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PALAEOMAGNETIC DATING OF WEATHERED PROFILES

by

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CHAPTER VIII

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INTRODUCTION

The ages of laterites are of considerable importance for omorphic studies. They define the lower limits of antiquity laterite-capped land surfaces, and provide time markers for the evolutionary history of landscapes in regions where veral laterites coexist at different altitudes. Laterite ages may used to compare landform developments between widely separated regions, and in conjunction with other techniques such as palynology and K-Ar dating of basalts, would help to velop a framework for stratigraphic correlation of continental sediments. The ages may also be used to link lateritisation processes to environmental conditions, such as mate or tectonism, so that the dominant factors in laterite nesis can be identified.

The development of quantitative techniques for dating terites has lagged well behind the needs. This is attributable largely to technical difficulties of working on authigenic minerals that are almost invariably very fine grained, and nstitute open systems. It is also not always clear what stage the lateritisation process would be dated: the onset, termination or some intermediate stage. Of the possible methods, ting by fission particle track replication has been used ccessfully on authigenic micas in a Pliocene soil profile of Antarctica (Jackson *et al.*, 1977). Jackson *et al.* suggest that thigenic micas may be found more generally in confined il environments such as in saprolites, and that the method could therefore be used for other soils. Another techniques thermoluminescence dating, is currently being evaluated on eathered profiles of southeast Australia (Kellett, J. R., and vans, W. R., private comm.). Thermoluminescence of allogenic minerals would time the accumulation of surficial aggreates and therefore place older age limits on laterites. Theroluminescence ages would be especially useful in unravelling the evolution of multicyclic profiles that enclose aggradational surfaces. Oxygen and hydrogen isotope fractionations are other techniques currently under consideration (Chivas, A. R., private comm.) The methods are based on long-term changes in climate and is applicable to continents that have experienced a wide range of climates over the relevant time period. These techniques appear to have the advantage of being usable on a variety of minerals.

The best developed method at present uses the remanence of authigenic iron oxides in weathered profiles (Schmidt and Embleton, 1976; Schmidt *et al.*, 1976; Idnurm and Senior, 1978; Idnurm *et al.*, 1980; Bishop *et al.*, Schmidt *et al*, 1982; Schmidt *et al.*, 1983). The application of paleomagnetism to weathering phenomena is of relatively recent origin, and has so far been confined mainly to Australia. This chapter describes the underlying principles, methodology, and limitations of palaeomagnetic dating, and reviews briefly the present stage of development.

Principles of Palaeomagnetic Dating

Palaeomagnetic dating is based on the concept of apparent polar wander (APW), i.e. long-term movement of the geomagnetic pole across the globe. The successive positions of the pole define a trajectory, the apparent polar wander path, which is determined by remanence measurements on rocks of different ages. Where an APW path is available the ages of laterites may be obtained by measuring their remanence directions and comparing these with dated poles on the path. The principle is illustrated schematically in Figure VIII-1.

Apparent polar wander arises principally from continental drift, and since the various continents have had different drift histories (at least in the Cenozoic Era), their individual paths are unique. Each continent therefore presents a somewhat different problem for dating. Clearly continents that have the longest APW segments over the relevant time period give the best prospects for dating.

It is important to distinguish here between secular variations and apparent polar wander. The former are relatively rapid changes in the geomagnetic field that take place over the historical times and are therefore not suitable for long-term dating. Since the angular displacements in secular variations are comparable to APW displacements over tens of millions of years secular variations have to be eliminated from palaeomagnetic data. This is accomplished by taking the average directions of sample sets, where each set spans a sufficiently long period of time (generaly taken to be at least 10,000 yrs). A very important advantage in dating laterites is that their remanence is likely to have been acquired slowly, thereby cancelling out secular variations (Idnurm and Senior, 1978)

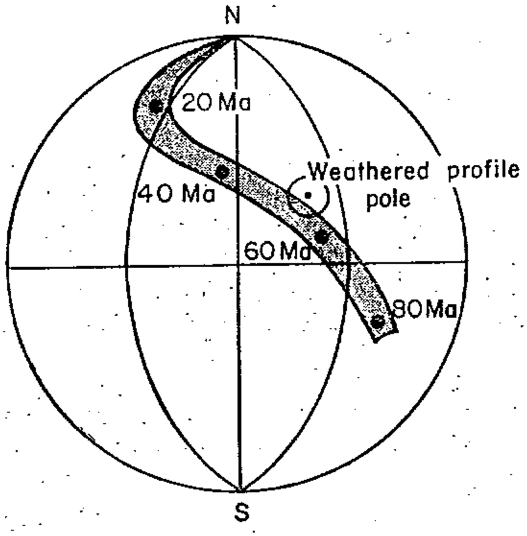

Figure VIII-1 : Principle of palaeomagnetic dating. The age of the weathered profile is estimated by interpolation between dated poles on the APW path.

This advantage is however offset by the likelihood of reversals of polarity of the geomagnetic field during long periods of magnetisation. Field reversals may introduce both normal and reversed magnetisation components into the same sample. Since the net magnetisation in such samples is the resultant of two nearly antiparallel vectors, deviations from strict antiparallelism will be greatly amplified causing scatter about the true direction. If the normal and reversed components are of nearly equal magnitude the scatter can be very high (>25°), as illustrated in Figure VIII-2. Such results should be discarded. Generally the effects of reversals are likely to be more subtle, and the only objective way of overcoming errors due to reversals is to measure a large number of samples so that the scatters would statistically average out. For a small number of samples, say studies based on directions from less than 20 samples, there is a possibility of serious error, and hence anomalous or even highly misleading results.

Palaeomagnetic dating is, of course, not restricted to weathered materials. It should also be noted that, unlike many other applications of palaeomagnetism, dating does not depend on the validity of the geocentric axial dipole model of the time-averaged geomagnetic field.

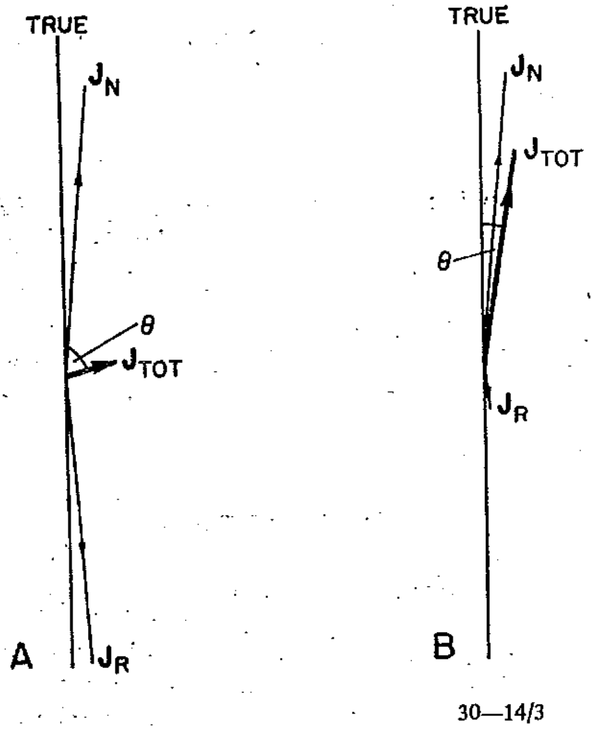

Figure VIII-2 : The effect of normal J_N and reversed J_R components on the remanence J_{TOT} of the sample. The angle θ is the deviation of J_{TOT} from the true field direction.

A : extreme case where J_N and J_R are of comparable magnitude.

B : J_N and J_R are of greatly differing magnitudes.

Methodology

The field and laboratory techniques of palaeomagnetism have been described by a number of workers (Irving, 1964, Collinson *et al.*, 1967, and McElhinny, 1973). The following gives a brief summary of the techniques, together with recent developments on data analysis.

In the field the samples are collected as either blocks or drillcores. The latter are generally 25 mm in diameter and are obtained by a small portable drill. Before removal from the outcrop the samples are oriented by a compass-clinometer. Because some rocks are highly magnetised and would therefore deflect the compass needle, the most suitable instruments incorporate a sun-compass (Creer and Sanver, 1967). Besides the sun angle the information required for orienting by the sun are the local time, date, and geographic co-ordinates of the site. A short calculator program for sun-compass data reduction is available in the literature (Embleton, 1979) but may need to be adapted to the specific type of calculator used.

If block samples are collected in the field they need to be subsequently cored in the laboratory workshop. The laboratory drilling machine uses a universal clamping jig that enables the samples to be rotated so that they are oriented in an analogous way to the field drill cores. With either of the above sampling methods the specimens for measurement are prepared usually as cylinders 25 mm in diameter and 22 mm high.

The field drilling method has the advantages that only a small bulk of material needs to be transported, and that a minimal time is needed to prepare specimens in the laboratory. Its main disadvantage is the requirement of water as coolant and lubricant, especially in dry climates or rugged terrains where water may represent a major logistical problem. Another disadvantage is that friable or water-soluble rock types, including some lateritic materials, preclude the use of water. Rock samples collected from such materials can be cored in the laboratory by means of a special adaptor to the drill which allows the use of compressed air instead of water.

A variety of rock magnetometers are employed for measuring the natural remanent magnetization (NRM). In the order of increasing sensitivity and speed these are i) astatic magnetometers (Blackett 1952, and Collinson *et al.*, 1967), ii) rock generator and ballistic magnetometers Collinson *et al.*, 1967), iii) flux-gate spinners (incorporating computers with automatic data reduction—Molyneux, 1971), and iv) cryogenic SQUID (Super-Conducting Quantum Interference Device) magnetometers (Goree and Fuller, 1976). The sensitivities range from 5×10^{-6} emu (5×10^{-9} Am^2) for astatic magnetometers to 5×10^{-8} emu (5×10^{-11} Am^2) for cryogenic magnetometers. The speeds of measurement corresponding to these sensitivities are a few measurements per hour to a measurement in less than one minute. Thus superconducting magnetometers have the advantage of both high speed and high sensitivity.

Although a certain portion of the magnetisation of a rock may have remained stable since its formation. the NRM is rarely composed of a single, primary, magnetic component, but contains also secondary components acquired at later times. The NRM is therfore the vector sum of a number of magnetisations, and is referred to as multicomponent remanence. The bulk of the laboratory work involves detailed demagnetisation treatments of the samples in order to eliminate unwanted components (magnetic cleaning), or to extract information for resolving the individual components.

The various demagnetisation techniques are discussed by Collinson *et al.* (1967). They were developed to remove preferentially the softer, and presumably secondary, components of magnetisation, thereby isolating the primary component. These techniques essentially activate the softer components by means of heat or by the application of alternating magnetic fields. When the activation process is removed, the magnetic components that have been affected become trapped again, but now in randomly oriented directions. In the course of demagnetisation the intensity of the treatment is increased steps, and the remanend is remeasured after each step.

Secondary components of remanence originate from a variety of causes. These may be categorised as i) viscous remanent magnetisation (VRM) which is recognised by the similarity of its direction to either the recent dipole direction or the present geomagnetic field direction; ii) thermal remanent magnetisation (TRM) which is often related to a specific geological event such as volcanism or tectonism; iii) isothermal remanent magnetisation (IRM), resulting from proximal lightning strikes that are especially likely along ridges and on hilltops; and (iv) chemical remanent magnetisation (CRM). As discussed in the next section the remanence of laterites and bauxites is largely CRM, although more recent VRM or IRM components are also usually present.

A knowledge of the stability characteristics of the different types of magnetisation aids the selection of the most appropriate demagnetisation method. Thus for rocks containing secondary magnetic components of types i) and ii) above, the most effective method is usually partial thermal demagnetisation, because both VRM and TRM are related to the blocking temperature spectrum and can therefore be removed thermally. IRM is best removed using alternating magnetic fiedls since the stability of this type of magnetisation is related to the coerecivity of the material. There appear to be no definite rules regarding the stability spectra of CRM. Very often a broad range of stabilities is present in CRM, resulting in a multicomponent magnetisation in which the individual components cannot be resolved either thermally or by magnetic fields. An alternative mthod, chemical demagnetisation by acid leaching, has been developed for such magnetisations (Collinson, 1967, Royand Park, 1974). Chemical demagnetisation proceeds in reverse order to the original crystal growth, removing the finest, and therefore presumably the most recent grains first.

Although laterites and other weathering products have predominantly a CRM, and chemical demagnetisation may therefore be the most appropriate method, these types of material often disintegrate in acids so that the alternative method, thermal demagnetisation, is usually adopted. If however a large IRM is diagnosed, then the specimens are usually pre-treated with AF before thermal demagnetisation.

Numerical analytic procedures for extracting the different components of remanence from demagnetisation data have been discussed in many articles. It is appropriate to begin here with the orthogonal projection plots as originally described by Zijderveldt (1967). Since the data from successive demagnetisation steps are remanence vectors, a complete analysis has to consider not only directions but also the relative intensities. Two diagrams are required to represent the data these may be a pair of planes onto which the vectors are projected orthogonally, or a stereographic projection of directions and a plot of intensities. Figure VIII-3A shows an example of the former. The data are synthetic and represent thermal demagnetisation treatments up to 600°C. The figure contains two planes that share in the usual convention a common axis: one plane is defined by the E-W and N-S axes, and the other is defined by the E-W and vertical axes. The shared E-W axis allows the points corresponding to the same direction in the plots to be readily identified. The straight line segments in the figure represent separate magnetic components. The direction of the first component removed during heat treatments may be visualised by imagining the origins of the respective diagrams to be made coincident with the breaks in the graphs, i.e. the points where the first component has been fully demagnetised.

The alternative representation of the same data is shown in Fig VIII-3B. It is slightly more difficult in Fig VIII-3B to visualise the direction of the first component, and very difficult to determine by inspection whether or not a linear segment indeed exists for the first part of demagnetisation.

Fig VIII-3 shows the ideal case where two components of remanence are annihilated at separate stages of demagnetisation. In more realistic behaviours there is usually a range of treatments over which both components are removed simultaneously, i.e. demagnetisation of the hard component starts before the soft component has been completely removed. To include data from the range of overlap in either of the line segments would bias the estimated direction towards the other component. Such overlap ranges should therefore be avoided or given special consideration. To summarise, for multicomponent analysis any pictorial representation the demagnetisation data has to show clearly the ranges of overlap. The stereographic plot commonly used in palaeomagnetic studies fails in this respect.

Many different methods have been developed for obtaining the best estimates of directions of magnetic components, but most of the methods are restricted to special cases. For example, if the zone of overlap of two components is extreme, then the great circle methods discussed by Khramov (1958), Halls (1976, 1978), McFadden (1977), and Hoffman and Day (1978) have been found effective. If magnetic components are well resolved, that is, if they appear on orthogonal plots as welldefined straight-line segments, then the method by vector differences described by Roy and Park (1974) has proved effective. None of the methods mentioned above is however as general as principal component analysis (PCA—Kirschvink, 1980) which yields least-squares lines for the linear segments, and least-squares

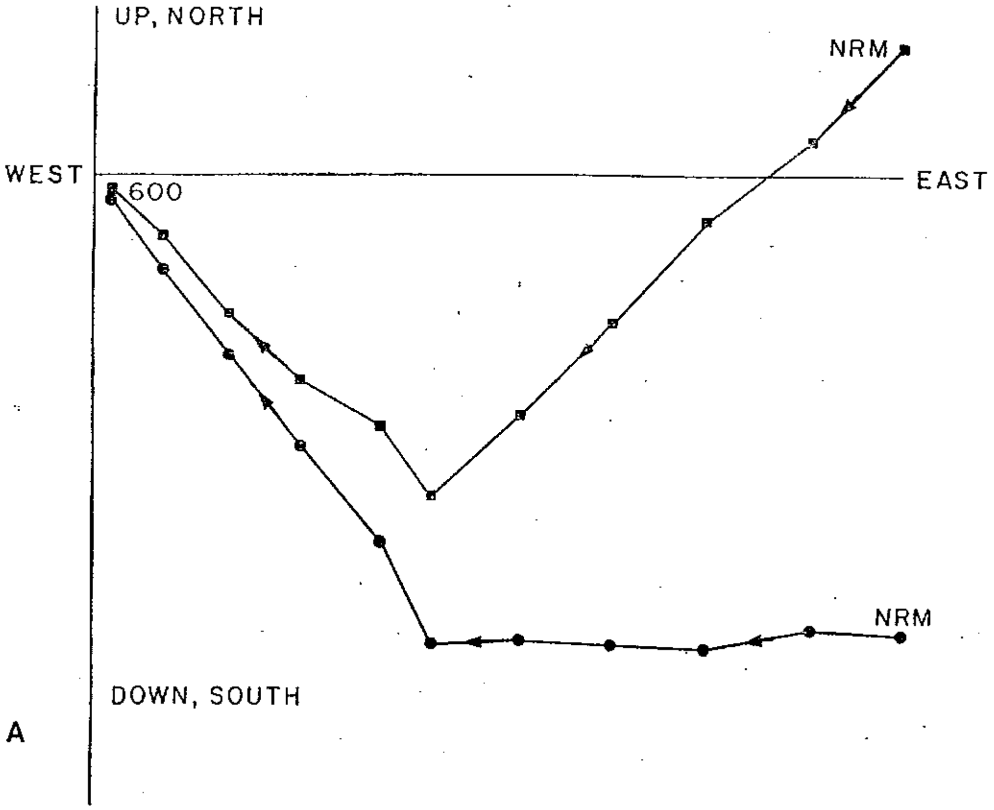

Fig. VIII-3A : Alternative diagrammatic representation of demagnetisation data.

Orthogonal projection of remanence vectors onto the E-W/N-S (square symbols) and E/W/VERTICAL (circle symbols) planes.

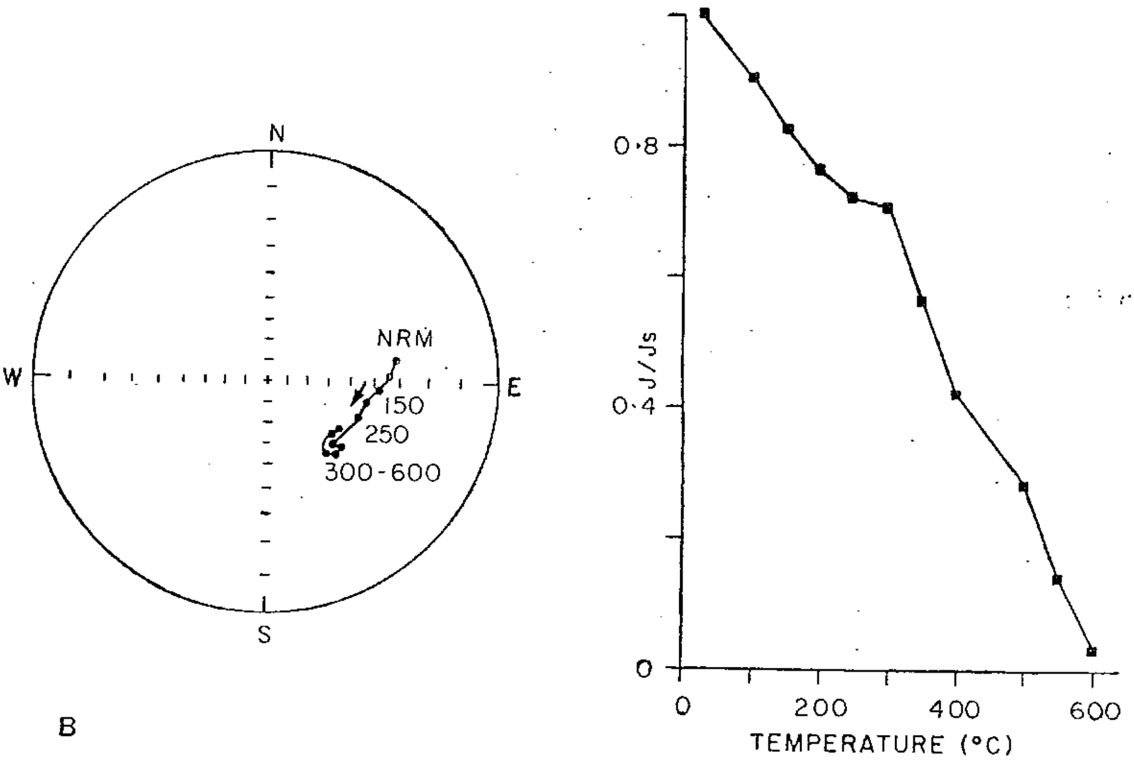

Fig VIII-3B : Alternative diagrammatic representation of demagnetisation data.

Stereographic plot of remanence directions and a plot of changes in the remanence intensities.

lanes for curved segment i.e. zones of overlap. When two mponents are simultaneously demagnetised then the pole of a least-squares plane through the curved segment represents the most unlikely direction of either of the components. his information may seem superfluous at first sight but can evertheless provide a very useful constraint for many studies.

A deficiency of the PCA method is the subjectivity of decisions on whether segments in the orthogonal projection plots are linear or curved. This problem has been discussed by Sch-idt (1982) who has accordingly developed a new technique uilt around PCA, called linear spectrum analysis (LSA). This technique, unlike PCA, uses information from more than ne specimen at a time, so that the idiosyncracies of data from dividual specimens are suppressed. The mechanics of the method are beyond the scope of this report. LSA provides an bjective basis for deciding what data to include in PCA, and used routinely it should in general improve the reliability and consistency of palaeomagnetic results.

rigin of Remanence in Laterites

Among the minerals that form during weathering processes ethite, hematite and maghemite carry a significant remance. Of these goethite and hematite are very common in laterites. Maghemite, while common in soils (Schwertmann and aylor, 1977) and ironstone-lag-gravels of especially tropical and semitropical regions, has been reported as a constituent of laterites only in isolated instances (Hamilton, 1964; Frankel and Bayliss, 1966; Faniran, 1970). Nevertheless maghemite could well be far more common than reported, and because of its high saturation magnetisation it can contribute substantially to remanence even in very small concentrations.

Goethite has a low but significant remanence which is attributed to an imbalance in its antiferromagnetic spin pairing (Strangway *et al.*, 1968). It has the low Neel temperature of 120°C, and consequently while magnetically stable at 20°C, goethite may demagnetise completely at moderate temperatures, such as those encountered at surfaces of outcrops exposed to the sun on a hot day. Except possibly in special circumstances goethite is therefore not suitable for palaeomagnetic dating of surficial materials. Its remanence contribution is eliminated in the early stages of laboratory thermal demagnetisation.

In general the most important mineral for palaleomagnetic dating of laterites is hematite. Hematite is principally antiferromagnetic but has a small ferromagnetic moment because of spin-canting and lattice defects (Stacey and Banerjee, 1974). As discussed below this remanence is highly stable for range of grain sizes. Hematite is also chemically stable within the regolith, except in temperate climates where it transforms to goethite (Schwertmann and Taylor, 1977).

The remanence of authigenic iron minerals in laterites is due to chemical remanent magnetisation (CRM): a process whereby an assemblage of ferro-or ferri-magnetic grains growing in the presence of a magnetic field becomes magnetised parallel to the field (Haigh, 1958). Besides weathered profiles CRM is common in both sedimentary and igneous rocks. A closely analogous case to weathering is the CRM acquired during diagenetic processes in red bed formation (Collinson, 1965; Turner, 1979; Walker *et al.*, 1981).

The main aspects of CRM acquisition are explained by Neel's theory of an assemblage of fine magnetised particles (Neel, 1949). The theory has been described elsewhere (McElhinny, 1973; Stracey and Banerjee, 1974); we summarise here only the elements that relate to dating. The fundamental premise in the theory is that the long-term stability of remanence of fine, uniformly magnetised grains arises from magnetic anisotropy. The anisotropy may be partly structural, partly magnetostrictive, and partly due to grain shape. Magnetostatic fields associated with the anisotropy constrain the magnetisation vector to one of a number of preferred directions. Thermal forces (lattice vibrations) tend to destory this alignment and cause remagnetisation in the presence of any new ambient field.

In the initial stages of grain growth when the grain size is very fine, thermal forces exceed the anisotropy forces. The net magnetisation of an assemblage of such grains is then realigned rapidly along any new field direction in the way paramagnetic atoms are realigned, and the grain are referred to as superparamagnetic. The rate of realignment (or equilibration) (Stacey and Banerjee, 1974) is described by the relaxation time (e.g. McElhinny, 1973)

$$\tau = \frac{1}{C} \exp \frac{VK}{kT}$$

where C is approximately 10^9 sec^{-1}, V is the grain volume, K is the anisotropy constant, k is the Boltzmann constant, and T is the absolute temperature. As seen from Equation 1, the relaxation time increases during grain growth, and because $K > > kT$ the transition from superparamagnetism to stable remanence occurs extremely rapidly with change of grain size. The narrow range of grain sizes in which the transition occurs is referred to as the superparamagnetic threshold. For hematite the threshold grain size centres at approximately 0.03 μm (Bando *et al.*, 1955; Banerjee, 1971).

An important concern for palaeomagnetic dating is the limiting grain size that yields a stable remanence in geological times. This may be estimated by expressing V and τ in Eq. 1 in terms of the corresponding values, V_0, τ_0, for the superparamagnetic threshold:

$$\frac{V}{V_0} = \frac{\ln C\tau}{\ln C\tau_0}$$

or alternatively

$$\frac{d}{d_0} \approx \left(\frac{\ln C\tau}{\ln C\tau_0}\right)^{1/3}$$

where d and d_0 are the grain diameters. Taking for hematite $\tau_0 = 1$ sec, $d_0 = 0.03$ μm and τ equivalent to 65 Ma gives $d = 0.04$ μm, i.e. if hematite is to retain remanence throughout the Cenozoic Era its grain size has to exceed 0.04 μm.

Besides the lower grain size limit there exists also an upper limit for stable remanence. This is determined by a rearrangement of the magnetic structure within the grain from a single domain to two or more domains. The reorganisation is caused by self demagnetising fields that increase with grain volume. For hematite the transition occurs at a grain size of 15 μm (Banerjee, 1971). Beyond 15 μm the remanence stability decrease gradually. An analytical expression corresponding to Eq. 1 does not exist for multidomain grains, but from coercive force determinations (Banerjee, 1971) hematite grains of size up to at least 100 μ m appear to be stable over geologic periods.

Table VIII-1 summarises some of the magnetic properties of hematite and maghemite. The superparamagnetic threshold grain size for maghemite has been estimated from Eq. 1 by taking $\tau = 1$ sec and $K = 1.1 \times 10^5$ erg cm^{-3} (McElhinny, 1973).

Table VIII-1

Magnetic Properties of Hematite and Maghemite

	Hematite	Maghemite	Ref
Curie temperature (°C)	683±8	675±10	Lindsey, 1982; Miche and Chaudron, 1935.
Saturation magnetization (emu cm^{-3})	2.2	450	McElhinny, 1973.
Superparamagnetic threshold grain size (μm)	0.03	0.025	Bando, *et al.*, 1955; Banerjee, 1971.
Single-domain-threshold grain size (μm)	15	0.06	Banerjee, 1971; Dunlop, 1981.

An important issue for the interpretation of palaeomagnetic dates is the period of time over which the remanence is acquired, i.e. the time span over which different grains grow through the superparamagnetic threshold. A lower limit for this time is obtained from the observation that Cenozoic weathered profiles commonly contain both normal and reversed magnetisations (Schmidt and Embleton, 1976; Schmidt *et al.*, 1976; Idnurm and Senior, 1978; Schmidt *et al.*, 1981). This implies that the magnetisation processes probably span at least one polarity interval. The average frequency for geomagnetic polarity reversals during the Cenozoic Era is approximately 3 per Ma (Stacey and Banerjee, 1974). Hence the period over which magnetisations are typically acquired is likely to exceed 300 000 yrs. This time span should be more than adequate to average out the secular variations in the geomagnetic field.

Physical Significance of Palaeomagnetic Dates

When considering palaeomagnetic ages of laterites it is important to distinguish at the outset between relict laterites and those forming at the present time, i.e between weathered and weathering profiles. For the former the processes of precipitation, leaching and reconstitution of iron sesquioxides and oxyhydroxides are assumed to have slowed down sufficiently to contribute at worst only a magnetic overprint. For the latter, the processes of intense weathering are still operating. There may be special cases where such a distinction does not apply. An example in this category is the ferruginisation at escarpments bordering extensive tablelands where seepage and precipitation take place continuously along permeable layers of rock. With continued precipitation of iron the seepage channels are ultimately blocked, and seepage may then divert to other localities along the escarpment, commencing there a new cycle of iron precipitation. The different localities would accordingly yield different ages. Such hybrid cases of ferruginisation should however be exceptional.

The central issue in interpreting laterite ages is the stage of the weathering cycle at which the magnetisation is acquired. On the one hand the magnetisation may be continuous throughout the entire period of intense weathering; on the other, magnetisation may commence after a certain stage of weathering is reached, in particular at the terminal stage. If remanence acquisition is continuous the age of magnetisation represents a mean age of weathering. Otherwise the age would represent the mean period of "maturity", the termination of lateritisation, or some period of time after the intense weathering has ceased.

Some insight into remanence acquisition of laterites may be gained from the present day processes of pedogenesis. Hematite, goethite, and to a lesser extent maghemite are prevalent in soils of tropical and subtropical regions(Schwertmann and Taylor, 1977), and are presumably forming there at present. In temperate regions the main iron minerals are goethite and its precursors, ferrihydrite and lepidocrocite (Schwertmann and Taylor, 1977). It is interesting to note that hematite does not usually form in soils of temperate regions (Schwertmann and Taylor, 1977), and that when derived for example from sedimentary rocks, it tends under temperate climates to transform to goethite (Schwertmann, 1971).

Although magnetic oxides apparently form from iron bearing solutions in present day soils it is questionable if normal pedogenesis could produce long-term, or even stable remanence. Firstly, several agents in soil solutions appear to inhibit crystal growth of the iron minerals (Taylor, *et al*, 1983). Mössbauer spectroscopy studies from various parts of the world confirm that the grains are indeed largely superparamagnetic (Ganges *et al*., 1973; Logan *et al*., 1976; Kodama *et al*., 1977; Bingham *et al*., 1978). It is not clear however whether such agents slow the grain growth down, in which case the magnetisation is merely delayed, or limit the ultimate grain size.

Secondly, it is unlikely that the grain orientations of magnetic minerals in soils are fixed, whether the minerals exists as independent grains or as overgrowths on other grains. Various physical and biological processes tend to modify the soil fabric in response to environmental changes. These include wetting and drying cycles (especially in the presence of the expanding clays). disturbance of soil particles by movement of groundwater (e.g. illuviation or lateral transport), activity of microorganisms in the upper soil layers, disturbance by root systems even at depth, and plastic deformation of soils due to gravitational instability or due to volume changes that accompany leaching out of the unstable minerals. Each of these processes would in principle update the remanence direction by aligning it along recent geomagnetic fields in a manner similar to the acquisition of post-depositional remanence in unconsolidated sediments (e.g., Versoub, 1977).

Stable remanence appears therefore to require ageing of the iron oxides and a degree of induration of the weathered material. Such conditions preclude continuous magnetisaion, and appear to be best met at dehydration reactions during the terminal stages of intense weathering, or shortly after the intense weathering has ceased.

While the genesis of laterites is debateable, there appear to be two general environmental conditions for forming deep chemically weathered profiles with which major laterites are associated:

1. A climate favourable to chemical weathering, e.g. warm and humid conditions. Palaeomagnetism would then date the termination of this climate.

2. A favourable, low-relief, topography that remains stable over long periods of time, and is finally destroyed by erosion, possibly following uplift. Palaeomagnetism dates the onset of instability.

In the above discussion it has been implicitly assumed that lateritisation has taken place over a single period of time. Weathered profiles developed on the older land surfaces are however likely to be polygenetic. Dating of the different periods of weathering in such profiles is complex, but in principle dates may be obtained by multicomponent analysis using the techniques described earlier in this chapter. This

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