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MAGNETIC AGES OF SOME INDIAN LATERITES

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ABSTRACT

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The results of an extensive palaeomagnetic investigation of laterites from peninsular India are described. From 62 samples, 693 specimens were step-wise thermally demagnetised to eliminate secondary magnetisations. The ages of laterite formation were estimated after calculation of pole positions from site mean directions and comparison with the Mesozoic—Tertiary apparent polar wander path (APWP) for India. The high-altitude laterites have undergone a complex magnetic history during the late Cretaceous and early Tertiary. The low-altitude laterites are mid- to late Tertiary in age. A fundamental mechanism in laterite formation and preservation is suggested. When the Indian laterite results are compared with those from Australia, they are seen to be consistent with the relative timing of the northward drift of India and Australia.

INTRODUCTION

Laterites and associated formations have considerable economic potential, which is reflected in the recent increase in their scientific investigation (Roychowdhury et al., 1981). First described in India by Buchanan (1807), such occurrences have since been recognised as a ubiquitous feature of the tropics and subtropics (e.g. Fermor, 1911; Woolnough, 1927). One of the major obstacles in deciphering the processes of lateritisation is the difficulty in determining the age of formation which should help to elucidate relationships between laterites on a regional and global scale. Under special circumstances it has sometimes proved possible to constrain the age of lateritisation stratigraphically, e.g. by radiometrically dating younger basalts to yield a minimum age (Exon et al., 1970), the maximum age being derived from the age of bedrock. However, there is a clear need for a dating method generally applicable to laterites. Until recently the palaeomagnetic method was not in routine use for dating laterites. Although palaeomagnetic investigations of laterites were ~~made as early as 1961 (Wilson, 1961), it was not until much~~ palaeomagnetic work was carried out on independently dated rock sequences that palaeomagnetism could be used to date the age of formation of laterites.

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The palaeomagnetic dating method appeals to the axial geocentric dipole field model and plate tectonics (Irving, 1964; McElhinny, 1973) in the following manner. First, over several thousands of years the mean magnetisation direction at any site averages to that of a dipole field axially oriented at the Earth's centre. Since the magnetisation of laterites is predominantly a chemical remanent magnetisation (CRM) and forms over such long periods of time, they are ideally suited to exploit this property. Secondly, the phenomenon of continental drift has the effect of producing apparent polar wander paths (APWP), with a particular pole position representing a specific age for the continent in question. Once the APWP for a continent is established, it becomes theoretically possible to estimate the age of a rock palaeomagnetically if a reliable magnetic direction representing its age of formation can be determined. Palaeomagnetic dating of laterites, or weathered profiles, in Australia has been carried out in Western Australia and the Northern Territory (Schmidt and Embleton, 1976), South Australia (Schmidt et al., 1976), Queensland (Idnurm and Senior, 1978) and New South Wales (Schmidt et al., 1982). All ages obtained were late Tertiary, with the exception of one result from Queensland which was earliest Tertiary to latest Cretaceous (Table I). The extension of studies to Indian laterites was undertaken principally as a comparison with the Australian results. India and Australia have occupied the same plate for the past 53 m.y. (Norton and Sclater, 1979), and both continents have undergone large latitudinal displacements throughout the Tertiary, thus optimising the resolution of the method.

In India laterite, with or without bauxite, occurs in diverse geologic-geomorphic environments in the Indian Peninsular. In terms of lithostratigraphy, lateritic duricrusts occur overlying the Archean metamorphics, Proterozoic sediments, the Cretaceous—Eocene Volcanics and the Tertiary

TABLE I

Summary of Australian laterite poles

Locality	N	Pole			References
		Lat. (°S)	Long. (°E)	A_{95} (°)	
Perth Basin (W.A.)	128	82.7	109.9	2.4	Schmidt and Embleton (1976)
Montejinni Limestone (N.T.)	12	76.4	107.2	14.1	Schmidt and Embleton (1976)
Springfield Basin (S.A.)	37	79.1	103.5	1.5	Schmidt et al. (1976)
Kangaroo Is. (S.A.)	8	86.9	076.9	8.4	Schmidt et al. (1976)
Canaway profile (Qld.)	10	74.1	115.1	6.6	Idnurm and Senior (1978)
Morney profile (Qld.)	37	59.8	118.5	3.8	Idnurm and Senior (1978)
Bunyan (N.S.W.)	10	76	168	9.7	Schmidt et al. (1982)
Bredbo (N.S.W.)	7	81	167	5.6	Schmidt et al. (1982)

Note: N is number of samples and A_{95} is half-angle of cone of confidence based on poles from sample directions (Fisher, 1953).

sediments. Morphologically analysing their localisation, they occur at different altitudinal ranges commencing from the plains and low hills near the coastline to the high hills in the hinterland. Samples collected for the present study, by and large, are representative of this diversity.

TECHNIQUES

Many details of the chemical and geomorphic development of laterites remain controversial (Roychowdhury et al., 1981) but from the point of view of their magnetic properties it is sufficient to realise that in tropical and subtropical environments the oxy- and hydroxy-forms of iron are usually stable. It is therefore to be expected that magnetic minerals such as goethite and the sesquioxides of iron (haematite, maghaemite) should be prevalent throughout laterite profiles. Indeed, these minerals are abundant and because of their insolubility (particularly that of haematite) they are relatively chemically inert; under suitable conditions they can remain in the laterite profile unaltered since the time of crystallisation. It is conceivable that organic acids might later remobilise the ferric iron, resulting in changes in remanence but such effects have not been investigated in any detail.

Other post-formational alterations that may affect the magnetisation of laterites (but not the chemical constituents) are viscous remanent magnetisation (VRM) and isothermal remanent magnetisation (IRM). The former process describes the logarithmic tendency of a magnetisation to equilibrate with the present geomagnetic field, while the latter is usually caused by large ground currents from lightning. Most often these disturbing effects may be eliminated, or at least minimised, through thermal and alternating field (AF) partial demagnetisation, respectively. These techniques are well established (Irving, 1964; Collinson et al., 1967; McElhinny, 1973) and are routinely applied to rock samples to "clean" their natural remanent magnetisation (NRM). The efficacy of each method depends upon the origin of the unwanted magnetisations. For instance, VRM is essentially thermally activated and hence specimens can be demagnetised with ease if they are heated, and then cooled in a magnetic-field-free space. This is the essence of thermal demagnetisation, bearing in mind that any particular specimen must be treated and measured many times at successively higher temperatures to establish the point when VRM is eliminated. The over-riding philosophy behind cleaning is to reverse the magnetic history. Overall, a total of 693 specimens were consecutively subjected to thermal demagnetisation at 200, 300, 400, 500 and 600°C. Since the Curie temperature (Tc) of haematite is 685°C, many specimens were not fully demagnetised, but it is thought that VRM and IRM should have been at least minimised. The vagaries of chemical remanent magnetisation (CRM), on the other hand, leave doubt in some cases whether a palaeomagnetic field direction has been isolated.

SAMPLING

Experience from laterite studies in Australia suggested that as much information is to be gained through the detailed investigation of a few large samples as of many small samples. Actually, the friable nature of the samples in question virtually precluded successful drilling in the field, thus necessitating the collection of large block samples. Consequently, two or three blocks were collected from each of 25 separate locations covering a large area of peninsular India (Fig.1). A total of 72 samples subsequently arrived intact at the rock magnetism laboratory of the CSIRO Division of Mineral Physics at North Ryde. Further attrition during sample preparation took a toll of ten samples, even though precautions extended to the use of a specially designed compressed air drilling rig. Thin-walled Felker drill bits were found to be indispensable. Also samples were set in plaster of Paris prior to coring. Up to 60 cylindrical subsamples, or specimens of nominal size 25 mm diameter and 22 mm height, were derived from some samples, although the yield of specimens averaged 32. Measurement of the remanent magnetisation, which in the case of laterites is largely CRM plus unknown proportions of VRM and IRM,

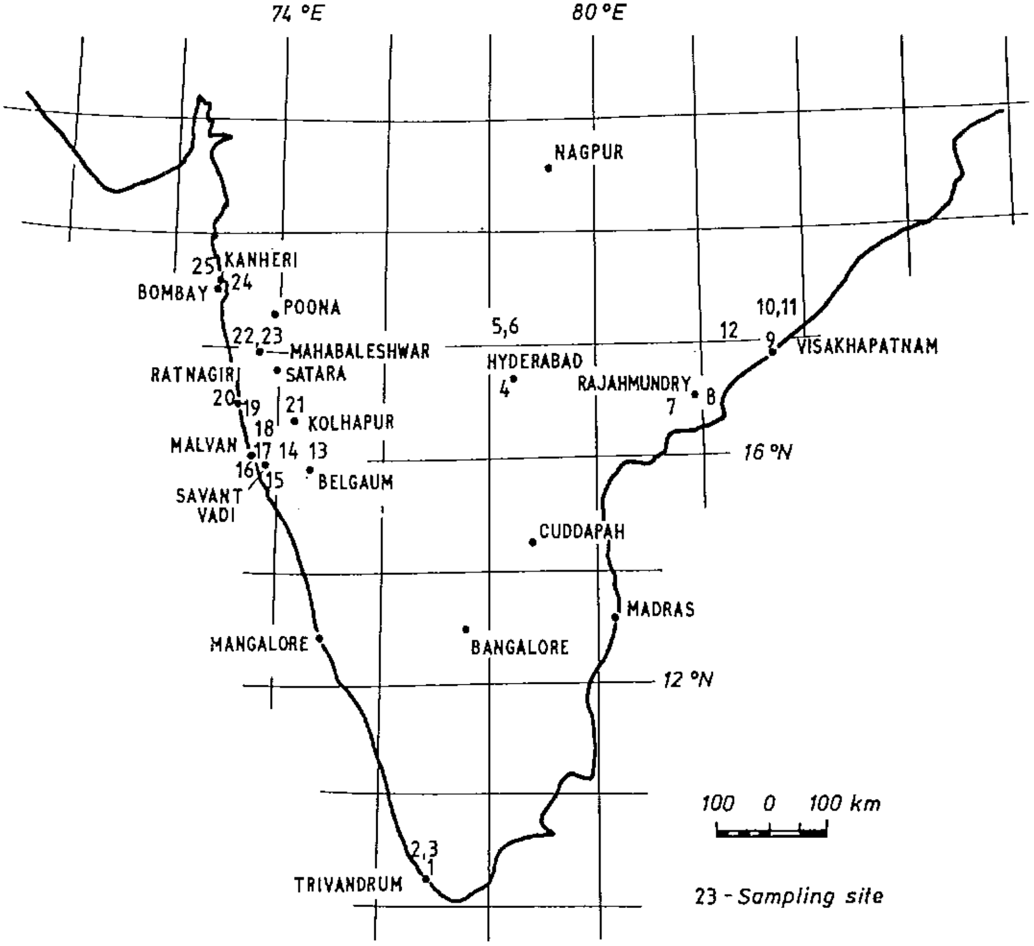


Fig.1. Site locations, see Table II for location names.

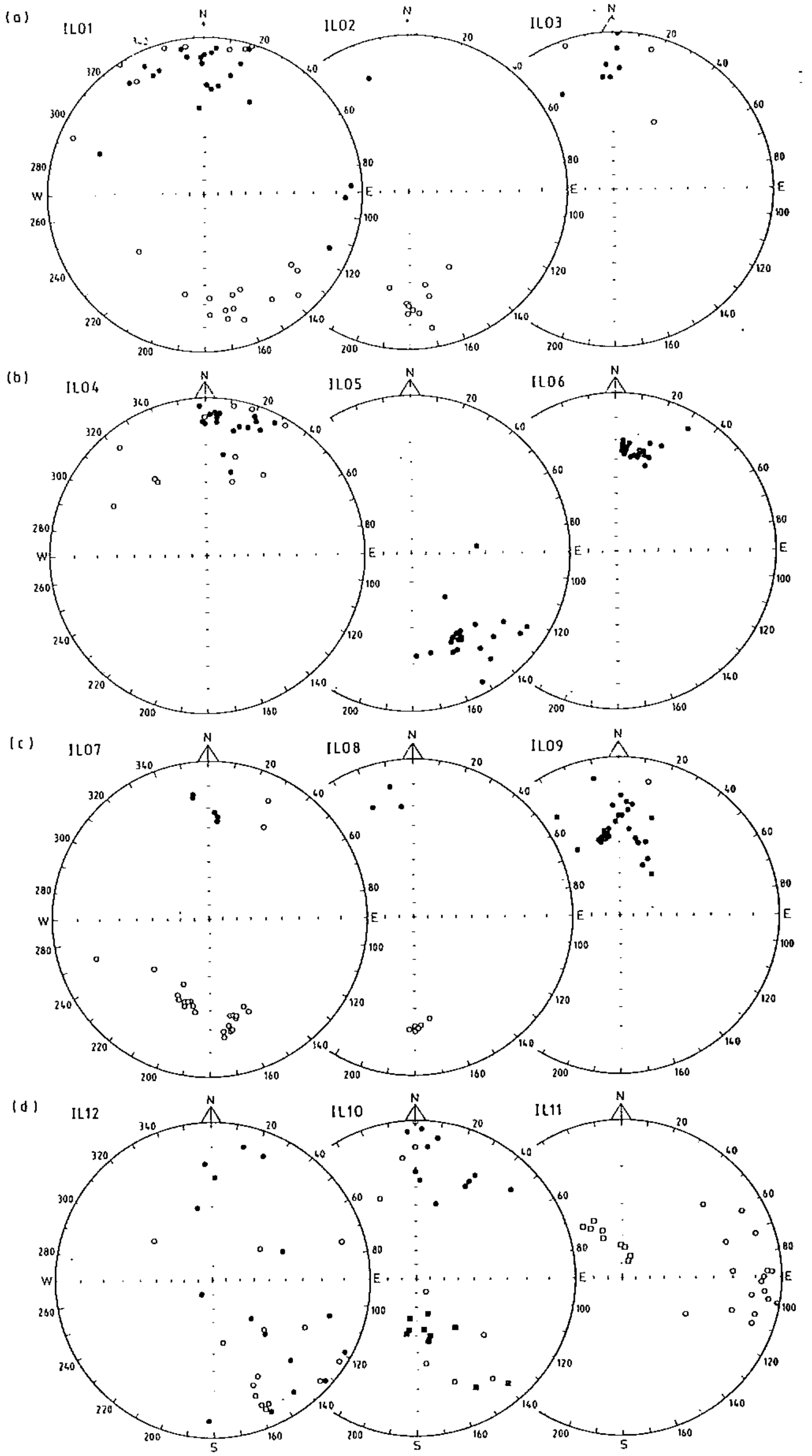
was performed using a DIGICO flux-gate spinner magnetometer. Susceptibilities were measured using a DIGICO susceptibility bridge. Demagnetisation was performed using Schonstedt thermal and AF apparatus, and a field-free furnace designed and built by CSIRO.

Directions of magnetisation were determined through the use of Zijderveld (1967) diagrams, principal component analysis (Kirschvink, 1980) and linearity spectrum analysis (Schmidt, 1982).

RESULTS AND COMMENTS

Most samples have been magnetised over sufficiently long periods of time that reversals in the polarity of the geomagnetic field have been recorded. For such magnetisations, variations due to short-period secular variation most probably can be neglected. Nevertheless, when two polarities are present, specimens display considerable scatter (Fig.2). This implies that longer-term variations are being reflected. These may arise from the intimate mixing of normal and reversed magnetisation and/or from the occurrence of considerable continental displacement during the lateritisation.

In view of the importance of the above possibilities to the interpretation, it was considered prudent to model the magnetisation process to develop a better understanding of the cause(s) of scattering. Fig.3 presents the directions of vectors resulting from various linear combinations (in 10% increments) of one normal magnetisation (dec. = 0°, inc. = 30°) and a reversed magnetisation, which is not exactly 180° away. Regarding this last point it is obvious that if the reversal is exactly 180° away, the resultant will lie exactly parallel to the normal or the reversed magnetisation, whichever dominates. Realistically a rock specimen containing both polarities would be expected to do so in such a way that the net sum of the reversed magnetisation is not exactly 180° away from the net sum of the normal magnetisation. This is modelled in Fig.3 with 170°, 160° and 150° quasi-reversals. The first is considered equivalent to small statistical variation from exact reversal while the last is probably equivalent to the occurrence of considerable continental displacements between the two magnetisations. A striking feature of these results is the high percentage of resultant directions which fall fairly close to ($\leqslant$15°) the pure end-members. With the 170° value a high percentage fall within about 10° of normal (40%) or reversed (40%), and even with the 150° value, only 40% of resultant directions are greater than 15° from the end-member. A point to remember regarding the 150° case is that, while the greater divergence from exact reversal does produce relatively more scatter, the resultant directions become more tightly constrained to lie in the plane of the two end-member vectors. This is often recognised in palaeomagnetic studies and is referred to as "streaking". Little evidence of streaking was found in the present study, except perhaps at sites 12, 18 and 22 (Figs.2d, f and h). In the majority of cases scatter found in the samples studied here must arise from almost exact reversals.


(a)
IL01
IL02
IL03
(b)
IL04
IL05
IL06
(c)
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IL08
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(d)
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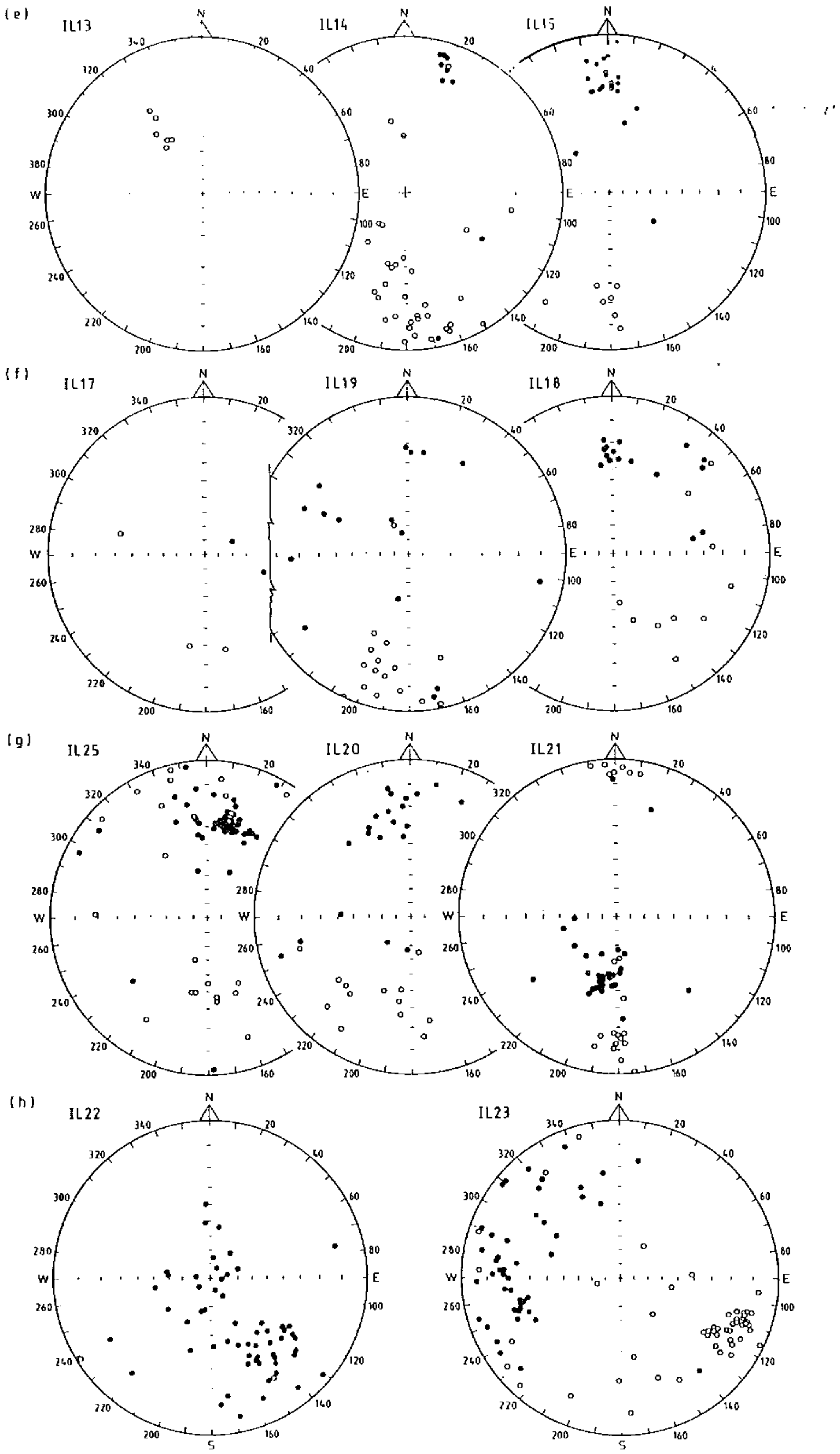

Fig.2. Stereographic projections of least-squares magnetisation directions. Open (solid) symbols refer to upper (lower) hemisphere.

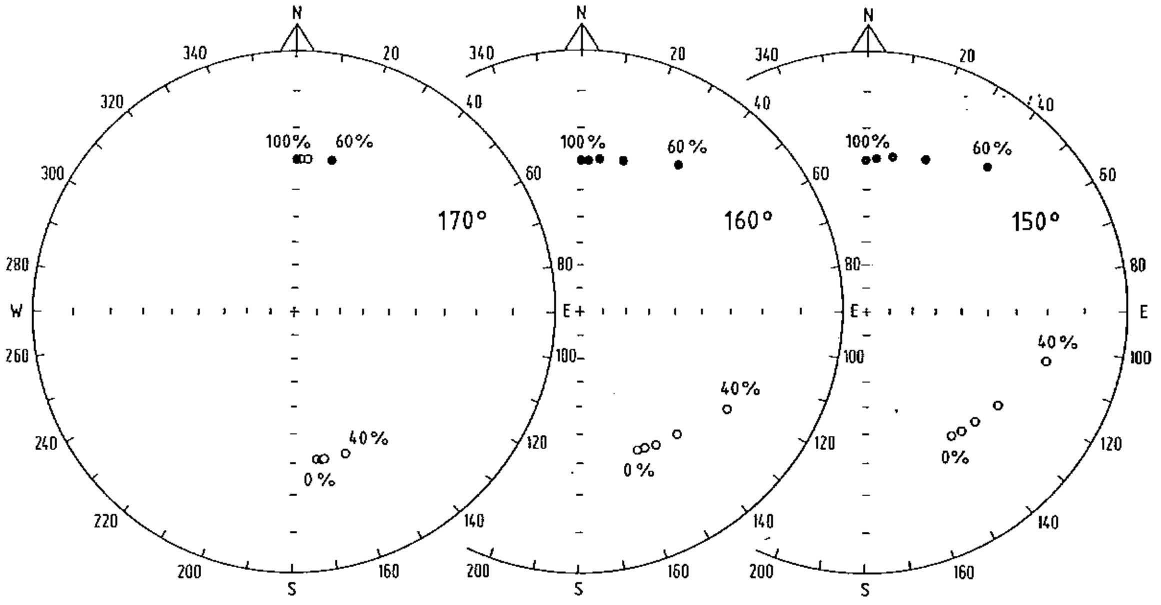

Fig.3. Calculated directions of various linear combinations of a normal magnetisation (000°, 30°) and a (nearly) reversed magnetisation of 170°, 160° and 150° removed from 000°, 30°.

The distributions of directions displayed in Fig.2 for sites 01, 07, 14, 15, 20 and 25 are considered to be typical of magnetisations of closely antiparallel directions intermixed in various proportions. For these examples the vast majority of directions lie close (<15°) to the mean magnetisation axis of each group as a whole (taking the polarity of directions into consideration). Table II summarises the distributions in terms of their mean directions and confidence limits with comments regarding their general behaviour.

For some other distributions displayed in Fig.2 (sites 03-06, 09 and 13) only one polarity has been observed and in such cases the assumption of complete averaging of secular variation may be invalid, although, as discussed above, from the nature of CRM it should be expected that systematic bias from this source is minimal. Two sites (06 and 09) revealed tight groups of normal magnetisation which most probably are carried by goethite of recent origin. This is supported by their low thermal demagnetisation stability (summarised in Table II) and the change of colour from yellow to red, although there was no increase in susceptibility on heating.

The behaviour of the demagnetisation of some representative specimens is displayed in Fig.4, where orthogonal projections (Zijderveld, 1967) of the vector end-points, measured after each demagnetisation step, are plotted. The most salient feature of these specimens is their demagnetisation trend towards the origin. This implies that while many of the specimens have not been completely demagnetised at 600°C no further cleaning is warranted. The magnetisation is either composed of a single polarity or mixed polarities (normal and reversed) which are being demagnetised at the same rate. This latter possibility is quite reasonable if both magnetisations are carried by the

TABLE II

Summary of Indian laterite magnetisations and pole positions

Location (site)	N	Direction				Comment	Pole				Apparent age
		dec. (°)	inc. (°)	R	α_{95} (°)		lat. (°S)	long. (°E)	dp^1 (°)	dm^1 (°)	
Padappakara (01)	24	353.0	2.9	20.599	12	reversed and normal in equal proportions	80.0	121.9	6.1	12.3	mid-Tertiary
Warkallai (02)	11	174.6	—19.6	10.767	7	mostly reversed, v. stable	84.4	184.0	3.8	7.3	late Tertiary
Vattaparra (03)	10	359.5	5.4	9.287	14	mostly normal	78.8	079.5	7.1	14.1	late Tertiary
Chevalla (04)	28	6.5	—0.9	25.078	10	predominately normal but reversals reflected in scatter	71.1	057.6	4.8	9.5	late Tertiary
Yerragutta (05)	22	146.2	24.7	20.785	8	reversed, v. stable	44.4	127.7	4.4	8.3	early Tertiary
Ebti Gutta (06)	21	11.8	23.9	20.765	4	low stability, normal	77.3	012.9	2.0	3.7	Recent
Elunu (07)	30	184.6	—25.1	27.680	8	mostly reversed, v. stable	84.2	030.6	4.5	8.3	late Tertiary
Rajahmundry (08)	9	174.8	—18.9	8.927	5	similar direction to 07 but large VRM present	81.1	117.2	2.7	5.1	mid-Tertiary
Visakhapatnam (09)	30	0.3	30.3	28.570	6	low stability, normal	88.3	073.7	3.7	6.7	Recent
Anantagiri (10) a)	10	164.2	46.6	9.281	13	two loose groups	79.7	078.0	7.0	13.7	late Tertiary
b)	20	0.9	15.7	17.275	13		41.4	101.7	11.8	18.3	late Cretaceous—early Tertiary
Anantagiri (11) a)	9	341.5	—60.7	8.717	10	two loose groups	27.6	098.5	11.5	15.1	late Cretaceous—early Tertiary
b)	18	87.7	—11.3	16.747	10		—0.4	179.2	7.0	13.8	?
Gudem (12)	30	144.5	—6.1	22.010	16	scattered and streaked	52.2	153.4	8.2	16.3	early Tertiary
Belgaum (13)	6	325.8	—40.2	5.915	9	one polarity	39.0	116.2	6.4	10.6	early Tertiary
Nangartaswadi (14)	44	179.7	—15.7	38.094	9	tight normal, scattered reversed	82.0	076.2	4.5	8.8	late Tertiary
Redi (15)	26	1.6	21.6	24.147	8	majority normal	85.2	054.4	4.5	8.4	late Tertiary
Banda (16)	—	—	—	—	—	no specimens recovered					—
Selti (17)	—	—	—	—	—	one sample showed scattered directions					—
Kumbharmatti (18)	26	3.7	27.9	20.257	15	one normal and one streaked from normal to reversed	86.2	002.6	9.2	16.8	late Tertiary
Phansop (19)	33	178.1	—14.3	24.589	15	predominantly reversed	80.2	084.4	7.8	15.2	late Tertiary
Bhagawati Fort (20)	36	184.4	—22.5	27.670	4	normal and reversed	83.4	033.6	2.4	4.5	late Tertiary
Panhala (21) a)	29	197.0	49.2	21.380	6	two principal axes of magnetisation	77.8	079.8	3.2	6.4	late Tertiary
b)	27	358.8	9.4	25.712	6		40.0	054.7	5.2	7.8	?
Panchagani (22)	22	139.9	27.8	21.237	6	scattered, some streaking	38.8	126.8	3.6	6.6	early Tertiary
Mahabaleshwar (23)	96	119.7	—18.3	79.312	7	streaking in evidence	31.0	163.9	3.6	7.0	?
Powai Lake, Bombay (24)	—	—	—	—	—	no specimens recovered					—
Kanheri Caves, Bombay (25)	76	2.2	20.9	66.464	6	well defined but some scattering	82.7	56.3	3.4	6.5	late Tertiary

[1] Half angles of ellipse of 95% confidence (Irving, 1964, p. 69).

The locations of the sites are given in Fig.1. In this analysis we have assigned unit weight to specimens since orientation errors are trivial compared with discrepancies often observed between adjacent specimens. From a time averaging point of view it would appear that the specimen is the most appropriate unit. Reversed magnetisations are considered as normal for the purpose of calculating site mean directions.

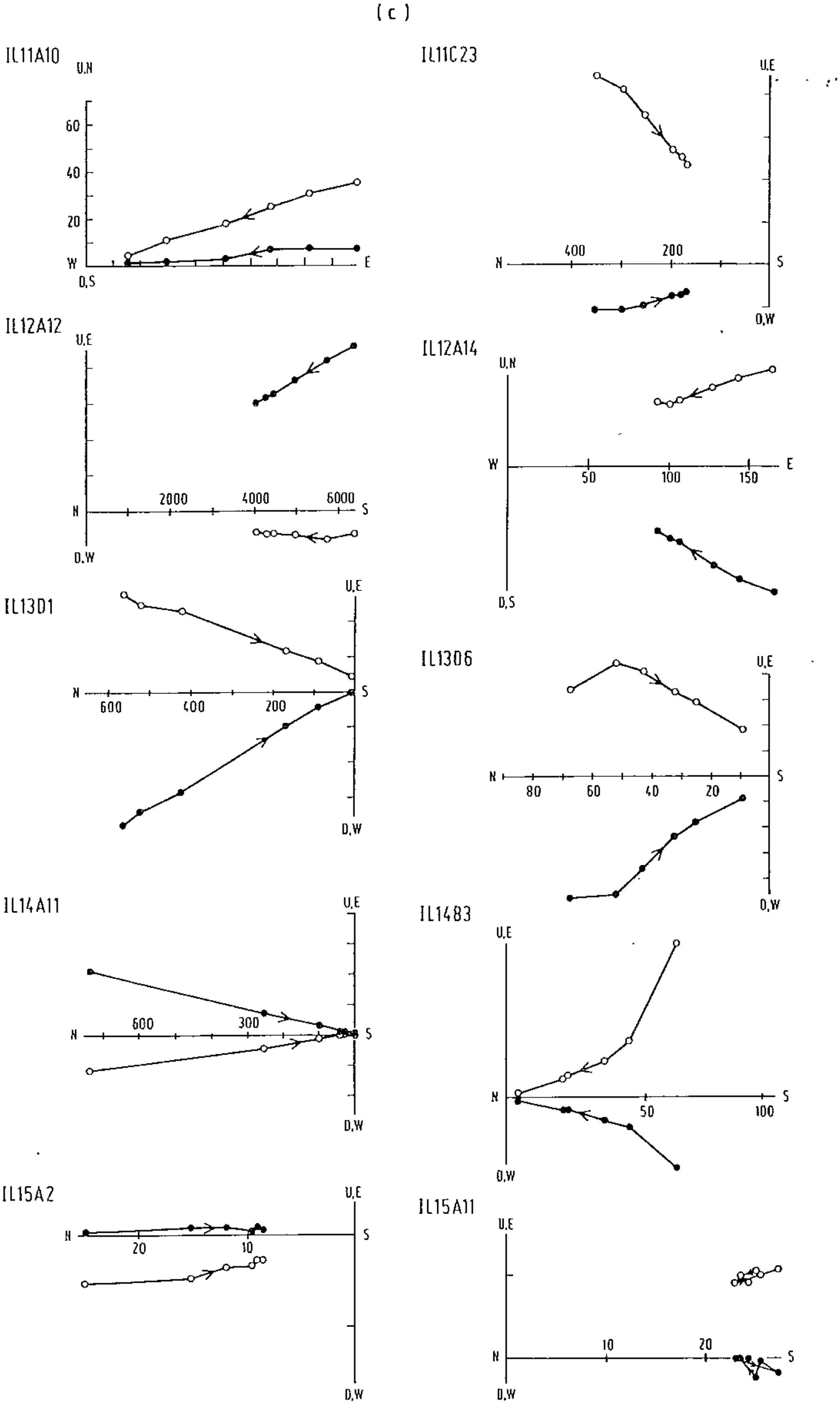

Fig.4c. For caption see p. 197.

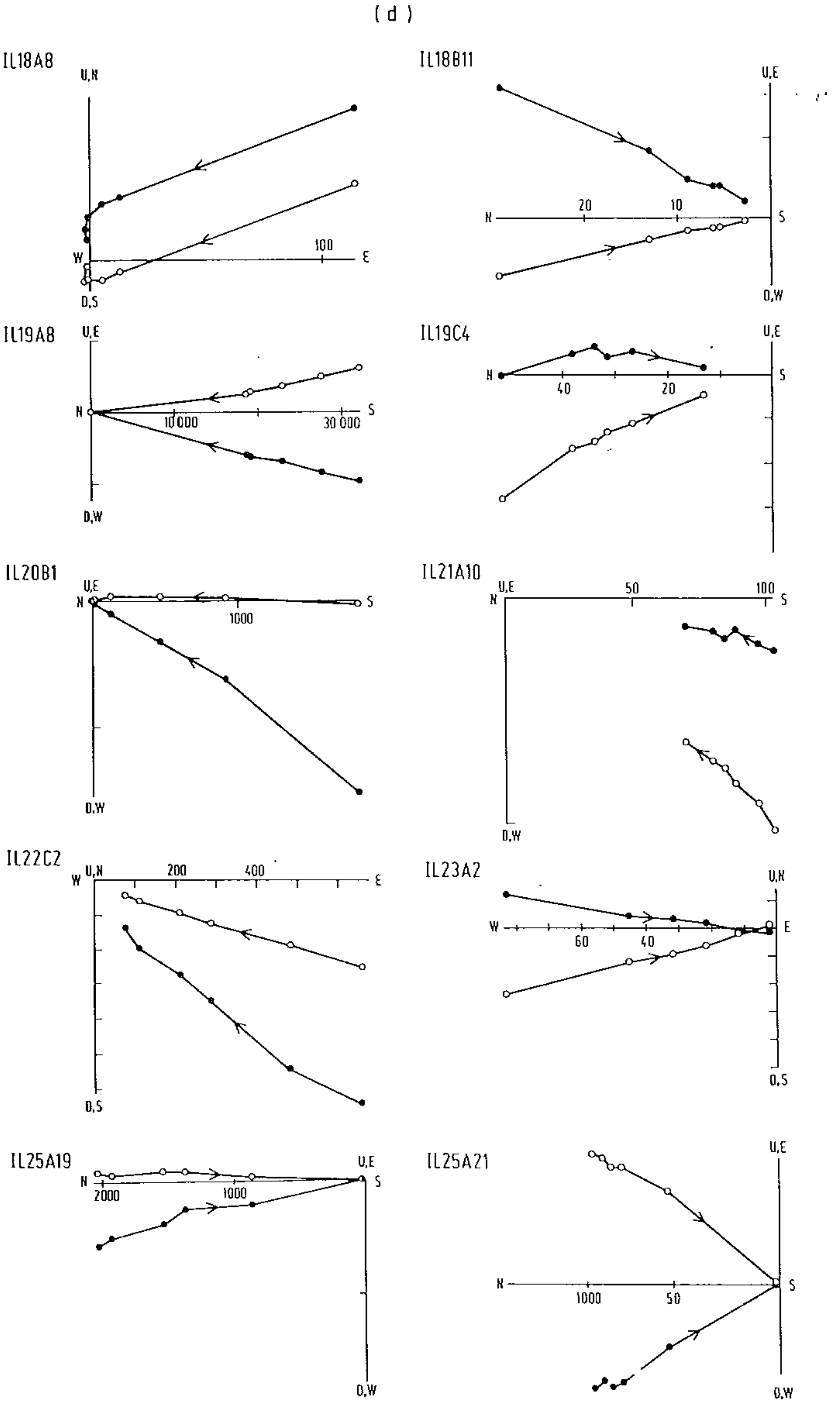

Fig.4. Orthogonal projections of vector end-points from NRM, 200—600°C in steps of 100°C. The solid circles refer to the horizontal plane while the open circles refer to the vertical plane. Scales are all in mA m^{-1} (= 10^{-6} emu cm^{-3}).

same mineral and are of a common chemical origin (CRM), as they appear to be here.

An example of the usefulness of thermal cleaning of specimens from a site containing both normal and reversed magnetisations is seen in Fig.4a. Specimens IL01A7 and IL01B1, while initially both normally magnetised (both northerly directed), after treatment at 200°C and removal of a large soft VRM assume opposite polarities. Specimens from site 07 on the other hand (IL07A24 and IL07A7, Fig.4b) require very little cleaning since their directions of magnetisation are hardly affected by thermal cleaning. Their NRM directions are almost 180° apart. Indeed over half the magnetisation remains even after 600°C, indicating the very stable nature of this magnetisation. Other examples of sites possessing very stable magnetisations requiring little cleaning are sites 02 (IL02A2 and IL02A3, Fig.4a), 05 (IL05A2 and IL05B7, Fig.4a), 10 (IL10A6 and IL1016, Fig.4b), 12 (IL12A12 and IL12A14, Fig.4c) and particularly 15 (IL15A11, Fig.4c). Not only does the direction of magnetisation of this last specimen not change on thermal cleaning to 600°C, but also its intensity does not change.

Although possessing very stable magnetisations, the examples cited from site 12 above display a scatter in direction which may indicate some significant continental displacement during the formation of these magnetisations, as discussed above with respect to the model of the acquisition of magnetisations over long periods. In this regard site 23 is also interesting, in that it displays scattered normal magnetisations, although the reversed magnetisations are more tightly clustered. The scattering could be the result of combined polarity reversals and significant continental displacement. While the tight grouping of the reversed magnetisations suggests that a reliable magnetic direction has been determined, the mean direction is somewhat anomalous. This is discussed further with regard to the aberrant pole position (Table II) from site 23 below. Other aberrant pole positions (11b and 21b) are also discussed below.

DISCUSSION AND CONCLUSIONS

The above results show a wide distribution of directions, but when reversals of magnetisation are taken into account the vast majority of magnetisations lie close to the present Earth's field direction. The existence of reversals, however, proves the antiquity of the magnetisations. In general, any similarity of a direction of magnetisation with the present geomagnetic field direction may be considered to be misleading in the presence of accompanying reversed magnetisations. In geological terms the present field is instantaneous, unlike the dipole field which is more fundamental. Magnetisations directed closely to the dipole field direction are considered to be very young (e.g. site 09), or if magnetisations are of normal polarity and of low thermal resistance (<300°C), then they are regarded as VRM of a recent origin. Many specimens possessed minor components of VRM but site 06 magnetisations appeared to consist wholly of VRM. Thus, the magnetisations of two sites (06 and 09) are regarded as Recent in age. It may well prove significant that the remanence of these samples appears to be carried by goethite.

Pole positions calculated from all mean directions of magnetisation are presented in Table II and Fig.5. The APWP in Fig.5 is taken from Klootwijk and Peirce (1979) and is calibrated in millions of years (m.y.). The pole from site 09 is indistinguishable from the present pole and, while the pole from site 06 is nearby, it appears to be significantly different from the present pole. The VRM of the specimens from site 06 has not completely averaged secular variation.

On the basis of pole positions, comparisons with the APWP age assignments have been made, although no errors are estimated (Table II). The problem of errors is statistically complex, and has not yet been solved. Thus ages are grouped as follows: late Tertiary, mid-Tertiary, early Tertiary or early Tertiary—late Cretaceous.

Poles 10, 11a and 12, all derived from the East Coast Bauxites, range in age from late Cretaceous to early Tertiary (some 15—20 m.y.). Reconstructing the geomorphic evolution of the East Coast Bauxites, Ramam (1981)

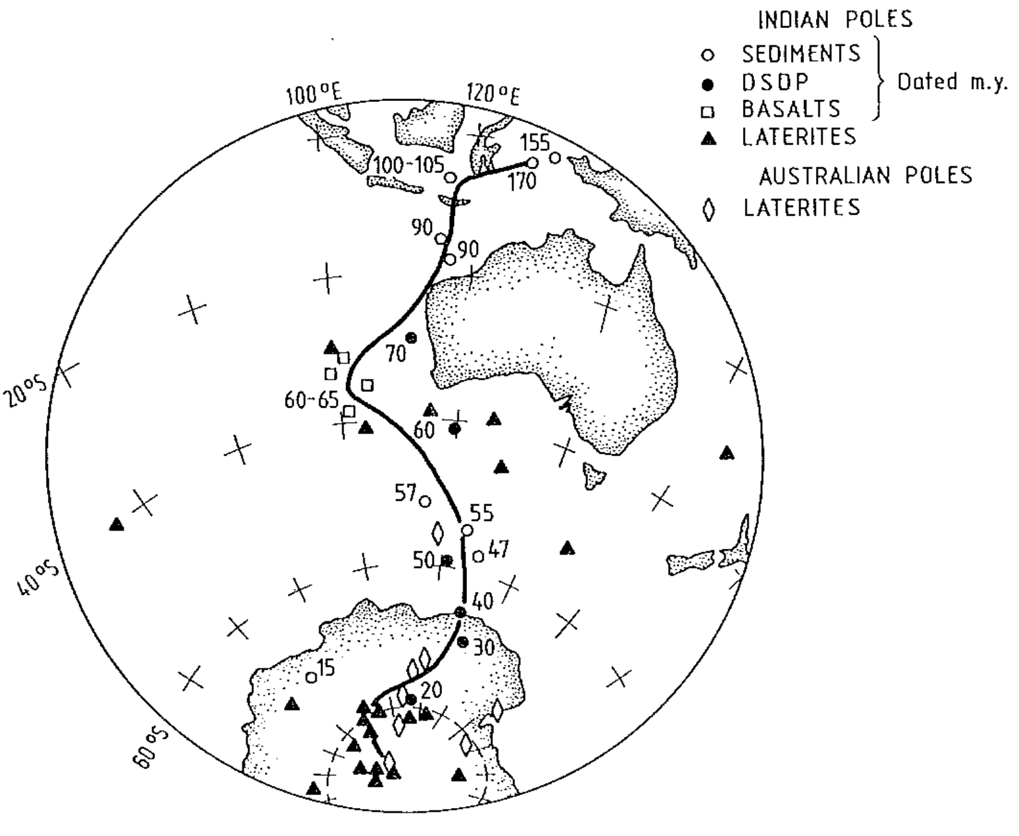

Fig.5. The Mesozoic—Tertiary APWP for India following Klootwijk and Peirce (1979). The diamonds represent Australian laterite pole positions (Table I) and the triangles represent Indian laterite pole positions. Other symbols represent pole positions from rock formations dated independently of their magnetisation. DSDP refers to deep sea drilling project pole positions.

opined "... after attaining stability and with the onset of monsoonal climate in upper Cretaceous promoted the process of residual chemical weathering. Chemical leaching was accentuated and optimised during upper Tertiary/ Quaternary when there was copious rainfall with less of evapotranspiration, resulting in thick bauxite duricrusts". Poles 13 and 22 from the western Ghats are also early Tertiary, suggesting that a general relationship might exist between altitude and age. Without exception the low-level laterites appear to be mid-late Tertiary while the high-level laterites are late Cretaceous—early Tertiary. Of course one restriction on the age of these weathered profiles must be the age of the bedrock. One interesting observation is the early Tertiary age assigned to laterites from the Deccan Traps which are late Cretaceous in age. These lavas must have undergone lateritisation almost as soon as they were extruded. Deeply weathered lava tops, covered by fresh lava, should be common. Another lateritised basalt from site 05 near Hyderabad also yields an early Tertiary age. Other bedrock ages to be borne in mind are:

(1) Late Tertiary sediments — sites 01, 02, 03, 08, 19
(2) Deccan Traps — sites 05, 13, 20—25
(3) Gondwana sediments — site 07
(4) Precambrian basement — sites 06, 09, 10, 11, 12, 15

Pole positions which fall close to the APWP do not conflict with the above.

Some pole positions are clearly aberrant and require some discussion. Poles 11b, 21b and 23 (Table II) lie well to the east of the Mesozoic—Tertiary APWP and cannot represent an axial geocentric dipole for those times. The origin of these magnetisations may be transitionary, while the field is changing polarity. Although this is contrary to the belief that the magnetisations represent a long period of time, the possibility must be considered. Other more exotic reasons can be conceived but the real solution will require more sampling. It is of interest that these poles are derived from the well-developed weathered profiles from the eastern Ghats (11b) and the western Ghats (21b and 23), which appear to have undergone protracted weathering histories during the late Cretaceous and/or early Tertiary.

In a recent article, Bailey and Hale (1982) described laboratory experiments on CRM and concluded that when titano-magnetites oxidise they may acquire a remanence direction midway between the original NRM and the ambient field direction. The laterites at sites 21 and 23 are derived from Deccan Trap basalt and could well be reflecting this phenomenon. These suggestions require further investigation.

Finally, a comparison of the results reported here with Australian laterite results (listed in Table I and plotted in Fig.5) is pertinent. Because India and Australia have not moved with respect to each other from 53 m.y. ago, they share a common APWP since that time. Poles from Australian laterites appear to range in age from early to late Tertiary, spanning a significantly shorter period than the Indian laterite poles, which date from the late Cretaceous to late Tertiary. This is consistent with India's rapid passage into the tropics between 65 m.y. and 53 m.y. ago (Norton and Sclater, 1979) and Australia's much slower northward progress. The palaeoclimatic significance of the regional study of the age distribution of laterites, and other deep weathering phenomena, will only become apparent when a much larger data base is at the disposal of investigators than is presently available. Conclusions drawn from the results reported here clearly require confirmation through a larger sampling program. This should also allow the investigation of the apparently anomalous results. Speculation that the ages of laterites reflect altitude suggests a testable model. Although laterites may age to about 20 m.y. in the tropics at low altitudes, they stand a greater chance of being reworked and therefore only become preserved after uplift. Thus high-altitude laterites might be consistently older than lower-altitude laterites.

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