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PALEOMAGNETISM OF THE DECCAN TRAPS IN THE WESTERN GHATS NEAR POONA (INDIA)

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ABSTRACT

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Paleomagnetic results are presented from a study of basalts of the Deccan Traps near Poona, India. The traps have an Upper Cretaceous to Lower Eocene age. In five separate sections a total of circa 600 samples were collected from 97 lava flows, both by drilling and by hand-sampling. All samples were subjected to partial progressive a.c. demagnetization procedures and were measured with astatic magnetometers. The virtual magnetic pole computed from the mean value of the characteristic magnetizations is located at 34.5°N and 76.4°E with $dp = 3.4°$ and $dm = 5.1°$. Apart from the uppermost flows in three of the sections, the sequence of basalts has a reversed magnetic polarity. A northerly drift of the Indian subcontinent during the period of the Deccan volcanic activity seems likely.

THE DECCAN TRAPS

In the western and central parts of the peninsula of India plateau basalts cover an area of some 200,000 sq. miles (inset of Fig.1). These lavas, generally referred to as Deccan Traps, in part overlie Precambrian metamorphic and sedimentary deposits, in part Mesozoic sediments of the continental Gondwana formations. Apart from a frequently occurring thick cover of laterites, derived from the volcanics, younger rocks do not overlie the Deccan formation.

One of the most outstanding features of this volcanic sequence is the uniform horizontality of the flows. Only at a few localities do the strata have an appreciable amount of dip; e.g. on Bombay Island, where a western dip from 10 to 15 degrees is measured.

The petrography of the mainly non-porphyritic Deccan lavas is undiversified. The rocks are poor in olivine; whereas augite, mainly an enstatite-augite, and labradorite make up 90% of the rock; irregular grains of magnetite are common; the presence of leucoxene points to titaniferous minerals, and thin platelets of ilmenites are also seen. Glass is rather common and may amount to 20%. Chemical analyses of lavas from different localities in the Deccan area show a striking uniformity: for instance, in all samples ferrous oxide and ferric oxide make up respectively circa 3 and circa 11%; titanium oxide is present in an amount of slightly over 3% (Washington, 1922).

Because of the uniformity of the lavas, a reliable detailed stratigraphy of the Deccan formation is difficult to establish. Generally a subdivision into three units is made: the Lower, the Middle, and the Upper Traps. There are some non-volcanic sedimentary inter-

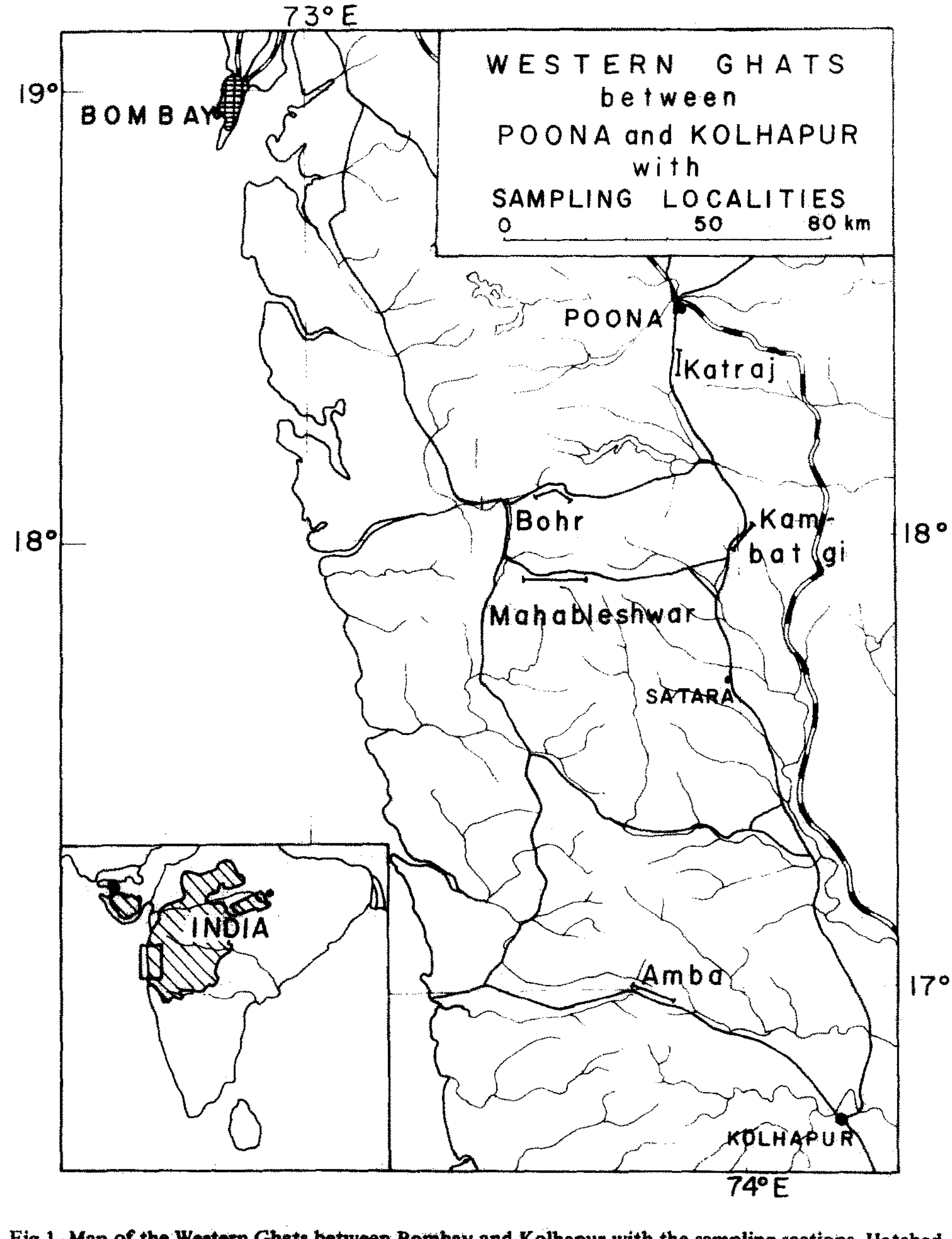

Fig. 1. Map of the Western Ghats between Bombay and Kolhapur with the sampling sections. Hatched part on inset map of India shows extension of the Deccan Traps.

calations. These mainly continental deposits, the so-called Inter-Trappean Beds, are very useful for the stratigraphy. Inter-Trappean Beds are intercalated in the Lower as well as in the Upper Traps. One comes across the Lower Inter-Trappean Beds in the eastern and north-eastern parts of the Deccan area: e.g. near Nagpur and in the Narbada valley. Here the beds overlie at most 150 m of lava flows resting in turn on pre-Deccan rocks. The Upper Inter-Trappean Beds, intercalated in basalts of the Upper Traps, are encountered on Bombay Island; however, these lavas are separated from the main sequence by a fault. In the Middle Traps non-volcanic sedimentary deposits have not been observed. The Western Ghats, an impressive mountain range along the Indian west coast which is the object of this study, consists for the greater part of lavas of the Middle Traps.

Only a rough estimate can be given for the thickness of the Deccan formation. At the west coast, where one finds the largest sections, the base of the sequence is not exposed. Moreover, a considerable part may have been eroded away from the top layers, whilst, in addition, the stratigraphical relation between the Upper Traps on Bombay Island and the remaining sequence is also obscure. A minimum thickness of 1,800 m can be ascertained, 1,200 m of which is taken up by the Middle Traps.

The age of the Deccan formation is still not exactly known. So far the radiometric age determinations from the basalts are poor, nor do the fossiliferous continental Inter-Trappean Beds yield conclusive results. From various discussions one may infer that, though the earliest traps may have an Upper Cretaceous age, the main bulk of the basalts probably dates from Lower Tertiary age (Krishnan, 1960; Pascoe, 1964).

PALEOMAGNETIC STUDY IN THE WESTERN GHATS

For a detailed paleomagnetic research on Deccan lavas the Western Ghats south of Poona were selected. In this region one comes across a number of well-exposed sections both along the main highway Poona-Kolhapur and along by-roads which cross the main range. In this paper the paleomagnetic results of five sections are presented; viz. from the Katraj and Kambatgi Ghats along the highway, and from along by-roads in the Ghats west of Bohr, west of Mahableshwar, and near Amba.

There are a number of reports on the paleomagnetism of the Deccan Traps (Clegg et al., 1956; Deutsch et al., 1959; Sahasrabudhe, 1963). In these publications the results are not based on a consistent and detailed sampling of lava flow sequences. In the present paper we discuss the secular variation of the earth's magnetic field during the period of extrusion covered by the sampled sections, and its value, if any, for a stratigraphical correlation between different sections. Moreover, mean values of the characteristic magnetizations for both the combined lower parts of the sections and the combined upper parts are presented, to examine whether or not a northward drift of the Indian peninsula is likely to have occurred during the period of volcanic activity. Finally, the stratigraphical significance of the paleomagnetic reversal is briefly hinted at.

The lavas exposed in the Western Ghats south of Poona belong to the Middle Traps, where non-volcanic sedimentary intercalations have not been found. Generally, individual lava flows can easily be separated in the field. Red partings between successive layers are often present. When these marker beds are absent an individual flow may be delimited at its base by a scoriaceous zone and at its top by a vesicular zone. The thickness of lava flows in this area varies between 5 and 40 m with an average of 25 m.

PALEOMAGNETIC PROCEDURES IN FIELD AND LABORATORY

The paleomagnetic sampling in the Deccan Traps was carried out during the winter season of 1966–1967. At the individual sections material was collected from all successively exposed lava flows. For the sampling a portable drill was used provided with a diamond core barrel of 2.5 cm inner diameter. A standard device was used for the orientation of the cores in the field; the measurements were taken with both magnetic compass and sundial. From a number of flows, however, oriented hand samples were taken. At least six cores or hand samples were collected from each flow.

In the laboratory the cores were sawn into cylinders of 22 mm length each. The lowermost specimen of each core was used only; where no conclusive results could be obtained more specimens of the same core, if available, were investigated. The hand samples were put in oriented position in cubes of plaster of Paris with ribs of 10 cm each. In this paper no distinction will be made between results of cores and hand samples.

The measurements for the detection of the intensity and the direction of the natural remanent magnetization – N.R.M. – and the demagnetization procedures, carried out in alternating magnetic fields, were executed in the Paleomagnetic Laboratory of Utrecht University with the help of standard equipment available.

The N.R.M. intensities of the specimens of four sections are presented in histograms (Fig.2). In the histograms the peak lies between 0.001–0.003 e.m.u. $\cdot$ cm^{-3} which is somewhat lower than in most Upper Tertiary and Quaternary basalts. In the Deccan Traps the field measurements, carried out with both a magnetic compass and a sun-dial, did not reveal appreciable differences. This may be due to the lower intensity of the N.R.M. of the basalts in this area.

For each flow the average N.R.M. direction was computed from the initial magnetization directions of the inidividual specimens. The mean directions of the lava flows of five Deccan sections were plotted on separate equal area projections (Fig.3). The projections show a large scatter indicating that the N.R.M. directions may be partly composite.

A partial progressive demagnetization in alternating magnetic fields – a.c. demagnetization – in at least 8 successive steps up to 500 Oe peak value was applied on one pilot specimen of each flow. After the successive measurements the results of this procedure were plotted in demagnetization diagrams where the paths of the decreasing magnetic vectors can be determined. This allows us to find out easily at which demagnetization step the secondary magnetic components, if there were any, were eliminated. For details on this useful method the reader is referred to Zijderveld (1967). The remaining specimens of each flow were treated with a few selected a.c. demagnetization steps only; to be on the safe side, these specimens were subjected to at least three steps.

For the bulk of the Deccan basalts an application of alternating magnetic fields of 300 Oe peak value turns out to be enough for the elimination of the secondary magnetization. After application of higher fields the magnetization of the rock does not change its direction any longer; it only shows a decrease in intensity. The eventual

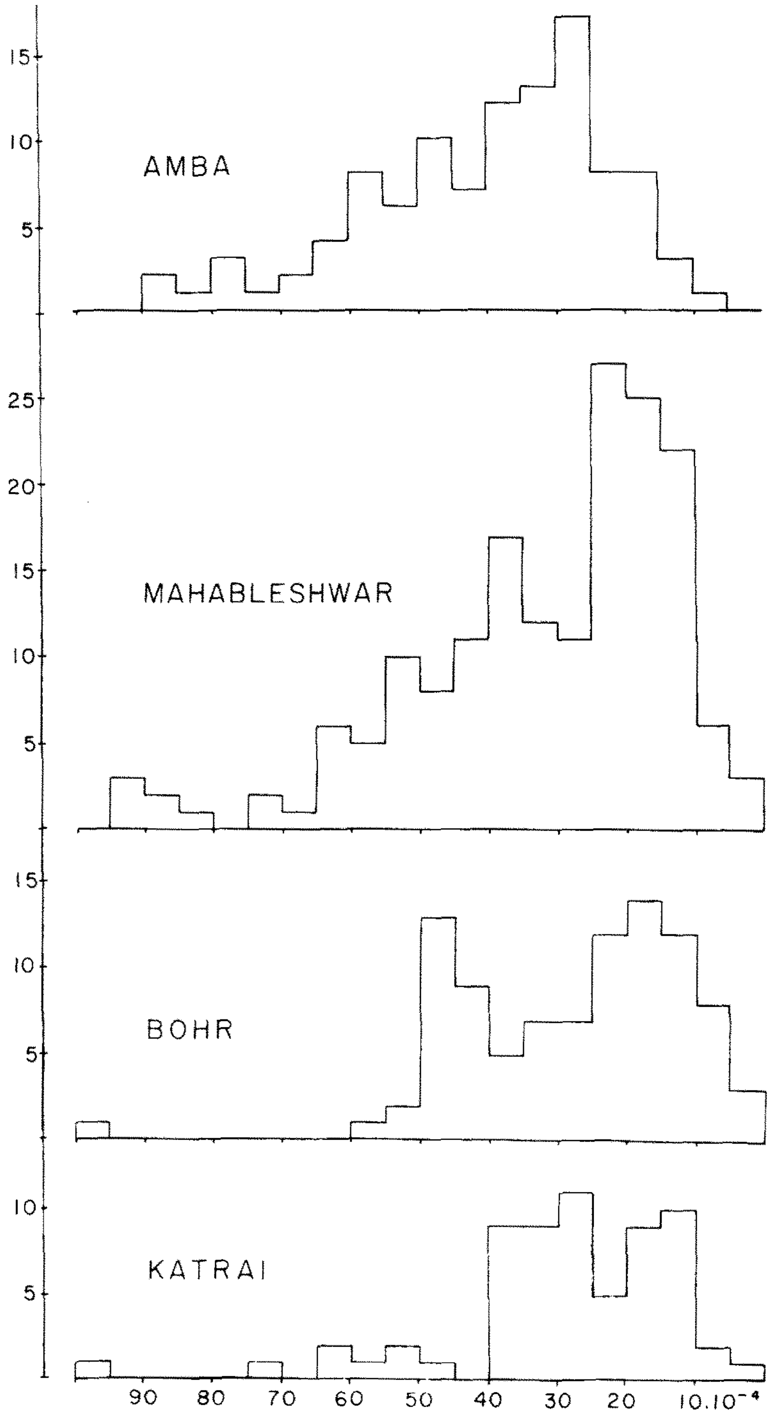

Fig.2. Histograms of the N.R.M. intensities of the specimens of four sections in the Western Ghats. The intensities in e.m.u. · cm^{-3} and the number of specimens are plotted on the horizontal and vertical scale respectively.

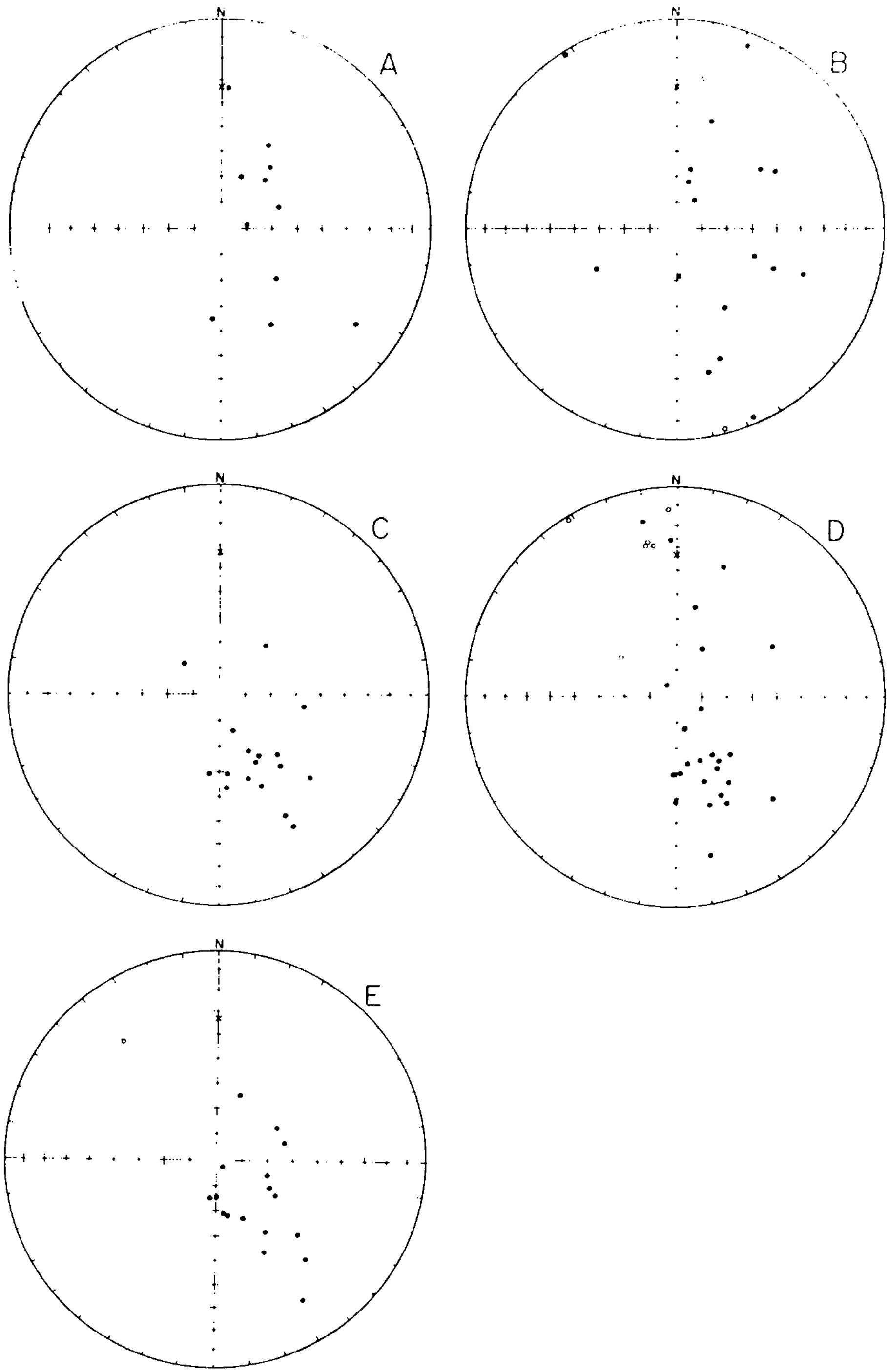

Fig.3. Equal area projections of the mean directions of N.R.M. of individual lava flows of five sections in the Western Ghats. *A*, *B*, *C*, *D*, and *E* are the Katrai, Kambatgi, Bohr, Mahableshwar, and Amba sections respectively.
A cross indicates the local direction of the field due to a geocentric axial dipole; full circles indicate that N-seeking poles are pointing downward; open circles denote that N-seeking poles are pointing upward.

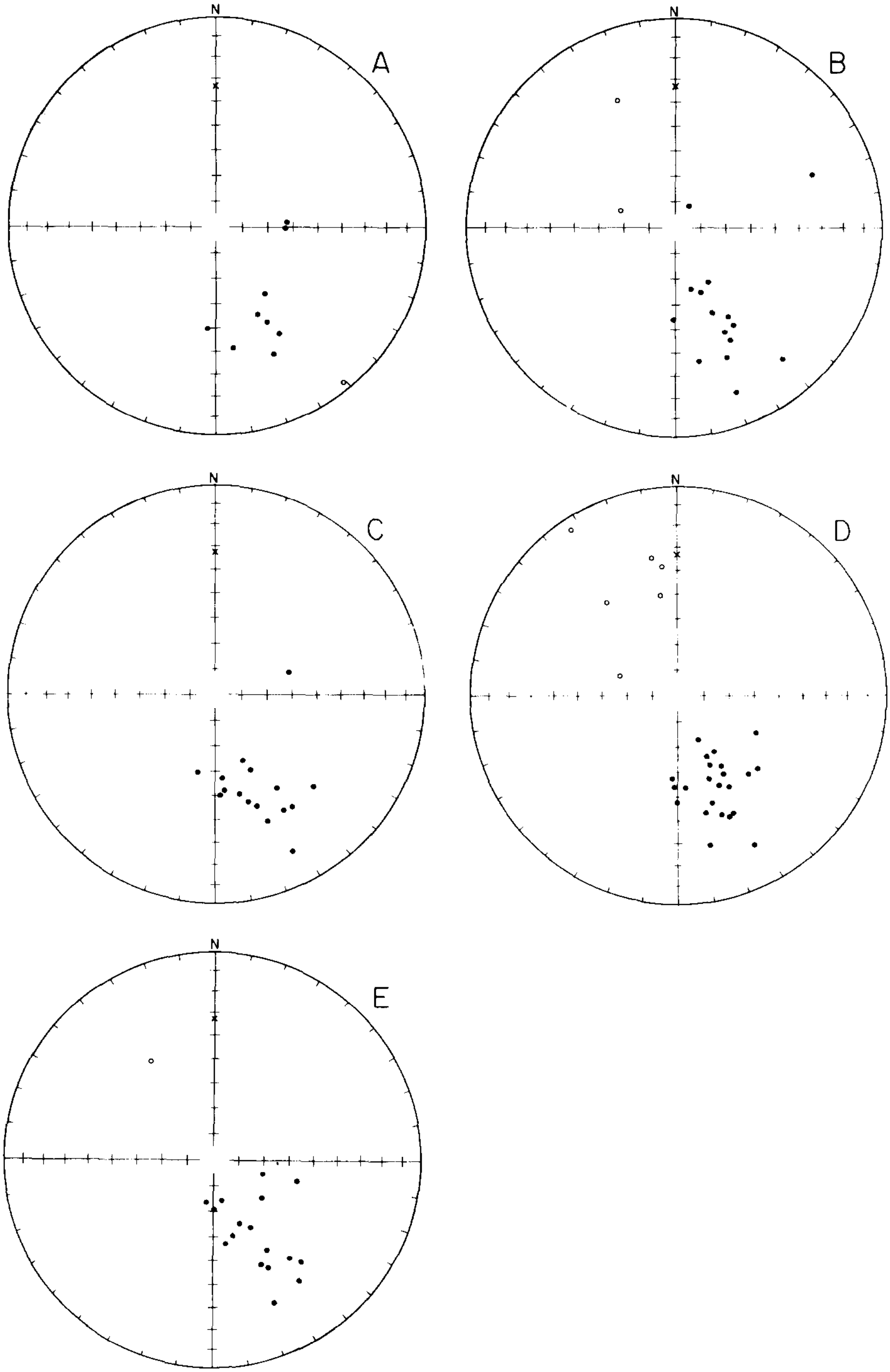

Fig.4. Equal area projections with the characteristic mean directions of magnetization of individual lava flows of five sections in the Western Ghats.after magnetic cleaning. For further explanation see Fig.3.

characteristic magnetic component is considered as the original thermo-remanent magnetization which the lava has obtained during its cooling.

After application of partial a.c. demagnetization of such a strength that the characteristic magnetic component had been singled out, the mean direction of magnetization for each flow was again computed. The latter directions have been plotted on the equal area projections of Fig.4, where one observes a striking decrease of the scatter with respect to the dispersion in Fig.3.

Several slightly decomposed lavas, from which fresh samples could not be collected, yielded difficulties during their paleomagnetic analyses. After demagnetization in a 100 Oersted peak value field the intensity of the magnetization was reduced to about 10% of the initial natural remanent magnetization. The Q-values, i.e. the ratios of remanent to induced magnetization, became very low for these particular rock samples. A part of these measurements was carried out on an astatic magnetometer placed in a field-free space in order not to be troubled by induced magnetization; however, some of these rocks appear to have a strong viscous magnetization. In a few cases a characteristic magnetic component could not be isolated at all. This was the case with seven lava flows out of 97. The results of these seven flows were disregarded.

DISCUSSIONS OF THE PALEOMAGNETIC RESULTS

The characteristic directions of magnetization in Fig.4 still show a considerable scatter. This is not so much the result of insufficient reliability of the mean directions, because only about 25% of all flows have semi-angles of the 95% cone of confidence of over 6°. Instead, the scatter as seen in Fig.4 can be explained in terms of secular variation of the earth's magnetic field during the extrusive period. Though the individual flows only present spot readings, because the time between successive flows usually is too long to follow the movement in detail, an impression of the order of magnitude of the secular variation can be obtained. For a further inspection the declinations and the inclinations of the characteristic magnetizations of successive flows are reviewed separately.

The diagrams of Fig.5 show the declinations irrespective of the polarity of the magnetization. In Fig.6 the same was done with the inclinations; here, the polarities are considered. In both presentations the positions of the successive points are plotted according to their elevations in the sections. When no flows are missing the successive points are connected with one another by full lines; a broken line between two points means that one or more lava flows is lacking.

In general, the maximal range of the declinations amounts to about 40° (Fig.4). However, some flows show strongly deviating declinations. The paleomagnetic data of these flows are definitely not less reliable. Such deviating characteristic directions of magnetization in detailed studies of rocks sequences are often met with. A conclusive explanation can seldom be given. When no geological explanation, e.g. an influence by intrusions, is likely, a transition to a polarity reversal may be responsible for deviating directions. There is, however, nothing to support this in our sections. According to Hospers and Van Andel (1969) anomalous paleomagnetic directions may be produced as a result of the directional instabilities of the geomagnetic field at the time, but perhaps also outside the time of polarity reversals of the earth's magnetic field. In his probability model for

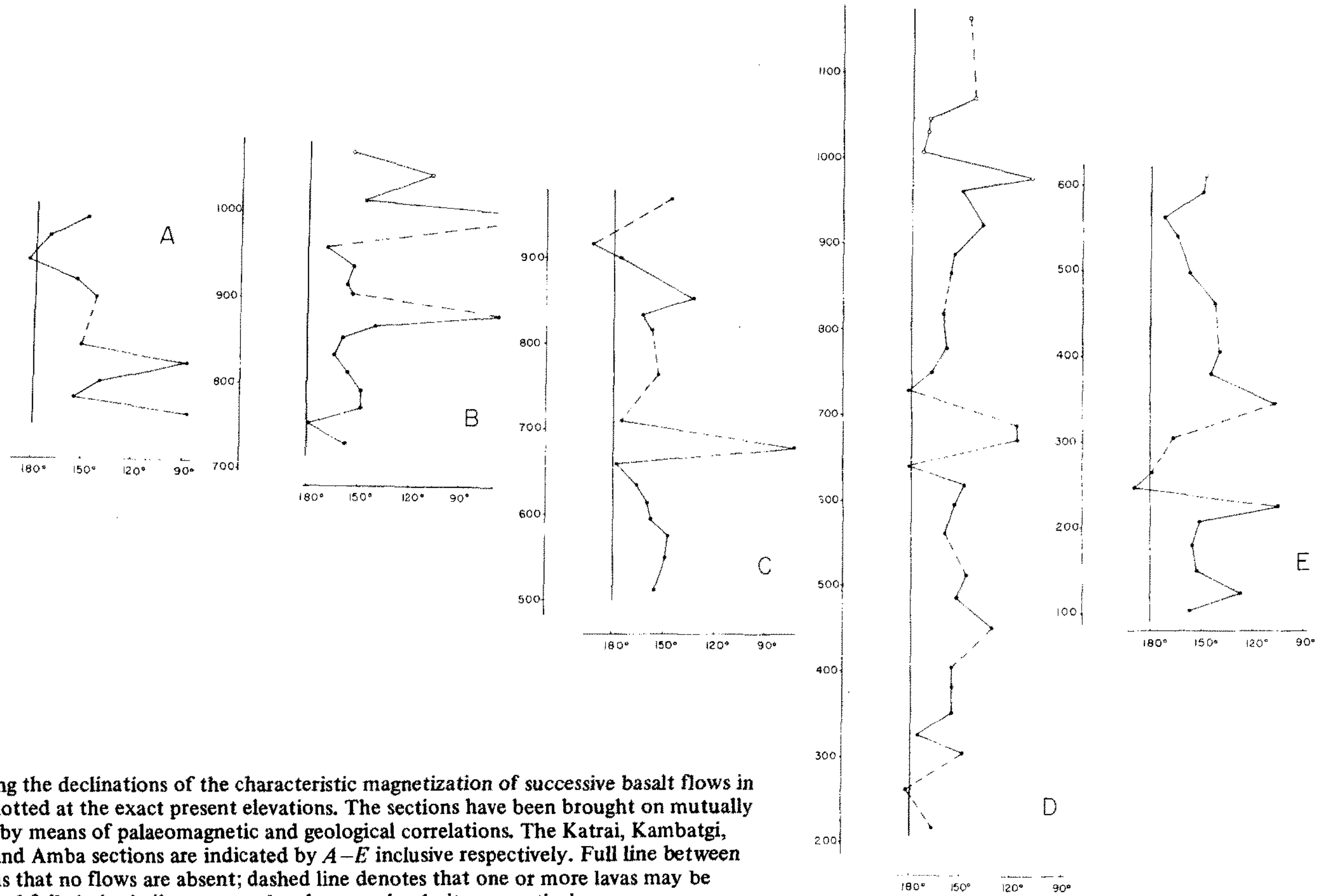

Fig. 5. Diagrams showing the declinations of the characteristic magnetization of successive basalt flows in five Deccan sections plotted at the exact present elevations. The sections have been brought on mutually corresponding heights by means of palaeomagnetic and geological correlations. The Katrai, Kambatgi, Bohr, Mahableshwar, and Amba sections are indicated by A–E inclusive respectively. Full line between successive points means that no flows are absent; dashed line denotes that one or more lavas may be missing. Open circles and full circles indicate normal and reversed polarity respectively.

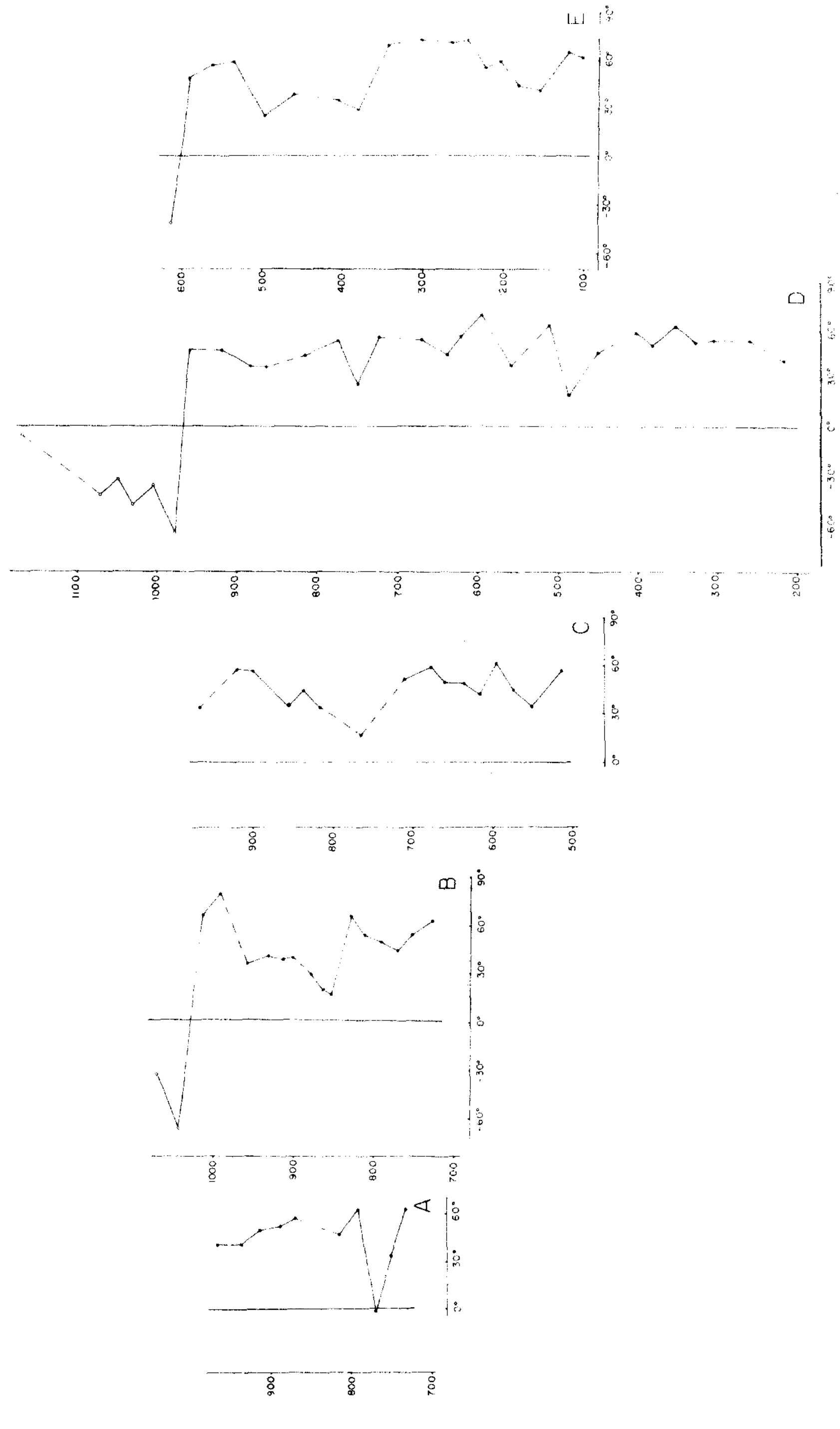

Fig.6. Diagrams showing the inclinations of the characteristic magnetization. For further explanation see Fig.5.

polarity reversals Cox (1968) showed that anomalous directions of magnetic field are not necessarily restricted to polarity reversals; in this model he considers the effect of the interaction between steady oscillations of the geomagnetic dipole and independent secular variations of the non-dipole field.

There are also a number of flows that have strongly deviating inclinations; these flows are not identical with those with strongly deviating declinations (Fig.6).

In the basalt flows from the Katrai and Bohr Ghats only positive inclinations were encountered. The upper flows of the Kambatgi and Mahableshwar sections have negative inclinations; the polarity reversal in these sections, which lie about 40 km apart is situated at an altitude of about 1,000 m. In the Amba section it is much lower, at an elevation of about 600 m. The distance between the Mahableshwar and Amba sections is roughly 100 km. This implies that if one assumes that the levels of the polarity reversal in both sections are identical, in this area the southern component of the general dip of the Deccan lavas amounts to no more than ¼°. This is likely to be true, because all known sections show one reversal only. In the Western Ghats the rough paleomagnetic stratigraphy based on the polarity reversal seems to be consistent with the striking horizontality of the lavas.

In plateau basalt areas single lava flows may have an extension up to more than 100 km. Thus, one may expect that in our part of the Deccan area a particular flow could be found in more than one section. This can be checked if there are exact determinations of the characteristic directions of magnetization of the lavas. A particular basalt flow which occurs in different sections may reveal identical directions of thermo-remanent magnetization. A similar study was carried out with encouraging results in an Upper Tertiary plateau basalt sequence in France (Wensink, 1970).

The readings of the Deccan sections show considerable scatter (Fig.4–6). Provided one starts from the level of the polarity reversal, a tentative correlation can be made between a number of flows at different sections if one compares the declinations and inclinations in flows of neighbouring sections. Although some flows have corresponding characteristic directions, the results are inadequate for a detailed correlation.

The average directions of magnetization of the individual sections were computed from the flow means. They are listed in Table I with the data both from before and after a.c. demagnetization; the values of the mean directions combined for all five sections also is presented. The virtual pole positions calculated from the mean directions of characteristic magnetization of Table I are listed in Table II. In Table III an average pole position that is computed from the mean poles of all five sections is given. This pole, indicated by the abbreviation M.P., is shown in Fig.7. The position of this pole deviates only slightly from the earlier published combined Deccan Traps pole (Irving, 1964).

All earlier paleomagnetic results from rocks of Upper Carboniferous up to and including Eocene age in India have indicated that during this period the Indian subcontinent was situated far to the south of its present position. This implies that for India a rapid northward-directed drift during Tertiary times must be accepted. According to McElhinny (1968) one should assume a speed of drift of 10 cm/year supposing that India started to move when the extrusions of the Deccan lavas had ended and that it reached its present position in the Miocene. In order to answer the question whether or not there was drift during the period of volcanic activities in the Deccan, McElhinny (1968), with the help of Sahasrabudhe's (1963) data, compared the paleomagnetic results of the lower reversed

TABLE I

Mean magnetization directions for some Deccan Traps localities[1]

Locality	Number of flows	E	Natural remanent magnetizations							
			before demagnetization				after a.c. demagnetization			
			D (degr.)	I (degr.)	k	α_{95} (degr.)	D (degr.)	I (degr.)	k	α_{95} (degr.)
A Katraj	11	1	95.4	+69.9	7.1	19.5	147.9	+47.1	9.5	16.5
B Kambatgi	19	2	136.1	+55.7	3.5	22.3	148.3	+50.2	9.9	11.9
C Bohr	17	1	147.9	+57.9	16.7	9.3	155.9	+47.8	17.4	9.1
D Mahableshwar	32	3	151.6	+54.9	4.4	14.4	156.8	+48.4	21.3	5.9
E Amba	18	0	135.2	+63.9	11.1	10.8	149.0	+54.2	18.8	8.2
All sections			136.8	+61.6	49.8[2]	10.9	151.7	+49.6	402.7[2]	3.8

[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.
[2] Sections unit value.

TABLE II

Pole positions of some Deccan Traps sections

Localities	Positions sites		Positions poles			
	latitude N (degrees)	longitude E (degrees)	latitude N (degrees)	longitude W (degrees)	δp[1]	δm[1]
A Katraj	18.40	73.86	33.9	71.8	13.8	21.4
B Kambatgi	18.00	74.00	32.3	73.8	10.7	16.0
C Bohr	18.13	73.61	37.5	79.6	7.7	11.9
D Mahableshwar	17.93	73.58	37.7	80.7	5.1	7.8
E Amba	16.96	73.77	30.5	76.8	8.1	11.5
All sections	17.85	73.78	34.5	76.4	3.4	5.1

[1] δp and δm are the semi-axes of the oval of 95% confidence for the pole position of the section(s).

TABLE III

Pole position calculated by combining pole positions of the sections[1]

N	K	A_{95}	Latitude N (degrees)	Longitude W (degrees)
5	335	4.2	34.44	76.47

[1] 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.

(with positive inclinations) lavas with those of the upper normal (with negative inclinations) lavas. He concluded that there was little or no virtual polar movement during the extrusive period and thus no drift occurred at that time.

To carry out a similar test with our material one should make use of equivalent rock units if possible. In our sections the upper normally magnetized lavas are, however, poorly represented or even absent. Therefore, the boundary between a lower and an upper rock unit must be placed elsewhere. This is done for the Kambatgi, Bohr, Mahableshwar, and Amba sections by means of a central zone about half way up the basalt sequences. The rock units situated below and above this zone are equivalent for the test. In the central zone some flows were disregarded to avoid an overlap of time between units from different sections.

In Table IV the mean directions of characteristic magnetization for both the lower parts and the upper parts of four sections are given, together with their corresponding pole position. The mean pole positions computed from the individual poles listed in Table IV are given in Table V. These virtual pole positions are shown in Fig.7; they are provided with circles of 95% confidence. There is a significant difference between the virtual magnetic poles derived from the lower part and from the upper part of the sections. The results of this test strongly support the thesis that India has moved northward in the period of outflow of the Deccan lavas.

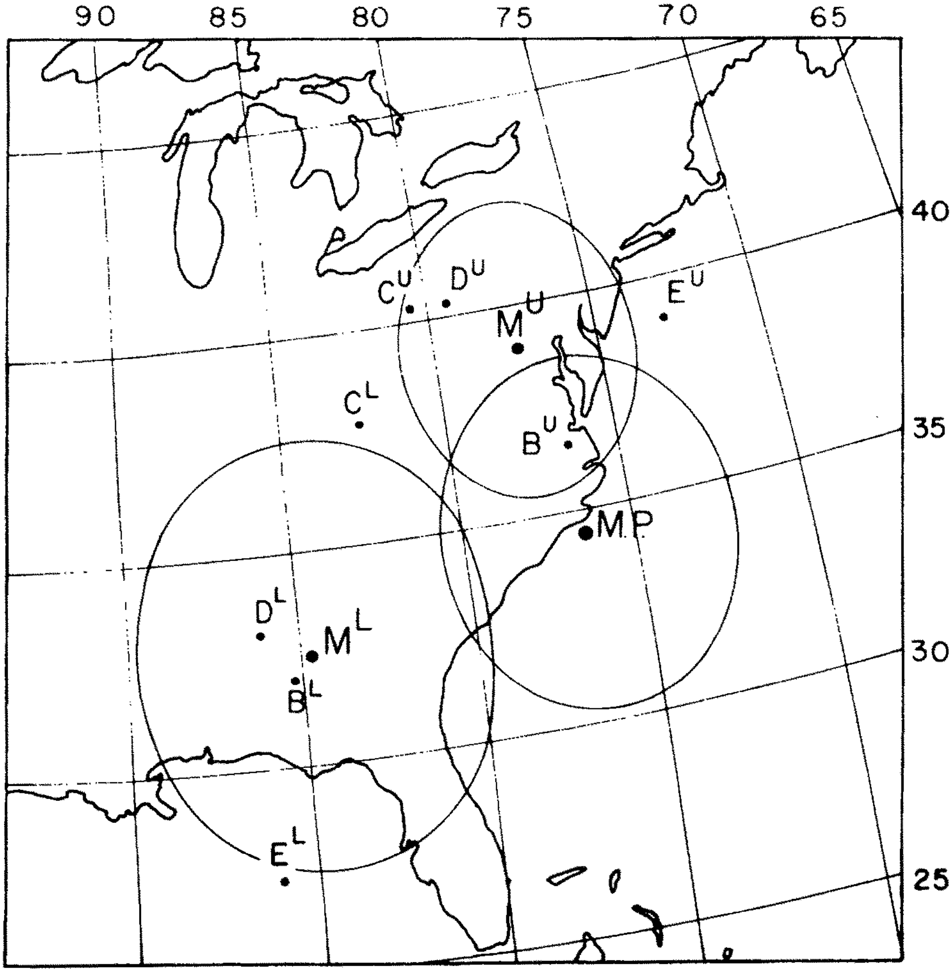

Fig.7. Map of the western part of North America with some virtual magnetic pole positions of the Deccan Traps.
M.P. is the mean pole computed from the pole positions of the individual sections. B^L, C^L, D^L, and E^L are the poles of the lower parts of respectively the Kambatgi, Bohr, Mahableshwar, and Amba sections; B^U, C^U, D^U, and E^U, are those of the upper parts of the sections. The poles indicated with M^L and M^U are the mean poles of the combined lower parts and the combined upper parts of the four sections.

In the basalt sequences of the Western Ghats one comes across only one reversal of magnetic polarity. In general, nearly always in Upper Cenozoic lavas several polarity reversals are found. Does this mean that the Deccan lavas have extruded in a relatively short interval of time, say about 2 million years? The presence of red partings between some successive lavas as well as the thoroughly decomposed character of a number of flows do not support this view. Very little is known about the length of the magnetic polarity epochs

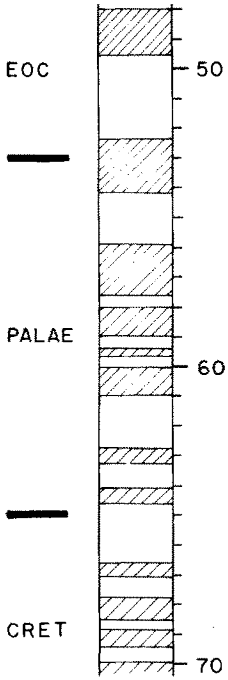

Fig.8. Lower part of the geomagnetic time scale (after Heirtzler et al., 1968). White parts and hatched parts are the periods with normal and reversed polarity respectively.

TABLE IV

Directions of magnetization and corresponding pole positions for both lower and upper parts of 4 Deccan Traps sections[1]

Localities	Number of flows	Mean characteristic direction of magnetization				Pole position			
		D (degr.)	I (degr.)	k	α_{95} (degr.)	Lat. N (degr.)	Long. W (degr.)	δp	δm
B - upper	6	153.3	+47.7	17.2	16.6	36.6	76.6	14.1	21.7
C - upper	6	158.1	+45.3	19.7	15.5	40.3	80.5	12.5	19.6
D - upper	12	157.2	+44.9	28.8	8.2	40.4	79.3	6.6	10.4
E - upper	7	151.6	+44.1	32.3	10.8	39.1	72.8	8.5	13.5
B - lower	6	158.2	+55.6	58.3	8.8	32.1	85.3	9.0	12.6
C - lower	7	158.3	+49.0	50.6	8.6	37.6	82.5	7.5	11.3
D - lower	13	159.2	+54.7	41.7	6.5	33.3	86.1	6.5	9.2
E - lower	7	155.8	+60.5	28.9	11.4	27.4	86.0	13.2	17.4
All-upper	–	155.0	+45.5	920.4	3.0	39.1	77.3	2.4	3.8
All-lower	–	158.0	+55.0	287.9	5.4	32.7	84.9	5.5	7.7

[1] For explanation of symbols see Table I and II.

TABLE V

Pole positions calculated by combining the pole positions of both the upper and the lower parts of 4 Deccan sections[1]

Sections	N	K	A_{95}	Latitude N (degrees)	Longitude W (degrees)
Upper	4	644	3.6	39.11	77.28
Lower	4	337	5.0	32.61	85.02

[1] For explanation of symbols see Table III.

during the Lower Tertiary. Recent information is given by Heirtzler et al. (1968) who published an extrapolated geomagnetic time scale with polarity reversals for the last 70 million years. Their study is based on the data of the magnetic anomaly patterns in the oceans and on the supposedly constant spreading rates of the oceanic crust. The time scale shows fairly long periods of reversed magnetic polarity during the Lower Tertiary (Fig.8). It is striking that the greater part of our sequence has a reversed magnetic polarity. If this extrapolation is valid, our reversed polarity epoch may correspond to one of the longer reversed epochs of Heirtzler's scale.

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