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^{14}C AGES AND MAGNETIC STRATIGRAPHY IN THREE AUSTRALIAN MAARS

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ABSTRACT. Detailed radiocarbon chronologies from three volcanic crater lakes (maars) in southeast Australia are examined in relationship to the magnetic mineral stratigraphies within lakes, and the magnetic secular variation stratigraphy between lakes. Some implications for magnetic dating are considered.

INTRODUCTION

On a time scale of millions of years reversals of the geomagnetic field preserved in geologic sequences have proved valuable as time-stratigraphic markers. Initial hopes that geomagnetic excursions would provide a similar global stratigraphy for the last few tens of thousands of years have yet to be fulfilled (Verosub and Banerjee, 1977). Two further classes of regional magnetic stratigraphy are relevant to Quaternary studies: 1) magnetic mineral contents, as measured by low field magnetic susceptibility, NRM, ARM, or IRM,[1] enable cores or exposures from a given sedimentary sequence to be correlated, and 2) under favorable circumstances, sequences of contrasting magneto-chemistry may simultaneously record the secular variation in the direction of the geomagnetic field.

Establishment of a secular variation stratigraphy is considerably more laborious as it is necessary to demonstrate that the directions of remanence in each sequence are controlled primarily by variations in direction of the earth's field. Further complications arise from the possibility of a time lag between deposition and the onset of a stable magnetic remanence, and from post-depositional diagenetic changes in magnetic minerals resulting in the acquisition of a chemical remanent magnetization.

Radiocarbon dating has assumed considerable importance in providing a time scale for palaeoecologic and palaeolimnologic studies. Nevertheless, our understanding of carbon exchange processes in lacustrine environments is still rudimentary, and most workers rely on internal consistency checks to validate their ^{14}C ages. Detailed radiocarbon chronologies are now available for the sediments in three neighboring lakes in southeastern Australia where it has been possible to establish precise within-lake magnetic mineral stratigraphies and a reliable magnetic secular variation stratigraphy between lakes. It is, thus, possible to test the reproducibility of ^{14}C age determinations for 1) given horizons at different parts of a single lake basin, and 2) sequences from different lakes which are palaeomagnetically contemporaneous.

Stuiver (1971) has used systematic departures from linearity in sedimentation rates in lakes scattered around the globe to infer trends in

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[1] NRM — natural remanent magnetization; ARM — anhysteretic remanent magnetization; IRM — isothermal remanent magnetization

the atmospheric ^{14}C budget. Such effects can be examined at a single site by using a dendrochronologic calibration scheme to transform radiocarbon years to calendar years. Provided there is no compensating mechanism matching atmospheric ^{14}C changes with climatically induced sedimentation rate changes, an improvement in apparent uniformity of sedimentation after age calibration is supporting evidence for the calibration scheme.

A more pertinent problem is the determination of atmospheric ^{14}C concentrations beyond the limit of reliable tree-ring data (~8000 years BP). Magnetic dating of lake sediments offers an alternative to the conflicting varve chronologies of Tauber (1970) and Stuiver (1970) for providing an independent time scale (Stuiver, 1978). As Stuiver pointed out, the weakness of this method lies in the assumption of a constant periodicity in cycles of declination or inclination changes. Although this does appear to be the case for the Lake Windermere (Mackereth, 1971) and Black Sea (Creer, 1974) records used by Stuiver, it has yet to be established as a global phenomenon. Sedimentary sequences commonly record strong oscillations in either declination or inclination, but not both, as would be predicted for most sites by a simple westward drift of the present nondipole field pattern. Furthermore, there is often a significant difference in the dominant declination and inclination periodicities. Attempts to model the magnetic secular variation during the past in terms of oscillating radial dipole sources within the earth's core (Creer, 1977) have met with some success, but suffer from a high degree of nonuniqueness due to the lack of data from a sufficiently wide geographic network of sites. If we accept that the longer period (1 to 3Ky)[2] secular variation is dominated by radial dipole sources, then the justification for the constant periodicity assumption inherent in the westward drift model must be abandoned.

This paper summarizes results relating to the above problems which are presented in detail by Barton, Bowler, and Polach (ms in preparation), on magnetic stratigraphy, properties and ^{14}C ages of the sediments, and Barton and McElhinny (ms in preparation) on magnetic secular variation results. Figures are taken or redrawn from these manuscripts. Radiocarbon ages are reported in years BP, *ie,* years before AD 1950, base on a half-life of 5568 years.

Lakes and sediments

The three maars studied in detail, Lake Keilambete, Lake Gnotuk, and Lake Bullenmerri, occupy steep-walled, flat-bottomed volcanic craters in the Newer Volcanics of western Victoria, approximately 100km west of Melbourne. Beneath a surficial cap of late Pliocene to Holocene olivine basalts and tuffs lies a Miocene limestone basement that outcrops at points around the sides of the lakes. Sets of cores were collected from each lake using 1½m, 6m, and 12m Mackereth corers.

The sediments are mostly dark brown to black organic muds, with typically 70 percent of the particles <2μm. Both the Keilambete and

[2] Ky — 10^3 years

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Gnotuk sequences terminate in a dense gray clay at about 4m that formed during the lake dry period from about 15,000 to 10,000 years BP. The Bullenmerri sequence continuously spans this period, but only the upper 6m (9000 yr) of the record is considered here. In Lakes Keilambete, Gnotuk, and Bullenmerri, salinities were 61350ppm, 59450ppm, and 8990ppm in 1977, organic carbon contents are typically 7 percent, 10 to 20 percent, and 20 to 40 percent, and carbonate contents are 20 percent, 12 percent, and 5 percent, respectively. The sediments retain high water contents: 70 to 80 percent by weight, 80 to 88 percent by volume. The Keilambete and Gnotuk sequences contain fine white aragonite laminae that can be traced in every core and provide precise stratigraphic markers. These are almost completely absent from the more homogeneous, less saline Bullenmerri sequence.

Magnetic stratigraphies

The Keilambete sequence yielded the most precise magnetic stratigraphy, illustrated in figure 1 for the horizontal component of NRM in four cores. Stratigraphies in the Bullenmerri and Gnotuk sequences were of nearly equal precision, though complicated in the case of the former by gaps within the cores caused by the expansion of gas pockets. In all three sequences, the variation with depth of low field susceptibility, ARM (imparted in a DC field of 0.05mT with a parallel exciting field of 100mT), or IRM (imparted in a DC field of 200mT) yielded a stratigraphy of comparable quality. In practice, NRM and susceptibility profiles were used for correlation, as these parameters are easier to measure than ARM or IRM. The results were in complete agreement with correlations based on visible features such as aragonite laminae.

Radiocarbon ages

Pre-existing total organic ^{14}C ages for the *Keilambete sequence* (Bowler and Hamada, 1971; Dodson, 1974) were augmented with six new determinations and are plotted in figure 2A as a function of equivalent depth in the master core for the sequence, KF. Figure 2B shows a similar plot after transforming from radiocarbon ages to calendar ages between 0 and 6500 years BP, using Clark's (1975) dendrochronologically based calibration scheme. To eliminate apparent sedimentation rate changes caused by varying compaction of the sediments, water contents and pore-water salinities were measured as a function of depth. They were then used to compute the overburden of dry sediment as a function of depth after correction for the weight of solids dissolved in the pore-water. The resulting curves (fig 2C, D) show that the step at 2500 years BP is partly due to sedimentologic changes, and partly to atmospheric ^{14}C changes implicit in the age calibration scheme. The curve passes through the origin within the uncertainty in the data.

A comprehensive set of dates for the *Bullenmerri sequence* were obtained with a view to determining the reliability of ^{14}C ages in this fairly typical, mildly saline lacustrine environment. Total organic fractions from 24 samples were dated. They were mostly from magnetically correlated horizons, in four cores spread across the lake. Before dating, some samples were split into 2 or 3 adjacent 5cm long fractions (fig 3). Since 5cm lengths of core correspond to an average time interval of 65 years, true ^{14}C ages for adjacent samples should agree well within the quoted one standard deviation counting errors. Out of the 11 adjacent pairs measured, agreement only happened 5 times, allowing for a 65-year difference. This implies that the quoted one standard deviation counting uncertainties are a poor indication of actual errors in the ^{14}C ages. At the two standard deviation level, the number of coincidences is still five. Outliers were classified according to the difference between their age and the mean age of the set of remaining adjacent plus magnetically correlated dates. Ages that show departures

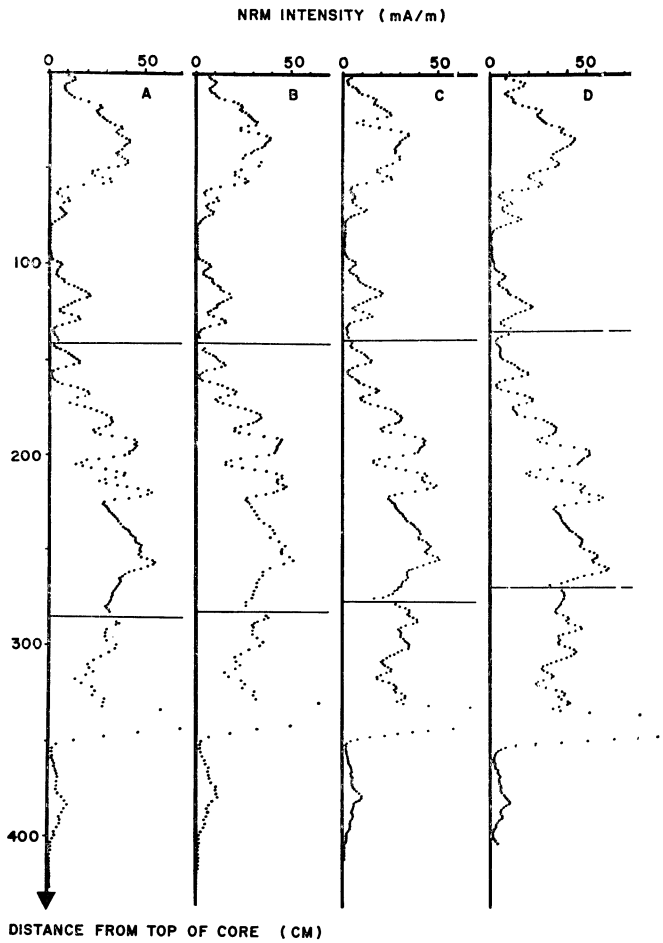

Fig 1. Horizontal component of NRM of 4 cores from Lake Keilambete collected along a radius from the center of the lake. Horizontal lines show where the cores were sectioned. All cores from the lake can be correlated with the same precision.

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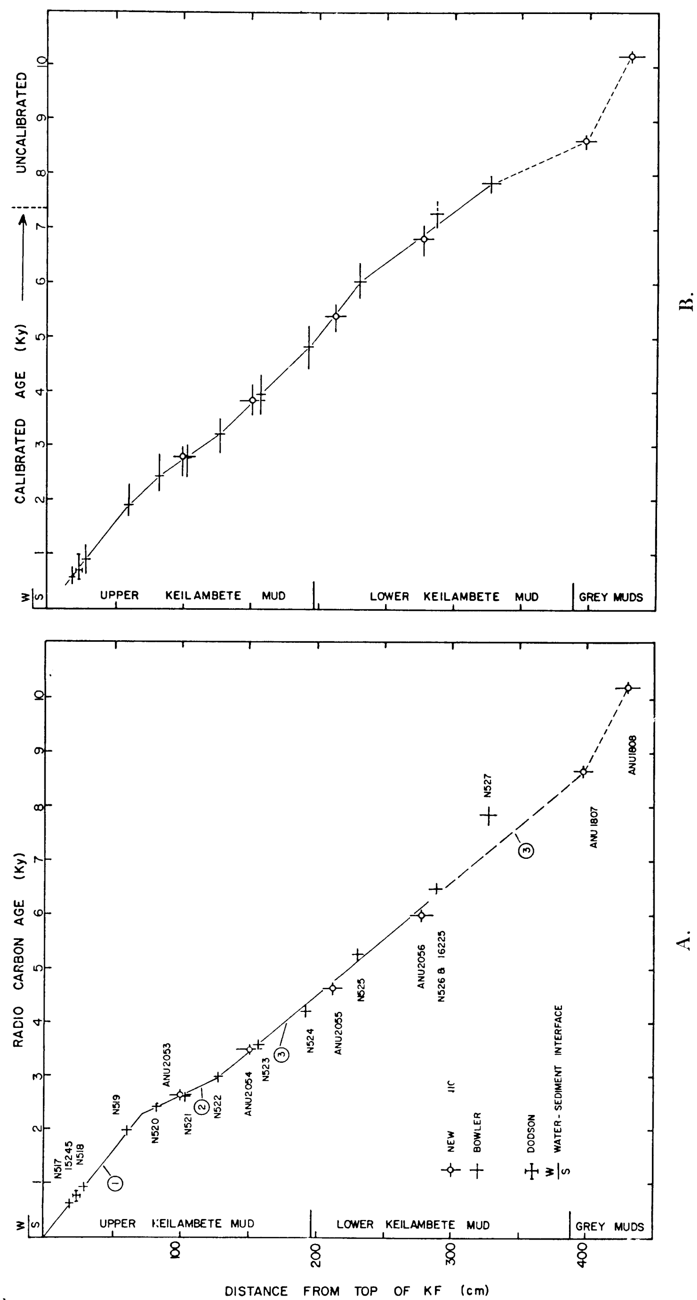

Fig 2

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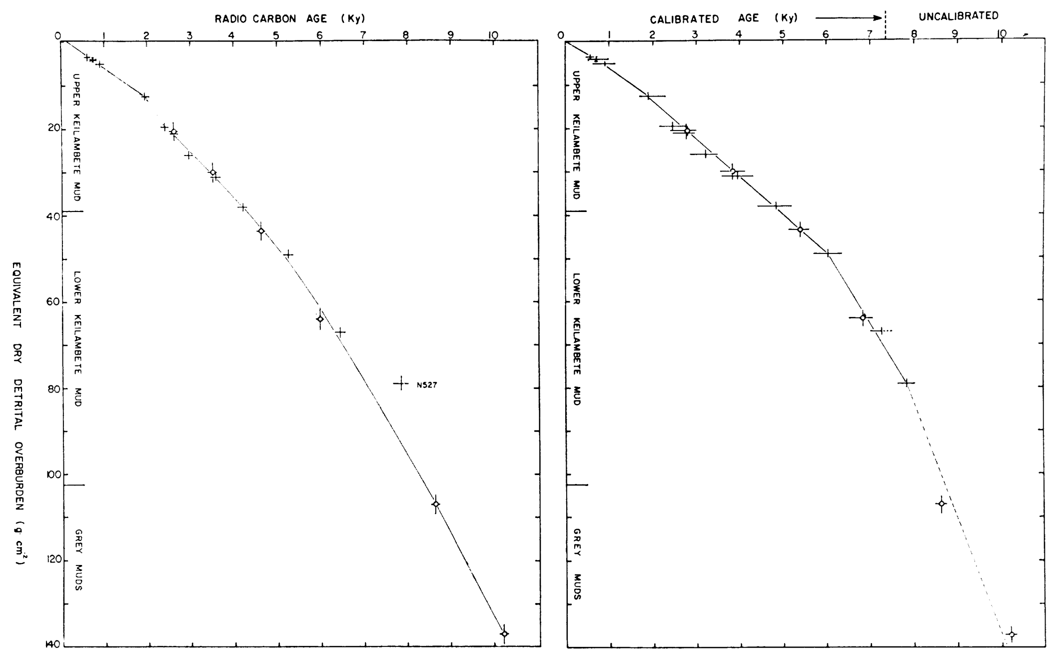

C. D.

Conventional and calibrated ^{14}C ages of total organic fractions from Lake Keilambete plotted against equivalent depths in master core KF (A, B), and against the overburden of dry detrital sediment (C, D). Ages from Bowler and Hamada (1971) and Dodson (1974) are included. Calibration is according to Clark (1975). Lines 1, 2, and 3 are linear regressions through three groups of points.

>20 percent are indicated by solid boxes in figure 3, and constitute 25 percent of the well correlated samples below a 70cm depth. An age-depth plot (omitting the 20 percent outliers) using equivalent depths in the master core, BJ, is shown figure 4. It includes three dates from the upper half of '12m' core BH and one from BJ. The dating coverage is not as good as for Lake Keilambete and does not resolve changes in sedimentation rate due to irregularities in the ^{14}C time scale. Time equivalents of uncertainties introduced by the depth correlation with core BJ can be ignored in comparison with the true dating uncertainties, so the scatter in ages beyond 6000 years BP must reflect problems in dating these older sediments. The water sediment interface is estimated to be 50cm above

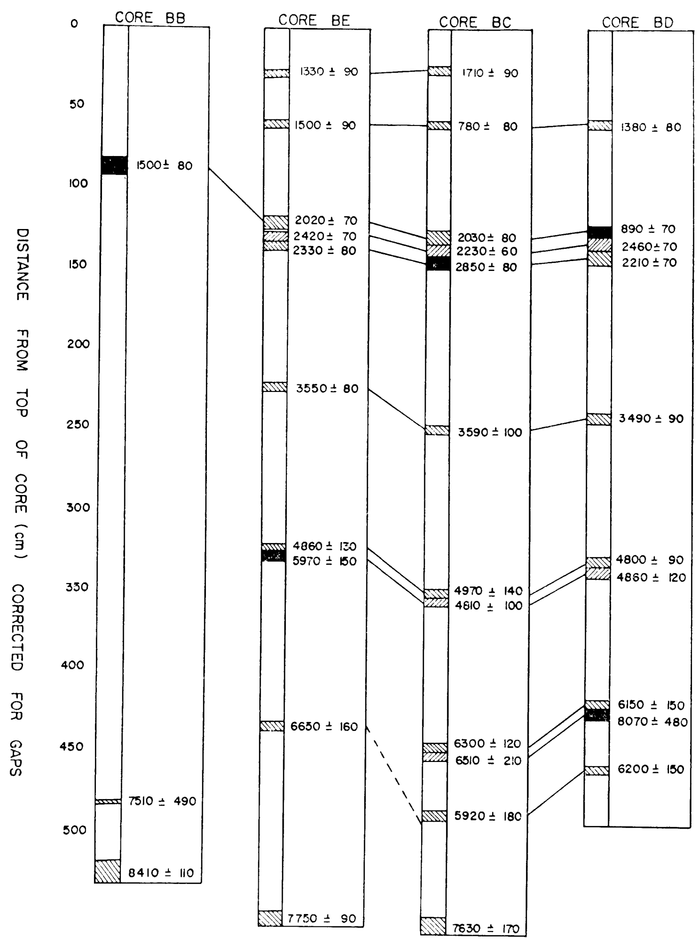

Fig 3. Distribution of, and magnetic correlation between ^{14}C dated samples from 4 cores from Lake Bullenmerri. Ages shown by solid rectangles differ by more than 20 percent from the mean of the remaining block of adjacent plus magnetically correlated samples. Solid/dashed bars indicate a good/tentative correlation.

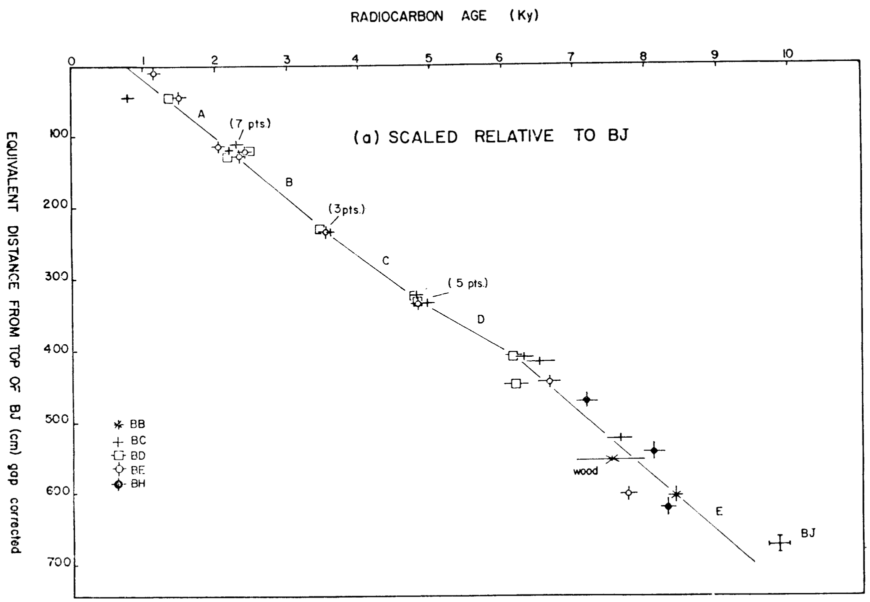

Fig 4. Conventional ^{14}C age-depth plot for the Bullenmerri sequence. Depths are expressed as equivalents from the top of master core BJ after correction for gaps within the cores.

the top of core BJ, and is, therefore, intersected by regression line A at an age of 200 years.

The *Lake Gnotuk* ^{14}*C chronology* (fig 5) combines 4 total organic dates from Yezdani (ms) with 4 new ones from the ANU laboratory. Though less comprehensive than the Keilambete and Bullenmerri chronologies, it shows a high degree of linearity, but does not cover sufficiently young ages to reveal a step around 2500 years BP. A linear regression through the ANU data intercepts the inferred position of the water-sediment interface at 295 years BP. As there are no ages younger than 3500 years BP, this value may not be reliable.

Magnetic secular variation results

After AF[3] cleaning to remove secondary (viscous) components of magnetization, NRM's of sets of cores from each lake were measured using a superconducting magnetometer (Goree and Fuller, 1976). Depth scales were transformed to that of a master core for each sequence by linear interpolation between a large number of tie points based on visual and magnetic mineral stratigraphies. The data from 6 long (nominally 6m) and 2 short (1½m) cores from Lake Keilambete, 8 long and 2 short cores from Lake Bullenmerri, and 3 long cores from Lake Gnotuk, were subjected to a filtering routine to remove spurious data, then stacked to obtain a composite secular variation record for each sequence. Piece-wise linear (least squares) fits to the ^{14}C age-depth plots were used as a

[3] AF — alternating magnetic field

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basis for transforming from depth to ^{14}C time scales. Smoothing was accomplished by ranking the data within 100-year intervals, discarding the upper and lower 25 percent of points, and taking the mean of the remaining 50 percent per interval. This technique is highly insensitive to large random fluctuations in the data. Values obtained by using the median point per 100-year interval were found to differ only slightly from those obtained by the above method.

Inclination and declination 100-year means for the three lakes are compared in figure 6. Well-defined oscillations are present in the inclination records that correlate well between lakes, apart from the 2500 to 3500 years BP section for Lake Gnotuk. This section coincides with a zone of low NRM intensity and poor magnetic stability. Declination profiles are relatively flat and are correspondingly difficult to correlate.

SUMMARY AND DISCUSSION

Radiocarbon ages for total organic fractions from the two highly saline lakes, Keilambete and Gnotuk, exhibit a high degree of internal consistency which is not matched by that for the less saline, more organic rich Bullenmerri sequence. In the latter, we find a 25 percent probability of a particular ^{14}C age being in error by more than 20 percent. This provides empirical justification for discounting ages that imply improbable (or impossible) sedimentation rates, and illustrates the dangers of

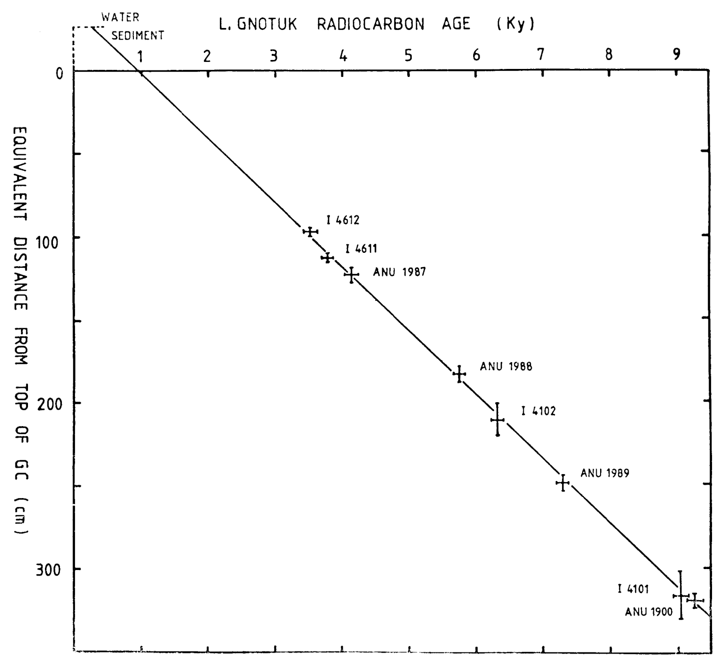

Fig 5. Conventional ^{14}C age-depth plot for the Gnotuk sequence. Depths are expressed as equivalents from the top of master core GC. Sample numbers prefixed by I are from Yezdani (1970).

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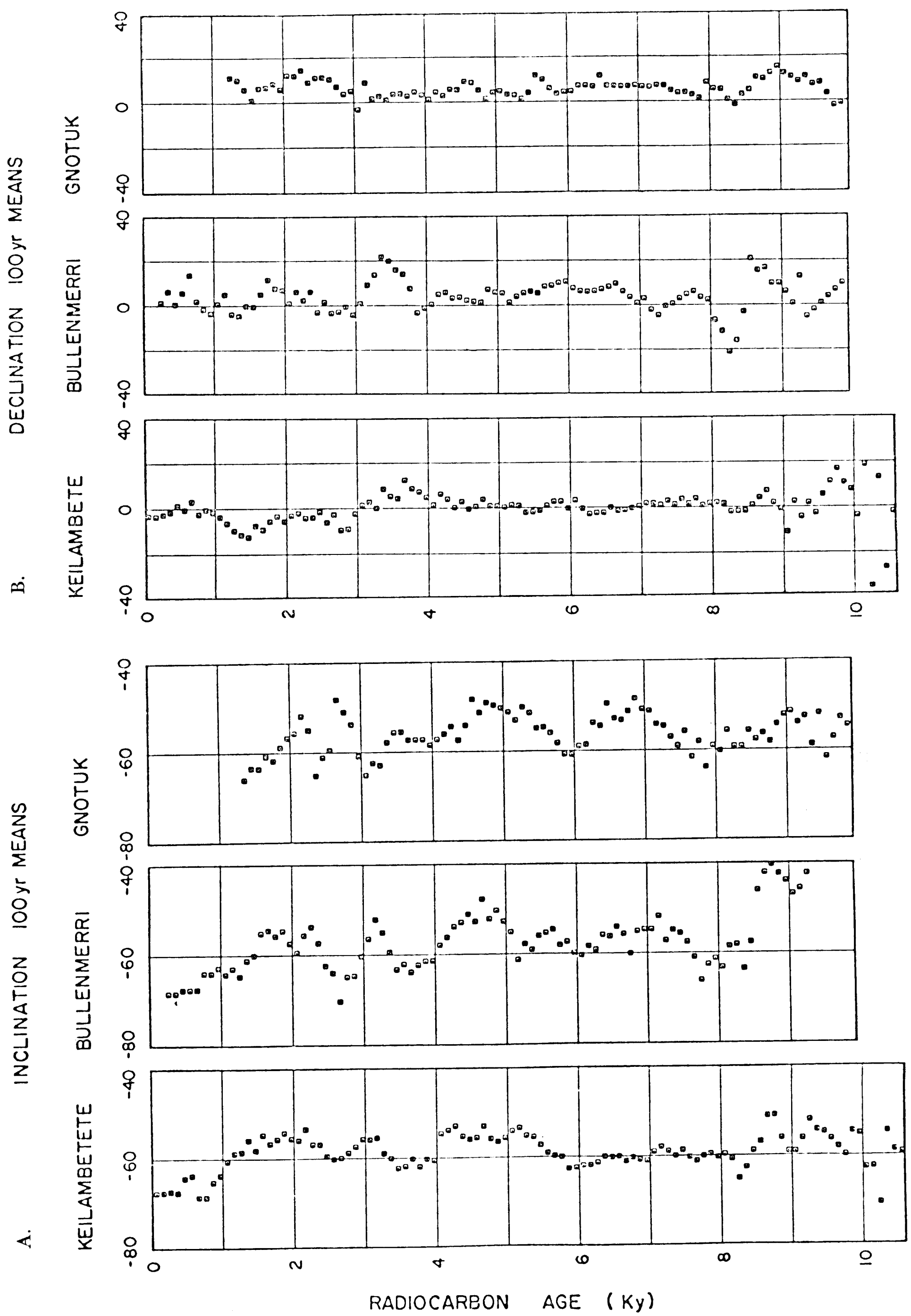

Fig 6. (A) inclination and (B) declination 100-year interval means.

dating individual horizons by spot ^{14}C determinations rather than by establishing a sedimentation rate curve from a set of dates. There is a strong case for dating at least two samples per horizon as a standard procedure in lacustrine work.

Sedimentation rate curves for each of the three sequences extrapolate to near the origin, giving apparent ages at the water-sediment interface of always less than 300 years, and probably less than 200 years. This indicates the absence of any systematic increase in ^{14}C ages due to the assimilation of ancient carbon (from the limestone basement, eg) into the organic content of the sediments. We note that the test fails to detect any such 'limestone dilution' effect that occurred in the past but has now ceased to be of importance. Nevertheless, it is reasonable to treat the measured ^{14}C ages as valid measures of the age of deposition of the sediments.

In view of the large quantity of data on which the secular variation 100-year means are based, we consider the correlation between lakes, notable for inclinations, to be definitive proof that directions of remanence in the sediments are controlled by the past geomagnetic field. The secular variation pattern observed is the converse of that deduced from the Lake Windermere sediments (Mackereth, 1971) which shows strong declination and weak inclination oscillations. The implications of this contrast are beyond the scope of this paper. We note, however, that the dominant inclination swings in southeastern Australia do not have a constant period and, therefore, cannot be extrapolated beyond the range of the data for magnetic dating purposes (see Stuiver, 1978). On the other hand, the characteristic morphology of the inclination swings helps to eliminate the ambiguity inherent in using sinusoidal magnetic oscillations as a reference base for dating.

We cannot be sure that the amplitude of the geomagnetic signal is faithfully recorded by these sediments. If partial remagnetization occurs gradually over periods of many thousands of years (*ie,* longer than the dominant periods in the secular variation) then attenuation of the recorded signal will occur as an increasing function of age (depth). Both the results from southeastern Australia and from Lake Windermere display such attenuation. Until suitable archaeomagnetic data or palaeomagnetic measurements on lava flows are available, it will not be possible to decide if this effect is a real characteristic of the geomagnetic field.

Relative displacement of the secular variation pattern between lakes could arise from either a differential in the delay between deposition and the onset of stable remanence, or from systematic displacements of ^{14}C ages that do not affect the lakes equally. Due to the large salinity contrast between Lake Bullenmerri and the other two lakes, it seems unlikely that a common shift in apparent ^{14}C ages could occur. Laboratory redeposition studies (Barton and McElhinny, 1979; Barton, McElhinny, and Edwards, 1980) show that stable depositional remanence is acquired by these sediments within 1 or 2 days after deposition, although such measurements are not capable of detecting long-term post-depositional remagnetization. Comparisons between historical observations of the magnetic field and archaeomagnetic data, and secular variation patterns recorded in short cores from the three lakes (which, unlike 6m cores, recover the upper sediments in a relatively undisturbed condition) indicate that any lag between deposition and acquisition of the observed NRM must be less than about 300 years. This result is only tentative due to the brevity of the historical record and the paucity of archaeomagnetic data.

If the inclination curves for the three lakes are superimposed, the age displacements (gauged by eye) which result in an optimum fit of consecutive 1000-year lengths of records are always <200 years and are often zero (except for the unstable Gnotuk section at 2500 to 3500 years BP). These shifts are of the same order as the uncertainty in the ^{14}C age determinations. Assuming that delays in the onset of stable remanence and systematic shifts in ^{14}C ages are not mutually self-cancelling, then the above result sets a limit of about 200 years on the differential between the three sequences in any lag between deposition and acquisition of the NRM. We conclude that the ^{14}C ages of total organic fractions from sediments from each of the lakes are a good measure of ages of deposition.

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