Palaeont. afr., **23**, 35–40 (1980)

AN OVERVIEW OF PALAEOMAGNETIC CHRONOLOGY WITH SPECIAL REFERENCE TO THE SOUTH AFRICAN HOMINID SITES

by

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ABSTRACT

The phenomena of secular variation, polarity reversals and apparent polar wander are discussed. The calibration of each of these phenomena for use in palaeomagnetic chronology is outlined and the use of each of these calibrated scales for dating is briefly explained. A successful application of the polarity reversal dating technique is presented as an example of the potential for palaeomagnetic chronology in South Africa. In this example it is shown that the age of the important Member 3 in Makapan is about 3 My. It is concluded that palaeomagnetic chronology has a vast potential in South Africa; a palaeomagnetic laboratory specifically oriented to chronological problems would be extremely valuable.

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INTRODUCTION

In the study of fossils it is extremely important to know the age of specimens so that temporal relations between specimens, particularly from different localities, can be determined. To this end it is necessary to have available a wide range of dating techniques. For any system to be used as a dating tool there must exist some phenomenon which alters with time, causing a measurable change within the system. If the temporally correlated phenomenon is inherent to the system, proceeds in a uniform direction with time and occurs at a known rate, then the system may be used as an absolute dating tool. The most widely used example is radioactive decay, resulting in radiometric geochronology. If, however, the temporally correlated phenomenon is external to the system (the system now acting solely as a recording device) and proceeds at a randomly varying rate, then the system cannot be used as an absolute dating tool but must be considered as a correlative dating technique. Evidently optimum value from a correlative technique is obtained only after calibration with respect to an absolute dating technique. Examples of this are faunal correlation and palaeomagnetic chronology. For faunal correlation the external temporally correlated phenomenon is morphological change occurring in animals as it appears in the fossil record. For palaeomagnetic chronology the phenomenon is change in the earth's observable magnetic field which is recorded magnetically by the rock.

Disadvantages of correlative techniques

Frequently the correlative phenomenon used does not alter smoothly or continuously but radomly and often discontinuously. For example, with faunal correlation the morphology of a given animal may remain constant for an extended period of time and then alter rapidly and significantly to another stable form. Thus, on a given correlative scale it may be impossible to distinguish two points in time which may in fact be quite widely separated, owing to the lack of any change in the measured parameters of the system during the time interval.

Calibration of a correlative scale can only be performed at a finite and frequently small number of points, thereby producing the problem of interpolation. For a discontinuous alteration it is frequently impossible to interpolate, and, even when a continuous alteration exists, because the alteration is external to the system, the actual point of calibration may not have been recorded in the system. Further, the recording of a calibrated event does not ensure its observation in sampling.

Finally, the state of the event being calibrated may not be unique to that particular point in time. For instance, the direction of the earth's magnetic field may return to a specific direction on several different occasions. Great care must therefore be taken to avoid errors resulting from such ambiguities.

Advantages of correlative techniques

Although the advantages of correlative techniques are few, they are of vital importance. The obvious advantage is that they often allow the extension of chronological investigation to systems which are not amenable to absolute methods and which would otherwise remain undated. Occasionally vast amounts of data can be used to determine the calibration of a point on a correlative scale with a far greater precision than is possible with a single absolute reading. Further, since several types of absolute techniques may sometimes be brought to bear in calibrating a point on a correlative scale, the accuracy of the age of the calibrated point may be known with greater reliability than is possible with a single absolute method.

PALAEOMAGNETIC CHRONOLOGY

In palaeomagnetic chronology use is made of changes in the earth's observable magnetic field. The most useful changing parameter is the direction although for the very recent past the intensity is sometimes used. In this paper discussion will be restricted to the use of changes in direction. Tarling (1971), McElhinny (1973) and Brock (1977) are all useful references.

Geomagnetic observations from all parts of the world have been subjected to spherical harmonic analysis. This has shown that the observable field can be represented by hypothetical multi-poles at the geocentre. The first is called the *inclined geocentric dipole* which at present makes an angle of about 11½° with the spin axis. This inclined geocentric dipole may be resolved into three components; the largest along the rotational axis called the *geocentric axial dipole* and two of much smaller magnitude in the equatorial plane. The higher harmonics constitute the *non-dipole field*. With the passage of time the non-dipole field drifts and the orientation of the inclined geocentric dipole wanders. This gives rise to the phenomenon of *secular variation* which is observed on the surface of the earth as a gradual alteration in the direction of the magnetic field. Owing to the presence of the non-dipole field, the rate and direction of change at one point on the earth's surface may be very different from the change at another locality even if the localities are quite close together. Over a period of some tens of thousands of years the various components of the magnetic field average out to give a geocentric axial dipole. As a result of palaeomagnetic investigations it has been discovered that at irregular intervals the geocentric axial dipole component actually reverses its direction, giving rise to the phenomenon of *polarity reversals*.

These two distinct types of change in the direction of the earth's magnetic field plus the existence of slow tectonic processes within the earth give rise to three phenomena — secular variation, polarity reversals and *apparent polar wander* — each of which may be calibrated for chronological purposes.

Secular variation

The magnetic direction is defined by two angles, the *declination* and the *inclination*. Declination is the angle measured in a horizontal plane between true north and magnetic north. Inclination is the angle between the direction of the magnetic field and the horizontal, measured in the vertical plane. Both of these angles must be calibrated, and in a few places direct instrumental observations of the earth's field have been made over a period of several hundred years, thus providing the initial part of the curve. In the Cape direct observation records exist from as far back as 1595, and a comprehensive list was published by Beattie (1909). For areas in which historical readings are not available, and in any case for the period before direct observation, carbon-dated material has to be used to construct the calibration curve. Evidently, therefore, the secular variation method can only be used back to about 2 000 years B.P. The main field of application is consequently archaeomagnetism, a good review of which is given by Aitken (1970).

Secular variation is essentially a local phenomenon, and a given calibration curve thus provides only very limited coverage of the earth's surface. For example, a calibration curve for Cape Town cannot be used for a study in the Johannesburg vicinity. Herein lies the main problem with use of the secular variation model, since individual studies frequently require their own calibration curve.

Polarity reversals

As a result of careful magnetic measurements over oceanic ridges, of recent lavas and within sedimentary ocean cores, it is now a well documented fact that at irregular intervals the geocentric axial dipole component reverses its direction. The present direction is referred to as *normal* and the opposite as *reversed*. This change takes place without any other significant change. Naturally, when performing a polarity study, the effect of secular variation is observable but rarely useful. The polarity reversal phenomenon is global, that is, when a *reversal* occurs, it is experienced at all points on the earth's surface. Thus data may be collected from all over the world in order to calibrate a single scale with global application. This is, of course, in contradistinction to the locality restriction of a secular variation calibration. Since reversals are faithfully recorded in lavas which may be dated accurately by radiometric techniques, it is possible to calibrate a reversal scale accurately. Further, because the data may be collected worldwide, an extremely large number of data is available, allowing the use of statistical techniques which date the actual reversals themselves with far greater precision than is possible with a single radiometric measurement. This was done by Cox (1969) who drew up a calibrated polarity timescale extending back to 4,5 My and more recently by Mankinen and Dalrymple (1979). The frequency at which reversals occur is very variable and fairly high (23 reversals in the last 4,5 My) These two facts make the phenomenon of polarity reversal useful as a dating tool. However, because of this fairly high reversal rate, for older rocks the imprecision in absolute dates becomes greater than the time between reversals. It thus becomes impossible to calibrate the reversals as distinct events with correct temporal relation. Hence there will always be a limit consequent on the precision of absolute dating methods beyond which reliable calibration of the reversal scale will not be possible. The reversal pattern is now fairly well known for the past 20 My and well known for the past 5 My.

The earth's field has remained essentially normal over the past 0,69 My, and so reversal dating is not possible for rocks younger than this. Noel and Tarling (1975) and Barbetti and McElhinny (1976) have summarized the evidence for a number of very brief excursions in the Brunhes normal epoch (0,69 My to present) during which the earth's field was either reversed or very strongly displaced from its normal direction. These excursions are real, but it remains possible that they are regional rather than global phenomena. Further, because of their briefness, they may easily be missed in sampling. Much more work is needed before they can become an agreed part of the timescale and be used as a correlation tool.

Apparent polar wander

The phenomenon of apparent polar wander is caused by tectonic processes within the earth, not by changes in the earth's magnetic field. It is referred to as apparent because it is actually the continents which move, relative to the spin axis, over the surface of the earth. Thus, from the point of view of the continent the spin axis (and therefore the direction of the earth's magnetic field) appears to move. This observed variation for a continent may be calibrated against radiometric dates and then used as a dating scale for that particular continent. Evidently, when performing an apparent polar wander study, the phenomena of polarity reversal and secular variation are observable.

The apparent variation in direction of the magnetic field resulting from continental drift is usually measurable only over periods of the order of tens of millions of years. In addition, for the past 5 or 10 My, the continents have remained essentially in their present positions. Thus, although apparent polar wander is valuable in the dating of old rocks, it is of little or no value in the dating of recent material.

USE OF THE CALIBRATED SCALES

Unfortunately the magnetization processes within a rock do not terminate subsequent to formation of a sedimentary rock or initial cooling of an igneous rock. Thus, the observed magnetization in a rock specimen is usually the resultant of the original plus several secondary magnetizations. Owing to the processes by which a rock acquires its magnetization, it is usually the case that the original magnetization is the most stable and most difficult to remove. Thus, it is frequently possible through careful analysis of a specimen's magnetization in conjunction with all other available information to elucidate the original direction of magnetization. Evidently it is only this direction of magnetization that can be used to date the time of formation or intrusion of the rock, and great care must be taken in any study to ensure that this direction has been obtained.

Since it is a direction which is of interest, careful orientation of each specimen must be performed. Owing to the existence of secular variation and, in particular, the non-dipole field, orientation with respect to the earth's magnetic field is a questionable process. This is further complicated by the extremely localized anomaly in the magnetic field caused by the presence of one's own sampling equipment and other pieces of stray iron. Thus orientation should be performed solely with respect to the earth's spin axis. This process can complicate sampling, particularly when working underground or in caves, since the sun is not visible. However, in the interest of reliable results absolute orientation should be performed.

Secular variation dating

In arachaeomagnetism in particular there may be an extremely small number of specimens available. Thus one often cannot fall back upon statistical techniqes to obtain high precision and to average out errors for the obtaining of accuracy. High precision and accuracy are therefore required in each measurement for a secular variation study. However, since secular variation is a continuous phenomenon occurring fairly smoothly and which, particularly for very recent times, often possesses a one-to-one relation between direction and age, it is possible to obtain a date for a single specimen.

As already mentioned, in a secular variation study the material of interest is frequently of an archaeological rather than a geological nature. Baked or heated material, such as earth, fireplaces and hearths, acquires magnetization in the direction of the earth's magnetic field as it cools. Having obtained a reliable calibration curve for the locality, it is then possible to determine an age for the last heating of the material. Since it is the date of the last thorough heating that is obtained, the effect of intense bush fires must be considered, particularly for surface material.

Polarity reversal dating

Polarity reversal is a discontinuous phenomenon with only two stable states. Clearly, neither of these states is unique to a particular point in time, and it is thus impossible to date a single specimen. Hence, to obtain a date, it is necessary to make magnetic measurements on a large number of samples from an accurately known stratigraphical section, determine the recorded polarity pattern within this section and compare it with the calibrated reversal scale. In theory this is simple, but in practice it is extremely difficult. Three main difficulties exist: (i) determining the stratigraphy, (ii) obtaining the samples, and (iii) interpreting the polarity pattern.

In many studies neither the stratigraphy nor the sampling present serious problems. However, this has not been the case with the South African hominid sites. Determining the stratigraphy of a formation which constitutes the filling of a solution cavity is a complex problem. Since accurate knowledge of the stratigraphy is central to the reversal dating method, this problem has to be solved before even considering palaeomagnetic sampling. The simplest sample to orient precisely is a straight core, obtained by pushing a rotating diamond-tipped cylinder (driven by a heavy petrol motor) into the rock face. Sampling in the hominid sites required that this feat be performed on a vertical face several metres above ground level. Obtaining a straight, unbroken core under these conditions is by no means an easy task and without the suicidal tendencies of Professor Dai Jones (University of Zimbabwe) and the mountaineering skills of Dr Dick Metcalfe (National University of Lesotho) several of the crucial samples would have remained right where they were, in the rock!

Having determined the original direction of magnetization in an oriented specimen, it is then possible, using the known stratigraphy and sampling scheme, to draw up the original polarity pattern in the rock formation. The remaining problem is that of interpretation which is frequently very difficult.

The two major interpretation problems are of a geologic nature. The sedimentation rate both within and between members is not constant, and so equal thicknesses of sediment do not necessarily represent equal time intervals. This causes a distortion of the observed polarity pattern relative to the calibrated scale (fig. 1). An even greater problem is that of unconformities which represent breaks in the original record. These breaks produce further ambiguities in the interpretation which can lead to totally incorrect conclusions unless great care is taken. These two problems generally impose the constraint that other information must be used to locate the observed polarity pattern correctly with respect to the calibrated scale, that is, to obtain accuracy. The palaeomagnetic chronology then gives the dates at the horizons where reversals are observed to occur with high precision. It is then necessary to interpolate roughly between these horizons to obtain the age of any other horizon.

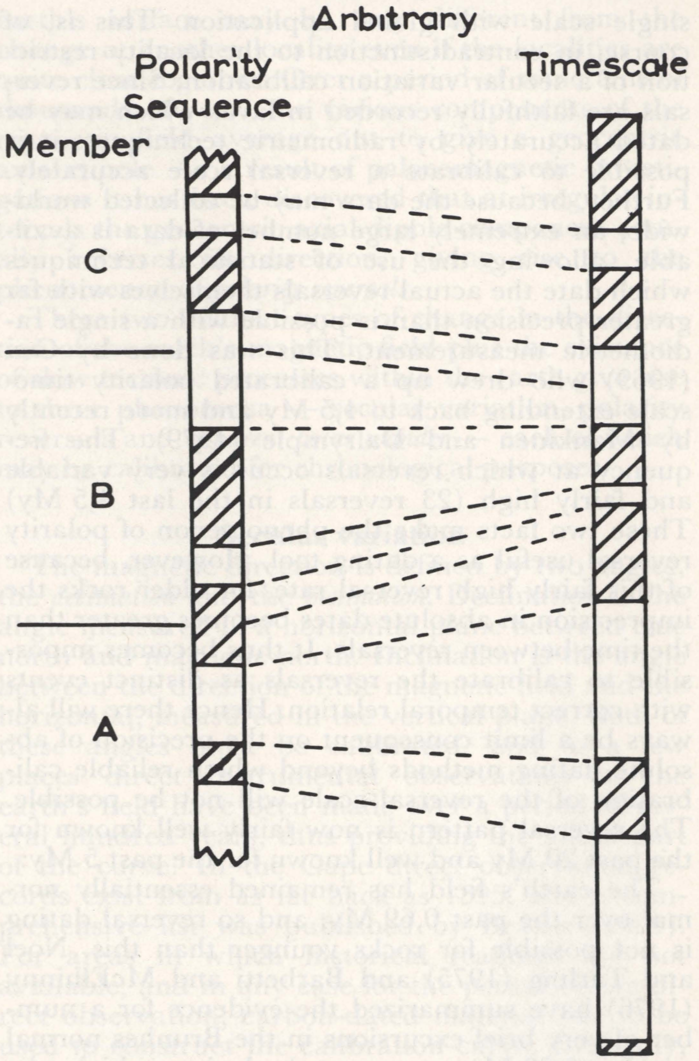

Figure 1. Distortion of observed polarity pattern resulting from variability in deposition rates.

It is important to note that it is not the fossils themselves which are dated but the time of formation of the rock in which the fossils are found. However, since the bones were included in the rock at the time of its formation, it is not unreasonable to apply the deduced age to the fossils themselves.

Apparent polar wander dating

The phenomenon of apparent polar wander occurs over periods of the order of several millions of years. The time-scale is thus one in which the time divisions are essentially of the order of several millions of years. Hence the time of formation of a rock unit, even though it may be large, may usually be considered as representing a single point on the time-scale. Statistical techniques can be used to obtain accuracy and high precision. Having obtained the apparent position of the pole relative to the rock unit at the time of its formation, it is then a simple matter to interpolate the age from the calibrated apparent polar wander path for that continent. This interpolation quite evidently lacks precision.

THE SOUTH AFRICAN HOMINID SITES

Four sites have been studied: Swartkrans, Sterkfontein, Kromdraai and Makapan. Swartkrans, Sterkfontein and Kromdraai are very close to each other and have all, regrettably, given inconsistent results. In contrast, Makapan has yielded very good results. This almost certainly relates to the conditions of sedimentation at the different localities, the conditions at the three unsuccessful sites being very similar.

The Makapan stratigraphy has been described by Partridge (1979), and it is on the basis of his stratigraphy that the polarity pattern has been constructed. Despite the difficulties of sampling, sufficient samples were obtained to permit elucidation of the age of the deposits. The lowest member (Member 1) is thin and exposed at ground level. Sampling was therefore simple and thorough. Member 2 is a thick (2 to 10 m), water laid sediment, sedimentation occurring pene-contemporaneously in two apparently separate depositories. Sampling in this member was not simple, but extensive coverage was obtained. The important Member 3 was not sampled because such sampling would necessarily have damaged many fossils, and from the appearance of the rock it was decided that useful results would probably not be obtained. The relation between Members 2 and 3 is unconformable. In most parts of the cave Member 4 unconformably overlies Member 2, and only in a small section can it be seen to overlie remnants of Member 3. It is a thick (3 to 15 m) deposit containing angular chert and dolomite fragments. The frequency of occurrence and size of these fragments increases upwards within the member to the point where it was not possible to obtain a useful palaeomagnetic sample of the matrix in the upper half of the member. However, the lower half was sampled quite extensively. The relationship between Member 4 and the uppermost member (Member 5) is clearly unconformable and may represent a considerable lapse of time. The whole of this member was extensively sampled.

The Makapan polarity pattern

Member 1 was entirely reversed and Member 2 was entirely normal apart from a polarity transition right at the base. Then follows a break in the record as a result of the lack of sampling in Member 3 and the unconformities between Members 2, 3 and 4. The base of Member 4 is normal, followed by a distinct reversal very low in the member. This is followed by another normal period and then another reversal at the highest point at which it was possible to sample. Unfortunately the rock type of Member 5 was magnetically unstable, so no useful temporal information could be obtained from this member.

Interpretation

The observed polarity pattern could be fit to Cox's (1969) time-scale without reference to other information. There are in fact two simple fits leading to two interpretations which are very little different from each other. A full description of the Makapan analysis is given in Brock *et al.* (1977) and McFadden *et al.* (1979).

Clearly most of the section is normally magnetized and thus most probably dates from a normal epoch containing at least two reversed events. This effectively identifies the normal portions as being within the Gauss normal epoch (fig 2). The observed polarity pattern is most simply related to

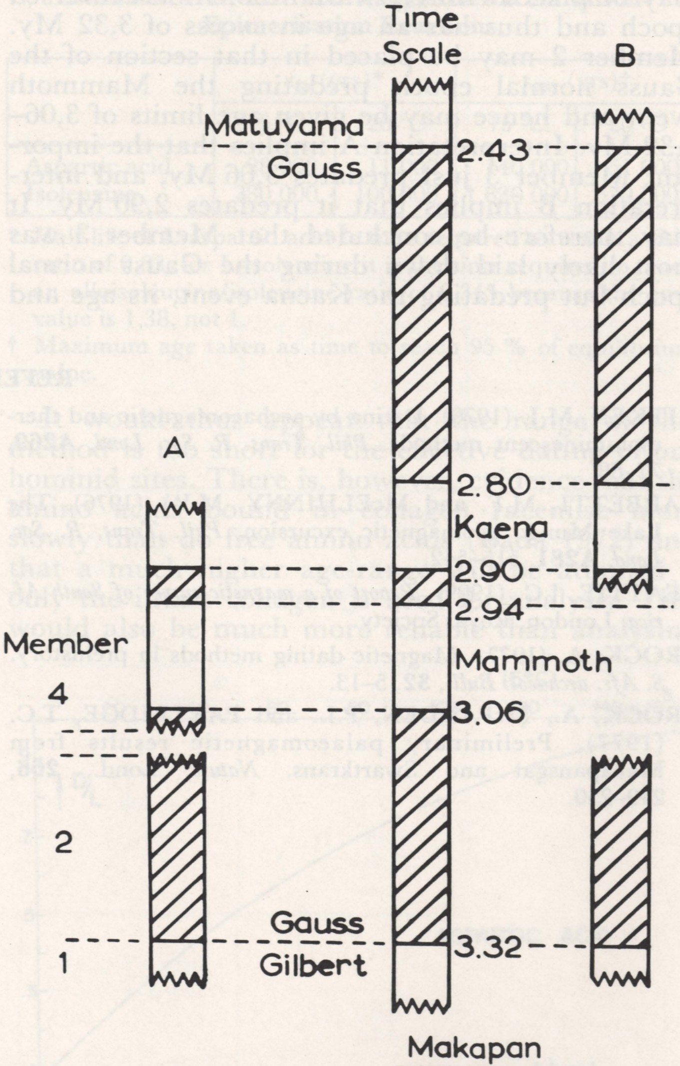

Figure 2. Comparison of the observed polarity pattern in the Makapan formation with a portion of the polarity reversal scale of Cox (1969). The dates are in millions of years (My) and the cross-hatched sections indicate normal polarity of the earth's magnetic field.

the polarity time-scale by postulating that the reversed Member 1 lies within the last period of the Gilbert reversed epoch. The transition low in Member 2 then corresponds to that between the Gilbert and Gauss epochs at 3,32 My and the remainder of Member 2 lies entirely within that section of the Gauss epoch predating the reversed Mammoth event.

The simplest interpretation (A of fig. 2) of the Member 4 pattern is that the two reversed zones represent the Mammoth and Kaena events within the Gauss normal epoch. However, the break in the record also allows interpretation B (fig. 2). The reversal low in Member 4 would then be the Kaena event, and the upper transition from normal to reversed would be the transition from the Gauss normal to the Matuyama reversed epoch.

Age conclusions

Fairly definite conclusions may be drawn regarding the ages of Members 1 and 2. Member 1 may be placed entirely within the Gilbert reversed epoch and thus has an age in excess of 3,32 My. Member 2 may be placed in that section of the Gauss normal epoch predating the Mammoth event and hence may be given age limits of 3,06–3,32 My. Interpretation A implies that the important Member 3 just predates 3,06 My, and interpretation B implies that it predates 2,90 My. It may therefore be concluded that Member 3 was most likely laid down during the Gauss normal epoch but predating the Kaena event, its age and therefore that of the fossils it contains being about 3 My.

CONCLUSIONS

Palaeomagnetic chronology falls into three distinct methods — secular variation, polarity reversals and apparent polar wander. Apparent polar wander is an extremely useful phenomenon in the dating of old formations but is of no value for recent formations. Polarity reversal dating finds extensive use for recent formations whose age extends beyond 0,69 My. At present the useful range is limited to 5 My, but if the precision of absolute dating methods can be improved, this limit may eventually be pushed back quite substantially. The technique has been used successfully on the Makapan hominid deposits, yielding the age of the important Member 3 as about 3 My. The secular variation method is applicable to very recent material (approximately the last 2 000 years), especially that of an archaeological nature. However, for secular variation to be useful in any specific locality much work is needed for the production of the necessary calibration curve.

In South Africa a vast amount of important chronological investigation is necessary in all three of the time domains covered by palaeomagnetic chronology. Thus a palaeomagnetic laboratory, specifically oriented to chronological problems, would be assured of a long and extremely useful existence.

REFERENCES

AITKEN, M.J. (1970). Dating by archaeomagnetic and thermoluminescent methods. *Phil. Trans. R. Soc. Lond.* **A269**, 77–88.

BARBETTI, M.F. and McELHINNY M.W. (1976). The Lake Mungo geomagnetic excursion. *Phil. Trans. R. Soc. Lond.* **A281**, 515–542.

BEATTIE, J.C. (1909). *Report of a magnetic survey of South Africa.* London, Royal Society.

BROCK, A. (1977). Magnetic dating methods in prehistory. *S. Afr. archaeol. Bull.*, **32**, 5–13.

BROCK, A., McFADDEN, P.L. and PARTRIDGE, T.C. (1977). Preliminary palaeomagnetic results from Makapansgat and Swartkrans. *Nature,* Lond., **266**, 249–250.

MANKINEN, E.A. and DALRYMPLE, G.B. (1979). Revised K-Ar polarity time scale for the interval 0–5 m.y. B.P. *J. geophys. Res.*, **84**, 615–626.

McELHINNY, M.W. (1973). *Palaeomagnetism and plate tectonics.* Cambridge University Press.

McFADDEN, P.L., BROCK, A. and PARTRIDGE, T.C. (1979). Palaeomagnetism and the age of the Makapansgat hominid site. *Earth Planet. Sci. Lett.*, **44,** 373–382.

NOEL, M. and TARLING, D.H. (1975). The Laschamp geomagnetic "event". *Nature*, Lond., **253**, 705–707.

PARTRIDGE, T.C. (1979). Reappraisal of the lithostratigraphy of Makapansgat Limeworks hominid site, *Nature*, Lond., **279**, 484–488.

TARLING, D.H. (1971). *Principles and applications of palaeomagnetism.* London, Chapman and Hall.