference frame. Such westward motion implies that the lithosphere involved in orocline formation is detached from its lower lithospheric root zone which lies to the east. The spatial correspondence of oroclinal bending with a region that underwent an earlier phase of extension and crustal melting (Bundarra and Hillgrove suites, Figure 2) [*Cawood et al.*, 2011] suggests that thermal weakening of the crust may have facilitated development of a decollement above which the orocline formed. The westward motion of the orocline onto the foreland, as opposed to eastward motion, may reflect buttressing by the rigid oceanic lithosphere of the Pacific plate that restricted eastward motion of the arc system as it was deformed. The marked eastward stepping out of the post-260 Ma magmatic arc corresponds with the area of orocline formation. In Queensland, this younger arc is superimposed in part on the older arc system with the locus of activity within the older arc and forearc regions as opposed to the subduction complex to the south.

[25] Spinel lherzolite xenoliths from Tertiary basaltic rocks at Allyn River within the southern Tamworth Belt (Figure 2) have yielded in situ sulfide Re-Os T_{RD} ages in the 500–600 Ma range with another analysis yielding an age of 840 ± 70 Ma [*Powell and O'Reilly*, 2007]. Similarly, *Shaw and Flood* [2009] and *Shaw et al.* [2011] have reported Lu-Hf depleted mantle model ages from zircons of the New England Batholith as old as early Neoproterozoic. These authors interpreted this data to indicate ancient lithospheric mantle and crust beneath the New England region. This contrasts with the interpretations based on the Paleozoic tectonic setting of the region, which is indicative of an initial intraoceanic arc evolving into a continental margin arc [*Cawood*, 2005] suggestive of an overall juvenile lithospheric structure (and age). Westward transport of the upper crust of the southern New England region however, requires that the upper crust is allochthonous with respect to the subcontinental mantle lithosphere and lower crust, and thus data from either the upper or lower lithosphere cannot be used to constrain the pre-oroclinal structure of the other within a vertical profile after orocline formation (i.e., post-265 Ma).

8. Conclusions

[26] Geologic, geochronological and paleomagnetic data suggest the New England Orocline formed through lithospheric scale vertical axis buckling of an originally linear older Paleozoic arc system during oblique sinistral strike-slip motion across the boundary between the paleo-Pacific and Gondwana plates in the early Permian. A pre-existing phase of lithospheric extension and asthenospheric upwelling associated with emplacement of I-type and S-type granitoids at c. 290 Ma, and marking a phase of subsidence and sedimentation, may have thermally weakened the lower crust and enabled the development of a detachment associated with craton-ward transport of the Paleozoic arc system during buckling, crustal thickening and orocline formation.

[27] Formation of the orocline represents part of the Gondwanide Orogeny. In eastern Australia the orogeny is divisible into an earlier Tablelands Phase and a succeeding Hunter-Bowen Phase [*Cawood et al.*, 2011]. Orocline formation marks the transcompressional pulse associated with the start of the Hunter-Bowen phase (Figure 3). Orogenesis along the evolving Gondwana–paleo-Pacific plate margin involved stabilization of the Gondwana lithosphere through the complex interplay of contractional and extensional deformation, magmatism, metamorphism and sedimentation. Orogenesis was accompanied by termination and deformation of a long established Paleozoic magmatic arc system and the establishment of a new Permian–Triassic outboard arc.

[28] Two stages of orogenesis have also been recognized along the strike of the Gondwana margin in South America [*Bahlburg and Herve*, 1997; *Cawood*, 2005; *Cawood and Buchan*, 2007]. Orocline formation overlaps with dextral transpressional deformation in the Ventana Fold Belt [*Cobbold et al.*, 1991], associated with the second phase of orogenesis in the Andes.

[29] The model for formation of the orocline through buckling and progressive northward (sinistral) translation of the pre-Permian arc system against the northern segment, which is pinned relative to cratonic Gondwana, shows some similarities to that proposed by *Johnston* [2001, 2008] for formation of the Alaska Orocline. He suggested the orocline constituted a linear ribbon continent that became pinned and deformed as it was progressively accreted from the lower to upper plate during transpressional plate margin accretion. Formation of the New England Orocline differs from the Alaskan example in that the deformed arc system was part of the upper plate Gondwana margin and not part of a ribbon continent prior to orocline formation.

[30] The New England and Alaskan oroclines formed within accretionary orogens during ongoing plate margin interaction. In contrast, the Iberian-Armorican orocline formed during Pangea assembly within the collisional Variscan orogen, which marked the termination of plate margin interaction. Lithospheric thickening during formation of the Iberian-Armorican orocline resulted in delamination, asthenospheric upwelling and post-deformation granite emplacement [*Gutiérrez-Alonso et al.*, 2004, 2011]. In contrast, post-orocline formation igneous activity in New England and Alaska is subduction-related convergent plate margin magmatism [*Johnston*, 2008; *Cawood et al.*, 2011].

[31] On a global scale, Gondwanide orogenesis (circa 310–230 Ma) overlaps with assembly of Pangea (circa 320–250 Ma). *Cawood and Buchan* [2007] proposed that termination of major subduction zones during collisional orogenesis associated with assembly of Laurussia and Gondwana must have resulted on a constant radius Earth in

major plate re-organization, which drove orogenesis, including orocline formation, within the Terra Australis orogen along the margin of Gondwana.

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