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Paul Bishop [a], Peter Hunt [b] & P.W. Schmidt [c]
[a] Department of Geography, University of Sydney, N.S.W., 2006
[b] School of Earth Sciences, Macquarie University, North Ryde, N.S.W., 2113
[c] Division of Mineral Physics, CSIRO, P.O. Box 136, North Ryde, N.S.W., 2113

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Paul Bishop[1], Peter Hunt[2] & P. W. Schmidt[3]

[1] *Department of Geography, University of Sydney, N.S.W. 2006.*
[2] *School of Earth Sciences, Macquarie University, North Ryde, N.S.W. 2113.*
[3] *CSIRO Division of Mineral Physics, P.O. Box 136, North Ryde, N.S.W. 2113.*

ABSTRACT

The age of formation of the Lapstone Monocline has been long considered to be late Pliocene/early Pleistocene (the Kosciusko Uplift) but it is now generally thought to be much older. Palaeomagnetic data from haematite-rich beds within the Hawkesbury Sandstone on and about the monocline indicate that it formed before the oldest haematite was introduced to these beds. The age of this oldest haematite is 15 ± 7 Ma. On the basis of these data, the age of the monocline is unlikely to be less than 8 Ma, probably exceeds 15 Ma, and could be older than 22 Ma.

KEY WORDS: Palaeomagnetism, haematite, Hawkesbury Sandstone, Lapstone Monocline, eastern highlands.

INTRODUCTION

The Lapstone Monocline (Figs 1 & 2), west of Sydney, is a prominent, scarp-forming, structural complex that marks the boundary between the Blue Mountains (part of the southeastern Australian highland) and the low-lying Cumberland Plain (David, 1896, 1902; Branagan, 1969). On the monocline, the generally flat-lying sedimentary rocks of the Permo-Triassic Sydney Basin are folded to dips of up to 60°, to form one of the major tectonic/physiographic features of the Basin. Steeply-dipping Hawkesbury Sandstone and the overlying Wianamatta Group outcrop on the scarp immediately west of the Nepean River from Penrith to Kurrajong, and good exposures occur on the major roads that ascend the scarp to the lower Blue Mountains (Fig. 3).

Traditional interpretations of the Blue Mountains portion of the southeastern Australian highland and the Lapstone Monocline, placed uplift/folding in the late Pliocene/early Pleistocene, during the Kosciusko Uplift (or Kosciusko Stage). This age of folding—first suggested by Andrews (1910, 1934) and reiterated by many others, including Browne (1969) and Scheibner (1976)—was based on a Davisian interpretation of eastern Australian landforms. Osborne (1948) suggested that the fold may be considerably older, but only more recently, with the advent of the K-Ar isotopic dating method and the determination of the physical ages of many basalts throughout eastern Australia, has there been any real emphasis on the antiquity of the southeastern Australian highland. The bulk of these dates was provided by Wellman & McDougall (1974) who drew attention to the great age of many of the surfaces on which basalts are found in highland areas adjacent to the Blue Mountains.

Branagan (1975) proposed that folding of the Lapstone Monocline could be related to the opening of the Tasman Sea, 60 to 80 Ma ago, and hence suggested a late Cretaceous to early Tertiary age for the monocline. Langford-Smith (1976) suggested that uplift of the Blue Mountains probably occurred before the Miocene, basing his estimate on a suggested correlation between the ages of duricrusting in southern Queensland and eastern N.S.W.

The age of fluvial sediments, which mantle the face of the monocline (and hence pre-date it), and which were apparently deposited by a palaeo-Wollondilly/Nepean River system, implies a maximum age for the folding of the monocline. David (1896) inferred a late *Mesozoic*–early *Tertiary* age for the sediments, but did not use this age specifically to constrain the time of folding. Gobert (1978) argued that these 'Rickabys Creek Gravels' were deposited in the Miocene prior to folding.

The limitation of all of these approaches is that none rely on evidence derived from the monoclinal fold itself. Rather, they rely on inferred links between the monocline (or the highlands which it borders) and other 'datable' features in the highlands. In this paper we present palaeomagnetic data from the fold itself, in order to place constraints on the age of folding.

METHOD

The technique of palaeomagnetism relies on the capacity of certain types of iron-bearing minerals to preserve ancient magnetic field directions, and in this study we use palaeomagnetic data from iron-rich beds

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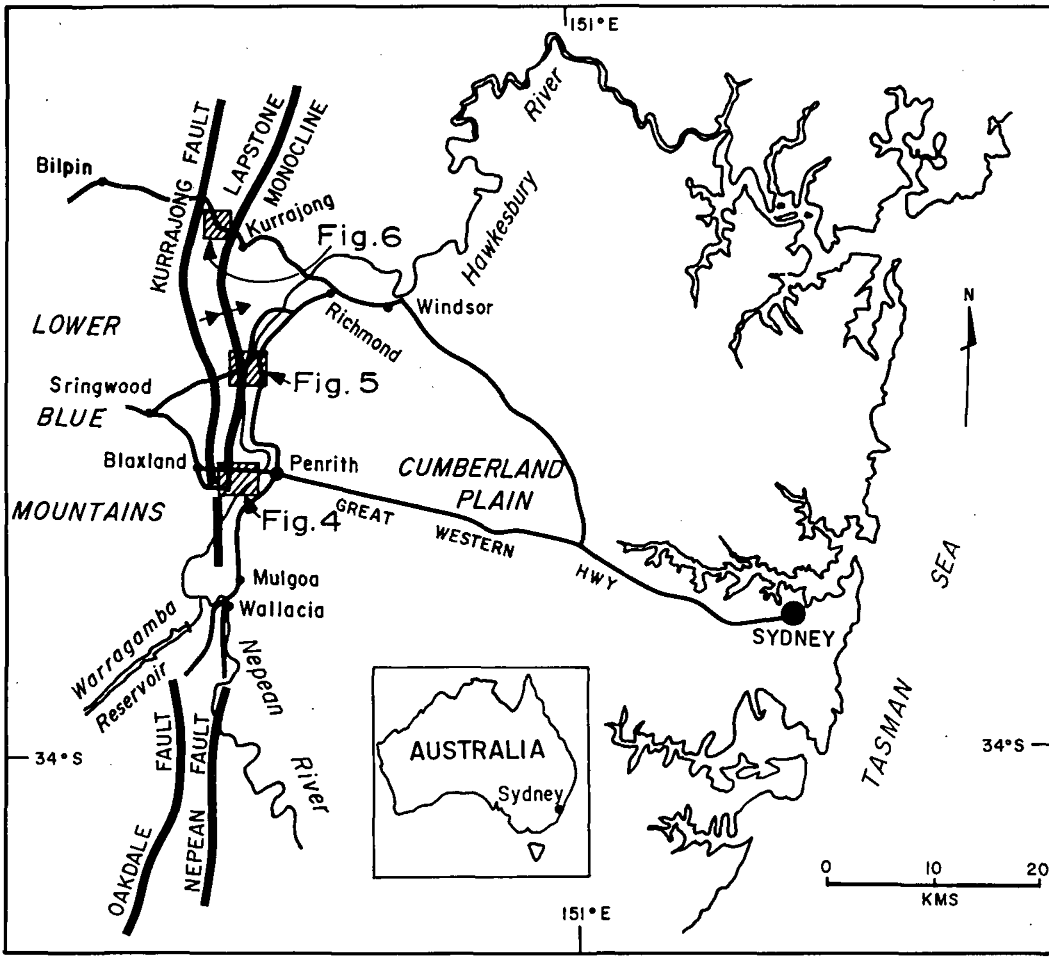

Fig. 1. Map showing the location of the Lapstone Monocline and associated structures, and general locations of the palaeomagnetic study sites.

within the Hawkesbury Sandstone on and adjacent to the monocline.

Iron, in various mineralogical forms, is widely distributed throughout the Hawkesbury Sandstone (Osborne, 1948; Hunt et al., 1977). In fresh bedrock (usually drill core samples) siderite is the most abundant iron-bearing mineral, but in surface outcrop it rarely occurs (Standard, 1964, 1969). In fact, surface outcrop is generally depleted in all iron minerals, but they are locally abundant, occurring as concentrations of goethite and/or haematite, with occasional maghemite (Hunt et al., 1977). Concentrations of both goethite (which is unsuitable for palaeomagnetic work) and haematite occur in the Hawkesbury Sandstone on the monocline, but maghemite was not detected. The haematite occurs most commonly as a pore-filling cement in the open, sandy quartz fabrics of the Hawkesbury Sandstone 'sheet facies' (Conaghan & Jones, 1975).

Palaeomagnetism affords a method of establishing the time at which this haematite was introduced into the Hawkesbury Sandstone. Individual crystals of haematite acquire a permanent chemical remanent magnetisation (CRM) consistent with the direction of the Earth's field, when a critical or minimum 'blocking' volume is reached (Haigh, 1958). This CRM can be measured and compared with the Australian Apparent Polar Wander Path (APWP), to give the age of the haematite introduction. The calibration of the APWP depends on combined K-Ar dating and palaeomagnetic studies (Wellman et al., 1969), although *relative* dates may be inferred from palaeomagnetic poles alone, if their physical age differences are sufficient.

For the Lapstone Monocline, the time of folding can be constrained by determining whether the haematite was introduced before or after the folding, by comparing the directions of magnetisation of the haematite in sandstone beds on the monocline and in adjacent flat-lying beds. If the haematite was introduced after the folding, the preserved directions of magnetisation would be independent of the amount and direction of dip. In this case the age of the haematite would set a minimum age for the folding.

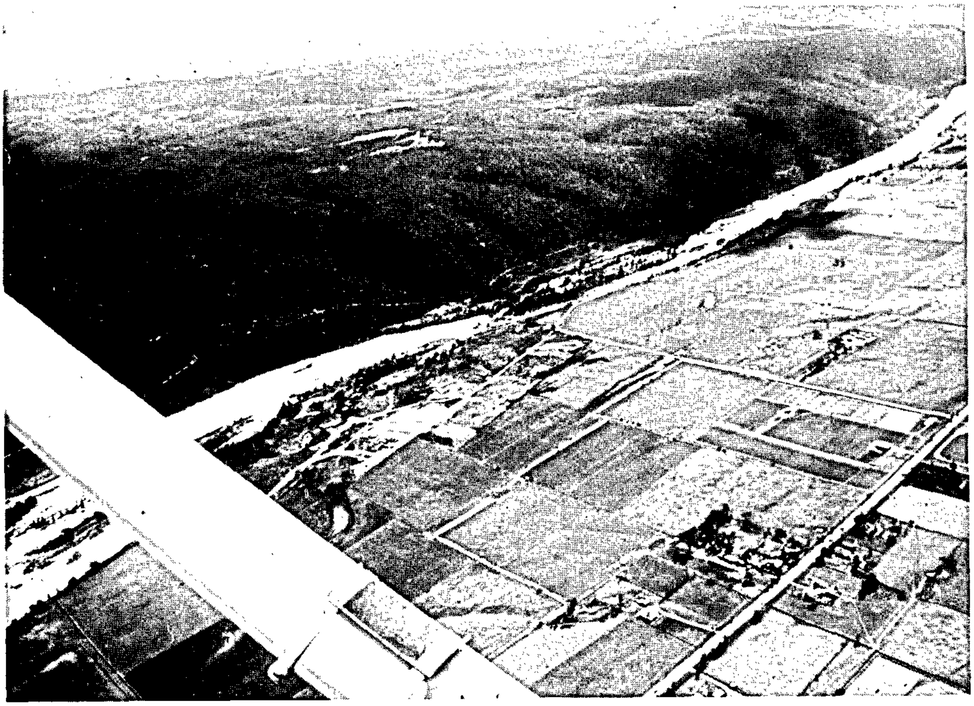

Fig. 2. The scarp that marks the Lapstone Monocline near Upper Castlereagh (view looking towards NW). The Nepean River flows northwards at the base of the monocline and is joined by Fitzgerald's Creek in the centre of the photograph. Photo courtesy of T. Langford-Smith.

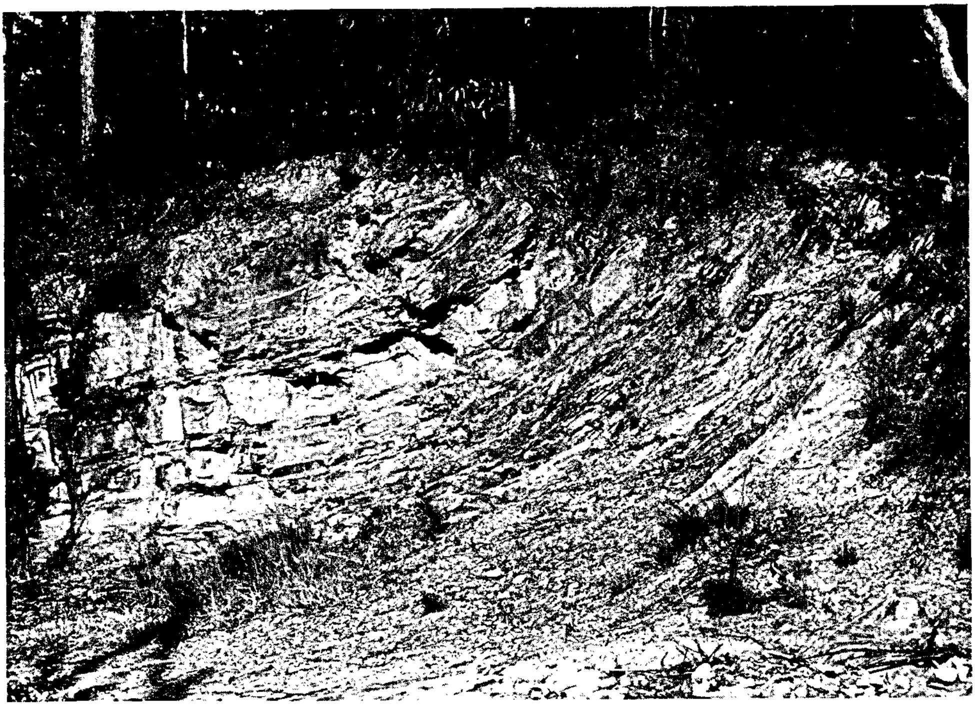

Fig. 3. The hinge of the Lapstone Monocline exposed in a cutting on Mitchell's Pass (Lennox Bridge) Road. Sites HS 40 and HS 42 are shown in this photograph. East is to the left.

However, if the introduction of the haematite preceded folding the preserved directions of magnetisation would be displaced (by an amount consistent with the dip and strike of the fold) from the directions preserved in horizontal rocks, and this would set an upper age limit to the time of folding.

SAMPLING AND LABORATORY METHODS

A portable drill was used to collect cores from the variously dipping haematite-rich sandstones at a number of sites on or near the monocline. A 'site' was generally defined as a single haematite-rich bed of constant dip, although in two sites this criterion could not be satisfied because of the thinly bedded nature of the sandstone. At least 6 samples (cores) were drilled from each site, and 157 samples (cores) were drilled from 17 sites (Figs 4 to 6). Cores were 6 to 15 cm long and were oriented using both sun and magnetic compasses (Embleton & Edwards, 1973).

From each core, two to five specimens (each 2.2 cm long) were prepared, and one specimen per core was thermally demagnetised through 8 to 14 steps from 200°C to 660°C. This procedure ensured that viscous components of magnetisation, acquired either *in situ* (in the present magnetic field direction) or after collection, were eliminated. Specimens were demagnetised in a non-magnetic Schonstedt furnace, and remanence was measured in a Digico spinner magnetometer (Molyneux, 1971). Treatment to 660°C resulted in the complete removal of magnetic remanence in most specimens. Between demagnetisation treatments, specimens were stored in field-free shields. The exact number of demagnetisation steps for any particular specimen depended on both the intensity and stability of the remanence, being more closely spaced for those specimens with low NRM (NRM $< 20 mAm^{-1}$) or a remanence that decayed rapidly at low temperatures.

ANALYSIS

Of the 17 sites sampled, four were eliminated from the subsequent statistical analysis. These sites (HS 25, HS 26, HS 45 and HS 52) were excluded because in all cores collected the NRM intensities were very low ($< 5 mAm^{-1}$) and/or the cleaned directions very scattered. This eliminated 23 cores from the analysis.

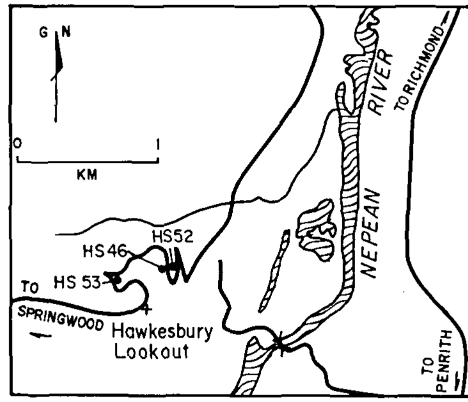

Fig. 5. Location of Lapstone Monocline study sites on the Springwood Road.

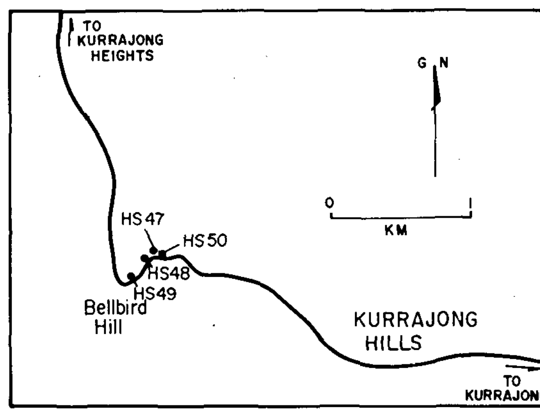

Fig. 6. Location of Lapstone Monocline study sites on Bell's Line of Road.

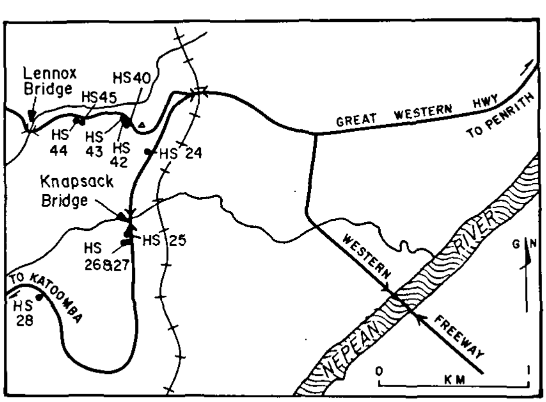

Fig. 4. Location of Lapstone Monocline study sites on the Great Western Highway and Mitchell's Pass (Lennox Bridge) Road.

The thermal demagnetisation data from the remaining 13 sites (134 specimens) were analysed using the procedures described by Kirschvink (1980). The technique is based on principal component analysis (PCA) which, in effect, yields the least-squares fit of a line to a set of points in three dimensions (i.e., the vectors representing successive demagnetisation steps of a specimen). A set of points is selected by a search routine, which defines points, the co-linearity of which exceeds some pre-set value. Co-linearity is a measure of the alignment of the points and may be expressed as the magnitude of the vector difference between the bounds of the data set in question, divided by the sum of the magnitudes of the vector differences between the constituent data points. The co-linearity, or simply linearity, level chosen for this study was 0.975.

In virtually all specimens, the analysis yielded more than one linear segment, and in most cases the direction from the highest-temperature segment was selected for subsequent analysis. The high-temperature, and most stable, directions were chosen because

TABLE 1. Summary of location, bedding and palaeomagnetic data for Lapstone Monocline sites.

SITE	BEDDING		FIELD DIRECTION					SITE POLE POSITION*		
	Dip (deg)	Down-dip azimuth	Dec (deg)	Inc (deg)	n	R	α_{95} (deg)	Lat (°S)	Long (°E)	A_{95} (deg)
HS 24	6	094	6.3	-60.5	14	13.7572	5.5	80.7	124.4	8.0
HS 27	37	089	2.2	-53.7	6	5.9705	5.2	87.9	83.0	5.1
HS 28	5	093	8.7	-56.1	4	3.9893	5.5	82.2	85.1	7.4
HS 40	10	100	2.4	-60.9	10	9.9717	2.7	81.5	138.7	3.8
HS 42	26	056	0.5	-58.3	10	9.9619	3.1	84.5	147.3	4.2
HS 43	56	078	9.6	-57.9	10	9.9462	3.7	80.9	94.9	5.2
HS 44	23	122	0.2	-63.1	12	11.8511	5.1	78.5	150.2	7.4
HS 46	60	082	8.4	-59.0	7	6.9813	3.4	81.0	106.4	4.6
HS 47	17	082	187.6	58.9	9	8.9004	5.8	80.8	111.8	7.2
HS 48	14	072	8.1	-56.9	14	13.9072	3.4	82.2	96.2	4.5
HS 49	14	072	9.3	-54.2	6	5.9739	4.9	82.1	74.1	5.1
HS 50	13	083	182.1	64.5	7	6.9483	5.6	76.7	144.3	8.3
HS 53	0		3.3	-55.6	9	8.9320	4.8	86.3	106.4	6.3

Symbols: n - number of unit vectors

R - resultant magnitude of n unit vectors

α_{95}, A_{95} - half-angle of cone of confidence (95%) for directions and poles, respectively (Fisher, 1953)

* Site pole positions are sample pole position means.

they probably most closely resemble the original CRM direction. Where this direction varied markedly from the other directions in the site, it was rejected and the direction of the preceding temperature segment was used. Eight specimens were eliminated because the analysis yielded no systematic directions, and a further eight were eliminated because no linear segments were determined by PCA (i.e. their sequential demagnetisation steps did not satisfy the 0.975 linearity level).

The remaining specimen directions and pole positions (118 specimens from 13 sites) were averaged by site (Table 1, and Fig. 7a). Figure 7b shows directions of magnetisation at each site after unfolding to the horizontal.

DISCUSSION

The site mean field directions from the 13 sites have a clustered, elongate distribution (Fig. 7a) which becomes progressively more dispersed as the monocline is unfolded to the horizontal (Fig. 7b). This shows that the introduction of haematite into the sandstone post-dated the monocline formation and, therefore, the age of the haematite gives a minimum age for the monocline.

The presence of both normal and reverse magnetisations (Table 1) indicates that haematite has been crystallising in the Hawkesbury Sandstone on the monocline over a considerable length of time, sufficient to record at least one reversal in the geomagnetic field. Moreover, such reversals are often detected within individual sites (7 sites), both between specimens and even within an individual specimen. This indicates that deposition of haematite within a single sandstone bed can take place over a sufficient length of time to record at least one reversal. Such reversals occur over a period of about 10^{3-4} years (McElhinny, 1973, p. 137). This time period is probably sufficient to average the secular variation in the Earth's field and this implies that the mean directions of magnetisation of sites on the monocline are largely free from the effect of secular variation. Further, if secular variation was not being averaged during deposition of the haematite, one would expect some pole positions to lie on the far side of the South Pole relative to Australia, whereas all site poles are located between Australia and the present South Pole (Fig. 8). In fact, fewer than 10% of the poles calculated from the 118 *specimen* directions of magnetisation lie beyond the South Pole in the opposite hemisphere to Sydney. Further, using Watson & Irving's (1957) test, neither the specimen directions of magnetisation nor their corresponding poles are distributed according to Fisher's (1953) distribution ($p<0.001$) as they would be expected to be if they were simply recording secular variation in the Earth's field.

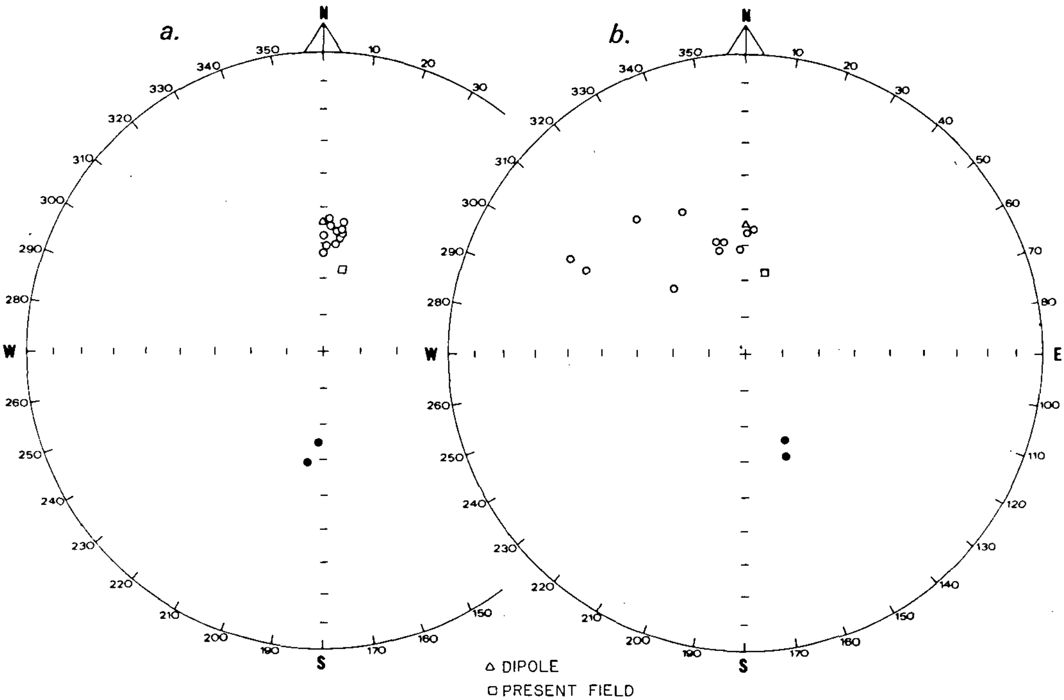

Fig. 7. Site mean cleaned directions of magnetisation from the Lapstone Monocline: (a) with respect to present horizontal; (b) with respect to palaeo-horizontal. Solid (open) symbols plot on lower (upper) hemisphere. The dominant polarity is shown for sites with mixed polarity.

This suggests that the differences in the mean directions of magnetisation of each site could be the result of Australia's northward drift during a prolonged period of haematite deposition in the Hawkesbury Sandstone, rather than from secular variation and/or statistical scatter associated with one relatively short event of haematite deposition. This interpretation was tested using two versions of the F-test, as outlined by McFadden & Lowes (1981).

The first version tests whether the pole positions of the various sites are statistically identical, as would be expected if there was only one relatively short period of haematite deposition. This test assumes that all the site pole positions have approximately equivalent K (precision) values, and the ratio of the largest to the smallest K can be used to test if this measure of precision is constant (McFadden & Lowes, 1981). By comparison with F-tables, a maximum K_1/K_2 ratio of about 2 satisfies this condition. The eight sites (HS 27, HS 28, HS 40, HS 42, HS 43, HS 46, HS 48, HS 49) which give a maximum K_1/K_2 of about 2, yield an F value of 2.141 ($0.01<p<0.025$), indicating that the true mean pole positions of the eight sites are not identical.

A second version of the F-test can be used to test whether the poles lying at either end of the spread of site poles along the Australian APWP (Fig. 8), are significantly different. As before, the condition that the K values must be approximately equal restricts the application of the test to comparing the pole of HS 27 with those of HS 46 and HS 43. For HS 27 and HS 46 ($K_1/K_2 = 1.005$), the F value is 4.185 ($p = 0.03$), and for HS 27 and HS 43 ($K_1/K_2 = 1.967$), the F value is 2.976 ($p = 0.07$). These results indicate that there is a significant difference between the pole positions at either end of the spread of site poles.

We argue, therefore, that the presence of normal and reverse magnetisations within both sites and specimens, the location of site and specimen poles almost exclusively between Australia and the South Pole, the non-circular distribution of specimen pole positions, and the results of the two versions of the F-test, support the conclusion that the spread of site pole positions is the result of Australia's northward drift during deposition of haematite. This, in turn, indicates that haematite deposition on the monocline spans some considerable length of time, although whether this deposition was continuous, or occurred during two or more episodes cannot be resolved satisfactorily with these data. The age of the oldest haematite therefore gives a minimum age for the monocline, and this age can be determined by comparison of pole positions with the Australian APWP. (It is emphasised that this dating procedure is indirect and relies upon the correlation of K-Ar dating studies and palaeomagnetic studies of Tertiary basalts from eastern Australia).

In Figure 8 site pole positions are plotted with the Australian APWP. The data from HS 46 (the oldest site with the greatest precision), indicate that haematite was crystallising in the Hawkesbury Sandstone

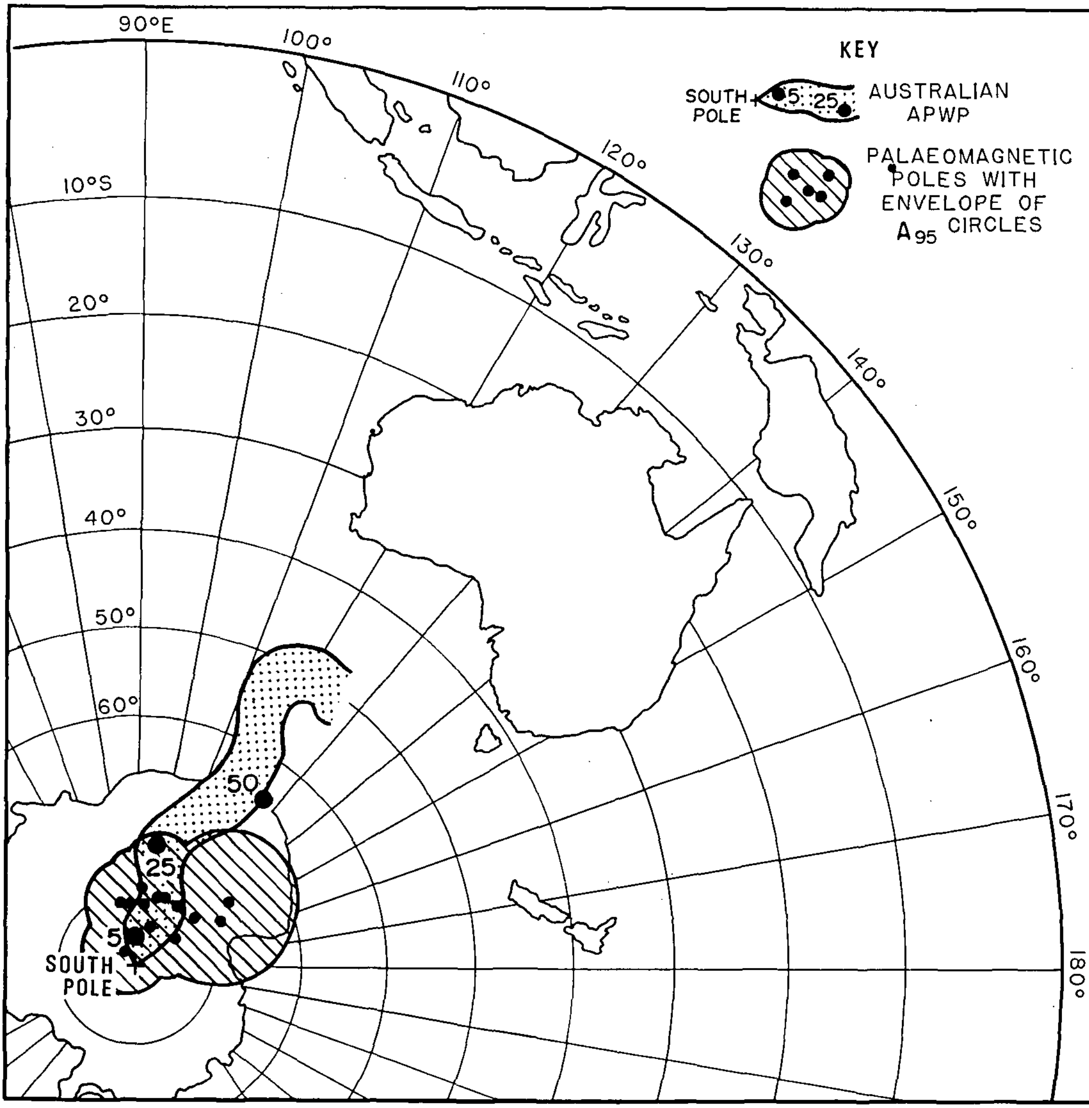

Fig. 8. Apparent polar wander path for Australia from the late Mesozoic to the present (after Embleton & McElhinny, 1982) and site pole positions and envelope of A_{95} circles from Hawkesbury Sandstone on the Lapstone Monocline.

about 15 ± 7 Ma ago. On the basis of these data, the age of the monocline is unlikely to be less than 8 Ma, probably exceeds 15 Ma and could be older than 22 Ma.

CONCLUSIONS

We conclude that the age of the oldest haematite in Hawkesbury Sandstone sampled on the Lapstone Monocline is Miocene (with an uncertainty of 7 Ma), and that the monocline had most probably formed by the mid-Miocene. The age of formation could, of course, be much older, given the unknown time gap between monoclinal folding and the introduction of the haematite into the sandstone beds. Thus data from the monocline itself confirm its antiquity and that of the Blue Mountains, which it borders. The results also imply that the Rickabys Creek Gravels, the palaeo-Nepean sediments that mantle the monocline, are probably older than mid-Miocene.

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