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Palaeomagnetic Dating of Late Cretaceous to Early Tertiary Weathering in New England, N.S.W., Australia

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ABSTRACT

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Palaeomagnetic dating of Australia's regolith is becoming more refined with advances in techniques and better definition of the Late Mesozoic and Cenozoic apparent polar wander path of Australia. The suspected great antiquity of parts of the regolith is being confirmed through the application of palaeomagnetic dating to authigenic iron oxides which form during weathering.

Earlier palaeomagnetic investigation tentatively suggested that deeply weathered volcanics in the New England area formed in the Mesozoic, implying that ideas regarding the palaeoenvironment of New England may need considerable revision. Published dates for other, unweathered, volcanics from this area are K-Ar ages of 21.8 Ma, 32.8 Ma and 25.1 Ma. The earlier palaeomagnetic conclusions were based on results from only one (the Sugarloaf) of the seven separate localities (nine sites) originally sampled, these results being the only results that were internally consistent. Follow-up work using a high sensitivity cryogenic magnetometer has now yielded consistent results from the six other localities which support those from the Sugarloaf, but a revised weathering age of about 60 Ma seems more likely. This age is virtually identical to that determined for the Morney Profile in southwestern Queensland.

1 INTRODUCTION

Palaeomagnetic dating of laterites and other deep weathering profiles is now a well established technique (Schmidt and Embleton, 1976; Schmidt et al., 1977, 1982, 1983; Idnurm and Senior, 1978). The results from a deep weathering profile in New England are presented below. Because the samples are magnetised during the formation of haematite and maghaemite, following the breakdown of primary ferro-magnesian minerals, they carry a chemical remanent magnetisation (CRM) acquired over a long period of time. This is advantageous in one respect, in that much of the secular variation of the geomagnetic field may be averaged in one sample. However, the

trade-off is with greater difficulty in laboratory cleaning of the remanence, because normal and reversed magnetisations coexist in most samples reflecting a protracted period of magnetisation involving a geomagnetic reversal. There is no a-priori reason to expect one polarity of magnetisation to be greatly more stable than the other, since the opposite polarities would be expected to have formed under roughly similar conditions. Although changes in magnetisation direction during thermal or alternating field (AF) cleaning may be detected, the isolation of stable end-points, or single polarity components, may be difficult in these materials. The effect of cleaning is thus to generate a set of planes, or great circles when plotted on a stereonet, each com-

prised of two random samples of partially averaged normal and reversed magnetisations. These great circles are sometimes referred to as remagnetisation circles, implying that one of the underlying components is original (i.e., acquired when the rock formed) and is not necessarily anti-parallel to the remagnetisation direction. The more general term of great circles is more relevant to the present scenario, where we are dealing with complete remagnetisation and the underlying components are nearly anti-parallel. Thus the complete data set may consist of some stable end-points and a set of great circles. There are several methods available to handle such data which are discussed below.

2 SAMPLING AND METHODS

The friable nature of the highly weathered material prevented more than a few samples being collected with a portable drill. All but five samples out of 53 were block samples, each weighing up to a few kilograms. Fig. 1 shows the locations of the seven sampling sites. These are Bald Knobs (NE03), Arthurs Seat (NE04, 05 and 06), McGarrity's Farm (NE07), Mt. Butler South (NE08), Richleigh Hill (NE09), The Sugarloaf (NE10) and Uralla Trig Station (NE11). Sample orientations were performed with a magnetic compass and a sun-compass whenever practicable. The blocks and drill-cores were sub-sectioned in the laboratory to provide as many as possible specimens (260 overall) of nominal size 2.5 cm diameter and 2.2 cm height. The block samples were set in plaster of Paris before coring, and during coring compressed air was used for cooling. The natural remanent magnetisations (NRMs) of these specimens were measured using DIGICO spinner fluxgate and CTF cryogenic magnetometers. The latter of these is installed inside three orthogonal Helmholtz coil sets that afford a great degree
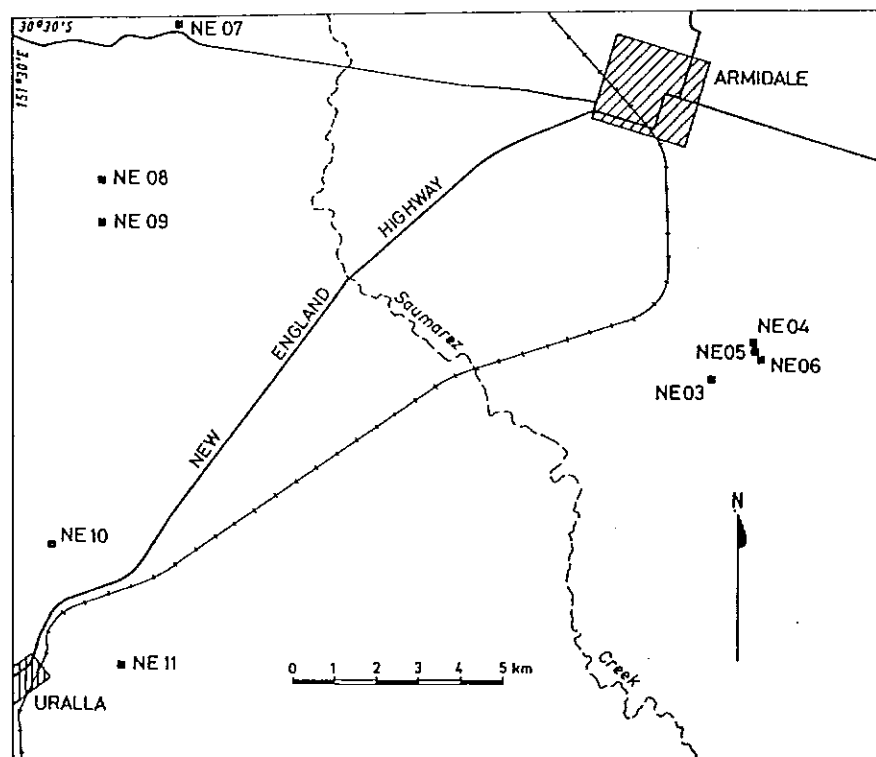

Fig. 1. Site localities in the New England region. Site 3 is Bald Knobs, 4–6 are from Arthurs Seat (in descending altitude), 7 is McGarrity's Farm, 8 is Mt. Butler South, 9 is Richleigh Hill, 10 is the Sugarloaf and 11 is the Uralla Trig Station.

of field control at the magnetometer mouth. This proved necessary to eliminate spurious magnetisations that otherwise may be acquired after almost complete demagnetisation, and would obscure the natural remanences. Step-wise thermal or alternating field (AF) demagnetisation of all specimens was performed using an automatic furnace (Coward et al., 1985) or a Schonstedt GSD-1 AF instrument. Because of rapid disintegration in acid, the specimens were not amenable to chemical demagnetisation methods. Thermal demagnetisation proved to be more satisfactory than AF demagnetisation. Routine palaeomagnetic and rock magnetic procedures are described in a number of standard texts (Irving, 1964; Collinson et al., 1967; McElhinny, 1973; Collinson, 1983; O'Reilly, 1984).

The demagnetisation data were analysed using linearity and planarity spectrum analysis (LSA and PSA, Schmidt, 1982) with the visual aid of orthogonal plots (Zijderveld, 1967) and stereo projections.

3 RESULTS

Representative results of thermal demagnetisation are presented as orthogonal plots (Zijderveld, 1967) in Fig. 2. By far the majority of samples reveal curvilinear trends rather than linear segments. Although some specimens appear to demagnetise directly towards the origin, a scrutiny of the detailed behaviour at high temperatures ($550°$ to $680°$ C) often reveals a distinctive bypass of the origin with the magnetisation vector greatly changing direction over the last few steps ($620°$, $640°$, $660°$ and $680°$ C). The blow-ups of the zones around the origins of several plots assist in the recognition of this, e.g. specimens NE05B1, B4 and NE09C2 of Fig. 2a. In Fig. 2, b and c, these general features are readily apparent but the behaviour of specimen NE07A1 (Fig. 2b) gives an insight into what comprises the magnetisations of these samples. Because of the correlation of grain size with magnetisation direction (a rare event) in

specimen NE07A1, thermal demagnetisation has enabled the multi-component nature of the NRM to be resolved. Although slightly noisy, presumably because the above correlation is not perfect, there is an indication of the presence of magnetic reversals within the one specimen. An examination of results from other specimens from site 07 (McGarrity's Farm) confirmed the presence of reversals. This is not the first discovery of this phenomenon in highly weathered material, and it has been commented on in the past (Schmidt and Embleton, 1976; Idnurm and Senior, 1978), but the coexistence of normal and reversed components has previously been inferred by physically splitting the specimen and examining the magnetisation of the individual parts. The magnetisation of red-beds has also revealed coexisting reversals (Roy and Park, 1974) with the clear implication that the magnetisation of the products of weathering and red-bed formation occurs over sufficiently long periods of time to span reversals of the geomagnetic field. This is an important aspect in the palaeomagnetic dating of these materials, because it suggests that much of the secular variation of the geomagnetic field is averaged, even on the scale of a specimen.

The multi-component nature of the magnetisation of these samples, and the low incidence of their resolution by thermal demagnetisation leads to the use of the great circle (GC) method to analyse the magnetisations present. Many workers (Khramov, 1958; Creer, 1962; Jones et al., 1975; Halls, 1976; McFadden, 1977; Hoffman and Day, 1978; Bailey and Halls, 1984) have used the GC method and at a glance the principle of their application seems simple and straightforward, however there are some pitfalls for the unwary. These have been detailed by Schmidt (1985), who points out that one of the sufficient conditions for the valid application of the GC method is satisfied if the mean magnetisation components for all specimens are anti-parallel (or nearly anti-parallel). Consider the consequence of their not being anti-parallel; it is not immediately clear to

such as those here, and if the precision parameter is set too high, too much data may be rejected. Of the 187 specimens analysed, 30 satisfied the above criteria and yielded well defined straight line segments.

Examples of great circle trends are shown in Fig. 3b. There is clearly a convergence towards the south-steep down direction, and towards the north-steep up direction, with a few specimens attaining stable end-points. Also note that some specimens from site 07 clean towards normal and other specimens towards reversed directions, confirming that mixed polarities are the cause of the scattered NRM directions. The poles of great circles were selected using the Planarity Spectrum Analysis (PSA) option of the LSA package (Schmidt, 1982). An analogous cut-off to that applied to LSA yielded the 105 poles plotted in Fig. 3c.

There are three main methods that have been used to analyse great circles. These are briefly discussed below.

(1) *The beta method* (Khramov, 1958). This method makes use of the intersections of great circles and is familiar to students of structural geology. Each intersection is treated as an estimate of the underlying magnetisation direction and is given unit weight in a standard Fisher (1953) analysis of errors. Clearly, the number of intersections will in general exceed the number of circles, and the intersections will not necessarily be distributed according to the Fisher distribution. This method is no longer considered appropriate.

(2) *The iterative convergence method* (Jones et al., 1975; McFadden, 1977). After fitting least-squares planes to the great circles (and

the centre of the unit sphere), this method uses the last observed magnetic direction for each specimen to calculate a mean direction to use as a seed direction. A new set of directions are calculated by projecting the seed direction onto each plane, and a new mean direction is calculated. This procedure is repeated until no significant change occurs between iterations. Any known end point directions can be incorporated at each estimation of the mean.

(3) *The pole of poles method* (Halls, 1976). As the name suggests, this method fits a least squares plane to poles of the great circles (themselves defined by least squares). The pole of this plane is used as the estimate of the magnetisation direction. Recently, Bailey and Halls (1984) have generalised this method to enable the incorporation of end point directions. It must be emphasised that these methods can only be used in special circumstances (Schmidt, 1985), and the fact that directions seem to trend towards each other is not, of itself, sufficient for the valid application of the method. This is implicit in the assumption by Bailey and Halls (1984) that the poles of the great circles are uniformly distributed around a great circle. The poles plotted in Fig. 3c are seen to satisfy this requirement. If the poles are restricted to a small segment of a great circle, then the analysis will be biassed. This is easily confirmed using only part of a complete data set, or by Monte-Carlo simulations.

The results of applying the McFadden and the Bailey and Halls methods to the end point directions plotted in Fig. 3a, and the great circle poles plotted in Fig. 3c are summarised

TABLE I

Summary of remanence direction estimates

	From combined poles and end pts.:					From poles only:				
	Dec	Inc	e1	e2	a	Dec	Inc	e1	e2	a
McFadden	208.7	71.4			2.3	208.6	71.1			3.0
Bailey and Halls	208.8	69.5	6.2	5.8		208.5	69.2	6.5	6.1	

Note: Dec = declination, Inc = inclination; e1 and e2 = major axes of 95% confidence ellipse (Bailey and Halls, 1984); and a = half-angle of 95% cone of confidence (Fisher, 1953).

in Table I. The statistical development given by Bailey and Halls (1984) allows the distributions of the directions and the poles to be compared. From this it was found that the precision parameters of the directions and poles are significantly different, and that the estimate of the true direction are probably different as well. At the probability level $P = 0.05$, the precision parameter ratio had a value of 2.02 as compared with $F_{105,58} = 1.45$, and the parameter Q, which is used to compare directions was 12.5 as compared to $F_{2,161} = 3.05$ (Bailey and Halls, 1984). The mean end point direction is Dec $= 235.4°$, Inc $= 82.7°$ ($A_{95} = 5.4°$). The reason for this difference seems to relate to the fact that the majority of the directions (end points) were derived from only three of the sites (sites 03, 05 and 06), and suggests that there are small but real differences between sites. The combined analysis is strictly only approximately valid because of this. Nevertheless, the analysis of directions and poles combined gave very similar results using either the McFadden method or the Bailey and Halls method. There is however a slight difference in the error analysis between the two methods (Table I), and it is considered more conservative to use the results which yield the greater error (Bailey and Halls, 1984). Therefore, the overall mean direction is estimated as Dec $= 208.8°$, Inc $= 69.5°$ (e1 $= 6.2°$, e2 $= 5.8°$), which yields a pole position at lat $= 59.2°$S, long $= 117.2°$E (dp $= 9.9°$, dm $= 9.1°$). This pole is plotted in Fig. 4 along with other Tertiary and Cretaceous pole positions (Idnurm, 1985a).

4 DISCUSSION

A comparison of the pole position calculated above with other Australian pole positions suggests that the weathered profile is about 60 Ma old (Fig. 4). This age is virtually identical to the weathering age determined from the Morney profile (Idnurm and Senior, 1978) of southwest Queensland suggesting that the New England profile and the Morney profile record the same weathering event. The error on the age estimate is fairly large due mainly to the small amount of apparent polar wandering attributed to non-dipole effects by Idnurm (1985b), and the 95% confidence limits correspond approximately to 80 Ma and 30 Ma. However, the correlation with the Morney profile and the likelihood that the late stages of weathering are probably recorded by the palaeomagnetism, rather than initial stages (for discussion see Idnurm and Schmidt, 1986), suggest that the age of weathering is Late Cretaceous to Early Tertiary and the age of the volcanics is therefore older. The discrepancy between the magnetisations as determined directly, and as determined by the GC method, probably reflects a real age difference with the former relating to older weathering. The predominance of reversed polarity, however, would seem to indicate an age younger than the Cretaceous Normal Chron (spanning 120 Ma to 80 Ma, Merrill and McElhinny, 1983).
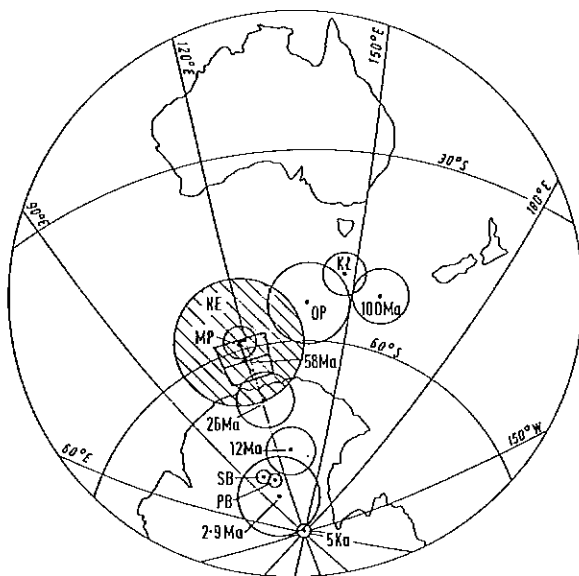

Fig. 4. Tertiary and Cretaceous poles for Australia (after Idnurm, 1985a). The New England profile pole (NE) is in close agreement with the south western Queensland Morney profile (Idnurm and Senior, 1978) pole position (MP). Other poles are OP, the overprint pole from the Sydney Basin (Schmidt and Embleton, 1981). Circles and squares denote 95% confidence limits.

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The new date for the weathering profile, about 60 Ma, has several implications for the geological and geomorphic history of the area. An early weathering profile is widespread in the area, occurring on both volcanic and non-volcanic rocks. It has been mapped by G. Francis (pers. commun., 1985) who called it the Dangarsleigh Pedoderm. The weathering has to be post-Triassic (since Triassic granites are exposed at the ground surface) and older than the Eocene lava flows, which leaves most of the Mesozoic for its formation. It is emphasised that the age determined here is likely to mark the end of the deep weathering.

Our proposed data is consistent with what we know of the palaeogeomorphology. In the Eocene the New England area was a broad plain, crossed by broad rivers with braided stream channels and lakes (now represented by the Armidale Formation). The origin of the coarse stream load remains a problem. The alluvial deposits themselves are deeply weathered and have indications of fluctuating water tables (Mann and Ollier, 1985), and the surrounding plains have ample time for very deep weathering and differentiation of deep weathering profiles, with pallid zones at depth and oxidised, ferruginous zones at the top.

At Bald Knobs the 20 Ma basalt on the hill top has basalt columns that have been weathered only a millimetre or so, and retain "chisel marks" on their surfaces. The underlying 30 m of red clay was originally basalt, so the change in weathering environments has been enormous. Whatever assumptions are made, the difference cannot be attributed simply to more time, and a different climate and/or groundwater hydrology is postulated to explain the more intense weathering in earlier times.

The younger basalts enable approximate erosion rates to be determined for the upper Tertiary (Ollier, 1982). These may be as high as 30 B (Bubnoff unit, mm/1000 a or m/Ma) but are more likely to be around 1.5 B. Compared with the world average for plains of 50 B this is very low. This appears even more anomalously low when it is allowed that much of the erosion was the stripping of deeply weathered profiles, rather than fresh rock.

5 ACKNOWLEDGEMENT

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