

NEWER PALEOMAGNETIC RESULTS OF THE DECCAN TRAPS, INDIA

H. WENSINK

Geological Institute, Utrecht (The Netherlands)

(Accepted for publication August 2, 1972)

ABSTRACT

Wensink, H., 1973. Newer paleomagnetic results of the Deccan traps, India. *Tectonophysics*, 17: 41–59.

The paleomagnetic results are presented from a number of sections of the Deccan traps, distributed all over the area. All samples were subjected to partial progressive demagnetization with alternating magnetic fields and were measured with astatic magnetometers. From c. 14% of the collected material no characteristic directions of magnetization could be obtained. In the ultimate analyses the material of 84 individual flows with a total number of 470 samples is included. The virtual magnetic pole position computed by combining the virtual pole positions of the sections is located at 34.8° N, 80.3° W with $A_{95} = 7.2^\circ$. Combined with the results of earlier obtained paleomagnetic data a preliminary paleomagnetic stratigraphy has been set up, where a subdivision into four paleomagnetic epochs has been proposed. The paleomagnetic results of the Deccan traps suggest that there was a fairly rapid drift of several tens of cm/year of the subcontinent during the period of extrusions; this seems to be compatible with the interpretation of the magnetic anomalies in the Indian Ocean, where a rapid N–S spreading took place from anomaly 30 through anomaly 21.

INTRODUCTION

In the Indian Deccan traps oriented samples were collected from successive lava flows in a number of sections for paleomagnetic research. The results obtained from the material of five large sections in the Western Ghats, south of Poona, were published earlier (Wensink and Klootwijk, 1971). In this paper the results will be presented from three other sections in the southern part of the Western Ghats, as well as from a number of other sections, distributed all over the Deccan area (Fig.1).

Earlier paleomagnetic research on the Deccan lavas was carried out by Clegg et al. (1956), by Deutsch et al. (1959) and by Sahasrabudhe (1963). Studies of the paleomagnetism of the basalts have recently been published by members of the Hyderabad research group (Athavale, 1970; Athavale and Verma, 1970; Pal et al., 1971).

GEOLOGY AND AGES OF THE DECCAN TRAPS

A nearly coherent area of c. 500,000 km² taken up with basalts occupies a considerable part of the Indian peninsula. The volcanic region is called Deccan traps, after traps – in order to indicate the terrace-like features, very typical for this region – of the “dakhn”,

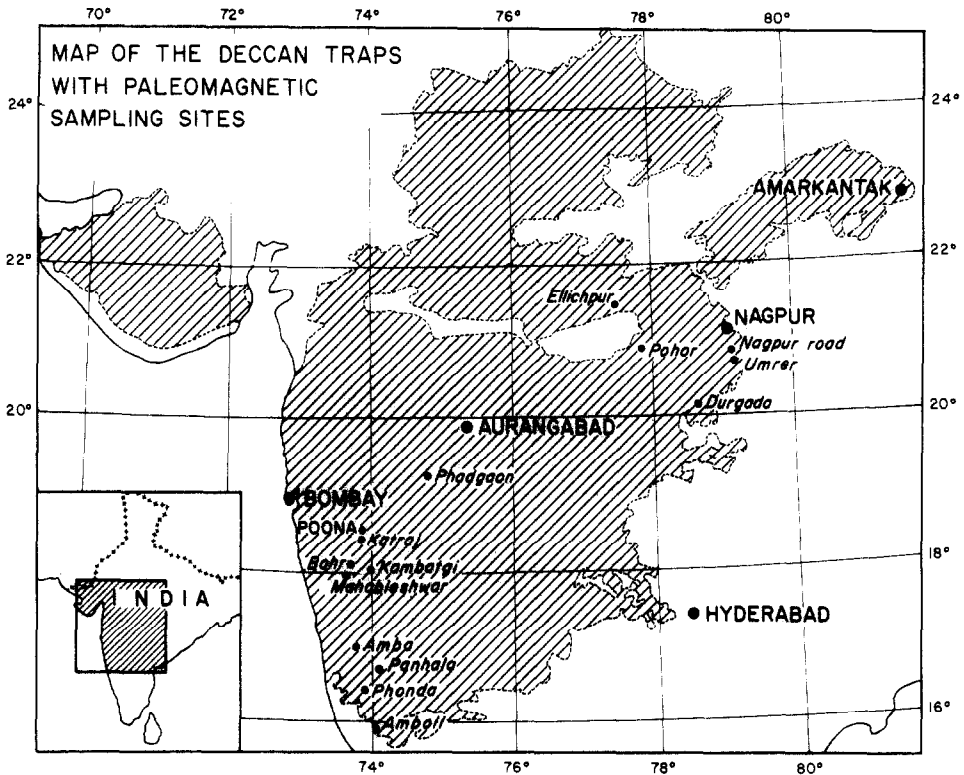


Fig.1. Map showing the outlines of the Deccan traps with the paleomagnetic sampling sections recorded in italics. Results of sections near Katrai, Kambatgi, Bohr, Mahabaleshwar, and Amba were discussed elsewhere (Wensink and Klootwijk, 1971).

the south, i.e., south of the Vindhyan Range.

In the western part of the Deccan traps, in the Western Ghats, great scarps are found of up to 1200 m in height. The abrupt differences in elevation decrease eastward, towards the interior of the subcontinent, though locally considerable scarps also are met with: e.g., in the Gawilgarch Hills near Ellichpur.

Fresh-water sediments of lacustrine or fluvial type are encountered at many places below the traps. These so-called Infra-trappean beds consist of limestones with subordinate sandstones and shales. These non-marine beds, the Lameta beds, may have the Bagh beds of the Narmada valley as their marine equivalents (Pascoe, 1964). The marine sediments, which have yielded fossils, are of roughly Turonian to Senonian age (Krishnan, 1960).

Because of the uneven surface of the Precambrian and the thin development of the sediments, the Lameta beds do not form a coherent cover. Therefore, the lower basalt flows may rest upon Lameta beds, but also on older Gondwana sediments as well as on Precambrian rocks.

The pile of basalts is subdivided into three formations, viz. the Lower traps, the Middle

traps, and the Upper traps with respective estimated thicknesses of 150 m, 1200 m, and 450 m (Pascoe, 1964). The Lower traps are believed to be confined to the eastern part, whereas the Upper traps are restricted to the western part of the volcanic area. Non-marine sedimentary beds are intercalated in both the Lower and the Upper traps. The Lower Intertrappean beds, rarely exceeding 6 m in thickness, consist of fresh-water and terrestrial sediments. Fossils do occur, which indicate a probable Early Tertiary age for these beds. The Upper Intertrappean beds, also of non-marine origin, which are much thicker, are mainly confined to the area around Bombay.

The Deccan basalts, which have a fairly uniform tholeiitic composition, are dark green to black volcanic rocks with a wide variety in textural character. Beds of volcanic ashes do occur, but mainly in the upper part of the sequence. Successive flows are very often separated by red partings which may be old lateritic soils. These soils indicate that there have been significant time intervals between successive outpourings of lava.

One of the most impressive features of the Deccan traps is the consistent horizontality of the lava flows. The basalts near Bombay dipping up to 15° west form one of the very few exceptions to this rule. The Bombay basalts are separated from the main pile of flows by a gigantic N-S trending fault, which follows the great scarp of the Western Ghats.

In the interior there are a number of post-trappean E-W trending faults: e.g., the Ellichpur fault, situated at the southern foot of the Gawilgargh Hills, which has a downthrow to the south.

A more exact thickness of the total sequence of basalts than given above, cannot be presented. In the Western Ghats near Mahabaleshwar, where one observes a vertical section of nearly 1400 m, the underlying rocks have not been reached. The estimated total thickness of 1800 m is considered to be the minimum value.

Radiometric age determinations of Deccan rocks were carried out by Rama (1964). He found ages of 65–60 m.y. and 45–42 m.y., which, in his opinion, may be indicative of two main phases of volcanic activity. Newer dating results (Wellman and McElhinny, 1970) do not support this conclusion. According to these authors, the younger ages obtained by Rama are due to a loss of argon. The newly measured ages of samples from four critical localities in the Deccan area range from 64–59 m.y. Unfortunately, the values obtained do not support the general view that the lavas in the eastern part belong to the older phases of extrusions.

The Rajmahal traps, another plateau basalt area in India, situated in Bihar State some 200 km NNW of Calcutta, have an age of 100–105 m.y. (Mc Dougall and McElhinny, 1970).

From the results of a paleomagnetic study on basaltic dykes of the Damodar valley Athavale and Verma (1970) concluded that there has been a continuous igneous activity since the Rajmahal volcanic phase through the hypabyssal phase of the Damodar dykes to the Deccan effusions. However, the reliability of the paleomagnetic data is not beyond doubt. The samples have been magnetically "cleaned" in a.c. fields up to only 200 Oe peak value; at this value the specimens became very weak in intensity. We know by experience from samples of our Deccan collection as well as from those of the Sonhat sill near

Bajkunthapur (C.T. Klootwijk, personal communication, 1972) showing this behaviour, that it is very difficult to get reliable characteristic directions of magnetization. Moreover, also the radiometric age determinations of the Rajmahal and Deccan lavas, with a difference in age of some 40 m.y., militate against this continuous igneous activity.

PALEOMAGNETIC SAMPLING

In the Deccan a number of sections along roads was selected in order to collect samples for paleomagnetic research. In these hilly and mountaneous areas the roads offer good outcrops with many fresh exposures. In the piles of flows samples were collected from almost every basalt layer. Sometimes, the transition between successive flows in a particular section is obscured by scree and more than one site may have been taken from a single flow; this, however, may be revealed through paleomagnetic research, as will be discussed further on.

In the Western Ghats, apart from the five earlier described sections (Wensink and Klootwijk, 1971), samples were collected from successive flows at sections near Phonda, Panhala, and Amboli. At another place in the Deccan area, a section was sampled near Phadgaon, along the road Poona—Ahmednagar. In the eastern part of the volcanic area short sections were taken near Pohor, Durgada, Umrer, and Nagpur. A very long section was sampled near Ellichpur in the Gawilgargh Hills (Fig.1). Altogether c. 550 samples were collected from 93 individual flows. No reliable results were obtained from the samples of nine flows.

In the field a portable diamond drill provided with a coring tube of 2,5 cm inner diameter was used. Six cores were drilled from each basalt flow. From some lava flows oriented hand samples were collected.

LABORATORY RESEARCH

The samples have been treated at the Paleomagnetic Laboratory of Utrecht State University. The cores were cut into cylinders of 22 mm length; the hand samples were placed in oriented position in blocks of plaster of Paris. The measurements and the alternating magnetic-field demagnetization procedures (a.c.) have been carried out with the standard equipment available. From every basalt flow one pilot sample has been progressively demagnetized in 8–10 successive steps up to at least 500 Oe peak value. After each step the sample was measured on an astatic magnetometer. Usually, the remaining samples of the site were treated in about four steps of gradually increasing a.c. fields.

The results of the progressive, partial demagnetizations are presented in diagrams — in orthogonal projection both on the horizontal and on a vertical plane — where the change of endpoints of the magnetization vectors can be followed during the treatment. Two examples are given in Fig.2, where it can clearly be demonstrated that during progressive a.c. treatment the magnetization vectors change their directions. This behaviour is due to the fact that the initial remanent magnetization is composed of at least two magnetic components which react differently to a.c. treatment. The secondary magnetizations are generally “soft”, and may be removed through alternating magnetic fields (Zijderveld, 1967).

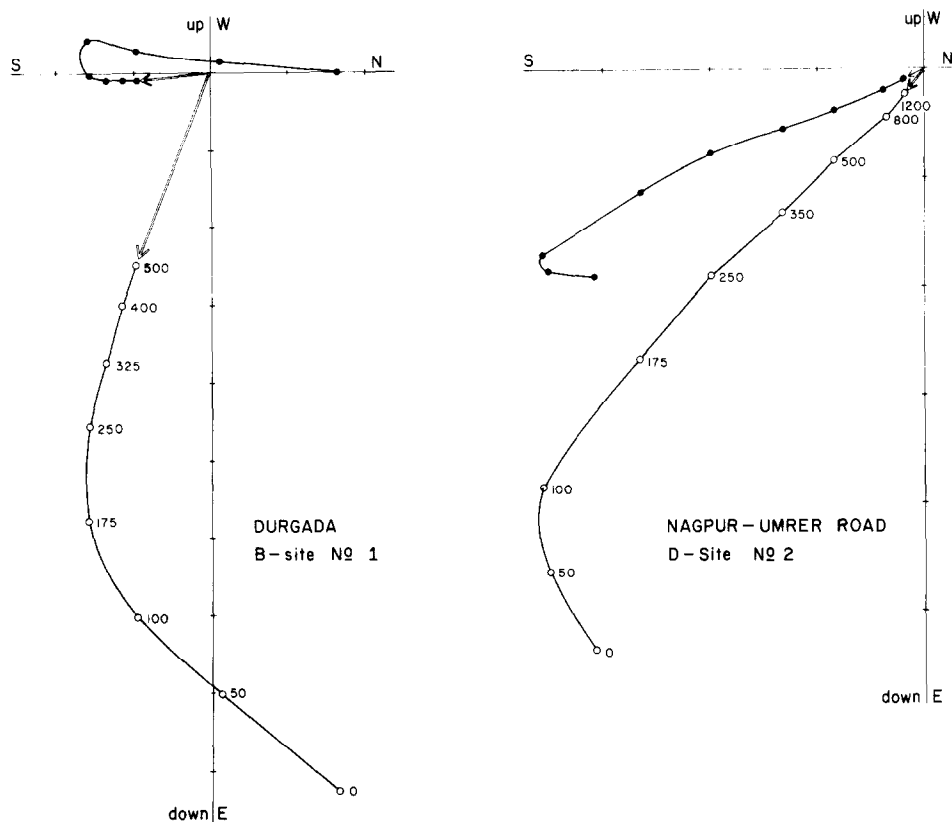


Fig. 2. Demagnetization diagrams of two Deccan samples. The points represent successive positions – in orthogonal projection – of the end of the magnetization vector during a.c. progressive demagnetization. Full and open symbols represent projections on the horizontal plane and on the north-south vertical plane, respectively. Numbers denote the peak strength in Oe of the a.c. demagnetizing field. Each unit on either axis represents 1.10^{-3} e.m.u./cm³ at the diagram on the left, and 5.10^{-4} e.m.u./cm³ at the diagram on the right.

Upon application of stronger a.c. fields, the resultant magnetization vectors do not any longer change their directions, but decrease along straight lines to the center of the coordinate system. Then one single component of magnetization is left, which is called the characteristic magnetization.

The characteristic direction of magnetization could not always be detected. Some slightly decomposed lava flows in the section near Ellichpur contain strong viscous magnetization. These flows are characterized by low Q -values, viz. low ratios of remanent to induced magnetization.

PALEOMAGNETIC RESULTS

The directions of the initial natural remanent magnetization of the flows of the greater

part of the sections were plotted in a number of equal-area stereograms (Fig.3). The stereograms show a considerable scatter in the directions. In stereogram D the projections are clearly lying in a broad belt directed from southeast downward, pulled towards the present direction of the earth's magnetic field. Most of these magnetization directions are composite.

In the stereograms of Fig.4 the mean directions of the magnetization of individual flows were plotted after treatment in alternating magnetic fields. The scatter of the mean directions has decreased considerably. For the individual sections as well as for some combined sections the average directions of magnetization were computed from the data of the individual lava flows both before and after a.c. treatment. The results are listed in Table I. For the pole positions the reader is referred to Tables II and III.

The scatter in the characteristic directions of magnetization of the stereograms of Fig.4, G—L, must be due to the secular variation of the geomagnetic field, as the within-site dispersion is small. Individual flows represent spot readings of the direction of the earth's field during the period of volcanic activity. Therefore, in order to give an idea about the variation of the characteristic direction of magnetization in a lava sequence one must carefully sample each successive lava flow. In Athavale's study (1970) on the basalts near Amarkantak this condition was probably not fulfilled; several pairs of successive sites also having small differences in elevation show hardly deviating directions of magnetization within each of the pairs of sites. It is not impossible that in several cases more than one site has been sampled from a single flow, thus giving a wrong impression of the variation of the stable magnetization direction.

In a few cases we may also have sampled more sites from a single flow. In the Panhala section (Fig.5) the sites nos. 3 and 4 from below have almost corresponding mean characteristic directions of magnetization with $D = 306.8^\circ$, $I = -51.6^\circ$, $\alpha_{95} = 8.4^\circ$ and $D = 302.9^\circ$, $I = -57.9^\circ$, $\alpha_{95} = 3.0^\circ$ respectively. It could not be settled in the field whether the sites belong to one or two lava flows. These difficulties also arose in the sections in the eastern Deccan; here, the sampled flows could not always be found in an incontestable succession. In the sections sampled both near Pohor and on the road from Umrer to Nagpur we are not sure that all sites do represent distinct lava flows.

There are some flows, which show anomalous, but very stable characteristic directions

Fig.3. Equal-area projections of the mean directions of the initial natural remanent magnetization of Deccan basalts. A, B, C, and D show the mean directions of flows from the Phonda, Panhala, Amboli, and Ellichpur sections, respectively; E shows the directions of flows sampled at the Durgada, Umrer, and Nagpur sections; F gives the mean directions of the nine Deccan sections of this paper as well as an overall initial mean direction with its 95% circle of confidence. Full circles denote that the N-seeking poles are pointing downward; open circles indicate that N-seeking poles are pointing upward; cross denotes the local direction of the field due to a geocentric axial dipole.

Fig.4. Equal-area projections of the mean directions of characteristic magnetization of Deccan basalts, obtained after partial demagnetization with alternating magnetic fields. The projections G, H, J, K, L, and M correspond to the projections A, B, C, D, E, and F of Fig.3, respectively. For further elucidation see the caption of Fig.3.

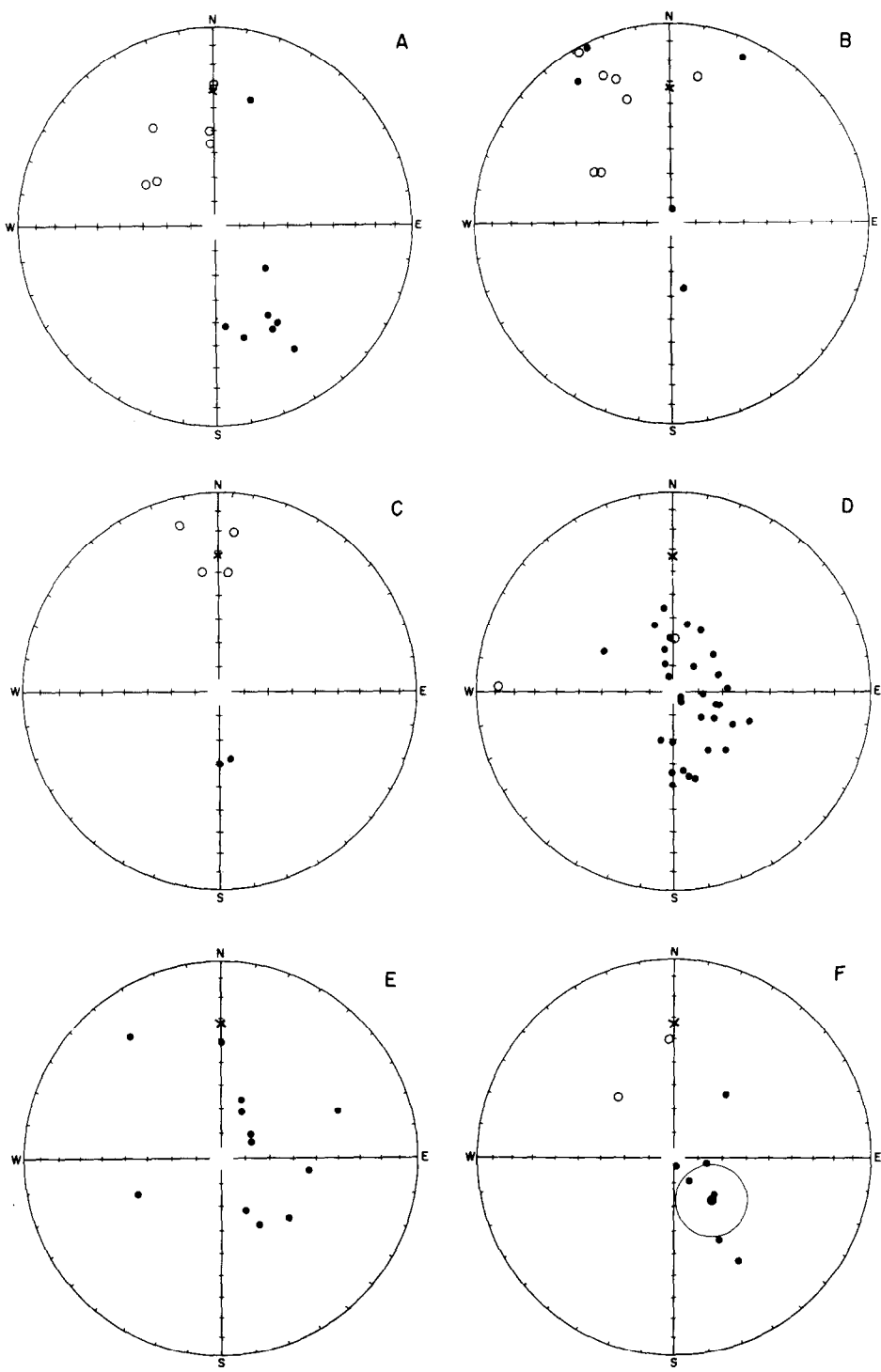


Fig.3.

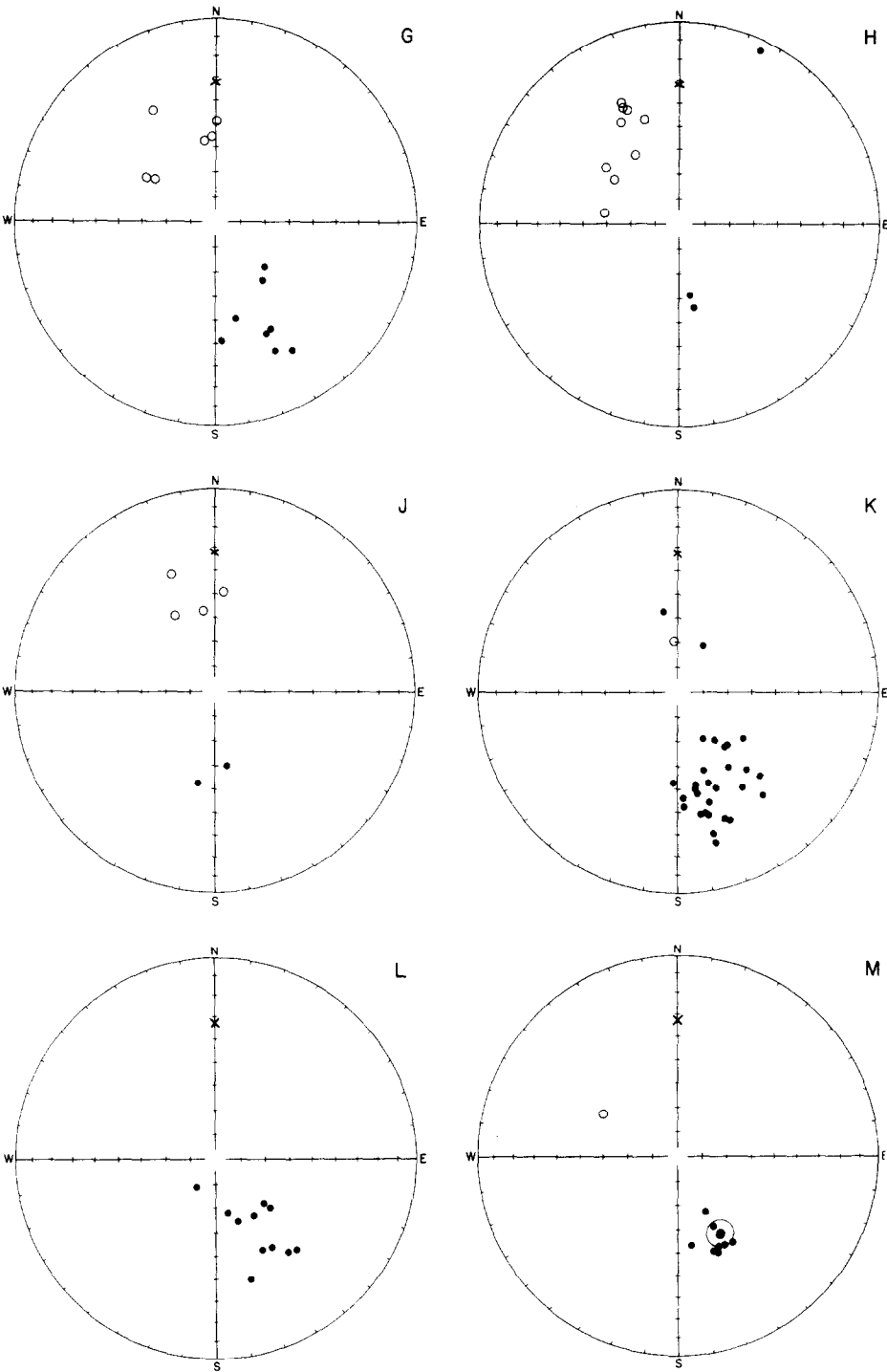


Fig.4. For legend see p. 46.

TABLE I

Mean directions of magnetization for localities of the Deccan traps*

Locality	Number of flows	E	Natural remanent magnetization				after a.c. demagnetization					
			initial		I (degr.)	k	α_{95} (degr.)	D		I (degr.)	k	α_{95} (degr.)
			D (degr.)	α_{95} (degr.)				D (degr.)	α_{95} (degr.)			
F Phonda	14	0	151.3	+51.6	8.8	14.2	155.1	+48.7	23.5	8.4		
G Amboli	6	6	356.9	-39.8	16.0	17.3	351.2	-52.5	47.3	9.8		
H Panhala	12	0	148.1	+39.2	4.0	25.0	140.9	+52.8	6.8	18.0		
id	12	2	-	-	-	-	151.7	+48.6	33.6	8.5		
J Phadgaon	6	1	132.9	+68.1	7.0	27.3	161.8	+39.1	45.6	11.4		
K Pohor	4	0	317.3	-55.0	3.2	61.5	300.5	-54.7	221.3	6.2		
L Durgada	4	0	169.7	+88.0	6.1	40.8	153.2	+57.6	27.3	17.9		
M Umrer	4	1	39.5	+55.6	6.4	53.6	152.8	+64.8	14.5	33.7		
N Nagpur	4	0	98.7	+76.6	3.0	-	146.6	+47.9	40.6	14.6		
O Ellichpur	36	6	146.1	+79.8	7.6	10.3	157.6	+51.4	13.7	7.4		
id	36	8	-	-	-	-	158.8	+47.8	27.8	5.3		
P L + M + N	12	2	-	-	-	-	148.0	+53.3	36.2	8.1		
Q All sections	9**	-	139.1	+67.1	10.5	16.7	150.8	+53.7	66.2	6.4		
R Deccan sect.***	14**	-	138.1	+65.0	15.2	10.5	151.1	+52.2	93.4	4.1		

* E is the number of flows excluded from the analysis; D and I are the declination and inclination of the magnetization direction; k is the precision parameter (Fisher, 1953); α_{95} is the semi-angle of the cone of 95% confidence.

** Number of sections included in the analysis.

*** Combined sections from both this and an earlier paper (Wensink and Klootwijk, 1971).

TABLE II

Virtual magnetic pole positions for some Deccan sections*

Locality	Positions sites		Positions poles		δp (degr.)	δm (degr.)
	latitude N (degr.)	longitude E (degr.)	latitude N (degr.)	longitude W (degr.)		
F Phonda	16.37	73.84	38.0	78.4	7.3	11.1
G Amboli	15.95	74.02	40.2	96.3	9.3	13.5
H Panhala	16.82	74.13	36.2	75.2	7.3	11.2
J Phadgaon	19.25	74.83	45.0	81.2	8.1	13.6
K Pohor	20.91	77.86	10.4	56.5	6.2	8.8
O Ellichpur	21.44	77.46	35.7	79.6	4.5	6.9
P L + M + N**	20.57	79.05	27.6	71.2	7.8	11.3

* δp and δm are the semi-axes of the oval of 95% confidence for the pole positions of the sections.

** Combined sections of Durgada, Umrer, and Nagpur (see Table I).

of magnetization. In the Durgada section one flow with a strongly deviating magnetization direction is intercalated between consistently, reversely magnetized flows. Such singular deviating directions are also found in table 2 of the paper by Pal et al. (1971), where flow-mean paleomagnetic directions of Deccan trap lava sequences are listed. The anomalous directions may be due to short excursions of the geomagnetic field. On theoretical grounds Cox (1968) and Hospers and Van Andel (1969) came to the conclusion that anomalous directions may occur, and that they are not necessarily restricted to periods of magnetic polarity inversions.

Apart from anomalous directions of magnetization a single flow with an inverted direction may be encountered in a series with a consistent magnetic polarity; viz. in the lower reversely magnetized part of the Phonda section (Fig.6) one normally magnetized flow occurs. This may point to the occurrence of a magnetic polarity event, a short term magnetic inversion during a much longer polarity epoch.

In the Deccan traps anomalous directions of magnetization which are intermediate at a

TABLE III

Pole positions calculated by combining pole positions of the sections*

	<i>N</i>	<i>K</i>	<i>A</i> ₉₅	Latitude N (degr.)	Longitude W (degr.)
Sections this paper**	6	87.4	7.2	34.8	80.3
All Deccan sections**	11	139.1	3.9	34.3	78.6

* *N* is the number of the sections; *K* is the precision of the section poles; *A*₉₅ is the semi-angle of the cone of 95% confidence for the mean pole position,

** Sections L, M, and N have been combined; section K (Pohor) is excluded for the analysis.

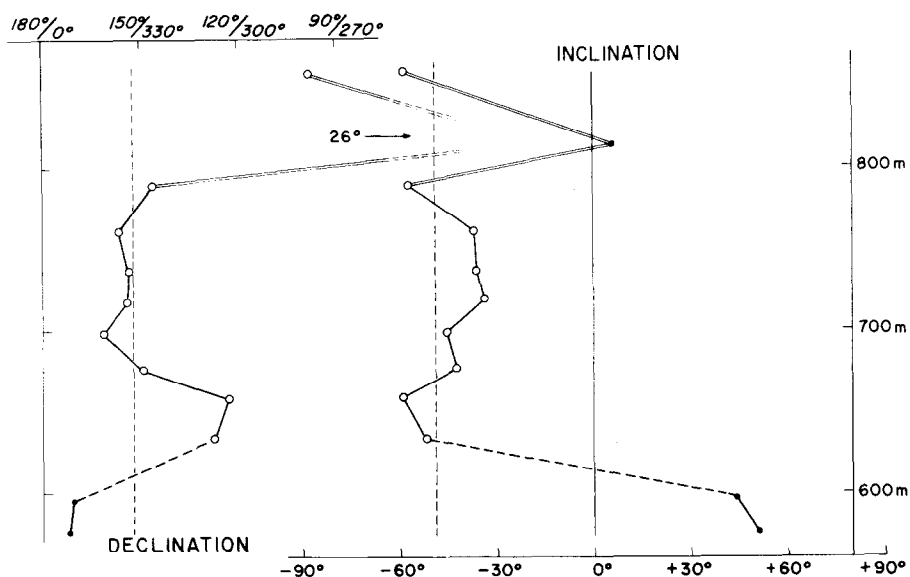


Fig. 5. Diagrams showing the declinations and inclinations of the characteristic magnetization of successive basalt flows of the Panhala section. Full line between successive points means that no flows are missing; dashed line denotes that one or more lava flows may be absent; a double line means a polarity transition. Full and open circles indicate reversed and normal magnetic polarity with respective declinations between c. 120° – 180° and c. 300° – 360° . The vertical dashed lines denote the mean values of the declination and the inclination for the section.

polarity transition (Ito and Fuller, 1969; Watkins, 1969) have not frequently been found. The volcanic area is not suitable for the presentation of this phenomenon, because the intercalated red partings between most of the flows suggest, that the basalts did not extrude in a very quick succession.

PALEOMAGNETIC STRATIGRAPHY (TENTATIVE GEOMAGNETIC TIME SCALE)

Using the combined results, a preliminary paleomagnetic stratigraphy for the Deccan traps based on polarity reversals will now be set up. The studies of rocks of the Western Ghats only revealed a simple paleomagnetic stratigraphy with a very thick sequence of reversely magnetized basalts overlain by a series of normally magnetized flows (Deutsch et al., 1959; Wensink and Klootwijk, 1971). This dual subdivision was also mentioned of the eastern Deccan near Jabalpur and Amarkantak by Athavale (1970), who correlated it with the Western Ghats. Pal et al. (1971) have recently combined the paleomagnetic results of the Deccan traps from several workers. In their opinion, the older classification of the Deccan basalts into only two polarity zones, a reverse zone overlain by a normal zone, cannot be retained. In their table 2 they have listed the characteristic magnetic directions of flows of several Deccan sections according to the elevations in the field. Pal et al. conclude



Fig.6. Diagrams showing the declinations and inclinations of the characteristic magnetization of successive flows of the Phonda section. For further explanation see Fig.5.

that there is not a simple correlation between magnetic polarity zones and elevations which is valid all over the Deccan area.

We agree with Pal et al. (1971) that there may be more than two polarity epochs in the Deccan and that an elevation criterion cannot be evolved everywhere, to demarcate the polarity inversion horizons.

In the Western Ghats, however, the inversion horizon of the magnetic polarity can be followed from near Poona to Amboli in the south (Fig.1). In the northern part this horizon dips very slightly south; the transition from reversed to normal magnetized flows at Kam-batgi and at Amba occurs at c. 1000 m and 600 m, respectively. From Amba southward the Phonda and Panhala sections show a level of polarity transition at c. 450 m and 600 m, respectively. At Amboli, further south, the transition is encountered at an elevation of c. 640 m.

At other places in the Deccan area correlations cannot easily be executed. Nevertheless with the data available an attempt has been made to set up a preliminary paleomagnetic

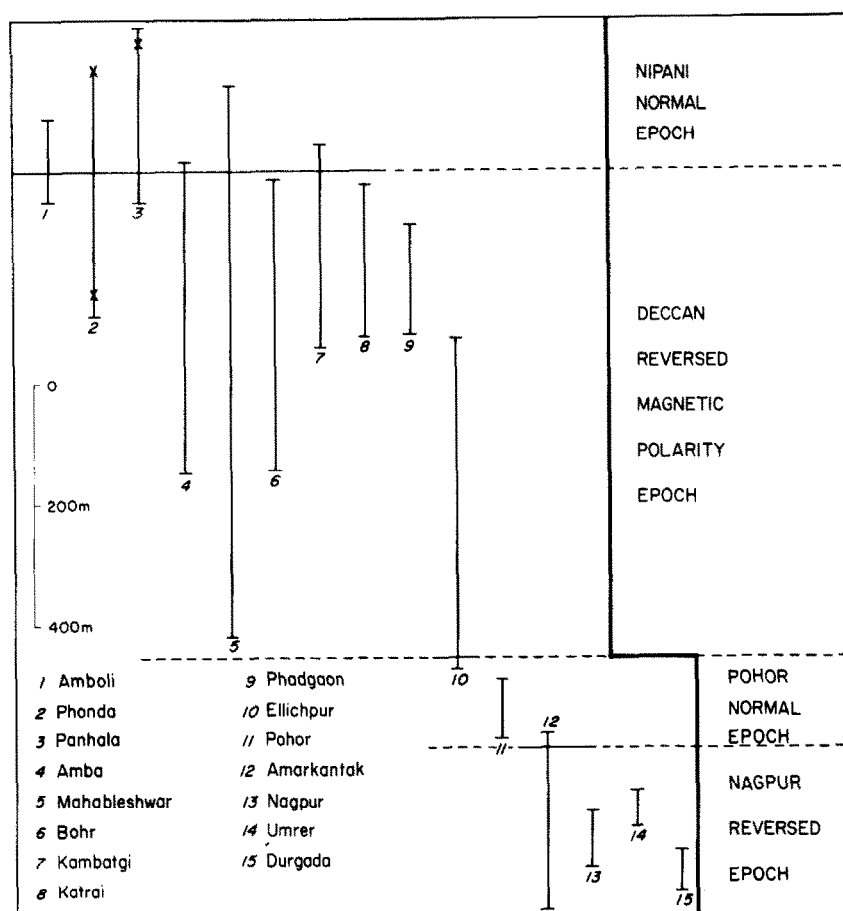


Fig.7. Tentative scheme of a preliminary paleomagnetic polarity time scale with four epochs with the aid of 15 paleomagnetically studied Deccan sections. Crosses in the sections denote the possible occurrences of paleomagnetic events.

stratigraphy. This is demonstrated in Fig.7, where names have been proposed for the successive polarity epochs as well.

According to Pascoe (1964) the early phases of eruption of the Deccan series can be found in the eastern part of the plateau basalt area around Nagpur. The sites sampled in sections near Durgada, Umrer, and Nagpur all reveal reversed magnetized flows and so does the earlier-collected material from Linga (Deutsch et al. 1959). The basalt flows near Amarkantak and near Jabalpur c. 180 km to the west also have reversed characteristic directions of magnetization. All these flows may belong to the oldest Deccan polarity epoch, for which we propose the name "Nagpur Reversed Polarity Epoch".

Athavale (1970), and Verma and Pullaiah (1967) (see Athavale, 1970) found normally magnetized flows on top of both the Amarkantak and Jabalpur sections. We came across a number of flows with normal magnetization along the road from Amravati to Pohor at

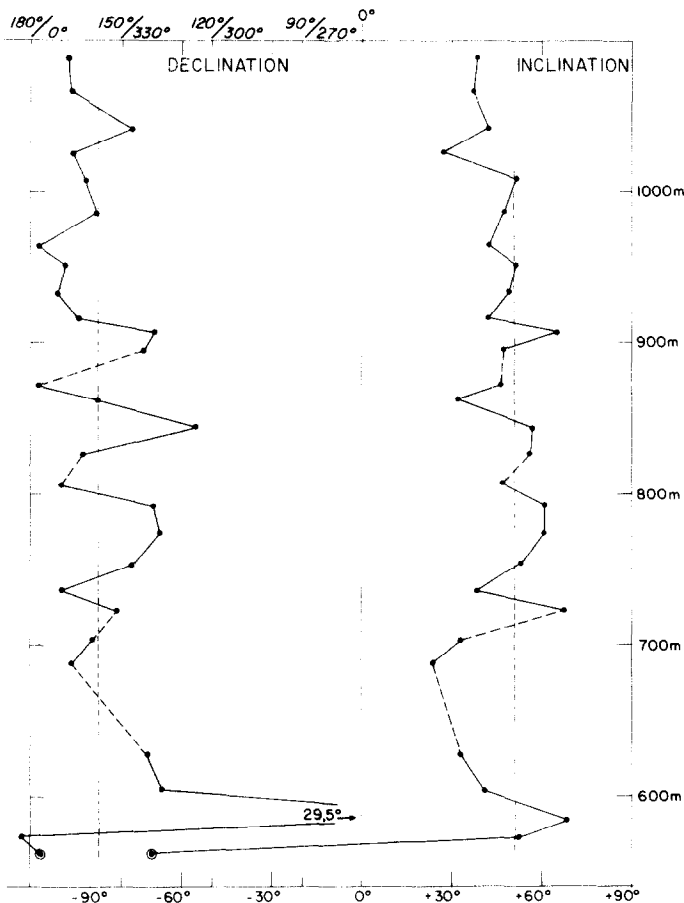


Fig.8. Diagrams showing the declinations and inclinations of the characteristic magnetization of successive flows of the Ellichpur section. For further explanation see Fig.5.

elevations of 300–400 m. North of it at an elevation of 560 m, the very long reversely magnetized section near Ellichpur revealed at an elevation of 560 m a normally magnetized basalt flow (Fig.8). Correlation here, however, may be hindered by faults. Anyhow, it seems likely, that a series of normal flows is intercalated between the reversely magnetized flows at Nagpur and Ellichpur respectively. For this time interval we propose the name “Pohor Normal Polarity Epoch”.

In the Gawilgargh Hills near Ellichpur a reversely magnetized series with a minimum thickness of 530 m has been observed (Fig.8). Though correlations over longer distances are quite uncertain, the Ellichpur section may be compared with the very long reversely magnetized section in the Western Ghats. The section near Phadgaon, situated between the Gawilgargh Hills and the Western Ghats also shows reversed flows only. In our opinion, the greater part of the Deccan flows have been poured out during this polarity interval for which

we propose the name "Deccan Reversed Polarity Epoch".

In the Western Ghats a number of sections show top series with normally magnetized flows. In the southern part of the Western Ghats normal flows were also reported from Nipani, as well as three other localities by Deutsch et al. (1959). This interval we call the "Nipani Normal Polarity Epoch".

During the discussion of the paleomagnetic results it has been pointed out that, within a paleomagnetic epoch, there are also short-term inversions of the geomagnetic field, the events. The example of one normal flow intercalated in an otherwise reversely magnetized series in the Phonda section has been noted already (Fig.6). Most probably the reversely magnetized top flow in the Phonda section as well as the reversed flow in the Panhala section, also represent events.

MOVEMENT OF THE SUBCONTINENT

In an earlier paper (Wensink and Klootwijk, 1971) it was put forward that during the Deccan volcanic activity the Indian subcontinent might have moved northward. The paleomagnetic results of both the lower and the upper parts of equivalent stratigraphical units of the Western Ghats' sections showed significant differences. On the other hand McElhinny (1968) was of the opinion that little or no movement had taken place during this period. His arguments are based on an analysis of Sahasrabudhe's material. For stratigraphical studies Sahasrabudhe (1963) collected c. 1000 samples at 71 sites from 30 lava flows and 13 dykes, spread all over the Deccan area. In his statistical analysis McElhinny combined the rock units on the basis of polarity irrespective of their location within the Deccan traps area.

The sections presented in this paper are less suited to decide whether or not the Indian subcontinent has moved at the time of the extrusions than those of the Western Ghats. The Ellichpur section is the longest with 36 sampled flows. This section has been subdivided into both a lower and an upper unit of 13 flows each, with an intercalated free zone of c. 100 m in thickness. The virtual pole positions computed from the mean directions of magnetization (Table IV) of these units are given in Fig.9 (nos. 2 and 3). There is an indication of a northward movement of the virtual poles during the period of extrusions, but their results are less reliable than those of the Western Ghats, because the Ellichpur units have quite large 95% ovals of confidence. In Table IV the combined paleomagnetic results of the probably oldest Deccan flows of the sections near Durgada, Umrter, and Nagpur are also given. Even though the number of flows included in the latter analysis is rather small, yet the virtual pole position (no. 1 in Fig.9) is compatible with the other results. The joint results imply a continuous northward movement of the subcontinent during the volcanic activity.

The floor of the Indian Ocean may definitely give information on the drift of the Indian subcontinent. Fisher et al. (1971) studied the evolution of the Central Indian ridge by means of topographic, magnetic, and earthquake epicentre data. They found, that the Indian Mid-Oceanic ridge had not been a zone of continuous sea-floor spreading since the

TABLE IV

Directions of magnetization and corresponding pole positions for a number of combined sites of part(s) of (a) section(s)^{*1}

Locality	Number of flows	Mean characteristic direction of magnetization				Paleolat.		Pole positions			
		D (degr.)	I (degr.)	k (degr.)	α_{95} (degr.)	S (degr.)		Lat. N (degr.)	Long. W (degr.)	δp (degr.)	δm (degr.)
Upper Ellichpur	13	162.7	+45.6	44.5	6.3	27.1		39.6	82.5	5.1	8.0
Lower Ellichpur	13	155.7	+50.3	22.7	8.9	31.0		33.5	77.6	8.0	11.9
L + M + N ^{*2}	12	148.0	+53.3	36.2	8.1	33.9		27.6	71.2	7.8	11.3
Upper W. Ghats ^{*3}	5 ^{*4}	155.0	+45.5	920.4	3.0	27.0		39.1	77.3	2.4	3.8
Lower W. Ghats ^{*3}	5 ^{*4}	158.0	+55.0	287.9	5.4	35.5		32.7	84.9	5.5	7.7

^{*1} For explanation of symbols see Tables I and II. All normally magnetized directions included in the analysis have been inverted by 180° for comparison with the other data.

^{*2} Combined sections of Durgada, Umrer, and Nagpur (see Tables I and II).

^{*3} Data copied from Wensink and Klootwijk (1971, table IV).

^{*4} Number of sections included in the analysis.

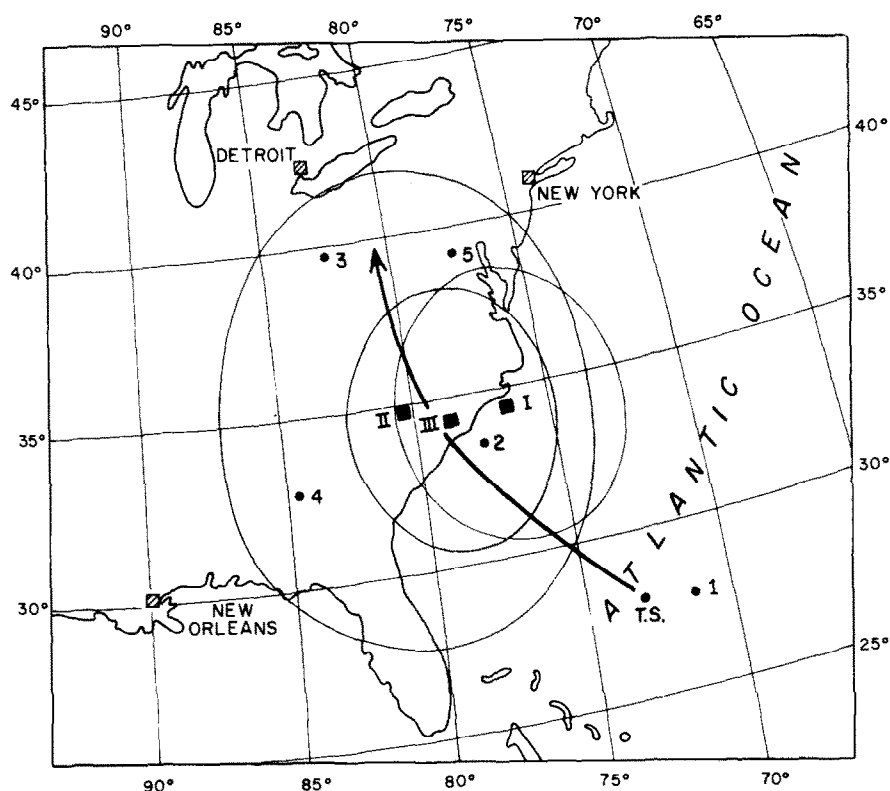


Fig.9. Map of eastern North America with some virtual magnetic pole positions obtained from Indian rocks. T.S. is the virtual pole of the Tirupati sandstones of Middle Cretaceous age (Verma and Pullaiah, 1967). The pole positions with arabic figures were derived from: (1) the combined Durgada, Umrer, and Nagpur sites; (2) the lower 13 flows of the Ellichpur section; (3) the upper 13 flows of the same section; (4) the combined lower parts, and (5) the combined upper parts of Western Ghats' sections. Poles 1 through 5 are listed in Table IV. The heavy line shows the path of the virtual magnetic poles obtained from Indian rocks from Middle Cretaceous through Lower Tertiary times. The other virtual magnetic poles, which are provided with the ovals of 95% confidence, are the respective poles of the Western Ghats (I) presented in an earlier paper; of this paper (II); and of the combined results of both papers (III).

Cretaceous. The magnetic anomalies 30 through 21 — i.e., Cretaceous–Eocene according to Heirtzler et al.'s time scale (1968) — belong to an E–W trending ridge. This ridge consisted of two main segments, the eastern part in the southeastern Indian Ocean and the western part in the Arabian Sea, both of which are linked by a very long N–S transform fault, the “Chagos Fracture Zone”. The magnetic anomalies 21 through 6 cannot be recognized in the Indian Ocean, but from anomaly 5 on, i.e., c. mid-Miocene, the spreading direction is NE–SW, with a calculated pole of relative motion between the Indian and Soma-lian plates located at 16.0°N , 48.3°E .

The paleomagnetic data reveal that during the Deccan volcanic activity, i.e., a period within the magnetic anomalies 30 through 21, a really very important drift of India oc-

curred. The northward movement of the subcontinent is compatible with the N–S spreading at that time. The paleomagnetic data do not furnish an exact amount of the drift during the period of volcanic activity. However, from our paleomagnetic data one can try to obtain a value for the rate of drift. The preliminary paleomagnetic stratigraphy based on polarity reversals as proposed in this paper for the Deccan traps (Fig. 7) may serve as a starting point. We selected pole positions computed for the Nagpur Reversed Polarity Epoch as well as from the combined Upper Western Ghats' units (Table IV). According to the time scale of Heirtzler et al. (1968) these poles may represent an age difference of 2–3 m.y., say 2.5 m.y. The mean inclination values of the selected units represent paleolatitudinal positions with a polar distance of 7° . From these data a drift movement of 30 cm/year can be deduced.*

About 60 m.y. ago the paleolatitudinal position of the Deccan area was 30° S; a continuous drift of India up to recent times means a northward movement of nearly 10 cm/year. If only intermittent movements have taken place, periods of very rapid drift must have occurred. The paleomagnetic data of the Deccan traps are in favour of a rapid drift; however, it must be emphasized that the accuracy of the data is not sufficiently large.

The sea-floor spreading since mid-Miocene times – from anomaly 5 on – may have caused a further northward drift of the subcontinent with a slight anticlockwise rotation. This is consistent with the preliminary paleomagnetic results obtained from the Miocene Lower Siwaliks of Pakistan (Wensink, 1972), which indicate that the India – Pakistan subcontinent was still far from its present position at that time.

ACKNOWLEDGEMENT

The author is much indebted to the late Prof. M.G. Rutten for his initiative to undertake this work. I express my sincere appreciation to Prof. J. Veldkamp and Mr. J.D.A. Zijdeveld for critically reading the manuscript. Thanks are also due to Mr. C.T. Klootwijk who kindly helped with the collection of samples.

REFERENCES

- Athavale, R.N., 1970. Paleomagnetism and tectonics of a Deccan trap lava sequence at Amarkantak, India. *J. Geophys. Res.*, 75: 4000–4006.
- Athavale, R.N. and Verma, R.K., 1970. Paleomagnetic results on Gondwana dykes from the Damodar valley coal-fields and their bearing on the sequence of Mesozoic igneous activity in India. *Geophys. J.*, 20: 303–316.
- Clegg, J.A., Deutsch, E.R. and Griffiths, D.H., 1956. Rock magnetism in India. *Philos Mag.*, 1: 419–436.
- Cox, A., 1968. Length of geomagnetic polarity intervals. *J. Geophys. Res.*, 73: 3247–3260.
- Deutsch, E.R., Radhakrishnamurthy, C. and Sahasrabudhe, P.W., 1959. Paleomagnetism of the Deccan traps. *Ann. Geophys.*, 15: 39–59.

* If one uses the paleomagnetic data of the Western Ghats only (Table IV), even an higher amount for the rate of drift is obtained.

- Fisher, R.A., 1953. Dispersion on a sphere. *Proc. R. Soc. Lond., Ser. A*, 217: 295–305.
- Fisher, R.L., Sclater, J.G. and McKenzie, D.P., 1971. Evolution of the Central Indian Ridge, western Indian Ocean. *Geol. Soc. Am., Bull.*, 82: 553–562.
- Heirtzler, J.R., Dickson, G.O., Herron, E.M., Pitman, W.C. and Le Pichon, X., 1968. Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. *J. Geophys. Res.*, 73: 2119–2136.
- Hospers, J. and Van Andel, S.I., 1969. Paleomagnetism and tectonics. *Earth-Sci. Rev.*, 5: 5–44.
- Ito, H. and Fuller, M., 1970. A paleomagnetic study of the reversal process of the geomagnetic field. In: S.K. Runcorn (Editor), *Palaeogeophysics*. Academic Press, London, pp. 133–137.
- Krishnan, M.S., 1960. *Geology of India and Burma*. Higginbotham, Madras, 4th ed., 604 pp.
- McDougall, I. and McElhinny, M.W., 1970. The Rajmahal traps of India – K/Ar ages and paleomagnetism. *Earth Planet. Sci. Lett.*, 9: 371–378.
- McElhinny, M.W., 1968. Northward drift of India – Examination of recent paleomagnetic results. *Nature*, 217: 342–344.
- Pal, P.C., Bindu Madhav, U. and Bhimasankaram, V.L.S., 1971. Early Tertiary geomagnetic polarity reversals in India. *Nature (Phys. Sci.)*, 230: 133–135.
- Pascoe, E.H., 1964. *A Manual of the Geology of India and Burma*, 3. Government of India Press, Calcutta, pp. 1345–2130.
- Rama, 1964. Potassium/argon dates of some samples from Deccan traps. *Int. Geol. Congr., 22nd, New Delhi, 1964, Rep.*, VII: 139–140.
- Sahasrabudhe, P.W., 1963. Paleomagnetism and the geology of the Deccan traps. *Semin. Geophys. Invest. Peninsular Shield. Osmania Univ., Hyderabad*, pp. 226–243.
- Verma, R.K. and Pullaiah, G., 1967. Paleomagnetism of Tirupati sandstones from Godavary valley, India. *Earth Planet. Sci. Lett.*, 2: 310–316.
- Watkins, N.D., 1969. Non-dipole behaviour during an Upper-Miocene geomagnetic polarity transition in Oregon. *Geophys. J.*, 17: 121–149.
- Wellman, P. and McElhinny, M.W., 1970. K/Ar age of the Deccan traps, India. *Nature*, 227: 595–596.
- Wensink, H., 1972. A note on the paleomagnetism of the Lower Siwaliks near Choa Saiden Shah, Potwar Plateau, West Pakistan. *Pak. J. Sci. Ind. Res.*, 15: 89–91.
- Wensink, H. and Klootwijk, C.T., 1971. Paleomagnetism of the Deccan traps in the Western Ghats near Poona (India). *Tectonophysics*, 11: 175–190.
- Zijderveld, J.D.A., 1967. A.C. demagnetization of rocks. In: D.W. Collinson, K.M. Creer and S.K. Runcorn (Editors), *Methods in Palaeomagnetism*. Elsevier, Amsterdam, pp. 254–286.