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Paleomagnetic results indicate pre-Permian counter-clockwise rotation of the southern Tamworth Belt, southern New England Orogen, Australia

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[1] Visean ignimbrites from three fault-bounded blocks within the southern Tamworth Belt, southern New England Orogen, Australia, retain a prefolding high-temperature component of remanence, carried mainly by magnetite. Paleomagnetic data indicate that the southern Tamworth Belt occupied low to moderate paleolatitudes during the early Carboniferous. Normal and reversed polarities with low to moderate inclinations suggest that the steep, reverse polarity latest Carboniferous to earliest Permian overprint is absent from the high-temperature component data set. The mean characteristic remanence direction of three early to middle Visean ignimbrite flows (32 sites) from the Rouchel block is: declination (dec) = 154.2° and inclination (inc) = 38.8° (α_{95} = 12.5°; k = 98.8), which corresponds to a paleo south pole at latitude 64.9°S, longitude 258.1°E (dp = 5.5°; dm = 9.2°, where dp is the angular length of the semiaxis of the ellipse of confidence of the calculated paleopole that lies along the pole to site great circle, and dm is the angular length of the semiaxis perpendicular to dp). Six middle to late Visean ignimbrite flows (29 sites) from the Gresford block retain a mean remanence of dec = 159.6° and inc = 54.1° (α_{95} = 13.7°; k = 24.7), corresponding to a paleo south pole at latitude 72.8°S, longitude 228.4°E (dp = 13.4°; dm = 19.2°). Despite widespread overprinting throughout much of the Myall block, reliable information was obtained from three late Visean ignimbrite flows (five sites), with a mean direction of dec = 118.1° and inc = 42.5° (α_{95} = 12.0°; k = 41.6), from which a paleo south pole of latitude 35.7°S, longitude 233.4°E (dp = 9.1°; dm = 14.7°) is calculated. The calculated paleo south poles do not fall on the early Carboniferous segment of the published apparent polar wander path for Australia and suggest that the southern Tamworth Belt has undergone significant counter-clockwise rotation relative to cratonic Australia. Inferred rotations for the Rouchel, Gresford, and Myall blocks are approximately 80°, 80°, and 120°, respectively. Stratigraphic and geological evidence suggest rotation took place between the mid-Namurian and latest Carboniferous and is thought to have resulted from sinistral strike-slip during compression at the eastern margin of Australia. *INDEX TERMS:* 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics (regional, global); 1527 Geomagnetism and Paleomagnetism: Paleomagnetism applied to geologic processes; 1540 Geomagnetism and Paleomagnetism: Rock and mineral magnetism; *KEYWORDS:* rotation, New England Orogen, Australia, Carboniferous, ignimbrites

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1. Introduction

[2] The Tamworth Belt (Figure 1), southern New England Orogen, Australia, contains Late Devonian to late Carboniferous sedimentary and volcanic rocks that accu-

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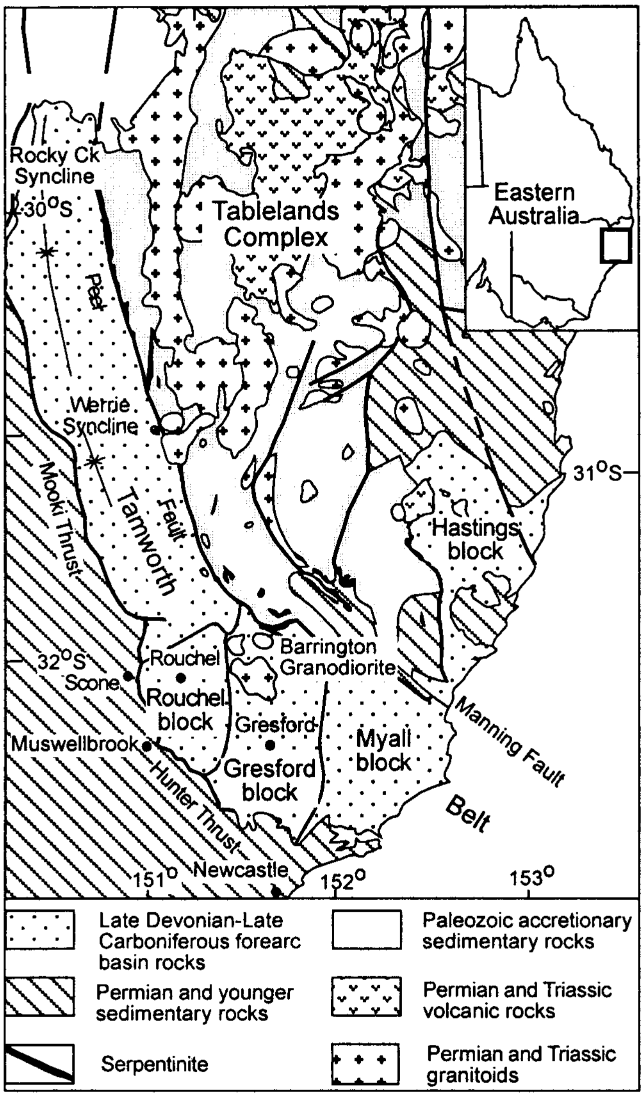


Figure 1. Pre-Cenozoic geology of the southern New England Orogen and the relationships of the Rouchel, Gresford, Myall and Hastings blocks.

mulated in a forearc basin east of a volcanic arc and west of an accretionary complex (Tablelands Complex; Figure 1). Volcanism was particularly active within the arc during the Visean to Westphalian stages of the Carboniferous [*Roberts et al.*, 1995a, 1995b]. Four major fault-bounded blocks, each of which contains a characteristic stratigraphy, have been recognized within the southern part of the Tamworth Belt [*Roberts et al.*, 1991]. From present west to east, they are: Rouchel, Gresford, Myall, and Hastings blocks (Figure 1).

[3] The terms early Carboniferous and late Carboniferous used in this paper equate with the Tournaisian-Visean and Namurian-Westphalian-Stephanian stages of Western Europe, respectively. The use of these subdivisions is necessitated by the absence of biostratigraphic, radiometric or paleomagnetic data, which would enable the recognition of the mid-Carboniferous boundary within Australia and other Gondwana continents. It follows previous and current accepted usage within Australia.

[4] Visean ignimbrites from the Rouchel, Gresford and Myall blocks of the southern Tamworth Belt (Figure 1) have been sampled to determine the paleo south pole position for each block. Careful examination of paleomagnetic data from this area is required in light of the widespread prefolding, steep, reverse polarity, latest Carboniferous to earliest Permian remagnetization found in many rocks from this part of the belt [*Lackie and Schmidt*, 1993; *Geeve*, 2000].

[5] This study establishes reliable paleomagnetic results for the southern Tamworth Belt for comparison with the current APWP for Australia. Discrepancies between paleomagnetic results from cratonic and stable Australia and the southern Tamworth Belt will be explained in terms of the geological history and tectonic evolution of the New England Orogen.

2. Previous Work

[6] *Irving and Parry* [1963] were the first to document a paleomagnetic result for a unit from within the southern Tamworth Belt when they noted the normal polarity of the Paterson volcanics. Later, *Irving* [1966] made a detailed study of many units from parts of the Tamworth Belt and concluded that Australia underwent a rapid movement toward the South Pole in the Carboniferous. *Irving and Parry*'s [1963] results from the normally magnetized Paterson volcanics were used to define the base of the Permo-Carboniferous Superchron, as the units sampled by these authors above the Paterson volcanics were reversely magnetized. Recent SHRIMP dating of zircons from the Paterson volcanics has led to a recalculation of their age to 328.5 ± 1.4 Ma (2σ) [*Claoué-Long et al.*, 1995], which is significantly older than the previously determined K-Ar age of about 308 Ma [*Roberts et al.*, 1991].

[7] Widespread latest Carboniferous to earliest Permian magnetic overprinting, mainly in sedimentary rocks, has been recognized in various parts of the Tamworth Belt [*Lackie and Schmidt*, 1993; *Geeve*, 2000]. Lackie and Schmidt found that the Late Devonian (Famennian) Borah (previously Kiah) Limestone had been remagnetized prior to folding in the southern Tamworth Belt. Similarly, Geeve documented a steep, prefolding, reverse remanence direction retained by all sedimentary units sampled in that study, while ignimbrites retained a prefolding, low to moderately inclined remanence of both polarities. A substantial proportion of volcanic rocks in the Tamworth Belt have survived this remagnetization [*Irving*, 1966; *Opdyke et al.*, 2000]. Ignimbrites within the Rouchel, Gresford and Myall blocks therefore provide a means of investigating the tectonic history of the southern Tamworth Belt.

[8] The Hastings block (Figure 1) is an allochthonous part of the Tamworth Belt, now located east of the accretionary complex [*Scheibner*, 1985; *Lennox and Roberts*, 1988]. *Schmidt et al.* [1994] studied the paleomagnetism of Carboniferous rocks in the Hastings block and found that overprinting had destroyed almost all Carboniferous remanences. The Namurian Kullatine formation, however, apparently withstood overprinting, retaining a prefolding remanent magnetization that yielded a pole position that did not fall on the Australian APWP [*Schmidt et al.*, 1994]. The results from the Hastings block have been interpreted as

indicating significant rotation (130° clockwise or 230° counter-clockwise) of the block since the Namurian [*Schmidt et al.*, 1994]. A 130° clockwise (or 230° counter-clockwise) rotation brought the Kullatine formation pole position into agreement with the APWP.

3. Sampling and Ignimbrite Stratigraphy

[9] The following section on ignimbrite stratigraphy, presented in Figures 2 and 3, is a summary of the work of *Roberts and Oversby* [1974], *Roberts et al.* [1991] and a number of unpublished student theses, with the bulk of the summary taken from *Roberts et al.* [1991]. A composite stratigraphy for the region [*Roberts et al.*, 1991], based on correlations using marine invertebrate zones and ignimbrites, provided the basis for a SHRIMP zircon-dating program [*Claoué-Long et al.*, 1992, 1995; *Roberts et al.*, 1995a, 1995b, 1996] on the most important ignimbrites; all SHRIMP dates quoted in this paper were determined using the SL 13 standard. The resulting revised correlation charts, especially of nonmarine units, now provide excellent age control on the Carboniferous rocks of the southern Tamworth Belt. A revised correlation chart is given in Figure 2 and a summary of the ignimbrite stratigraphy in Figure 3.

[10] In the Rouchel block, ignimbrites of the Isismurra formation include the lowermost, Native Dog Member and a younger group of three unnamed red ignimbrites. The Native Dog Member, which constitutes a thick and substantial part of the Isismurra formation in the western parts of the region, gives rise to two widely distributed tongues: the lowermost Curra Keith Ignimbrite (342.1 ± 3.2 Ma (2σ); *Roberts et al.*, 1995a) and the younger Oakfields Ignimbrite. In places, the Curra Keith and Oakfields Ignimbrites are separated by an unwelded red ignimbrite. Three unnamed, poorly to nonwelded red ignimbrites succeed the Native Dog Member and/or the Oakfields Ignimbrite (Ceia, Ceib, and Ceic on Figure 3), and are overlain high in the formation by the Martins Creek Ignimbrite Member (332.3 ± 2.2 Ma (2σ); *Roberts et al.*, 1995a).

[11] In the Gresford block, the Martins Creek Ignimbrite Member marks the base of the Newtown formation, which is also the highest ignimbrite in the Isismurra formation. The Martins Creek Ignimbrite Member is thus the first stratigraphic unit common to the Rouchel and Gresford blocks. Overlying the Martins Creek Ignimbrite Member is the Vacy Ignimbrite Member. The Newtown and Mowbray formations are referred to as the Gilmore volcanic group (Figure 2). Disconformably overlying the Mowbray formation is the Mount Johnstone formation, which is overlain by the Paterson volcanics (328.5 ± 1.4 Ma (2σ)) [*Claoué-Long et al.*, 1995].

[12] Within the Rosebrook Range, in the southwestern part of the Gresford block, the Johns Hill Ignimbrite may be stratigraphically equivalent to one of the unnamed red ignimbrites of the Isismurra formation, as, in both areas, the Martins Creek Ignimbrite overlies them. The Vacy and Breckin Ignimbrites are not present in the Rosebrook Range stratigraphy, but the Stanhope Ignimbrite [*Benson*, 1976] occupies their approximate position, and is followed by the Lambs Valley Ignimbrite. West of Gresford, the Mount Rivers Ignimbrite is present within the Flagstaff formation, a unit overlain by the Wallaringa formation and the Martins Creek Ignimbrite at the base of the Newtown formation. This places the Mount Rivers Ignimbrite as an approximate lateral stratigraphic equivalent of unwelded red ignimbrites in the upper, but not uppermost, Isismurra formation.

[13] In the northern part of the western Myall block, the Berrico Creek formation contains the Buggs Creek Ignimbrite Member at its base. The Buggs Creek Ignimbrite Member is the northern extension of the Nerong volcanics, a thick succession of ignimbrites confined to southwestern parts of the Myall block and the southeastern margin of the Gresford block. Both the Nerong volcanics and Buggs Creek Ignimbrite Member overlie marine to paralic sediments containing brachiopods of the *Linoprotonia tenuirugosa* subzone (*Delpinea aspinosa* zone), and overlain by sediments containing a rich fauna of the *Rhipidomella fortimuscula* zone. Both volcanics are late Visean in age and possibly stratigraphically equivalent to the uppermost parts of the Isismurra formation in the Rouchel block. In the southwestern Myall block, the Balickera Conglomerate overlies the Eagleton volcanics, and is the stratigraphic equivalent of the lower Mount Johnstone formation [*Rattigan*, 1966]. This places the Eagleton volcanics as possible stratigraphic equivalents of the Mowbray formation in the Gresford block.

4. Paleomagnetic Methods

[14] A portable, petrol-powered rock drill was used to collect six to eight 2.5 cm diameter samples at each site. Samples were oriented using both a magnetic compass and, when possible, a sun compass. Some ignimbrites that were difficult to drill, either because of their hardness or the orientation of the outcrop, were sampled by collecting oriented blocks, which were later drilled in the laboratory. All samples were sliced to 2.2 cm lengths resulting in six to 18 specimens per site with volume of 10.8 cm^3. Bedding was measured at each site on the pumice foliation, when possible, and at adjacent sedimentary units using a compass and clinometer.

[15] All measurement was undertaken at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Rock Magnetism Laboratory at North Ryde, New South Wales. The Natural Remanent Magnetization (NRM) and remanent magnetizations after stepwise demagnetization were measured using a three-axis CTF cryogenic magnetometer housed in a 4 m Helmholtz coil set.

[16] Low-temperature demagnetization using liquid nitrogen (−197°C) and alternating field pretreatment, were applied to specimens containing a large proportion of multidomain magnetite, the latter technique proving more affective in removing multidomain components. Thermal demagnetization was the most effective method of resolving magnetizations carried by pseudo single domain magnetite and hematite. Specimens were thermally demagnetized at 50°C intervals from 250 to 500°C, followed by closer increments until demagnetization was complete, in 14 to 20 steps, using a nonmagnetic three-stage carousel furnace. The furnace is housed in a 4 m ten coil Helmholtz set that provides automatic feedback to maintain a magnetic field free space.

[17] Demagnetization was usually achieved by 600°C, though in some specimens significant remanence persisted until 680°C. Specimens were transferred from the furnace to

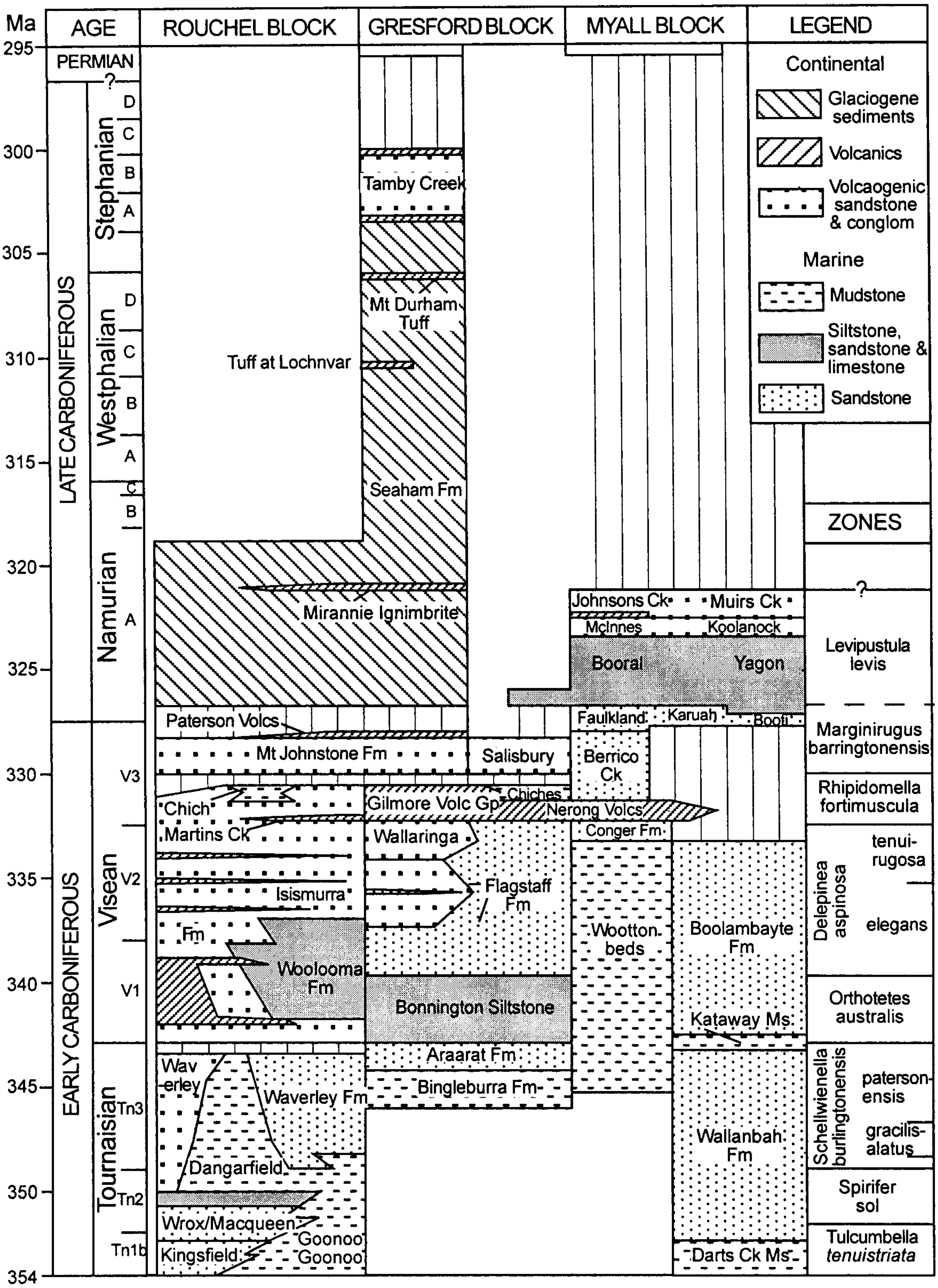


Figure 2. Carboniferous Permian stratigraphy of the Rouchel, Gresford and Myall blocks, modified from *Roberts et al.* [1995a, 1995b] and *Jones et al.* [2000]. Carboniferous brachiopod Zones from *Roberts et al.* [1993a].

the cryogenic magnetometer in magnetically shielded boxes. A Schonstedt single-axis GSD-1 alternating field (AF) Demagnetizer was used to perform AF demagnetization and AF pretreatment. AF demagnetization was applied along three orthogonal specimen axes in 10 to 12 steps from 1 to 85 mT. Remanence components were analyzed using the PCA method of *Kirschvink* [1980]. Components were only used where three successive steps

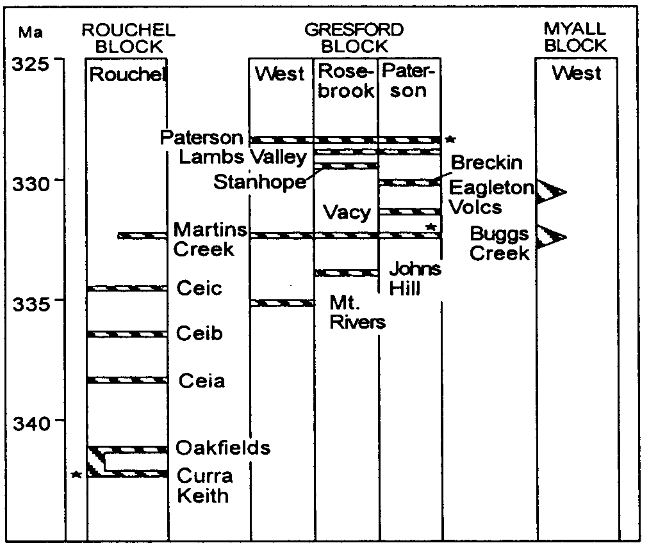


Figure 3. Stratigraphy of early Carboniferous ignimbrites from the Rouchel, Gresford and Myall blocks sampled for this study. Stars indicate SHRIMP dated ignimbrites.

had linearity greater than 90%. The origin was not included in any segments.

5. Rock Magnetic Properties

[18] In order to determine the grain size of the magnetic minerals in the ignimbrites sampled in this study, two experiments were undertaken. *Day et al.* [1977] plots are the standard method of determining grain size, and can be measured accurately and relatively quickly. The hysteresis properties required were determined using a Variable Field Translation Balance (VFTB). Low-field susceptibility versus temperature (k-T) curves are useful for identifying magnetic minerals and assessing their purity as well as grainsize distributions and some alteration products [*Schmidt*, 1993]. Susceptibility as a function of temperature was performed using a transformer bridge [*Ridley and Brown*, 1980].

[19] Day et al. plots for a representative group of the ignimbrites sampled are presented in Figure 4. All the sampled ignimbrites fall into the pseudo single-domain field or within or slightly above the multidomain field; no ignimbrites plot within the single-domain field. Some hysteresis loops are wasp-waisted indicating a bimodal grain-size distribution. Therefore H_c may be biased toward low values in some samples. The affect of this may be seen in Figure 4, in the samples that plot above the MD field and to the right of the PSD field. Some of these samples have PSD-like M_{rs}/M_s but MD-like H_{cr}/H_c.

[20] The k-T curves for the Oakfields Ignimbrite and the unnamed red ignimbrites in the Isismurra formation of the Rouchel block, with the Stanhope, Vacy, and Lambs Valley Ignimbrites and the Paterson volcanics of the Gresford block, and the Buggs Creek Ignimbrite and Eagleton volcanics of the Myall block have the same basic shape, and typical examples are presented in Figures 5a and 5b. They indicate a steady increase in susceptibility as temperature rises to about 180°C. Upon further heating susceptibility often increases rapidly to a peak at about 300°C and then rapidly decreases until about 400°C (Figure 5a). This peak is the classic signature of the presence of maghemite [*Schmidt*, 1993]. Some samples with this peak were allowed to cool from 400°C, whereupon the curve did not return via the heating path; instead, the susceptibility decreased slowly as temperature decreased. This indicates the maghemite had inverted to hematite during initial heating. The resumption of heating led to a steady increase in susceptibility to about 450°C, after which the susceptibility decreased steadily to almost zero. The rounding of the curve where it starts to fall and the slope as it approaches the maximum Curie point indicates a mixture in the composition of the magnetites, presumably with variable Ti content, which is common for magmatic magnetites and is further evidence that they are not secondary. Samples were then allowed to cool and the curves were generally reversible, with the absence of the maghemite peak.

[21] The presence of maghemite in rocks containing pseudo single-domain magnetite may reflect a relatively oxidized shell around an unoxidized core. Its apparent absence in rocks with coarser multidomain magnetite grains may simply reflect the much lower surface area to volume ratio of the larger grains. The k-T curves indicate that any remanent magnetization carried by the maghemite is destroyed above 400°C as the maghemite breaks down by this temperature.

[22] The k-T measurements for the Curra Keith and Martins Creek Ignimbrites and, to a lesser extent, the Breckin Ignimbrite, on the other hand, are quite different from those described above (Figure 5c). These units display k-T curves that have a large peak in susceptibility at about −150°C, corresponding to the isotropic point of magnetite. On further heating the susceptibility remains reasonably constant, with no maghemite peak, until, at the Curie temperature, susceptibility decreases moderately rapidly to almost zero. The curve is reversible on cooling.

6. Paleomagnetic Results

[23] Thermal demagnetization proved the most effective method of isolating the remanence components in the Visean ignimbrites of the southern Tamworth Belt. Alternating field demagnetization often failed to eliminate the present field component. Most sites retain two components

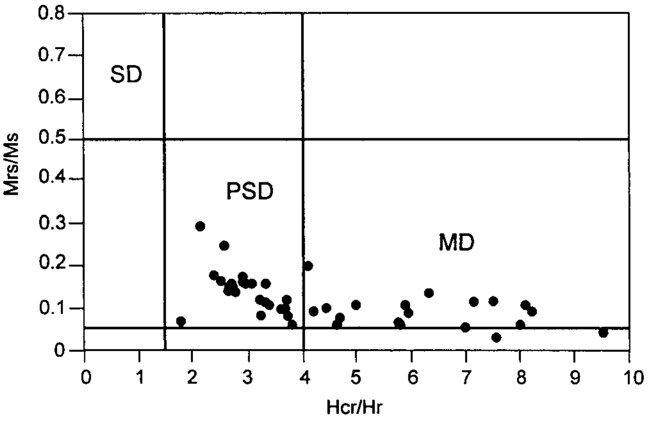


Figure 4. *Day et al.* [1977] plot of a representative sample of ignimbrites from the southern Tamworth Belt.

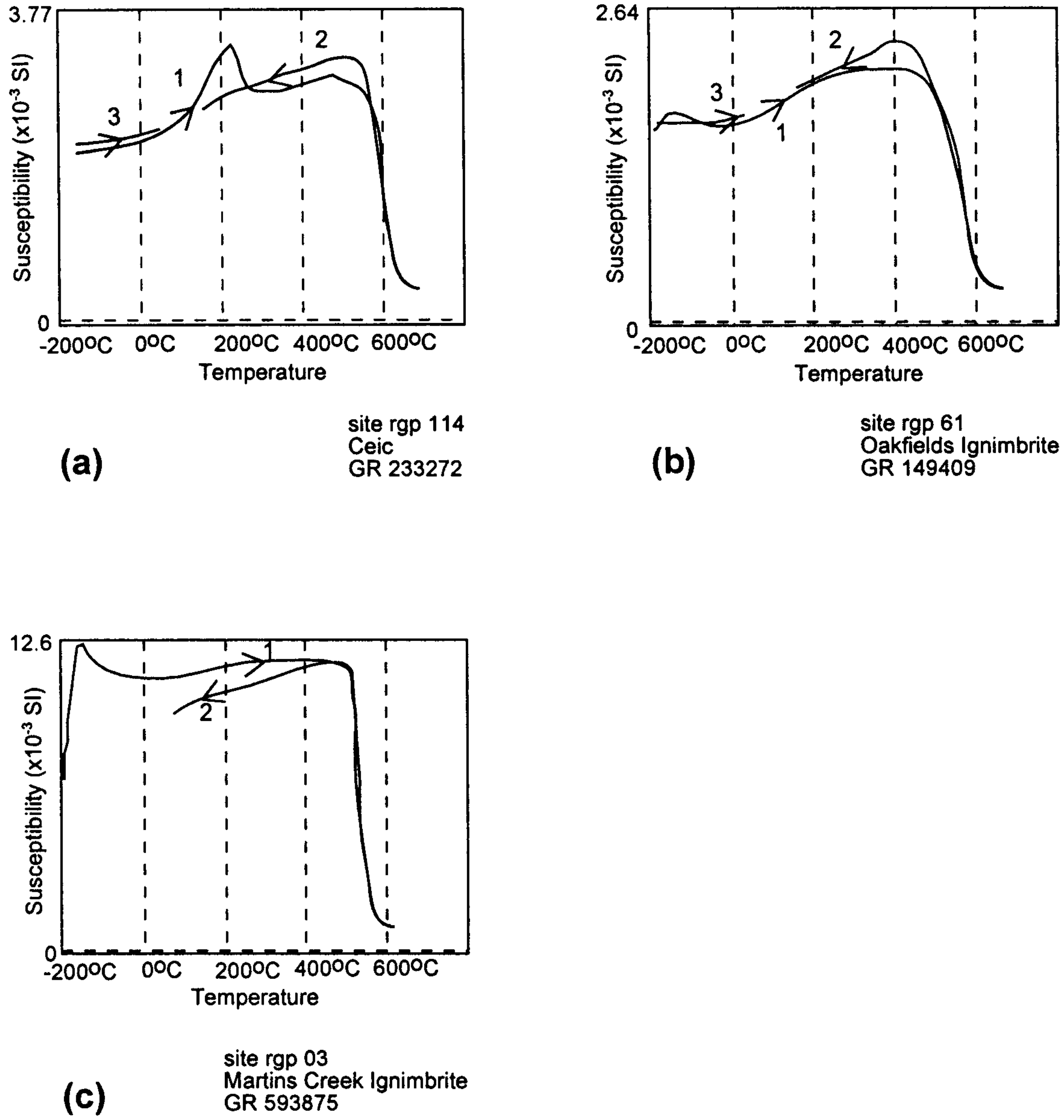


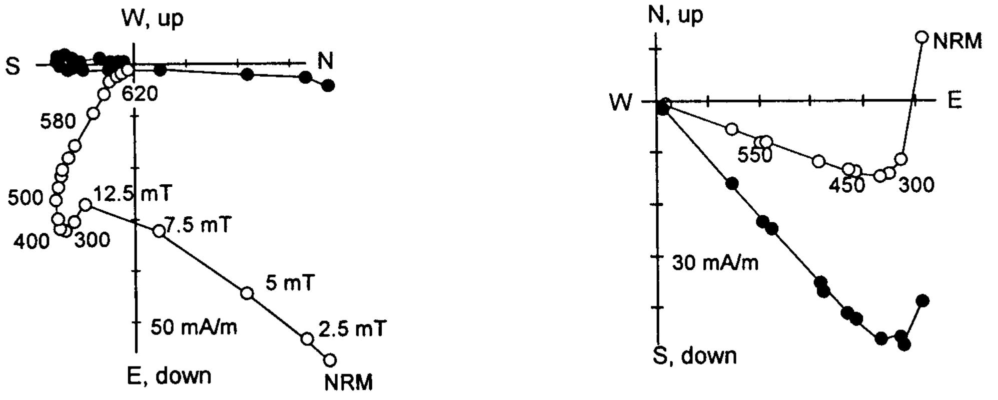
Figure 5. Low-field susceptibility versus temperature curves of selected (a and b) pseudo single-domain and (c) multidomain magnetite dominant ignimbrite sites from the southern Tamworth Belt. Numbers and arrows refer to heating/cooling sequence.

of magnetization (Figure 6): a low-temperature component that is usually removed by 300°C, has normal polarity and a similar direction to the present field or perhaps the dipole field; and a high-temperature component that is only moderately inclined after bedding correction, with both normal and reverse polarities. The former component has the same direction independent of rock type sampled and is interpreted as being a recent viscous overprint.

[24] Seven sites retain three components of magnetization (Figures 6a and 6c). A soft, low-temperature normal component, a midtemperature steeply down (after bedding correction) component and a high-temperature component that may be of either polarity and is moderately inclined (after bedding correction). The mean directions of the mid and high-temperature components of these sites after bedding correction are statistically different using the *McFadden and Lowes* [1981] discrimination test, indicating they were acquired at different times.

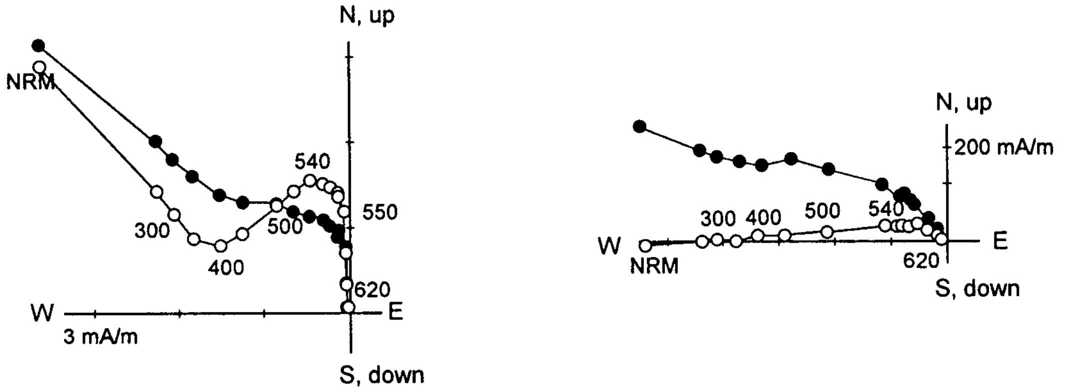
6.1. Rouchel Block

[25] The ignimbrites from the Rouchel block generally retain two components of remanence; a low-temperature, normal polarity component and a high-temperature component with both normal and reverse polarities. The high-temperature component usually unblocks between 350°C and 580°C, and rock magnetic experiments, described above, indicate that magnetite is the main magnetic mineral. Some sites, however, were not completely demagnetized until 670°C, indicating that some of the remanence is carried by hematite. Typical orthogonal plots of the demagnetization behavior of ignimbrites from the Isismurra formation are given in Figures 6a and 6f.



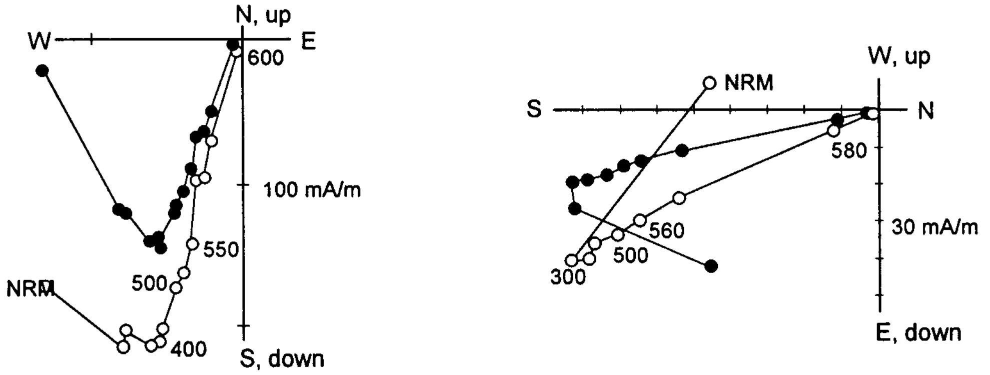
site rgp 224
Oakfields Ignimbrite
GR 153384

site rgp 19
Mt. Rivers Ignimbrite
GR 556073



site rgp 102
Buggs Creek Ignimbrite
GR 892419

site rgp 69
Vacy Ignimbrite
GR 648000



site rgp 01
Lambs Valley Ignimbrite
GR 624838

site rgp 112
Ceic
GR 303226

Figure 6. Typical in situ orthogonal plots of ignimbrites of the southern Tamworth Belt. Open (closed) circles refer to projections on a vertical (horizontal) plane (demagnetization steps in °C).

Table 1. Summary of Sampling Locations and Characteristic Site Mean Remanence Directions of Early Carboniferous Ignimbrites From the Rouchel Block of the Southern Tamworth Belt[a]

Site Name	Site Latitude	Site Longitude	GR	N	M_{rs}/M_s	H_{cr}/H_c	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α_{95}
Ignimbrite: CEIC												
rgp35	−32.4322	151.268	372103	7	0.117	7.16	169.0	19.2	005/52	144.0	66.6	5.8
rgp41	−32.210	151.10	209343	7	0.166	2.51	160.4	40.7	090/05	156.5	38.8	7.6
rgp112	−32.3205	151.1972	303226	6			163.2	23.3	070/16	156.2	23.2	2.4
rgp114	−32.2779	151.1237	233272	10	0.157	3.06	170.5	27.2	057/13	163.5	31.6	3.6
rgp116	−32.3274	151.0537	168216	6			174.8	60.2	094/15	152.4	54.8	1.8
rgp117	−32.3251	151.0835	196219	6			153.6	51.7	215/11	164.0	45.5	4.6
rgp177	−32.4448	151.1862	295088	5			160.3	33.9	080/16	150.5	29.8	4.8
rgp230	−32.1836	151.0875	197376	8	0.162	2.94	164.7	39.4	214/09	169.5	33.2	4.6
rgp234	−32.266	151.1134	223290	6	0.161	2.98	164.1	32.4	057/13	155.5	35.3	3.1
	N	Dec	Inc	α95	k	SCOS1	X, %	Y, %				
Fold Test [*McFadden*, 1990][b]												
In situ	9	164.5	36.5	9.0	33.8	3.667						
Corrected	9	157.8	40.0	9.4	30.8	2.570	47	42				
Site Name	Site Latitude	Site Longitude	GR	N	M_{rs}/M_s	H_{cr}/H_c	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec(*b*)	Rem Inc (*b*)	α_{95}
Ignimbrite: CEIB												
rgp28	−32.5044	151.3317	433024	5			319.5	−14.4	035/38	307.3	−20.1	3.0
rgp31	−32.4342	151.2692	373101	3	0.157	3.33	303.1	12.4	005/63	299.9	−18.2	11.4
rgp33	−32.4475	151.2625	367086	6	0.157	2.71	345.2	04.9	030/37	341.2	−20.1	6.7
rgp43	−32.1544	151.0869	196408	4			313.9	−44.5	145/08	315.1	−36.6	12.5
rgp108	−32.3948	151.1617	271143	5			323.7	−24.1	035/21	313.3	−29.0	6.9
rgp110	−32.3359	151.2033	309209	3			349.8	−55.2	080/30	314.1	−45.2	14.4
rgp206	−32.1883	151.0439	163368	7	0.204	4.08	353.1	−22.7	065/12	347.8	−25.9	5.6
rgp220	−31.9312	151.0367	144655	4			277.0	−35.6	228/52	329.9	−51.1	7.4
rgp223	−32.1693	151.0401	152391	4			352.7	−22.6	110/10	349.4	−17.7	2.0
rgp233	−32.1938	151.1053	214365	7			356.3	−22.6	030/14	351.8	−33.8	2.5
rgp236	−32.3377	151.2	306207	7	0.106	3.4	331.2	−38.7	045/18	316.0	−41.4	4.1
	N	Dec	Inc	α95	k	SCOS1	X, %	Y, %				
Fold Test [*McFadden*, 1990][c]												
In situ	11	330.2	−26.0	17.7	7.6	5.339						
Corrected	11	326.2	−32.3	11.5	16.6	1.169	100	100				
Site Name	Site Latitude	Site Longitude	GR	N	M_{rs}/M_s	H_{cr}/H_c	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α_{95}
Ignimbrite: Oakfields												
rgp54	−32.1058	151.0636	173462	6	0.248	2.57	183.3	40.9	138/15	176.1	29.6	5.4
rgp56	−32.1133	151.0731	182454	6	0.077	4.69	193.7	50.1	094/26	163.2	47.4	2.9
rgp61	−32.1528	151.0367	149409	6			126.3	83.7	150/30	145.7	54.1	13.0
rgp183	−32.015	150.9809	093560	5	0.29	2.12	199.5	61.9	038/18	173.5	77.6	2.6
rgp186	−32.0034	150.9272	042573	7	0.137	6.32	230.0	45.4	102/15	214.8	53.0	4.9
rgp199	−32.1544	151.069	179408	3	0.138	2.8	203.1	45.8	120/22	183.4	39.2	11.0
rgp200	−32.1482	151.0745	184415	5			134.7	46.1	135/18	134.7	28.1	3.6
rgp202	−32.1583	151.0244	137403	3	0.111	5.9	187.2	55.9	148/21	174.7	38.1	8.8
rgp203	−32.1881	151.0323	145370	6			171.1	34.6	050/13	162.1	40.4	3.5
rgp210	−32.0524	151.0045	116520	4	0.099	4.44	136.3	26.5	046/21	126.1	24.7	18.4
rgp219	−31.9159	151.0391	146672	8			112.0	−16.5	245/52	113.2	19.9	4.9
rgp224	−32.1757	151.041	153384	7			184.8	45.7	155/21	177.8	26.8	4.2
	N	Dec	Inc	α95	k	SCOS1	X, %	Y, %				
Fold Test [*McFadden*, 1990][d]												
In situ	12	172.3	50.0	19.4	6.0	4.799						
corrected	12	159.6	43.6	14.8	9.5	1.915	100	100				
	N	Dec	Inc	α95	k							
Overall Means[e]												
	3	154.2	38.8	12.5	98.8							
	Latitude	Longitude	dp	dm	Latitude							
Paleo South Pole[f]												
	−64.9	258.7	5.5	9.2	−64.9							

[a] GR, grid reference (Australian map grid zone 56); N, number of specimens; M_{rs}/M_s, ratio of saturation remanence to saturation magnetization; H_{cr}/H_c, ratio of coercivity of remanence to coercive force; rem dec/inc (*h*), in situ remanence declination/inclination; DDA/Dip, down dip azimuth/dip of bedding; rem dec/inc (*b*), bedding corrected remanence declination/inclination; α_{95} and k, *Fisher* [1953] statistics.

[b] Site mean location; latitude = 32.3°S, longitude = 151.0°E; paleopole; latitude = 68.1°S, longitude = 261.3°E, dp = 6.8°, dm = 11.3°.

[c] Site mean location; latitude = 32.3°S, longitude = 151.0°E; paleopole; latitude = 70.2°N, longitude = 105.9°E, dp = 7.3°, dm = 12.9°.

[d] Site mean location; latitude = 32.1°S, longitude = 151.0°E; paleopole; latitude = 70.9°S, longitude = 256.2°E, dp = 11.5°, dm = 18.4°.

[e] Paleolatitude; λ = 21.9°S, upper limit = 32.0°S, lower limit = 13.9°S.

[f] Site mean location; latitude = 32.2°S, longitude = 151.0°E.

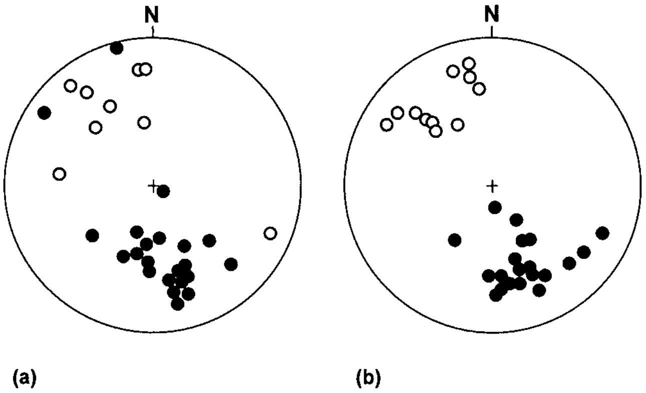


Figure 7. In situ (a) and bedding corrected (b) high-temperature site mean remanence directions of Isismurra formation ignimbrites (Rouchel block). Open (closed) circles refer to projections on the upper (lower) hemisphere; equal area projections.

[26] The fold test [*McFadden*, 1990] was applied to each ignimbrite flow with N > 2 separately and only those that passed were included in the data set used in this study. The Oakfields Ignimbrite and the unnamed red ignimbrites Ceib and Ceic passed these criteria. Table 1 summarizes the site means, and overall means for each ignimbrites flow and the overall mean for the Rouchel block, as well as the fold test results. Figure 7 presents the in situ and bedding corrected high-temperature site mean remanence directions of the Isismurra formation ignimbrites. The normal and reverse sites pass *McFadden and McElhinny*'s [1990] reversal test at the 95% confidence level, with the angle between the means of the normal and reversed data sets of 13.5°, the probability of exceeding this angle is 0.069, the critical angle is 14.3°, and is a "C" class result.

[27] Throughout this study all normal polarity sites have been converted to reverse polarity for calculation of the overall means for ease of comparison with the predominantly reverse polarity Permian period. Thirty-two ignimbrite sites from three ignimbrite flows within the Isismurra formation retain a high-temperature remanence which has a mean direction of delication (dec) = 154.2°, inclination (inc) = 38.8° (α_{95} = 12.5°; k = 98.8) after bedding correction, corresponding to a paleo south pole of latitude = 64.9°S, longitude = 258.7°E (dp = 5.5°; dm = 9.2°) and is plotted in Figure 8 (mnemonic is RB).

6.2. Gresford Block

[28] Ignimbrites within the Gresford block were sampled from the Mount Rivers Ignimbrite, Rosebrook Range section, Newtown and Mowbray formations and the Paterson volcanics. The Mount Rivers Ignimbrite in a continental succession of the Flagstaff formation may equate with one of the three unnamed ignimbrites (Ceia–Ceic) in the Rouchel block. The remaining ignimbrites in this stratigraphic sequence are all younger than those below the Martins Creek Ignimbrite in the Isismurra formation of the Rouchel block. The Mount Rivers and Johns Hill Ignimbrites, however, are slightly older than the Martins Creek Ignimbrite that elsewhere constitutes the base of the Gilmore volcanic group and appears continuous with the base of the Nerong volcanics.

[29] As with the ignimbrites of the Isismurra formation, two components of remanence are present. The high-temperature component usually unblocks between 350°C and 580°C, and magnetite is the main magnetic mineral. However, most of the remanence of the Johns Hill Ignimbrite unblocked above 590°C, indicating that its remanence is carried by hematite. Examples of orthogonal plots of the demagnetization behavior of ignimbrites from the Gresford block are given in Figures 6b, 6d, and 6e). The high-temperature component is of moderate inclination with a declination of northwest (for normal polarity sites) or southeast (for reverse sites) after bedding correction. Figure 9 presents the in situ and bedding corrected high-temperature site mean remanence directions of the Gresford block ignimbrites.

[30] The *McFadden* [1990] fold test was applied to each ignimbrite flow with N > 2 separately and only those that passed were used in this study. The Paterson volcanics, Lambs Valley, Breckin, Vacy, Johns Hill and Mount Rivers Ignimbrites passed these criteria. Table 2 summarizes the site means, overall means for each ignimbrite flow, and the overall mean for the Gresford block as well as the fold test results for each ignimbrite. The high-temperature component passes *McFadden and McElhinny*'s [1990] reversal test at the 95% confidence level. The angle between the normal and reverse site means is 5.6°, the probability of exceeding this angle is 0.646, and the critical angle is 15.2°, which is a "C" class result. The mean remanence direction of 29 ignimbrite sites from six ignimbrite flows within the Gresford block is dec = 159.6°, inc = 54.1° (α_{95} = 13.7°; k = 24.7) after bedding correction, which corresponds to a paleo south pole of latitude = 72.8°S, longitude = 228.4°E (dp = 13.4°; dm = 19.2°) and is plotted in Figure 8 (mnemonic is GB).

6.3. Myall Block

[31] The Buggs Creek Ignimbrite, a thin northerly extension of the Nerong volcanics, retains three components of magnetization; a low-temperature postfolding normal polarity viscous overprint, a prefolding steep, south-directed, reverse polarity, and a high-temperature prefolding moderately inclined normal polarity remanence (Figure 6c). The Eagleton volcanics retain two components of magnetization; a normal polarity postfolding viscous overprint and a prefolding reverse polarity moderately inclined remanence. The fold test was not applied to each Myall block ignimbrite individually, because there are only two sites of Buggs Creek Ignimbrite and both were collected from the same limb of a fold. The data were instead treated as a whole with N = 5.

[32] The high-temperature component site mean directions pass *McFadden*'s [1990] fold test at the 99% confidence level. The SCOS2 parameter was used for the fold test of the Myall block ignimbrite sites, because the mean of the in situ and bedding corrected site mean directions is very different. The reversal test of *McFadden and McElhinny* [1990] was applied using the simulation method, as there are only two sites of the Buggs Creek Ignimbrite, and provided a negative result. The angle between the normal and reverse data sets is 21.6°, with the probability of exceeding this angle being <0.01, and the critical angle is 8.5°. The value of this result is dubious as the Buggs Creek

Ignimbrite is a single flow and the two sites were collected from the same limb of a fold.

[33] An orthogonal plot of a Buggs Creek Ignimbrite site from the Myall block is given in Figure 6c. The in situ and bedding corrected site mean remanence directions of the Buggs Creek Ignimbrite and Eagleton volcanics are summarized in Table 3 and illustrated in Figure 10. The mean bedding corrected remanence direction of five sites is dec = 118.1°, inc = 42.5° (α_{95} = 12.0°; k = 41.6), which corresponds to a paleo south pole position of latitude = 35.7°S, longitude = 233.0°E (dp = 9.1°; dm = 14.7°) which is plotted in Figure 8 (mnemonic is MB).

7. Australian Apparent Polar Wander Path

[34] In a contribution to the study of rotated terranes of North America, *Van der Voo* [1989] recognized that the most important information required for detecting tectonic rotations is a well-established apparent polar wander path (APWP), based on reliable reference directions from the craton. He stated, "In most cases these reference directions should be those of the craton, and in essence it is no overstatement to claim that a detailed and reliable cratonic apparent polar wander path is the first prerequisite for sound paleomagnetic interpretations of any sort" [*Van der Voo*, 1989, p. 448].

[35] Over the past decade or two, high quality paleomagnetic data have been obtained from Devonian and early Carboniferous rocks from the Australian craton and the Lachlan fold belt [*Schmidt et al.*, 1986, 1987; *Hurley and Van der Voo*, 1987; *Li et al.*, 1988; *Thrupp et al.*, 1991; *Wahyono*, 1992; *Chen et al.*, 1993, 1994, 1995]. The APWP in this study has been constructed using only A and B class poles as defined by *Li and Powell* [1993] and is modified from *Chen et al.* [1995] by the addition of the Bathurst Granite pole of *Wahyono* [1992]. The progression of the APWP (Figure 8) is clockwise from the Early Devonian Snowy River volcanics (mnemonic is SRV) to the Carboniferous Bathurst Batholith pole (mnemonic Bath). The paleo south poles determined for the southern Tamworth Belt will be compared with this APWP for Australia.

8. Discussion

[36] Visean ignimbrites of the Rouchel and Gresford blocks sampled in this study retain a high-temperature prefolding remanent magnetization, which also passes the

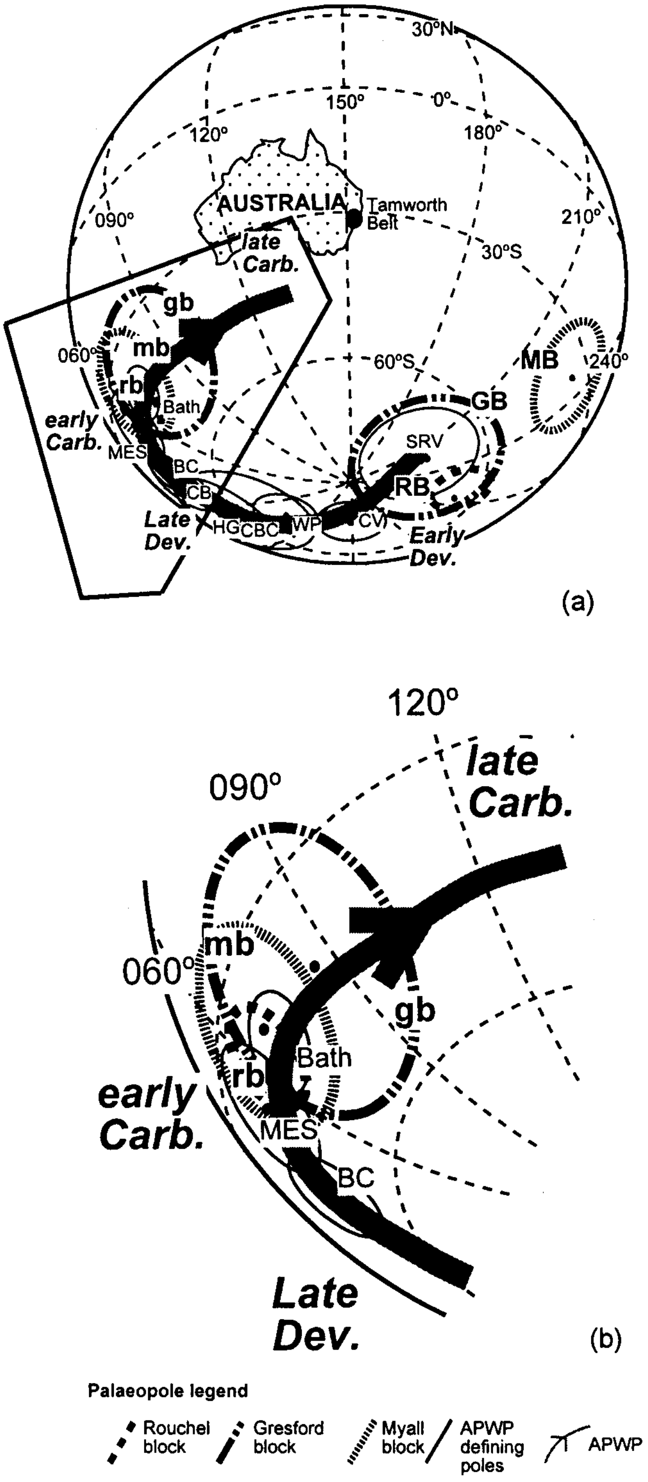


Figure 8. (opposite) (a) Early Devonian to late Carboniferous Australian apparent polar wander path (APWP) derived from "A" and "B" class poles, as defined by *Li and Powell* [1993], modified from *Chen et al.* [1994]. SRV, Snowy River volcanics [*Schmidt et al.*, 1987]; CV, Comerong volcanics [*Schmidt et al.*, 1986]; WP, Worange Point formation [*Thrupp et al.*, 1991]; CBC, Canning Basin [*Chen et al.*, 1995]; HG, Hervey group [*Li et al.*, 1988]; CB, Canning Basin [*Hurley and Van der Voo*, 1987]; BC, Brewer Conglomerate [*Chen et al.*, 1993]; MES, Mount Eclipse sandstone [*Chen et al.*, 1994]; Bath, Bathurst Batholith [*Wahyono*, 1992]. Thick gray line marks APWP. RB, GB, and MB indicate in situ paleo south pole positions of the Rouchel, Gresford and Myall blocks, respectively. The values rb, gb and mb indicate the rotation corrected paleo south pole positions of the Rouchel, Gresford and Myall blocks, respectively. (b) Expanded view of the Late Devonian to late Carboniferous section of the Australian apparent polar wander path (APWP) illustrating the overlap of rotation corrected early Carboniferous southern Tamworth Belt paleo south poles with the early Carboniferous Mount Eclipse sandstone and Bathurst Batholith paleopoles. Paleopole mnemonics as Figure 8a. Thick gray line marks APWP.

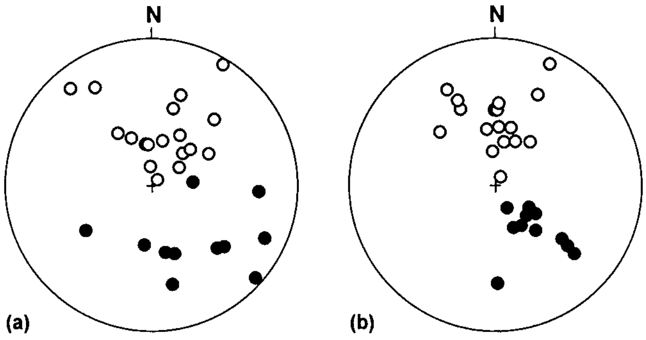


Figure 9. In situ (a) and bedding corrected (b) high-temperature site mean remanence directions of the Gresford block ignimbrites. Open (closed) circles refer to projections on the upper (lower) hemisphere; equal area projections.

reversal test, whereas ignimbrites from the Myall block only pass the fold test. Normal and reverse polarities are retained, with moderate inclinations. These directions are statistically different from the latest Carboniferous to earliest Permian remagnetization direction [*Geeve*, 2000] of dec = 059.7°, inc = 88.0° (α_{95} = 5.5°; k = 19.1; N = 37) using the discrimination test of *McFadden and Lowes* [1981]. It is therefore argued that the high-temperature directions in this study are most likely primary.

[37] The calculated paleo south poles for the major fault blocks of the southern Tamworth Belt sampled in this study do not fall on the early Carboniferous segment of the current APWP for Australia (Figure 8). In fact, the poles overlap the Early Devonian Snowy River volcanics pole [*Schmidt et al.*, 1987]. While it may be argued that the Snowy River volcanics pole represents a Visean overprint, evidence that this pole has a positive fold test, with folding having taken place during the Late Devonian, indicates the magnetization is almost certainly primary.

[38] When the remanence direction is of low to moderate inclination, paleomagnetism is a powerful means of testing for tectonic rotation. The paleo south poles determined here for ignimbrites from the Rouchel, Gresford and Myall blocks are significantly different from the early Carboniferous segment of the apparent polar wander path (APWP) for cratonic Australia. The paleolatitude of the Rouchel block is 21.9°S (upper limit = 32.0°S; lower limit = 13.9°S), the Gresford block 34.6°S (upper limit = 50.8°S; lower limit = 20.1°S) and the Myall block 24.6°S (upper limit = 35.0°S; lower limit = 16.4°S). These accord well with results from the Visean Mount Eclipse sandstone (paleolatitude of 20.6°S [*Chen et al.*, 1994]) from central Australia. The possession of similar paleolatitudes but declinations that are significantly different strongly suggests that the southern Tamworth Belt has been rotated relative to the craton.

[39] A statistical test for quantifying tectonic rotations was outlined by *Butler* [1992, pp. 306–308]. Using Butler's methods and the Mount Eclipse sandstone [*Chen et al.*, 1994] as the Visean reference pole, the amount of rotation of the Rouchel, Gresford and Myall blocks was calculated as 82.9° ± 10.7°, 77.5° ± 16.2° and 119.0° ± 10.9°, respectively, all in the counter-clockwise sense. Thus, within certainty, an 80° clockwise rotation about a vertical axis reconciles the Rouchel and Gresford block poles, and a 120° clockwise rotation the Myall block pole, with the Visean segment of the APWP where they overlap the Mount Eclipse sandstone and Bathurst Granite poles (Figure 8b).

[40] Analysis of the depositional history and events affecting the Rouchel, Gresford and Myall blocks (Figure 2) provides an insight into the nature and timing of the rotation of the blocks. Evidence of linkage or separation of adjacent successions is provided by local to regional episodes of volcanism and marine transgression and by the global change of sea level at the Tournaisian–Visean boundary. Four distinctly different Tournaisian to late Visean successions are present, two in the Myall block and one in each of the other blocks. Each of the successions is confined within a block or subblock and has its own characteristic stratigraphy and depositional history. These sequences appear to have been derived from different sources, deposited in distinctly different areas, and then moved into juxtaposition prior to a major late Visean volcanic event. The most likely means of transport was by syndepositional transcurrent faults such as those associated with oblique zones of subduction [*Ryan and Scholl*, 1989].

[41] Extensive cover units, both volcanic and sedimentary, overlie the older sequences and provide linkages between the blocks. Linking sequences of late Visean to Namurian age include the Martins Creek Ignimbrite throughout southern parts of the Gresford and Rouchel blocks; the Nerong volcanics in the Myall block and eastern part of the Gresford block; the Chichester formation in the Gresford and Rouchel blocks; and the Booral formation in the Myall block and eastern margin of the Gresford block [*Roberts et al.*, 1991] (Figure 2). Post-Visean successions are essentially identical in the Gresford and Rouchel blocks, suggesting that it remained amalgamated. That in the Myall block is more closely related to a coeval sequence in the southern Hastings Block [*Roberts et al.*, 1995c], suggesting close proximity between the two in the late Carboniferous. Marine formations predominate in the Hastings block [*Roberts et al.*, 1993b, 1995c] suggesting that it occupied a different part of the forearc to the Rouchel and Gresford blocks, both of which contain a high proportion of continental units [*Roberts et al.*, 1991].

[42] The timing of block rotation in the southern Tamworth Belt appears to be controlled by processes associated with events at the convergent margin of eastern Australia, including strike-slip faulting, the cessation of subduction because of eastward transfer [*Scheibner*, 1998] or slab breakoff [*Caprarelli and Leitch*, 1998, 2001] and the establishment of an extensional regime. The only likely mechanism that could produce the differential rotation of blocks in the southern Tamworth belt is strike-slip fault movement generated by oblique subduction.

[43] Rotation of crustal blocks in regions of oblique subduction has been identified in the Aleutian Arc [*Geist et al.*, 1988; *Ryan and Scholl*, 1989], the central Andes [*Dewey and Lamb*, 1992] and in western North America (see *Beck* [1989] for a summary of early work and *Horns and Verosub* [1995]). In these areas, where crustal blocks are undergoing dextral strike-slip, most rotations are clockwise, while for those experiencing sinistral shear, counter-clockwise rotations are the norm [*Beck et al.*, 1994; *Beck*, 1998]. Tectonic blocks along the west coast of the USA, where a transform margin is developed, have also experi-

Table 2. Summary of Sampling Locations and Characteristic Site Mean Remanence Directions of Early Carboniferous Ignimbrites From the Gresford Block of the Southern Tamworth Belt[a]

Site Name	Site Latitude	Site Longitude	GR	N	Mrs/Ms	Hcr/Hc	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α95	k
Ignimbrite: Paterson Volcanics													
rgp109	−32.3708	151.2478	351171	12	0.086	3.25	017.6	−71.8	105/19	331.5	−64.5	3.3	174.2
rgp134	−32.6045	151.6125	698917	6	0.176	2.92	307.9	−73.6	250/18	012.7	−73.4	4.0	288.0
rgp135	−32.5641	151.5556	644961	8	0.177	2.38	346.8	−65.3	000/00	346.8	−65.3	3.5	253.2
rgp147	−32.6608	151.7427	821856	4	0.119	3.24	285.6	−80.7	180/08	319.2	−76.2	5.2	309.6
rgp149	−32.4519	151.3052	407082	5	0.082	3.73	049.9	−63.1	086/22	357.0	−74.5	4.0	360.7
rgp151	−32.4202	151.3016	403117	8	0.092	4.2	005.1	−38.6	010/56	229.2	−83.9	1.0	2859.0
rgp152	−32.4998	151.3852	483030	5	0.046	9.51	360.0	−46.8	049/09	351.5	−52.2	2.3	1062.0
rgp241	−32.6575	151.682	764859	8	0.122	3.69	018.7	−80.0	170/15	001.7	−65.7	1.7	1013.0
rgp245	−32.4941	151.3651	464036	7			026.2	−68.0	074/13	351.5	−73.7	2.8	468.2
	N	Dec	Inc	α95	k	SCOS1	X, %	Y, %					
Fold Test [*McFadden*, 1990][b]													
In situ	9	004.6	−68.2	12.2	18.8	7.405							
Corrected	9	347.5	−71.5	7.9	43.9	1.019	69	100					
	Site Latitude	Site Longitude	GR	N	Mrs/Ms	Hcr/Hc	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α95	k
Ignimbrite: Lambs Valley													
rgp01	−32.6747	151.5322	624838	8	0.148	2.74	205.7	52.5	085/22	174.0	58.4	2.1	680.6
rgp12	−32.5933	151.4453	541927	4			033.2	−45.8	030/24	036.4	−69.7	5.0	339.6
rgp74	−32.5766	151.621	706948	9	0.07	1.79	082.6	79.0	175/26	150.7	62.3	3.3	241.0
rgp139	−32.5621	151.5396	629963	5	0.062	5.76	181.1	31.5	230/12	185.6	23.2	15.4	25.6
rgp242	−32.5576	151.4598	554967	8	0.105	4.95	119.6	29.0	263/53	169.1	58.4	2.0	781.0
	N	Dec	Inc	α95	k	SCOS1	X, %	Y, %					
Fold Test [*McFadden*, 1990][c]													
In situ	5	173.1	55.5	36.6	5.3	2.702							
Corrected	5	178.2	56.1	20.8	14.5	0.574	97	93					
	Site Latitude	Site Longitude	GR	N	Mrs/Ms	Hcr/Hc	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α95	k
Ignimbrite: Breckin													
rgp20	−32.554	151.7333	811974	8			317.8	−55.2	160/10	321.9	−45.8	6.4	75.8
rgp21	−32.5228	151.7392	816009	9			313.1	−47.9	045/13	299.2	−45.8	7.8	44.9
rgp68	−32.56	151.61	697969	7	0.064	3.81	312.8	−03.8	272/39	322.0	−31.7	8.2	54.8
rgp75	−32.5201	151.7373	814012	4	0.032	7.57	022.9	−12.1	045/13	021.2	−24.0	10.2	82.1
	N	Dec	Inc	α95	k	SCOS1	X, %	Y, %					
Fold Test [*McFadden*, 1990][d]													
In situ	4	334.4	−33.1	49.1	4.5	2.443							
Corrected	4	334.0	−40.7	34.9	7.9	1.641	N/A	N/A					
	Site Latitude	Site Longitude	GR	N	Mrs/Ms	Hcr/Hc	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α95	k
Ignimbrite: Vacy													
rgp69	−32.529	151.5604	648000	5			321.1	−16.8	313/25	323.3	−41.4	5.5	197.7
rgp72	−32.5422	151.6124	697986	7	0.115	22	325.7	−63.3	210/14	345.0	−55.0	1.9	1064.0
rgp76	−32.6092	151.7168	796913	5	0.111	3.35	008.3	−62.0	223/20	021.0	−44.2	21.7	13.4
rgp78	−32.4834	151.5154	605050	7			093.6	41.4	225/52	155.9	52.9	12.0	26.5
rgp248	−32.5413	151.6124	697867	6			329.3	−63.7	210/14	347.8	−54.8	3.5	376.6
	N	Dec	Inc	α95	k	SCOS1	X, %	Y, %					
Fold Test [*McFadden*, 1990][e]													
In situ	5	318.8	−53.6	28.8	8.0	4.398							
Corrected	5	346.5	−51.5	15.1	26.7	2.311	N/A	N/A					
	Site Latitude	Site Longitude	GR	N	Mrs/Ms	Hcr/Hc	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α95	k
Ignimbrite: Johns Hill													
rgp05	−32.6194	151.4481	544898	3	0.121	7.5	241.6	32.9	087/65	151.5	66.4	12.4	99.5
rgp08	−32.6067	151.4194	517912	4	0.097	8.23	178.4	51.1	036/18	157.2	63.3	11.8	110.6
rgp164	−32.6104	151.4312	528908	5			185.7	51.9	008/16	184.2	67.8	3.3	552.2
	N	Dec	Inc	α95	k	SCOS2	X, %	Y, %					
Fold Test [*McFadden*, 1990][f]													
In situ	3	205.5	49.2	43.1	9.3	2.985							
Corrected	3	163.6	66.5	11.1	124.7	0.794	N/A	N/A					
Ignimbrite: Mt. Rivers													
rgp19	−32.4619	151.4633	556073	3	0.09	5.95	137.7	15.0	280/18	142.4	28.8	4.3	815.5
rgp141	−32.3979	151.4562	548144	3	0.049	19	139.7	44.1	155/10	141.7	34.4	9.6	165.1
rgp144	−32.4355	151.5129	602103	7			144.9	45.6	110/06	141.8	40.5	4.2	210.8

Table 2. (continued)

Site Name	Site Latitude	Site Longitude	GR	N	Mrs/Ms	Hcr/Hc	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α95	k
	N	Dec	Inc	α95	k	SCOS1	X, %	Y, %					
			Fold Test [*McFadden*, 1990][g]										
In situ	3	140.4	35.0	27.2	21.6	2.949							
Corrected	3	142.0	34.6	9.0	189.8	1.233	100	100					
			Overall Means[h]										
	6	159.6	54.1	13.7	24.7								
Latitude	Longitude	dp	dm										
	Paleo South Pole[i]												
−72.8	228.4	13.4	19.2										

[a] GR, grid reference (Australian map grid zone 56); N, number of specimens; M_{rs}/M_s, ratio of saturation remanence to saturation magnetization; H_{cr}/H_c, ratio of coercivity of remanence to coercive force; rem dec/inc (*h*), in situ remanence declination/inclination; DDA/Dip, down dip azimuth/dip of bedding; rem dec/inc (*b*), bedding corrected remanence declination/inclination; α_{95} and k, *Fisher* [1953].

[b] Site mean location; latitude = 32.5°S, longitude = 151.5°E; paleopole; latitude = 64.7°N, longitude = 347.8°E, dp = 12.1°, dm = 13.8°.

[c] Site mean location; latitude = 32.5°S, longitude = 151.5°E; paleopole; latitude = 85.5°S, longitude = 170.6°E, dp = 21.5°, dm = 29.9°.

[d] Site mean location; latitude = 32.5°S, longitude = 151.7°E; paleopole; latitude = 65.3°N, longitude = 077.0°E, dp = 25.6°, dm = 42.2°.

[e] Site mean location; latitude = 32.5°S, longitude = 151.6°E; paleopole; latitude = 78.5°N, longitude = 059.7°E, dp = 13.9°, dm = 20.5°.

[f] Site mean location; latitude = −32.6°S, longitude = 151.4°E; paleopole; latitude = 69.5°S, longitude = 183.3°E, dp = 15.0°, dm = 18.2°.

[g] Site mean location; latitude = 32.4°S, longitude = 151.5°E; paleopole; latitude = 53.4°S, longitude = 253.5°E, dp = 5.9°, dm = 10.3°.

[h] Paleolatitude; λ = 34.6°S, upper limit = 50.8°S, lower limit = 20.1°S.

[i] Site mean location; latitude = 32.5°S, longitude = 151.6°E.

enced northward translation in addition to rotation [*Beck et al.*, 1994].

[44] Rotation of the Rouchel–Gresford and Myall blocks probably took place in a sinistral strike-slip regime related to subduction at the eastern margin of Australia, analogous to the above mentioned areas. Late Carboniferous slab breakoff proposed by [*Caprarelli and Leitch*, 2001], however, appears to preclude active subduction and hence strike-slip faulting during this interval, although it provides an explanation for prolific late Carboniferous rhyolitic volcanism and latest Carboniferous S-type granitoid intrusions. Rhyolitic volcanism throughout the Tamworth Belt began at about 320 Ma (J. Roberts, unpublished data, 2002). It continued until 306 Ma in the southern Tamworth Belt (J. C. Claoué-Long and R. J. Korsch, unpublished data, 2000) and into the Early Permian in the northern Tamworth belt (J. Roberts, unpublished data, 2002). We conclude that strike-slip faulting persisted until the imposition of an extensional regime because: (1) there is an inadequate amount of time available for rotation to have taken place prior to 320 Ma; (2) paleomagnetic data indicate similar amounts of rotation in the 306 Ma Mount Durham tuff (J. C. Claoué-Long and R. J. Korsch, unpublished data, 2000), the youngest dacitic ignimbrite, and Visean ignimbrites in the Gresford block; and (3) evidence for an extensional regime older than that identified by *Caprarelli and Leitch* [2001].

[45] While *Caprarelli and Leitch* [2001] identify a major extensional regime in the Early (but not earliest) Permian a

Table 3. Summary of Sampling Locations and Characteristic Site Mean Remanence Directions of Early Carboniferous Ignimbrites From the Myall Block of the Southern Tamworth Belt[a]

Site Name	Site Latitude	Site Longitude	GR	Unit	N	Mrs/Ms	Hcr/Hc	Rem Dec (*h*)	Rem Inc (*h*)	DDA/Dip	Rem Dec (*b*)	Rem Inc (*b*)	α95	k
rgp238	−32.686	151.811	855829	EV	8	0.145	2.65	045.8	84.3	120/35	110.8	53.0	3.1	326.0
rgp239	−32.983	151.781	857832	EV	8	0.01	3.59	116.5	81.2	120/35	119.2	46.2	2.0	797.4
rgp240	−32.684	151.785	861831	EV	4	0.065	7.96	110.4	72.8	135/20	123.0	53.6	9.3	99.1
rgp102	−32.159	151.886	892419	BCI	8	0.061	12.2	347.7	−54.3	077/51	299.9	−31.1	4.4	160.2
rgp159	−32.17	151.826	893401	BCI	4	0.064	11.9	340.5	−55.2	077/51	296.8	−27.8	9.5	95.1
	N	Dec	Inc	α95	k	SCOS2	X, %	Y, %						
		Fold Test [*McFadden*, 1990]												
In situ	5	146.5	72.4	17.7	19.7	4.162								
Corrected	5	118.1	42.5	12	41.6	0.882	N/A	N/A						
			Overall Means[b]											
	5	118.1	42.5	12.0	41.6									
Latitude	Longitude	dp	dm											
	Paleo South Pole[c]													
−35.7	233.2	9.1	14.7											

[a] GR, grid reference (Australian map grid zone 56); N, number of specimens; M_{rs}/M_s, ratio of saturation remanence to saturation magnetization; H_{cr}/H_c, ratio of coercivity of remanence to coercive force; rem dec/inc (h), in situ remanence declination/inclination; DDA/Dip, down dip azimuth/dip of bedding; rem dec/inc (b), bedding corrected remanence declination/inclination; α_{95} and k, *Fisher* [1953]. The Eagleton Volcanics (EV) and the Buggs Creek Ignimbrite (BCI), respectively, are lateral equivalents of the Gilmore Volcanics and Nerong Volcanics of the Gresford block (see Figure 2).

[b] Paleolatitude; λ = 24.6°S, upper limit = 35.0°S, lower limit = 16.4°S.

[c] Site mean location; latitude = −32.5°S, longitude = 151.8°E.

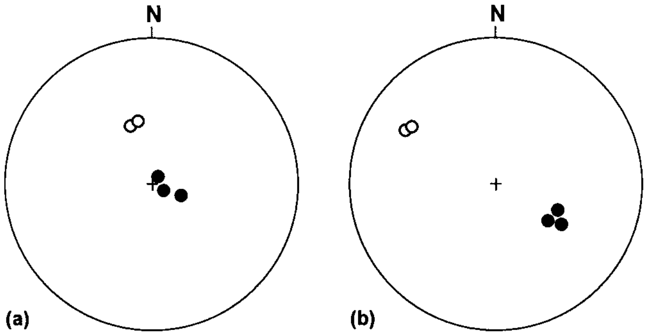


Figure 10. In situ (a) and bedding corrected (b) high-temperature site mean remanence directions of Myall block ignimbrites. Open (closed) circles refer to projections on the upper (lower) hemisphere; equal area projections.

significant change in the style of volcanism, that may indicate latest Carboniferous extension, is present in drill core from Tangorin 1 drilled on the southwestern margin of the Gresford block (J. C. Claoué-Long and R. J. Korsch, unpublished data, 2000). The Mount Durham tuff, a dacitic ignimbrite in the uppermost Seaham formation in Tangorin 1, dated at 306.2 ± 2.8 Ma (J. C. Claoué-Long and R. J. Korsch, unpublished data, 2000), is succeeded by latitic tuffs, volcanogenic sediments and basaltic conglomerate of the Tamby Creek formation. Tuffs at the base and top of the younger formation have been dated at 303.7 ± 2.4 and 300.3 ± 2.4 Ma, respectively (J. C. Claoué-Long and R. J. Korsch, unpublished data, 2000). The sudden change from dacitic-rhyolitic to basaltic volcanism may indicate the development of an extensional regime. It also coincides with significant events in the accretionary wedge, including substantial uplift, lowering of metamorphic grade [*Dirks et al.*, 1992], and the intrusion of primitive, uncontaminated gabbros geochemically resembling juvenile back arc basin basalts [*Landenberger and Collins*, 2000]; the gabbros of the Bakers Creek Suite are coeval with the 302 Ma S-type Hillgrove Granite suite [*Landenberger et al.*, 1995]. These features all suggest subduction had either ceased or moved away from the southeastern part of the orogen by the latest Carboniferous (~300 Ma).

[46] Rotation of the blocks in the southern Tamworth Belt could have commenced as early as the mid-Namurian, as indicated by the deposition of different successions in the amalgamated Rouchel-Gresford block and Myall block immediately following the early Namurian marine transgression across these blocks. Whether the southern Hastings block was involved with the Myall block at this time cannot be determined because overprinting has obliterated all remanent magnetism [*Schmidt et al.*, 1994]. Amalgamation of the southern and northern parts of the Hastings block could have taken place during a period of nondeposition and/or erosion between the mid-Namurian and earliest Permian [*Roberts et al.*, 1995c; *Briggs*, 1998; J. Roberts, unpublished SHRIMP data, 2001]. We suggest that rotation also took place during this interval, but concede the block may have suffered further relocation in the Late Permian to earliest Triassic; a constraint on further movement is provided by 228 Ma volcanics that overlap the Hastings block and accretionary wedge rocks to the west. *Leitch and Lara* [2000] compared fault and fold structures around the Peel fault (Figure 1) with those of the Kindee district, a small part of the southern Hastings block, and suggested their similarity indicated the Hastings block and Tamworth Belt were contiguous in the Late Permian. While the age of the Peel fault is Late Permian, that of the structures around Kindee is unknown. If they were also Late Permian in age there would be little time for rotation to take place prior to the linking volcanism at 228 Ma. The structural model of *Leitch and Lara* [2000], based on the Kindee data, suggests a counter-clockwise rotation of 150°. It may be significant that paleomagnetic data for a 230° counter-clockwise rotation are derived from the northern Hastings block [*Schmidt et al.*, 1994].

[47] From our new paleomagnetic data we tentatively propose the following basic tectonic history for the Tamworth Belt from the Visean to the Early Permian (Asselian). Subduction appears to have been oblique during the Tournaisian and much of the Visean to account for the juxtaposition of different sequences in all of the blocks by syndepositional strike-slip faults. Between the latest Visean and mid-Namurian, when the Rouchel, Gresford and Myall blocks were amalgamated, subduction was most likely at a high angle to the continental margin. Oblique subduction may have been reinstated at about the mid-Namurian, when successions in the Rouchel-Gresford and Myall blocks were again distinctively different, and continued until extensional events in the late Stephanian, providing the means of rotation. Counter-clockwise rotation of 80° and 120° in the Rouchel-Gresford and Myall blocks, respectively, was completed prior to the late Asselian. Marine sediments of the Early Permian Dalwood group, the oldest unit in the northern Sydney Basin [*Roberts et al.*, 1996], onlap Carboniferous rocks on the southern margins of the Myall and Gresford Blocks [*Hawley et al.*, 1994]. This relationship precludes rotation of the Rouchel-Gresford and Myall blocks during late Early Permian folding in the southern Tamworth Belt [*Roberts and Geeve*, 1999] or the terminal Late Permian to Triassic Hunter-Bowen Orogeny.

9. Conclusions

[48] Visean ignimbrites from the Rouchel, Gresford and Myall blocks of the southern Tamworth Belt retain a high-temperature prefolding remanent magnetization. The mean remanence directions have moderate inclinations, and both normal and reverse polarities are present. Calculated paleo south poles of the ignimbrites do not fall on the early Carboniferous segment of the Australian APWP. The southern Tamworth Belt was at moderate latitudes in the Visean. This accords with results from the Australian craton and the Lachlan fold belt and, renders it necessary to rotate the southern Tamworth Belt paleo south pole positions to match the APWP.

[49] The Rouchel, Gresford and Myall blocks contain different Tournaisian to middle Visean successions because of syn-depositional strike-slip fault movement generated by oblique subduction. All three blocks were amalgamated into a single unit in the late Visean. The Rouchel-Gresford block remained as a single entity throughout the remainder of the Carboniferous, but possible reimposition of oblique subduction led to the Myall block being more closely related to the southern Hastings block from about the mid-Namurian.

Counter-clockwise rotation of the blocks may have commenced as early as mid-Namurian, and probably terminated in the latest Carboniferous when an extensional regime developed in southeastern parts of the southern New England Orogen, or at the latest in the earliest Asselian prior to the deposition of onlapping Early Permian successions of the Sydney, Barnard and Nambucca Basins. All blocks within the southern Tamworth belt, the Rouchel, Gresford, Myall and Hastings blocks, have been rotated and are likely to be allochthonous.

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