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The Kiaman Reversed Polarity Superchron at Kiama: Toward a field strength estimate based on single silicate crystals

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ABSTRACT

We present the first geomagnetic paleointensity measurements on single plagioclase crystals from lavas formed during the ~262–318 Ma Permo-Carboniferous Reverse Polarity Superchron (commonly known as the Kiaman). Rock magnetic experiments suggest that feldspar crystals separated from two lavas of the Kiaman Superchron type area (near Kiama, Australia) carry pseudo-single domain low-Ti magnetic inclusions capable of faithfully retaining a primary paleointensity signal. Thellier paleointensity experiments yield virtual dipole moments of $8.5 \pm 0.2 \times 10^{22}$ Am^2 and $9.3 \pm 0.3 \times 10^{22}$ Am^2 for these crystals. Furthermore, these results lack the alteration problems that prohibit paleointensity (and sometimes paleodirection) determination using whole rock lava samples from the type area. The derived field strengths are 5–6 times higher than some other virtual dipole moment (VDM) values of Kiaman age derived from whole rock igneous samples. This suggests either high paleointensity variability during the Kiaman Superchron, or that unrecognized non-ideal magnetic behavior has compromised some prior paleointensity results reported from whole rocks elsewhere.

1. Introduction

The history of Earth's magnetic field provides a probe into the nature and evolution of the core and geodynamo. This history is comprised of geomagnetic reversals, secular variation and paleointensity. The chronology of reversals is well defined for the last 160 million years from marine magnetic anomalies; these have been confirmed and calibrated through magnetostratigraphic investigations (e.g. Opdyke and Channell, 1996). Sedimentary rocks preserved on the continents further afford the possibility of extending the reversal record to Mesozoic and Paleozoic times, older than the extant oceanic crust, a quest that is still in progress (e.g. Olsen et al., 1996; Gallet and Pavlov, 1996; Pavlov and Gallet, 2005). The exact chronology of reversals for still older Precambrian intervals may remain a mystery because rocks suitable for recording this history have been removed by erosion or compromised by remagnetization. Nevertheless, it may be possible to constrain gross changes in reversal rate (Dunlop and Yu, 2004; Coe and Glatzmaier, 2006). Secular variation data are available from studies of lavas and dikes, for the last 5 million years (e.g. Tauxe et al., 2003), Tertiary–Mesozoic (McFadden et al., 1991; Tarduno et al., 2002) and early Proterozoic/late Archean (Smirnov and Tarduno, 2004).

Paleointensity measurements provide insight into the basic features of the geomagnetic field and core evolution (e.g. Prèvot et al., 1990). For example, the "Mesozoic Dipole Low" has been suggested for the time during which the geomagnetic field had a strength much lower than that of the present-day based on Thellier–Thellier analyses of whole rocks (Prèvot et al., 1990). As originally postulated, it suggested a decoupling of field strength and reversal rate. Subsequent studies, however, revealed higher field intensities for some intervals, questioning the veracity of the Mesozoic Dipole Low (e.g. Goguitchaichvili et al., 2002).

In hindsight, the fact that views on the past strength of the field have been (and continue to be) challenged should not be surprising. Paleointensity is an extraordinarily difficult quantity to measure accurately. Lavas, dikes and baked contacts have been primary targets in paleointensity studies, in the hope that they might carry simple thermoremanent magnetizations. In practice, ubiquitous processes in the near-surface environment can complicate that signal.

Titanomagnetites, basic magnetic minerals in lavas, can easily undergo oxidation, forming titanomaghemites. This results in the

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partial replacement of the TRM with a chemical remanent magnetization (CRM). The efficiency at which the CRM records the original field intensity is uncertain, although it is generally thought to be much less than TRM. The weathering of magnetic carriers also sets the stage for further alteration during a typical paleointensity experiment, when a rock is exposed to a series of paired heating/cooling steps, because titanomaghemites typically invert with heating (e.g. Özdemir, 1987; Doubrovine and Tarduno, 2006).

Another, often overlooked issue is the hydrothermal alteration that can accompany lava or dike emplacement. These fluids can facilitate formation of new magnetite grains, which, if they grow through the superparamagnetic/SD size threshold, will carry a CRM. While the exact efficiency is again difficult to predict, Tarduno and Smirnov (2004) noted that existing estimates suggested a CRM might only be 50% of the TRM strength (e.g. Hoye and Evans, 1975). They further highlighted the possibility that rocks carrying CRMs related to hydrothermal activity might contribute to a bias toward low field values in paleointensity estimates derived from databases. This suggestion is supported by recent CRM experiments (Draeger et al., 2006).

In contrast to processes occurring at relatively low temperatures, lavas and dikes can also carry magnetic minerals that have undergone high temperature oxidation, resulting in near end-member magnetite. If this exsolution occurs at temperatures well above the Curie temperature of magnetite, it could result in the creation of fine magnetite grains potentially suitable for paleointensity study. If the exsolution process continues below the Curie temperature of magnetite, complex effects can result because the magnetization is in part a thermochemical remanence (TCRM) (Smirnov and Tarduno, 2005; Yamamoto, 2006; Draeger et al., 2006). Of course, should the oxidation occur at very high temperatures, the magnetite must still remain unaltered through subsequent geologic history to be a viable paleointensity recorder. And effects on the matrix must be accounted for if a bulk sample is used for paleointensity analysis. In particular, new magnetic minerals can form clays (formed by weathering of a whole rock matrix) during the heating of a typical Thellier experiment (Cottrell and Tarduno, 2000).

The paired issues of in situ and laboratory alteration have motivated a search for alternative paleointensity recorders. Here, we focus on the study of single plagioclase crystals, which can contain near single domain magnetic inclusions (Cottrell and Tarduno, 1999; Tarduno et al., 2006). The silicate matrix can protect the magnetic inclusion from in situ weathering. The crystals are separated from the clay-bearing matrix, greatly reducing their impact on the paleointensity results. We further address the potential relationship of field strength and reversal rate.

Because of difficulty of any paleointensity measurement, there has been a tendency to focus such studies on the extremes of reversal rate, especially superchrons, times of no (or very few) reversals. At present there is continued debate for results from the youngest of these, the Cretaceous Normal Polarity Superchron. Notwithstanding the embedded debate over the Mesozoic Dipole Low, some authors have reported bulk sample paleointensity results that show no apparent differences from values before or after the Cretaceous Normal Polarity Superchron (e.g. Zhu et al., 2004).

In contrast, data from single plagioclase crystals suggest higher field values (Tarduno et al., 2001, 2002) for the Cretaceous Normal Polarity Superchron, and lower values for the preceding and succeeding intervals of mixed polarity (Tarduno and Cottrell, 2005). The lowest field strengths are observed for the very high reversal rate of the Late Jurassic; low field values for this interval have also been inferred on the basis of marine magnetic anomaly amplitudes (McElhinny and Larson, 2003) and this may in fact be an actual Mesozoic "dipole" low similar to that proposed by Prèvot et al. (1990), albeit of much shorter duration, limited to a time of very rapid reversals.

In direct comparisons of plagioclase and whole lava paleointensity results (Cottrell and Tarduno, 2000; Tarduno and Cottrell, 2005), the latter reveal lower paleointensity values, attributable to in situ and laboratory alteration of magnetic carriers and clays. The tendency for higher field values in the Cretaceous Normal Polarity Superchron is also supported by some analyses of submarine basaltic glass (Tauxe and Staudigel, 2004) and NRMs from oceanic basalts (normalized for rock magnetic effects) (Wang et al., 2005).

Here, we apply for the first time the single silicate crystal paleointensity technique to the next oldest superchron, the Permo-Carboniferous Reverse Polarity Superchron (Irving and Pullaiah, 1976), at its type locality in Kiama, Australia. For convenience, we will refer to this as the "Kiaman", following the original usage (Irving and Parry, 1963). The nature of the lavas in Australia, and existing Carboniferous/Permian paleointensity results, will cause us to revisit many of the issues of paleointensity reliability discussed above.

2. Sampling and site selection

The upper Permian lavas of southeastern Australia (Joplin, 1964, 1965; Carr, 1985, 1998; Campbell et al., 2001) figured prominently in the recognition of polarity reversals, continental drift and superchrons. In particular, the early recognition of reversed polarity by Mercanton (Mercanton, 1926) was subsequently confirmed by studies of Ted Irving and his colleagues (Irving and Green, 1958; Irving and Parry, 1963), who used directional data, together with geological indicators (of past glaciation) to argue in support of motion of the Australian continent. In their study of these units, Irving and Parry (1963) first recognized the long period of reversed field polarity and applied the name "Kiaman". We refer readers to the classic paleomagnetic work and geologic description, and only outline some salient points below.

Upper Permian lavas (the Gerringong Volcanics) are exposed along the coast and hillsides of southeast Australia near the town of Kiama, approximately 120 km south of Sydney. Stratigraphic considerations indicate that the lavas where erupted near the end of the Kiaman Superchron. However, both the exact absolute age of the lavas, and the age of the end of the Kiaman Superchron are unclear. The Gerringong Volcanics consist of a series of basaltic to andesitic flows within the Broughton Formation and overlying Pheasant Nest Formation in the southern Sydney Basin. The Broughton Formation is characterised by shallow marine sediments containing brachiopods of the *Echinalosia runnegari-E. wassi* Zone of Briggs (1991). This zone, which is present in sedimentary basins throughout eastern Australia, was placed by Briggs (1991) within the uppermost two-thirds of the Ufimian Stage of the Upper Permian and, following Ross and Ross (1987), assigned an age of around 275–276.5 Ma. In the current Permian time scale (Gradstein et al., 2004) use of the term Ufimian is abandoned because the type section consists of a terrestrial to marginal marine facies within the upper Kungurian and overlying lower Kazanian Stages. The obsolete Ufimian Stage is shown to have an age of 270–272 Ma by Gradstein et al. (2004).

In the Hunter Valley of NSW, the Permian Mulbring Siltstone, a correlative of the Broughton and underlying Berry Formations, also contains the *E. runnegari-E. wassi* Zone. The Mulbring Siltstone, which is overlain by the coal-bearing Tomago and Wittingham Coal Measures, contains dated zircons (Roberts et al., 1996). A SHRIMP analysis from the Mulbring Siltstone gives an age of 266 Ma when converted from SL13 Standard to Temora 1 Standard. A single crystal zircon age of 266 Ma has also been obtained from the slightly older

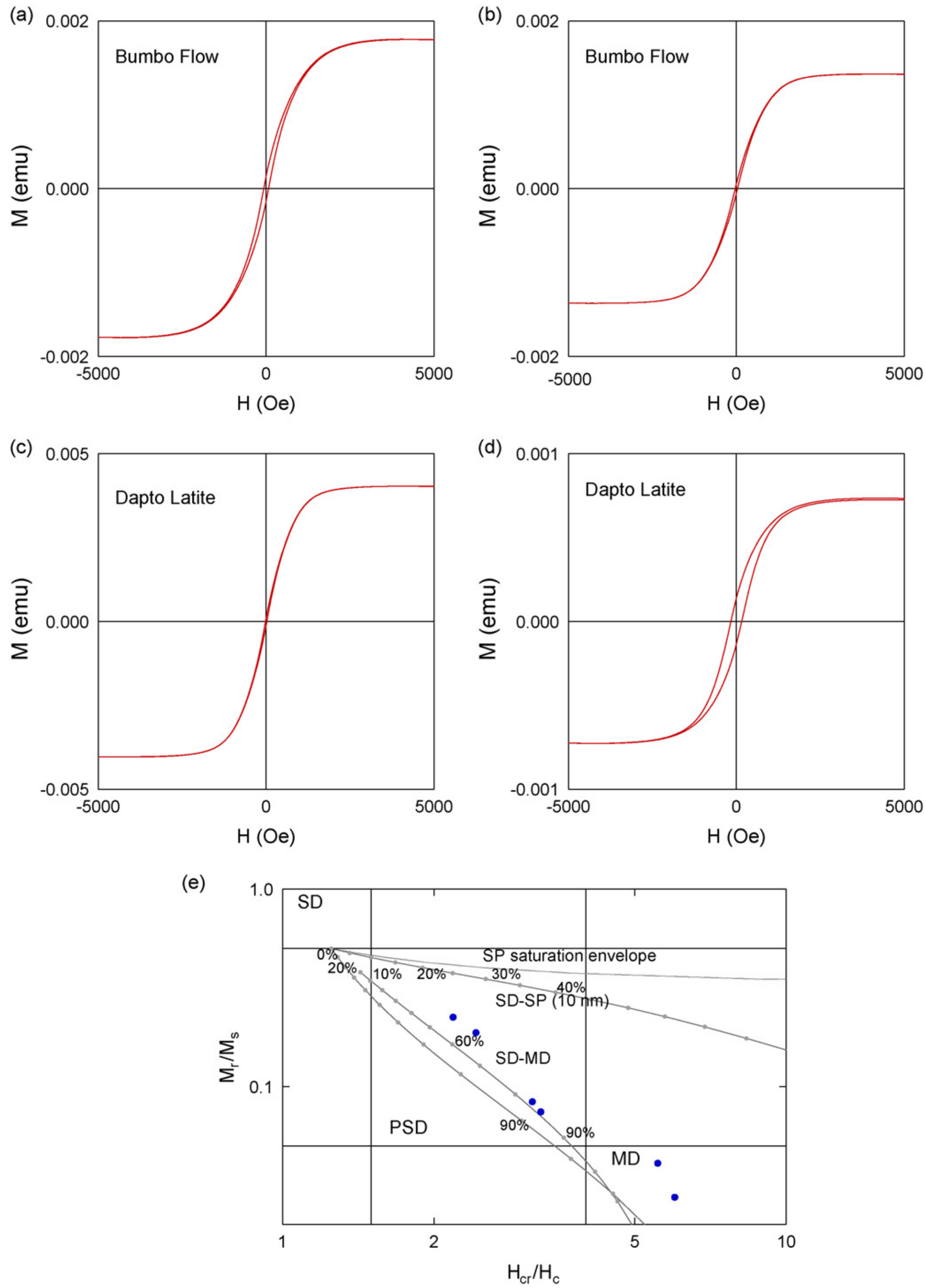

Fig. 1. (a–d) Magnetic hysteresis curves from whole rock samples of the Bumbo and Dapto lavas. (e) Day plot (Day et al., 1977) with mixing curves from Dunlop (Dunlop, 2002).

Belford Formation (Gulson et al., 1990). Hence, the latites within the Broughton Formation can be considered to be slightly younger that 266 Ma.

The regression from marine to continental and/or coal measure deposition throughout northern and southern parts of the Sydney Basin, recognized by Briggs (1991) to have been virtually simultaneous, therefore commenced shortly after 266 Ma. In the south this was followed by the onset of volcanism associated with the Middle Permian Gerringong Volcanics. In terms of the International Time Scale the Gerringong Volcanics can be equated with the middle part Guadalupian Series.

Roberts et al. (1996) suggested an age of approximately 263 Ma for the end of the Kiaman using Australian stratigraphic sequences, whereas Gradstein et al. (2004) assigned an age of 265 Ma on the basis of data from West Texas. Opdyke and Channell (1996) suggested an age of 262–320 Ma for the Kiaman Superchron, but highlighted that its termination had not yet been directly dated at any locality. Subsequently, Opdyke et al. (2000) constrained the base of the Kiaman to be at 318 Ma. Here we retain the age of ∼262 Ma for the end of the Kiaman, following Opdyke and Channell (1996), but again emphasize that the value is uncertain.

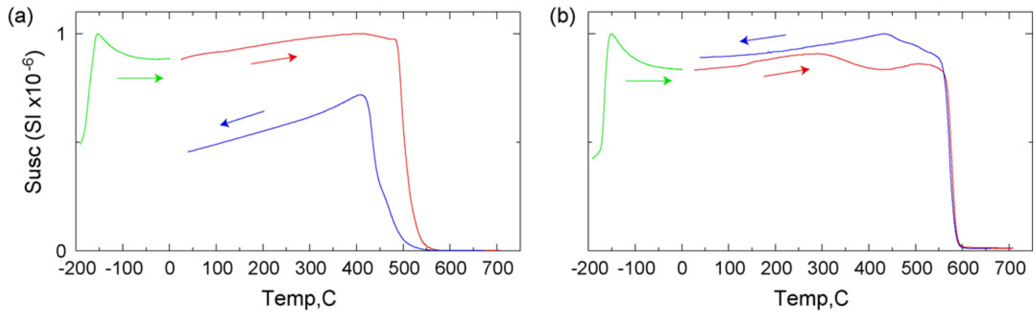

Fig. 2. Magnetic susceptibility versus temperature for bulk samples of the (a) Dapto and (b) Bumbo flows.

The lavas near Kiama commonly termed "latites" because of the presence of potassium feldspar along with plagioclase feldspar. The important lava flows, from oldest to youngest, are the Blow Hole Latite, the Bumbo Latite, the Dapto Latite and the Cambewarra Latite. These are generally separated by sandstones, indicating the passage of some time between lava units. They are thought to be compound flows, with each flow being emplaced within a period ranging from days to years (e.g. Campbell et al., 2001). Average thicknesses of the lowermost flows in typical exposures (Blowhole, Bumbo and Dapto) are tens of meters, whereas as the Cambewarra is much thinner (often less than 10 m).

Samples were collected (by J.T. and J.R.) as standard field-drilled cores from the Blowhole, Bumbo, Dapto and Cambewarra flows. The latter is only poorly exposed in forested hillsides west of Kiama, whereas the other flows are well-exposed along the coast. Core orientations were mainly taken with a Sun Compass using a Pomeroy orientation device; for a few of the shaded Cambewarra cores, only magnetic compasses were possible. For these cases, gross mis-orientations were excluded by using a second compass, and sighting to the orientation azimuth of the core in question at distance (2–3 m); in all cases the magnetic compass orientation near the core was confirmed.

Samples from the Bumbo flow were taken at two sites from a large quarry north of Kiama (for convenience, we will refer to this as the "Bombo Quarry"). One of these sites was adjacent to a dike of suspected Tertiary age (J. Roberts, personal communication). A series of recent road workings provided exceptional exposure of the Bumbo flow north of Kiama. Visible alteration of the flow was seen to be highly variable in these long lateral exposures. Unoriented hand samples were collected from an unusually fresh portion of the Bumbo flow at this exposure along a highway ramp having large (1–10 mm) plagioclase feldspars.

For paleointensity study we concentrate on a select set of these samples: only those that had plagioclase crystals that could be separated similar to those that have yielded paleointensity results meeting reliability criteria in previous studies (Cottrell and Tarduno, 2000; Tarduno et al., 2006). Specially, the crystals were nearly 1 mm in size and optically clear. This restricted us to a coarse-grained Dapto site, and the Bombo highway ramp site.

3. Rock magnetic and directional data from bulk samples

As a prelude to single crystal analysis, we first discuss rock magnetic and directional results from bulk samples of the Dapto and Bumbo flows. All rock magnetic, paleomagnetic and paleointensity analyses were conducted at the University of Rochester. Magnetic hysteresis data measured on a Princeton Measurements Corporation Alternating Gradient Force Magnetometer show multidomain (MD) to pseudo-single domain (PSD) behavior (Fig. 1).

Magnetic susceptibility versus temperature data (in an Argon atmosphere) were collected using a Kappabridge KLY-4S with CS-3 furnace and CS-L low temperature cryostat (Fig. 2). Samples from the Dapto flow show evidence for the Verwey transition, the cubic to monoclinic crystallographic change in magnetite at 120 K (−153 °C). Apparent Curie temperatures are near 580 °C for some samples, but somewhat lower for others, and a variable pattern of alteration is observed after cooling from high temperature. Samples from the Bumbo flow show similar behavior: the presence of the Verwey transition at low temperature, near magnetite Curie temperatures, but with variable alteration detected after cooling from high temperature.

Standard paleomagnetic cores were thermally demagnetized in air using an ASC thermal demagnetization device. Remanence was measured using a 2G DC SQUID magnetometer. Samples from the Dapto flow displayed variable responses to thermal treatment, but the principal component of magnetization did not begin to be resolved until treatments higher than 400 °C (Fig. 3). In some cases, directions were scattered until treatments of 500 °C. Interestingly, a component with unblocking temperatures greater than 580 °C (trending to the origin of the orthogonal vector plots) was observed in some whole rock samples.

The samples from the Bumbo flow displayed an even greater variation in direction behavior. For some (for example, one of the Bombo quarry sites) the demagnetization had similarities to that of the Dapto flow, with definition of a principal component at high temperature, but in this case with a well-defined secondary component of magnetization (Fig. 3). In another Bombo Quarry site, however, the directions were unstable during demagnetization. As in the Dapto flow, a component with unblocking temperatures greater than 580 °C was observed in some whole rock samples. While too few samples are available for a formal directional analysis, the characteristic remanent magnetization directions from these cores are in general agreement with directions reported by Irving and Parry (1963).

4. Magnetic hysteresis data from single plagioclase crystals

The rock magnetic and direction data from bulk samples provide several starting points for single crystal analysis. While high temperature unblocking components (carried by magnetite) are clearly present in some samples of these lavas, the domain state is not ideal for paleointensity analysis. In addition, the magnetic carriers appear to alter during heating, highlighted by the differences seen between the short heating (in Ar) behavior during the magnetic susceptibility versus temperature data and the longer heating (in air) during thermal demagnetization.

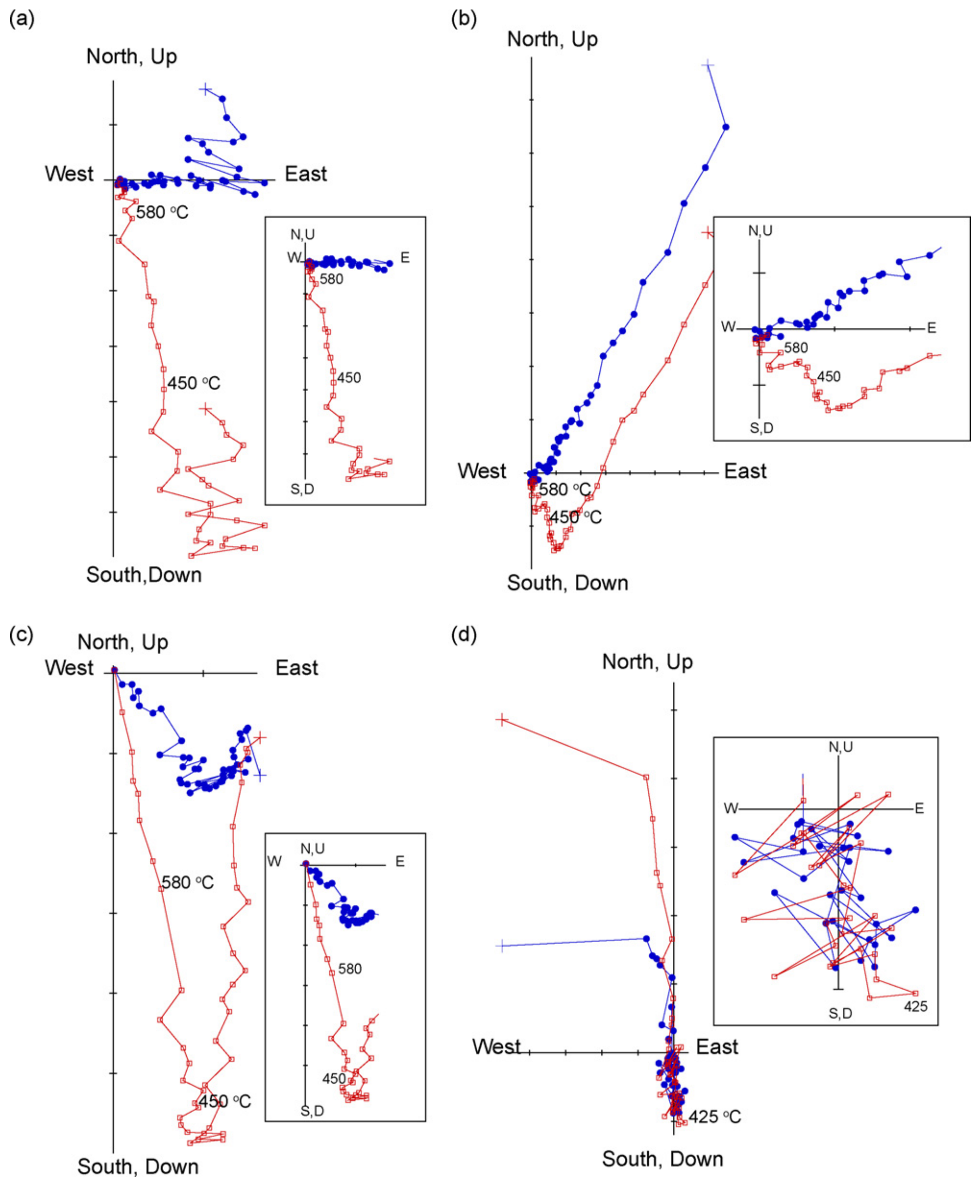

Fig. 3. Orthogonal vector plots of thermal demagnetization of bulk samples of the (a and b) Dapto and (c and d) Bumbo flows, showing varied behavior. Insets for each orthogonal vector show the 200 °C temperature steps through to the end of demagnetization at 690 °C.

Plagioclase crystals were separated from paleomagnetic core and hand samples first by crushing using a mortar and pestle and hand picking under a binocular microscope. Crystals were further cleaned using by sonicating in distilled water. Where iron staining was prominent in the hand sample, crystals were also sonicated briefly in dilute hydrochloric acid. Only visibly clear crystals were chosen for subsequent analysis. Magnetic hysteresis curves from plagioclase crystals from the Dapto and Bumbo flows are largely PSD in character, and thus more suitable for paleointensity analyses than the whole rocks samples (Fig. 4).

A concern for paleointensity analysis using single crystals is alignment of magnetic inclusions; alignment could bias the acquisition of partial thermal remanent magnetization (pTRM) during a paleointensity experiment. To test for this possibility, magnetic hysteresis data were collected rotating the crystal by 45° increments on parallel and perpendicular P1 probes of the AGRM. If an anisotropy large enough to bias pTRM acquisition was present, we should see it in these data. Instead, no anisotropy of magnetic hysteresis parameters was observed for the Dapto and Bumbo plagioclase crystals (Figs. 5 and 6).

5. Paleointensity data

Paleointensity data were collected using the Thellier (Thellier and Thellier, 1959) method as modified by Coe (1967), in air using an ASC thermal demagnetization device with field coil. Samples were mounted at the ends of 3 mm diameter glass tubes. An applied field of 60 μT was used for the field-on steps.

For both the Dapto and Bumbo flows, orthogonal vector plots of the field-off steps (Figs. 7 and 8) show that a principal component of magnetization is not isolated until temperatures higher than 400 °C, similar to the behavior of the bulk samples. Unlike the whole rocks, however, this component appears to have a maximum unblocking temperature between 550 and 580 °C. NRM/TRM data define a linear trend over this unblocking temperature interval, and pass pTRM checks and other reliability criteria (see Cottrell and Tarduno, 2000 and Table 1).

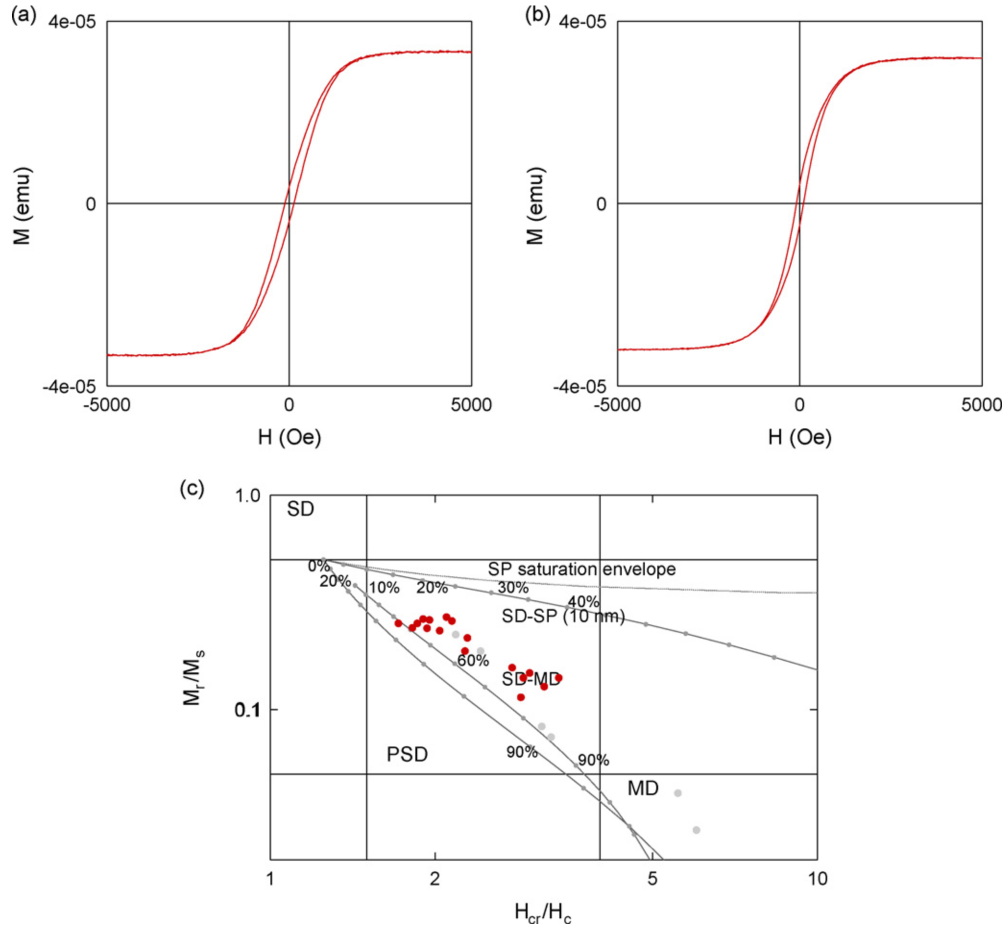

Fig. 4. Magnetic hysteresis results from plagioclase crystals separated from the Dapto (a) and Bumbo (b) lavas. (c) Day plot (Day et al., 1977) with mixing curves from Dunlop (Dunlop, 2002). Bulk sample results shown in grey.

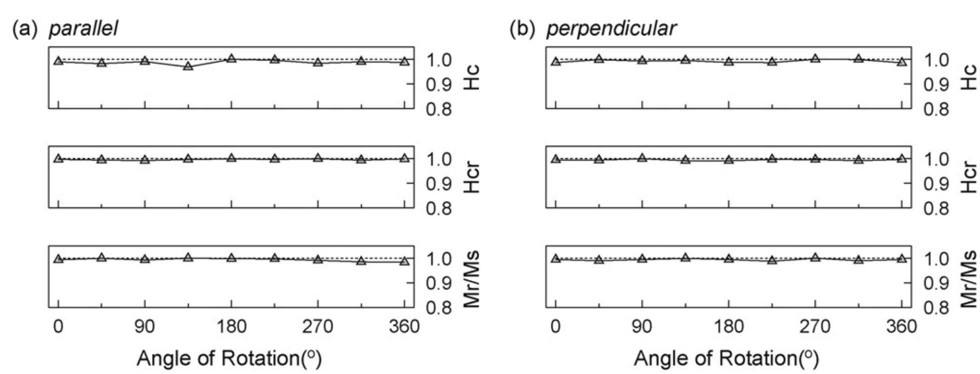

Fig. 5. Normalized magnetic hysteresis parameters versus rotation angle measured on a plagioclase crystal from Dapto Flow. The crystal was rotated by ~45° increments on the stage of a Princeton Measurements Alternating Force Magnetometer parallel (solid line and triangles) and perpendicular (dashed line, only mean shown) P1 probes. Abbreviations are M_r/M_s, saturation remanence/saturation magnetization ratio; H_{cr} coercivity of remanence; and H_c, coercivity.

The success rate of the paleointensity experiments was approximately 27%. Nearly half of the samples failed to meet the reliability criteria because of erratic demagnetization behavior during the paleointensity measurements with unstable directions of the field-off steps. Other samples dropped significantly in NRM magnetization after the first 200° of demagnetization. A total of 44 plagioclase crystals were measurement for paleointensity, with 12 yielding reliable results. The mean paleointenity value for the Dapto flow ($N = 5$) is 58.7 ± 1.2 μT. The mean paleointensity value for the Bumbo flow ($N = 7$) is 64.5 ± 2.0 μT. Using the Australia reference pole for the 256–290 Ma interval (McElhinny and McFadden, 2000) these field values correspond to virtual dipole moments (VDMs) of $8.5 \pm 0.2 \times 10^{22}$ Am^2 and $9.3 \pm 0.3 \times 10^{22}$ Am^2 for the Dapto and Bumbo flows, respectively (Table 2).

6. Discussion

Several secondary processes are expected to have left their mark on the magnetization of the New South Wales Permian lavas. One is the variable hydrothermal alteration that occurred on, or soon after, lava emplacement (Carr et al., 1999). Another process is a larger scale thermo-viscous effect related to opening of the Tasman Sea (Schmidt and Embleton, 1981). Both directional and

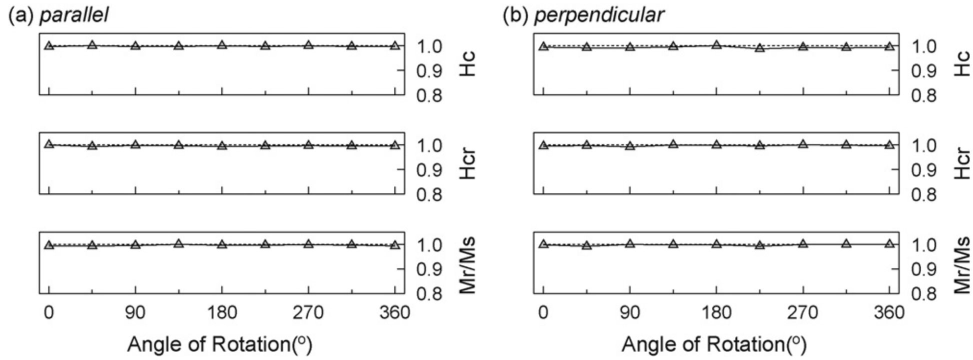

Fig. 6. Normalized magnetic hysteresis parameters versus rotation angle measured on a plagioclase crystal from Bumbo flow. The crystal was rotated by ∼45° increments on the stage of a Princeton Measurements Alternating Force Magnetometer parallel (solid line and triangles) and perpendicular (dashed line, only mean shown) P1 probes. Abbreviations are M_r/M_s, saturation remanence/saturation magnetization ratio; H_{cr} coercivity of remanence; and H_c, coercivity.

paleointensity results from the select lavas of New South Wales studied here yield values only after thermal treatments at relatively high values (greater than approximately 400 °C). This observation suggests that the secondary processes have indeed affected the magnetization of these rocks, but that the deleterious effects have likely been adequately removed by thermal demagnetization. We cannot exclude the possibility that some secondary magnetite related to hydrothermal activity resides in the groundmass; however, this is excluded from our paleointensity analyses through our selection of pristine plagioclase crystals for analysis.

We first compare our new VDMs with other instantaneous field values derived from Kiaman-age lavas. If we restrict our analysis to Thellier results (i.e. Tarduno and Smirnov, 2004), two means are available for the 270–295 Ma and 300–320 Ma intervals, of $7.36 \pm 0.38 \times 10^{22}$ Am^2 (N = 75) and $8.21 \pm 0.37 \times 10^{22}$ Am^2 (N = 42), respectively (although it should be emphasized that the age range of the latter interval extends to ages older than the Kiaman). Interestingly, our new paleointensity values from the Australian plagioclase crystals are close to (although slightly higher than) the mean values. However, the range of values encompassing these means is large extending from more than 12×10^{22} Am^2 to 2×10^{22} Am^2.

To the best of our knowledge, there are no time-averaged paleomagnetic dipole moments yet reported for the Kiaman, but the Garcia et al. (2006) results from the 301–270 Ma Great Whin Sill are interesting in this regard as they might be expected to average some geologic time. Specifically, the complex is composed of several sills and dikes, and paleomagnetic directions suggest several intervals of emplacement. Both Thellier and microwave methods were applied and the paleointensity results from the techniques were reported as being consistent (Garcia et al., 2006). Two mean values ($1.6 \pm 0.8 \times 10^{22}$ Am^2 and $2.1 \pm 1.1 \times 10^{22}$ Am^2) were derived which Garcia et al. (2006) feel represent the latest Carboniferous and early Permian (respectively). In contrast, the Bumbo and Dapto flow mean paleointesity results are 5 to 6 times higher.

A more detailed analysis, however, reveals some clear, unexplained differences between the Thellier and microwave results; paired comparisons of samples that have Thellier and microwave results show that the microwave technique sometimes yields values over 3 times weaker than those using the Thellier technique. Overall, there is a bias toward lower values for the microwave data (Fig. 9). A paired t-test to directly compare Thellier with microwave results from sister samples has a two-tailed p-value of 0.007 (t = 3.3, 12 degrees of freedom). Irrespective of the cause of the differences between the Thellier and microwave data, the ensemble of field strength values reported by Garcia et al. (2006) are among the lowest paleointensities reported for the Kiaman. Moreover, they are extraordinarily low as gauged against all paleointensity results if the individual means average some time. Support that the means average time is found in k values of direction data (a summary of all prior directional studies, Table 1, reported by Garcia et al., 2006) which range from 29.7 to 31.3.

Possible explanations for the apparent discrepancy between the paleointensity values from the lavas at Kiama and the results from the Great Whin Sill include (i) the Great Whin Sill paleointensity results only represent two instantaneous mean values and the

Table 1
Paleointensity reliability criteria

Sample	Temperature (°C)	Paleofield value (μT)	R^2	N	b	σ_b	f	g	q
Bumbo									
hs	400–550	67.7	0.985	7	−1.128	0.087	0.185	0.777	1.86
hs	450–550	63.2	0.987	5	−1.054	0.100	0.267	0.742	2.10
hs	400–550	64.4	0.984	7	−1.074	0.088	0.356	0.803	3.49
c1	400–550	61.8	0.996	7	−1.029	0.043	0.389	0.787	7.34
c1	375–550	63.8	0.995	8	−1.064	0.043	0.459	0.839	9.50
c2	400–525	64.3	0.996	6	−1.072	0.045	0.359	0.784	6.64
c2	375–550	66.3	0.990	8	−1.106	0.064	0.421	0.815	5.97
Dapto									
c1	400–550	60.0	0.998	7	−1.000	0.026	0.333	0.781	9.93
c1	375–550	59.9	0.993	8	−0.998	0.049	0.403	0.827	6.85
c1	375–550	57.6	0.997	8	−0.960	0.028	0.415	0.817	11.56
c2	350–550	58.8	0.997	9	−0.980	0.030	0.489	0.862	13.71
c2	375–550	57.4	0.997	8	−0.957	0.030	0.432	0.852	11.81

Sample, temperature range, paleofield value (in μT), regression coefficient (R^2), number of temperature steps used in line fit (N), slope (b), standard deviation of line fit (σ_b), fraction of NRM used in line fit (f), gap factor (g) and quality factor (q). After Coe et al. (1978). hs, hand sample; c, drill core.

Table 2
Summary paleointensity results

Flow	Paleofield value (μT)	σ (μT)	VDM	σ_{VDM}
Bumbo	67.7	5.2	9.81	0.75
	63.2	6.0	9.15	0.87
	64.4	5.3	9.33	0.77
	61.8	2.6	8.95	0.38
	63.8	2.6	9.24	0.38
	64.3	2.7	9.60	0.39
	66.3	3.8	9.31	0.55
Mean	64.5 ± 1.96		9.34 ± 0.29	
Dapto	60.0	1.6	8.69	0.23
	57.6	2.9	8.34	0.42
	59.9	1.7	8.68	0.25
	58.8	1.8	8.52	0.26
	57.4	1.8	8.31	0.26
Mean	58.7 ± 1.23		8.51 ± 0.18	

Virtual dipole moments (VDM) are calculated using the Australia reference pole for the 256–290 Ma interval (McElhinny and McFadden, 2000). Units are $\times 10^{22}$ Am^2.

variation of field strength was large during the Kiaman. (ii) The Great Whin sill results (and some other Permo-Carboniferous values) are biased to lower field values due to subtle alteration (weathering or hydrothermal alteration) and therefore they represent only minimum field values. In any case, a renewed rock magnetic investigation of the Great Whin Sill is warranted to better understand the existing results, whereas new results from silicate crystals of it and other units could help move us toward a definition of the true field strength and variation during the Kiaman. However, the first Kiaman paleointensity results based on single silicate crystals indicate that an inverse relationship between reversal rate and field strength (Cox, 1968), supported by data for the 0–160 Ma interval (Tarduno et al., 2001; Tarduno and Cottrell, 2005; Tarduno et al., 2006) is a viable hypothesis for a time interval extending at least to the Kiaman Reversed Polarity Superchron.

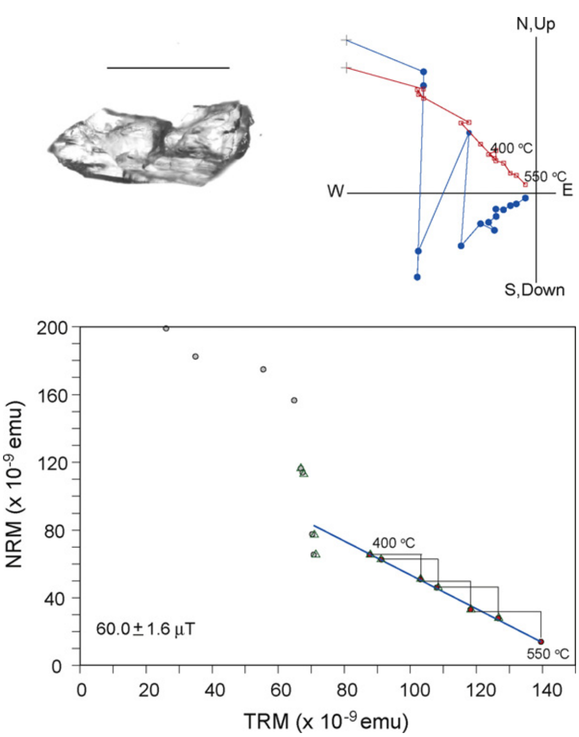

Fig. 7. Paleointensity results from the Dapto Flow. (a) Photo of measured crystal (1 mm scale bar). (b) Orthogonal vector plot of field-off thermal demagnetization steps. (c) Natural remanent magnetization versus thermal remanent magnetization data resulting from Thellier experiment. Triangles are p-TRM steps.

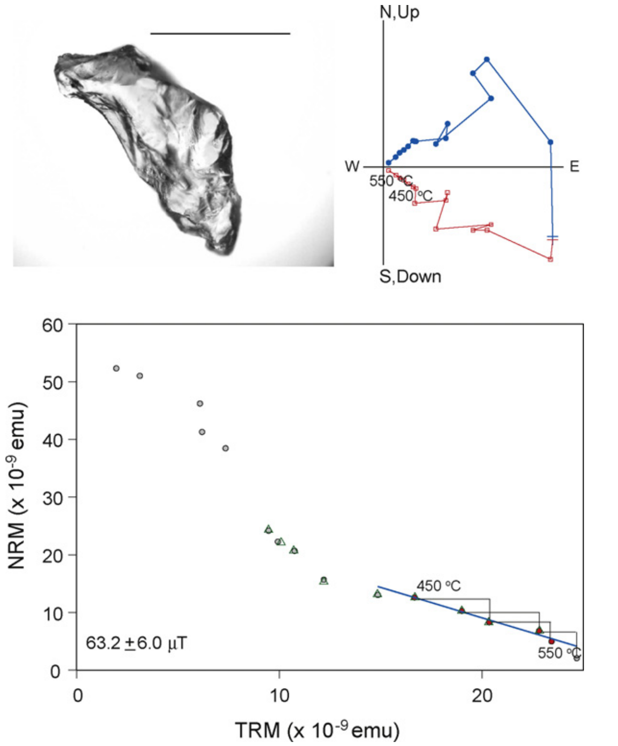

Fig. 8. Paleointensity results from the Bumbo flow. (a) Photo of measured crystal (1 mm scale bar). (b) Orthogonal vector plot of field-off thermal demagnetization steps. (c) Natural remanent magnetization versus thermal remanent magnetization data resulting from Thellier experiment. Triangles are p-TRM steps.

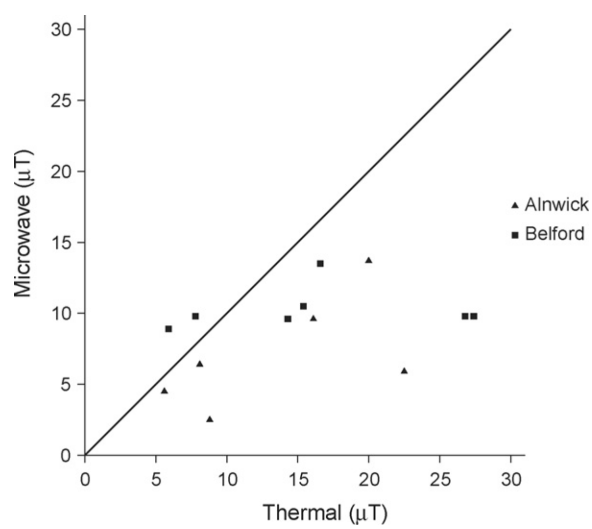

Fig. 9. A comparison of microwave and Thellier paleointensity results from the Great Whin Sill (triangles represent paired results from Alnwick, squares represent paired results from Belford). A paired t-test with a null hypothesis that these results are indistinguishable, fails at the 95% confidence level.

7. Conclusions

Primary paleomagnetic directions can be obtained from the Permian volcanics of New South Wales, as suggested in classic studies (Mercanton, 1926; Irving and Parry, 1963), but care must be taken in the demagnetization because of potential thermally induced alteration. Variable alteration in nature within the lavas also is a limiting factor. While paleomagnetic directions are preserved, the mean domain state and alteration characteristics suggest these rocks are not good candidates for bulk rock paleointensity analyses. Single plagioclase crystals separated from some of the lavas, however, have near SD magnetic behavior and pass paleointensity reliability criteria. Results from two of the flows yield virtual dipole moments of approximately 9×10^{22} Am^2, slightly higher than the modern field.

The Permian values from New South Wales are only instantaneous readings of the geomagnetic field near the end of the Kiaman Reversed Polarity Superchron. However, when compared with results reported from elsewhere, they suggest large temporal changes in intensity during the Kiaman, and/or the alternative hypothesis, that whole rock paleointensity results from some other Permo-Carboniferous units are affected by subtle in situ alteration and therefore record only minimum field strength values. Continued paleointensity data collection using single silicate minerals is needed to evaluate the former possibility, whereas refined rock magnetic studies of bulk samples are needed to judge the latter hypothesis.

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References

Briggs, D.J.C., 1991. Permian Productidina and Strophalosiidina from the Sydney-Bowen Basin and New England Orogen: systematics and biostratigraphic significance. Assoc. Australas. Palaeontol. Mem. 19, 1–258.
Campbell, L.M., Conaghan, P.J., Flood, R.H., 2001. Flow-field and paleogeographic reconstruction of volcanic activity in the Permian Gerringong Volcanic Complex, southern Sydney Basin, Australia. Aust. J. Earth Sci. 48, 357–375.
Carr, P.F., 1985. Geochemistry of Late Permian shoshonitic lavas from the southern Sydney Basin. In: Sutherland, F.L., Franklin, B.J., Waltho, A.E. (Eds.), Volcanism in Eastern Australia. Geological Society of Australia, New South Wales Division, Sydney (Publication 1).
Carr, P.F., 1998. Subduction-related Late Permian shoshonites of the Sydney Basin, Australia. Mineral. Petrol. 63, 49–71.
Carr, P.F., Pemberton, J.W., Nunan, E., 1999. Low-grade metamorphism of mafic lavas, upper Permian Broughton formation, Sydney Basin. Aust. J. Earth Sci. 46, 839–849.
Coe, R.S., 1967. The determination of paleointensities of the earth's magnetic field with emphasis on mechanisms which could cause non-ideal behaviour in Thelliers method. J. Geomag. Geoelect. 19, 157–179.
Coe, R.S., Grommé, C.S., Mankinen, E.A., 1978. Geomagnetic paleointensities from radiocarbon-dated lava flows on Hawaii and the question of the Pacific nondipole low. J. Geophys. Res. 83, 1740–1756.
Coe, R.S., Glatzmaier, G.A., 2006. Symmetry and stability of the geomagnetic field. Geophys. Res. Lett. 33, L21311.
Cottrell, R.D., Tarduno, J.A., 1999. Geomagnetic paleointensity derived from single plagioclase crystals. Earth Planet. Sci. Lett. 169, 1–5, doi:10.1016/S0012-821X(99)00068-0.
Cottrell, R.D., Tarduno, J.A., 2000. In search of high fidelity geomagnetic paleointensities: a comparison of single crystal and whole rock Thellier–Thellier analyses. J. Geophys. Res. 105, 23,579–23,594, doi:10.1029/2000JB900111.
Cox, A., 1968. Lengths of geomagnetic polarity intervals. J. Geophys. Res. 73, 3247–3260.
Day, R., Fuller, M., Schmidt, V.A., 1977. Hysteresis properties of titanomagnetite: grain-size and compositional dependence. Phys. Earth Planet. Int. 13, 260–267.
Doubrovine, P.V., Tarduno, J.A., 2006. Alteration and self-reversal in oceanic basalts. J. Geophys. Res. 111, B12S30, doi:10.1029/2006JB004468.
Draeger, U., Prevot, M., Poidras, T., Riisager, J., 2006. Single-domain chemical, thermochemical and chemical remanences in a basaltic rock. Geophys. J. Int. 166, 12–32.
Dunlop, D.J., 2002. Theory and application of the day plot (Mrs/Ms versus Hcr/Hc): 1. Theoretical curves and tests using titanomagnetite data. J. Geophys. Res. 107, 2056, doi:10.1029/2001JB000486.
Dunlop, D.J., Yu, Y., 2004. Intensity and polarity of the geomagnetic field during Precambrian time. In: Channell, J.E.T., Kent, D.V., Lowrie, W., Meert, J.G. (Eds.), Timescales of the Paleomagnetic Field. AGU Geophysical Monograph Series, vol. 145, pp. 85–100.
Gallet, Y., Pavlov, V., 1996. Magnetostratigraphy of the Moyero River Section (North-Western Siberia): constraints on geomagnetic reversal frequency during the early Palaeozoic. Geophys. J. Int. 125 (1), 95–105.
Garcia, A.S., Thomas, D.N., Liss, D., Shaw, J., 2006. Low geomagnetic field intensity during the Kiaman superchron: Thellier and microwave results from the Great Whin Sill intrusive complex, northern United Kingdom. Geophys. Res. Lett. 33, L16308.
Goguitchaichvili, A., Alva-Valdivia, L.M., Urrutia, J., Morales, J., Lopes, O.F., 2002. On the reliability of Mesozoic Dipole Low: New absolute paleointensity results from Paranà Flood Basalts (Brazil). Geophys. Res. Lett. 29, 1655, doi:10.1029/2002GL015242.
Gradstein, F.M., Ogg, J.G., Smith, A.G., 2004. A Geologic Time Scale 2004. Cambridge University Press, Cambridge, 610 pp.
Gulson, B., Diessel, C.F.K., Mason, D.R., Krogh, T.E., 1990. High precision radiometric ages from the northern Sydney Basin and their implication for the Permian time interval and sedimentation rates. Aust. J. Earth Sci. 37, 459–469.
Hoye, G.S., Evans, M.E., 1975. Remanent magnetization in oxidized olivine. Geophys. J. Roy. Astron. Soc. 41, 139–151.
Irving, E., Green, R., 1958. Polar movement relative to Australia. Geophys. J. 1, 64–72.
Irving, E., Parry, L.G., 1963. The magnetism of some Permian rocks from New South Wales. Geophys. J. Roy. Astron. Soc. 7, 395–411.
Irving, E., Pullaiah, G., 1976. Reversals of the geomagnetic field, magnetostratigraphy, and relative magnitude of paleosecular variation in the Phanerozoic. Earth Sci. Rev. 12, 35–64.
Joplin, G.A., 1964. A Petrography of Australian Igneous Rocks. Angus and Robertson, Sydney.
Joplin, G.A., 1965. The problem of potash-rich basaltic rocks. Mineral. Mag. 34, 266–275.
McElhinny, M.W., Larson, R.L., 2003. Jurassic dipole low defined from land and sea data. Eos Trans. Am. Geophys. Union 84, 362–366.
McElhinny, M.W., McFadden, P.P., 2000. Paleomagnetism, Continents and Oceans. Academic Press, New York, 386 pp.
McFadden, P.L., Merrill, R.T., McElhinny, M.W., Lee, S., 1991. Reversals of the Earth's magnetic field and temporal variations of the dynamo families. J. Geophys. Res. 96, 3922–3923, doi:10.1029/90JB02275.
Mercanton, P.L., 1926. Inversion de l'inclinaison magnètique terrestre aux âges geologiques. Terr. Magn. Atmos. Elec. 31, 187–190.
Olsen, P.E., Kent, D.V., Cornet, B., Witte, W.K., Schlische, R.W., 1996. High-resolution stratigraphy of the Newark rift basin (early Mesozoic, eastern North America). Geol. Soc. Am. Bull. 108, 40–77.
Opdyke, N.D., Channell, J.E.T., 1996. Magnetic stratigraphy. International Geophys. Ser., vol. 64. Academic Press, New York, 346 pp.
Opdyke, N.D., Roberts, J., Claoue-Long, J., Irving, E., Jones, P.J., 2000. Base of the Kiaman: its definition and global stratigraphic significance. Bull. Geol. Soc. Am. 112, 1315–1341.
Özdemir, Ö., 1987. Inversion of titanomaghemite. Phys. Earth. Planet. Int. 46, 184–196.
Pavlov, V., Gallet, Y., 2005. A third superchron during the Early Paleozoic. Episodes 28, 78–84.
Prèvot, M., Derder, M.E., McWilliams, M.O., Thompson, J., 1990. Intensity of the Earth's magnetic field: evidence for a Mesozoic dipole low. Earth Planet. Sci. Lett. 97, 129–139, doi:10.1016/0012-821X(90)90104-6.
Roberts, J., Claoué-Long, J.C., Foster, C.B., 1996. SHRIMP dating of the Permian System of eastern Australia. Aust. J. Earth Sci. 43, 401–421, 1996.
Ross, C.A., Ross, J.R.P., 1987. Late Palaeozoic sea levels and depositional sequences. Cushman Found. Foraminiferal Res. 24, 151–168 (Special Publication).
Schmidt, P.W., Embleton, B.J.J., 1981. Magnetic overprinting in southeastern Australia and the thermal history of its rifted margin. J. Geophys. Res. 86, 3998–4008.
Smirnov, A.V., Tarduno, J.A., 2004. Secular variation of the Late Archean-Early Proterozoic geodynamo. Geophys. Res. Lett. 31, L16607, doi:10.1029/2004GL020333.
Smirnov, A.V., Tarduno, J.A., 2005. Thermochemical remanent magnetization in Precambrian rocks: are we sure the geomagnetic field was weak? J. Geophys. Res. 110, B06103, doi:10.1029/2004JB003445.
Tarduno, J.A., Cottrell, R.D., 2005. Dipole strength and variation of the time-averaged reversing and non-reversing geodynamo based on Thellier analyses of single plagioclase crystals. J. Geophys. Res. 110, B11101, doi:10.1029/2005JB003970.
Tarduno, J.A., Cottrell, R.D., Smirnov, A.V., 2001. High geomagnetic field intensity during the mid-Cretaceous from Thellier analyses of single plagioclase crystals. Science 291, 1779–1783, doi:10.1126/science.1057519.
Tarduno, J.A., Cottrell, R.D., Smirnov, A.V., 2002. The Cretaceous Superchron Geodynamo: observations near the tangent cylinder. Proc. Natl. Acad. Sci. 99, 14020–14025, doi:10.1073/pnas.222373499.
Tarduno, J.A., Cottrell, R.D., Smirnov, A.V., 2006. The paleomagnetism of single silicate crystals; recording geomagnetic field strength during mixed polarity intervals, superchrons, and inner core growth. Rev. Geophys. 44, RG1002, doi:10.1029/2005RG000189.
Tarduno, J.A., Smirnov, A.V., 2004. The paradox of low field values and the long-term history of the geodynamo. In: Channell, J.E.T., Kent, D.V., Lowrie, W., Meert, J.G. (Eds.), Timescale of the Paleomagnetic Field. AGU Geophysical Monograph, vol. 145, pp. 75–84 (dedicated to N.D. Opdyke).

Tauxe, L., Constable, C., Johnson, C.L., Koppers, A.A.P., Miller, W.R., Staudigel, H., 2003. Paleomagnetism of the southwestern USA recorded by 0–5 Ma igneous rocks. Geochem. Geophys. Geosys. 4, 8802.
Tauxe, L., Staudigel, H., 2004. Strength of the geomagnetic field in the Cretaceous Normal Superchron: new data from submarine basaltic glass of the Troodos Ophiolite. Geochem. Geophys. Geosyst. 5, doi:10.1029/2003GC000635, Q02H06.
Thellier, E., Thellier, O., 1959. Sur l'intensitè du champ magnètique terrestre dans le passè historique et gèologique. Ann. Geophys. 15, 285–376.
Wang, D., Van der Voo, R., Peacor, D.R., 2005. Why is the remanent magnetic intensity of Cretaceous MORB so much higher than that of mid to late Cenozoic MORB? Geosphere 1, 138–146.
Yamamoto, Y., 2006. Possible TCRM acquisition of the Kilauea 1960 lava, Hawaii: failure of the Thellier paleointensity determination inferred from equilibrium of the Fe-Ti oxide. Earth Planets Space 58, 1033–1044.
Zhu, R.X., Lo, C.H., Shi, R.P., Shi, G.H., Pan, Y.X., Shao, J., 2004. Palaeointensities determined from the middle Cretaceous basalt in Liaoning Province, northeastern China. Phys. Earth Planet. Int. 142, 49–59.