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The northward motion of India since the Late Cretaceous

John W. Peirce[*] *Massachusetts Institute of Technology, Woods Hole Oceanographic Institution Joint Program in Oceanography, Woods Hole, Massachusetts 02543, USA*

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Summary. Palaeomagnetic data are presented from the sediments and basalts at DSDP sites 213, 214, 215, 216, and 217 on or near the Ninetyeast Ridge in the eastern Indian Ocean. The palaeolatitudes confirm that the ridge is attached to the Indian plate and that both have moved rapidly northwards since the Late Cretaceous. The Indian plate moved northwards with respect to the South Pole at an average rate of 14.9 ± 4.5 cm/yr from 70 Myr ago until about 40 Myr ago when it slowed to its present rate of 5.2 ± 0.8 cm/yr.

Basement palaeolatitudes on the Ninetyeast Ridge indicate that its volcanic source was approximately fixed in latitude near 50° S, supporting the concept that the ridge is the trace of the Kerguelen hotspot on the northward moving Indian plate. The existence of a 'mirror ridge' on the Antarctic plate and the very shallow depths of basement formation on the ridge suggest that the Indian/Antarctic spreading centre must have remained near the hotspot from 80 to 40 Myr in spite of one-limb spreading rates of up to 12 cm/yr. This is unexpected in view of the apparently small amount of motion of the Antarctic plate during this time. It is suggested that Antarctica was held nearly fixed by the geometry of other plate motions, and therefore the Kerguelen hotspot caused asymmetric accretion of new plate material at the southwestern end of the Ninetyeast Ridge. Evidence of such asymmetry has been reported in the form of an 11° southerly migration or jump of that spreading centre.

The Ninetyeast Ridge palaeolatitudes are consistent with the Deccan Traps palaeomagnetic poles. However, a comparison of the Australian palaeomagnetic poles and these data shows a major inconsistency between 50 and 40 Myr. Although the reason for this inconsistency is not known, the error may be in the age of the Barrington volcano pole for Australia. The two data sets compare favourably in both rate and palaeolatitude back to 40 Myr. Prior to 50 Myr they compare favourably in rate but the DSDP data imply that India was 13° farther south than the Australian poles indicate.

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[*] Present address: Department of Geology, Dalhousie University, Halifax, Nova Scotia, Canada.

1 Introduction

There is a wealth of palaeontologic, geomagnetic, and tectonic evidence to suggest that the Indian plate has experienced large and rapid northward motion during the Late Cretaceous and Tertiary. One of the remarkable features of this plate is the Ninetyeast Ridge, a 4500 km long, linear, aseismic ridge which lies near the 90th meridian. It runs from about 32° S to about 10° N, where it comes buried under the sediments of the Bengal Fan. Legs 22 and 26 of the Deep Sea Drilling Project (DSDP) drilled five holes along the length of the Ninetyeast Ridge. The stratigraphy and palaeontology of these sites (von der Borch *et al.* 1974; Davies *et al.* 1974; Luyendyk 1977) provide evidence of extensive northward motion but there is no direct estimate of the rate or the amount of motion.

In this paper I present palaeomagnetic data from DSDP sites 214, 216, and 217 on the Ninetyeast Ridge, and also from sites 215 and 213 on either side of it. These data come from several biostratigraphic horizons in the Tertiary and uppermost Cretaceous sediments, as well as from the underlying basalts. They allow a direct, quantitative estimate of the rates of northward motion of the Indian plate. The tectonic implications of these palaeolatitudes for the origin of the Ninetyeast Ridge and the relative motion between India and Australia are discussed in detail.

2 Tectonics of the Indian Ocean

The Indian Ocean has the most complicated tectonic history of any of the world's oceans because its floor has been shaped by the complex breakup and dispersal of the Gondwanaland continent. In the early Cretaceous this huge landmass started to break up, and the formation of the Indian Ocean began (McKenzie & Sclater 1971; Sclater & Fisher 1974; Luyendyk 1974). The Indian subcontinent moved rapidly northward, and eventually it began to collide with Asia. Two long aseismic ridges, the Ninetyeast Ridge to the east, and the Chagos–Laccadive Ridge to the west, marked the transform faults which once bounded the oceanic portion of the Indian plate (Fig. 1). Both of these transform faults had active portions which were thousands of kilometres in length. To the east of India lay the Sunda plate (now subducted) and the Wharton Basin–Australian plate (Fig. 2). To the west lay the African plate and the Chagos Transform Fault.

The Ninetyeast Ridge is a curious feature which dominates the topography of the eastern Indian Ocean (Fig. 1). It is some 4500 km long, roughly 50–100 km wide, and its relief above the surrounding ocean floor averages about 2 km. Bathymetric profiles across the ridge are usually asymmetric, often showing a scarp along the eastern side (Laughton, Matthews & Fisher 1971). A fracture zone lies near the foot of this escarpment (Bowin 1973).

The Ninetyeast Ridge itself has been variously interpreted as a horst (Francis & Raitt 1967); as the result of overriding plates (Le Pichon & Heirtzler 1968); as the trace of a mantle plume (hotspot) beneath the northward moving Indian plate (e.g. Morgan 1972a, b); and as a volcanic mass erupted at the junction of a spreading centre and a transform fault (Sclater & Fisher 1974). The gravity and seismic data presented by Bowin (1973) indicate that the ridge is nearly isostatically compensated, hence they are not compatible with either the horst or the overriding plate theory.

Sclater & Fisher (1974) found that the crust west of the ridge becomes older to the north while that east of the ridge becomes older to the south. They postulated that the fracture zone east of the ridge marks an old transform fault (Ninetyeast Fault) which separated the Wharton Basin and the Indian plate during the early Tertiary. A precursor to the present Southeast Indian Ridge lay at the southern end of this transform fault on its western side.

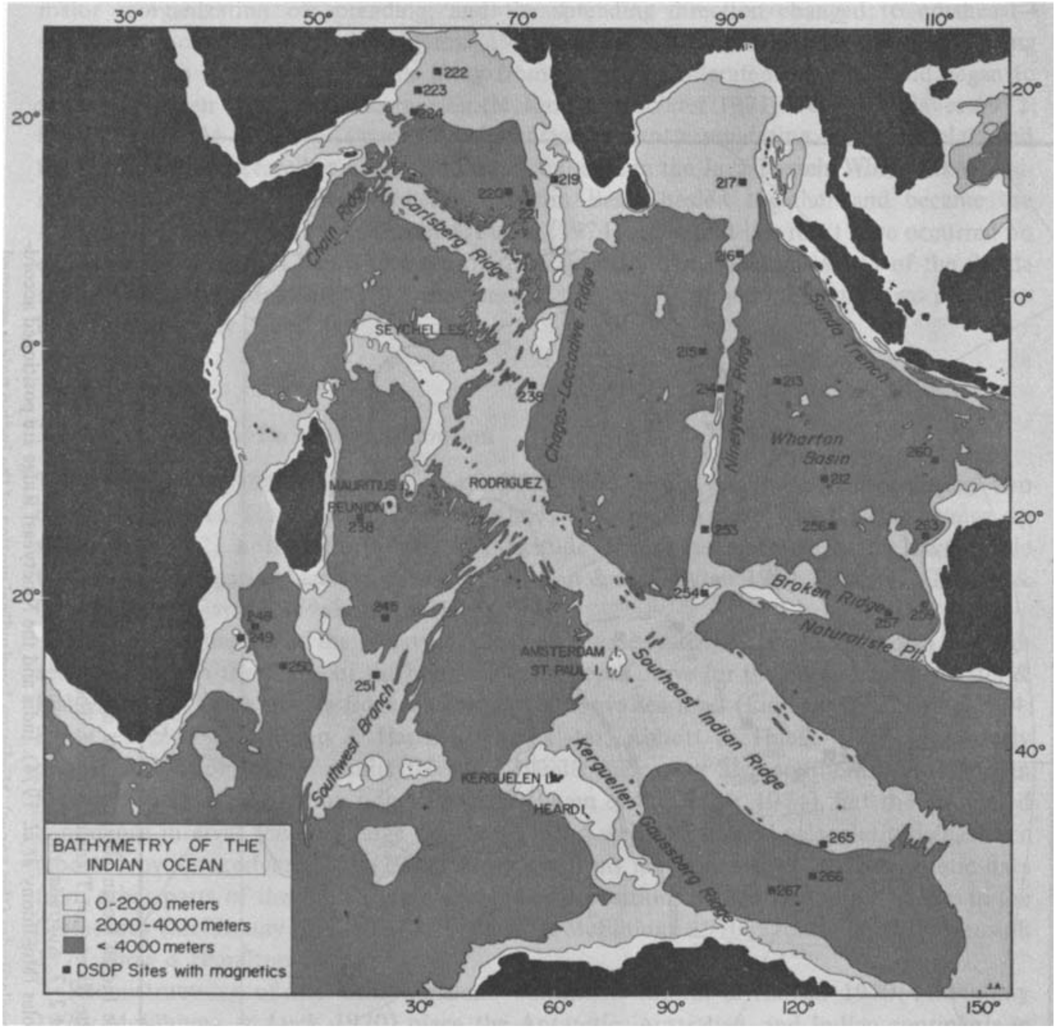

Figure 1. Bathymetry of the Indian Ocean. Contours are from a recent Russian chart (Burakova ed., no publ. date). The small squares indicate the DSDP sites for which some palaeomagnetic data have been reported. Note the positions of the Kerguelen–Gaussberg and Broken Ridges relative to the Ninetyeast Ridge.

On the eastern side of the fault, at the northern end, was an easterly striking spreading centre separating the Wharton Basin from the Sunda plate (Fig. 2). Note that the Ninetyeast Ridge is always attached to the Indian plate in this interpretation.

Magnetic anomalies west of the Ninetyeast Ridge appear to be offset about 9° in a left lateral sense along the 86° E fracture zone. The equivalent transform fault on the active SE Indian Ridge is offset about 2° in a right lateral sense. Consequently, Sclater & Fisher (1974) proposed that the ridge segment between 86° E and 90° E jumped about 11° to the south sometime after basement at DSDP site 215 was formed 58–63 Myr ago, but before anomaly 22 time (53 Myr, according to the revised timescale proposed by Sclater *et al.* 1974).

The early spreading between India and the Antarctic was in a north–south direction (McKenzie & Sclater 1971; Sclater & Fisher 1974, Fig. 2). Between the time of anomalies 15 and 18 (37.5–43 Myr, according to the timescale of Sclater *et al.* 1974), there was a

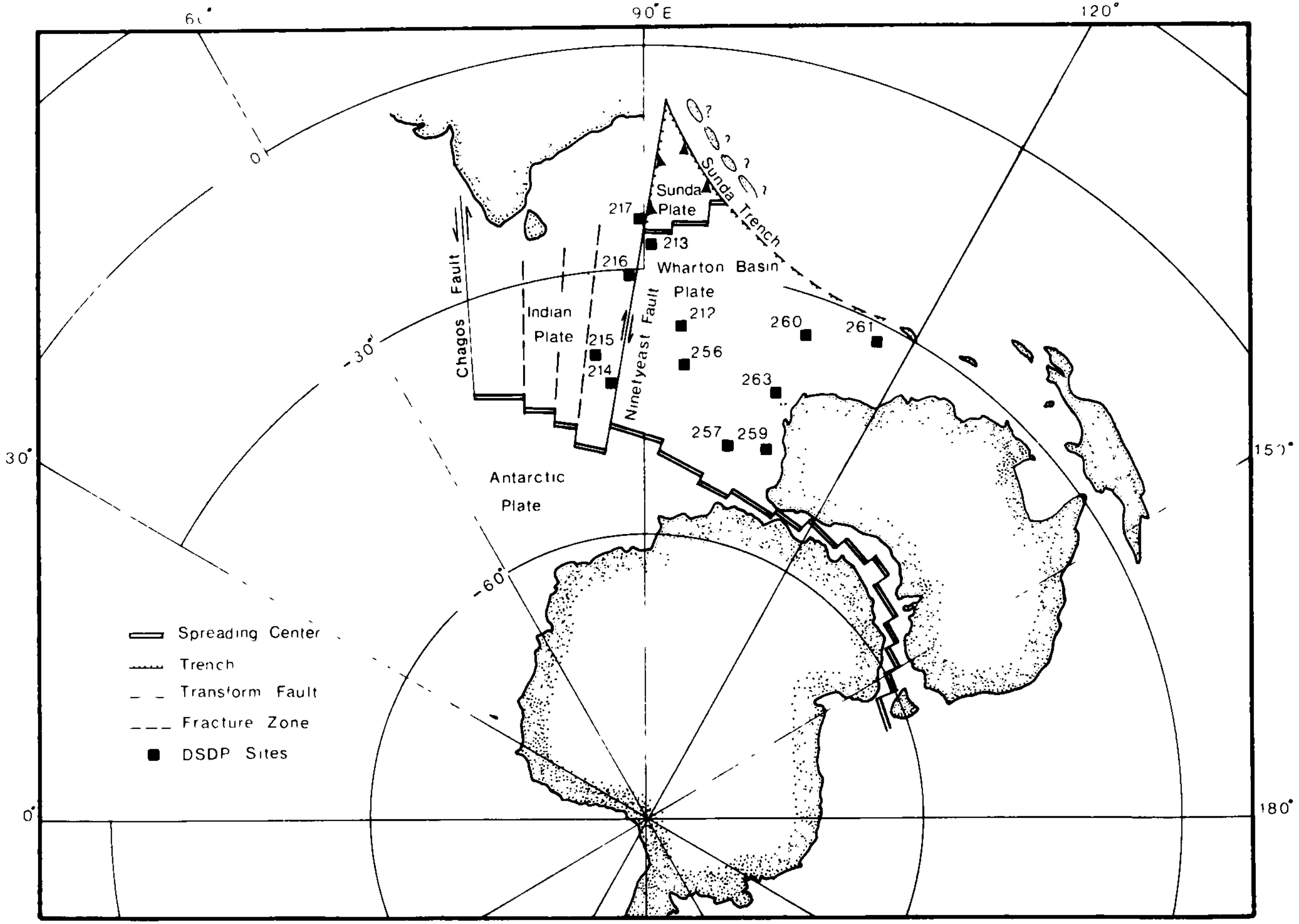

Figure 2. Sketch map of the Indian Ocean about 53 Myr ago. Note the relative positions of the four plates involved and the length of the Ninetyeast Transform Fault. The position of the Ninetyeast Ridge is delineated by DSDP sites 214, 216, and 217. Australia, the Wharton Basin, and Antarctica are positioned according to the Australian palaeomagnetic poles (McElhinny *et al.* 1974). India and the Ninetyeast Ridge are positioned according to the DSDP site 216 palaeolatitudes (this paper). Minimum longitudinal motion of the Indian pole is assumed.

major reorganization of spreading, and the spreading direction changed to northeast–southwest (Sclater, Luyendyk & Meinke 1976). As part of this reorganization, the spreading pattern which was rifting Australia away from Antarctica migrated westward and began to separate Broken Ridge from Kerguelen (McKenzie & Sclater 1971; Weissel & Hayes 1972; Bowin 1974). At about the same time, the spreading centre separating the Sunda plate and the Wharton Basin ceased spreading and was subducted in the Java Trench. When this spreading ceased the Indian plate and the Wharton Basin healed together and became the Australian plate as it is today. Sclater & Fisher (1974) argue that this must have occurred no earlier than anomaly 17 on the basis of their anomaly identifications south of the Sunda trench. Norton & Molnar (1977) disagree and they place the joining of the two plates no later than anomaly 22.

3 Previous evidence for northward motion

The palaeontology and palynology of the DSDP sites on the Ninetyeast Ridge display two distinctive trends: (1) a shallow, or sometimes subaerial, to deep water facies change up section, and (2) a transition from high-latitude temperate assemblages to low-latitude tropical assemblages up section (Gartner, Johnson & McGowran 1974; Pimm, McGowran & Gartner 1974; Harris 1974; Kemp & Harris 1975).

The present depths of the Ninetyeast Ridge increase systematically to the north in rough accordance with the shape of the empirical age–depth curve for the ocean basins (Sclater & Fisher 1974). Much of the ridge was originally above sea level (Luyendyk & Davies 1974; Pimm *et al.* 1974; Kemp & Harris 1975; Sclater, Abbott & Thiede 1977). Previously published palaeomagnetic results from the basalts indicate a high southern latitude origin for the southern end of the ridge (Peirce, Denham & Luyendyk 1974), but the associated confidence interval was very large (Peirce 1976). A well-constrained palaeolatitude has been reported by Cockerham *et al.* (1975) which confirms this conclusion. Palaeomagnetic data from other parts of the Indian plate also indicate positions in high southern latitudes in the Cretaceous (McElhinny 1968, 1973; Wellman & McElhinny 1970; Klootwijk 1971; Wensink 1973; Blow & Hamilton 1975).

Reconstructions of the Gondwanaland continents (Smith & Hallam 1970; McElhinny 1970; McElhinny & Luck 1970) place the Antarctic, Australian, and Indian continents in close proximity. Using Australian palaeomagnetic data (Wellman, McElhinny & McDougall 1969) for palaeolatitude control, Sclater & Fisher (1974) have reconstructed the evolution of the eastern Indian Ocean from magnetic anomalies. Their reconstructions also indicate southern latitudes for the Ninetyeast Ridge as it formed.

4 Basalt palaeolatitudes

Palaeolatitudes are calculated from the palaeomagnetic data at sites 213, 214, 215, and 216. Sites 214 and 216 are on the Ninetyeast Ridge, and both palaeolatitudes lie near 50° S. Site 213 is 400 km east of the Ninetyeast Ridge in the Wharton Basin and is about the same age as site 214. The basement at this site formed near the northern end of the old Ninetyeast transform fault, hence its low palaeolatitude of 18° S. The difference between the palaeolatitudes at sites 213 and 214 is 32° ± 16°, implying that the total offset of the Ninetyeast Transform Fault and a possible fault at 93° E was some 3500 km.

Site 215 lies to the west of the Ninetyeast Ridge, and it is slightly older than site 214. It's palaeolatitude of 64° S is not consistent with the Ninetyeast Ridge data or with the results from the overlying sediments. Because the magnetic directions at this site were often characterized by unstable behaviour (Peirce 1977) this palaeolatitude is not considered reliable.

The palaeolatitudes and associated confidence intervals are calculated according to the method developed by Cox (1976). Using this procedure, the data are averaged by cooling unit, and the size of the confidence interval is determined by: (1) the modelled secular variation at the estimated palaeolatitude; (2) the within unit dispersion of the palaeomagnetic directions; (3) and the number of independent cooling units. Independent cooling units are those which represent independent samplings of the geomagnetic vector at the site.

Ideally, several tens of independent cooling units spaced over at least 50 000 years are needed to average completely the secular variation of the geomagnetic field. In practice, many adjacent geological cooling units have very similar inclinations, suggesting that they are not independent. Consequently, I have considered cooling units to be independent only when the mean inclination of one unit lies more than two standard errors of the mean away from the mean inclination of the adjacent units. Similar methods have been used to identify separate cooling units on DSDP Leg 37 (Ade-Hall *et al.* 1975; Hall & Ryall 1977). Units with inclinations of opposite sign have always been assumed to be independent as all of these palaeolatitudes lie far from the equator. As a result of this method, the number of independent cooling units at a given DSDP site is relatively few and the confidence interval of the palaeolatitude remains highly dependent on it. Because my interpretation of cooling unit independence is crucial to an evaluation of the palaeolatitude reliabilities, a description of it is included below in the discussion of the data quality at each site.

The palaeolatitudes and their associated statistics are listed in Table 1. The values listed here are revisions of the preliminary results reported by Peirce (1976). The differences in the palaeolatitudes are small, but the confidence intervals are often larger because of more strict criteria for cooling unit independence. The uncorrected palaeolatitudes for each cooling unit are plotted in Fig. 3.

Table 1. Basalt palaeolatitudes.

Site	Age (Myr)	N[1]	$\bar{I}$	±2 SM[2]	Corr.[2] palaeolat.	95 per cent C.I.[1]	Rating[2]	Comments
213	58–63	35/38	31.6	7.6	–17.5	–9.7 –25.2	B*	Five normal and two reversed units; consistent with other Wharton Basin palaeolatitudes
214	57–60	30/30	63.7	9.1	–47.3	–37.9 –57.6	B?*	Two normal and four reversed units; roughly consistent with other Ninetyeast Ridge palaeolatitudes
215	58–63	24/34	74.8	13.6	–65.0	–49.2 –90.0	C?	Two normal and one reversed units, disagrees with basal sediment palaeolatitude; many discordant directions omitted from calculation
216	67–72	42/42	+67.6	10.2	–52.0	–41.2 –63.9	C*	Five reversed units; consistent with basal sediment palaeolatitudes
254	30–40	9/9	+67.8	16.2	–52.3	–35.3 –73.0	D*	Two reversed units; consistent with other Ninetyeast Ridge palaeolatitudes (Peirce *et al.* 1974)

[1] The first number is the number of sample directions which passed the acceptance criteria (see text). The second number is the total number of cleaned sample directions.

[2] See Peirce (1976) for definition of these parameters. After the rating, * implies that the data are consistent with other independent data; ° implies dubious consistency, and ? implies inconsistency.

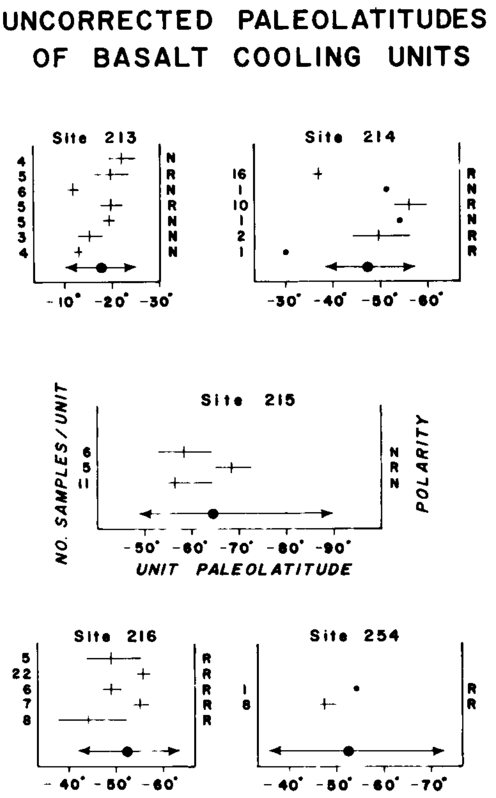

Figure 3. The uncorrected virtual geomagnetic latitudes of the independent basalt cooling units of sites 213, 214, 215, 216 and 254 are shown arranged in stratigraphic order. The number to the left is the number of samples in each unit, and the letters N and R on the right denote whether the unit was normally or reversely polarized. The length of the horizontal bar of each unit indicates the range of two standard errors of the mean of the palaeolatitudes. Units with only one sample are indicated by a closed circle. The corrected palaeolatitude and 95 per cent confidence interval from Table 1 is shown by the large dot and arrows for comparison.

The total number of basalt specimens measured was 143. Of these, 44 were partially demagnetized in alternating fields (AF) in a stepwise manner up to 800 Oe as pilot samples from the inferred cooling units. The stereonet plots and normalized intensity curves for a representative set of these are included in the appendices of Peirce (1977) along with the cleaned directions of all specimens.

About 10 per cent of the basalt specimens exhibited unstable behaviour or anomalous directions, and these were omitted from the data set used for palaeolatitude calculations. Most of these were from site 215 where back to back specimens sampled from the same piece of core often exhibited discordant directions. The criteria used for rejecting basalt specimen directions were as follows:

(1) If the palaeomagnetic direction did not stabilize to less than a 5° change between two successive demagnetizing steps (NRM, 100, 150, 200, and 400 Oe), it was rejected. Exceptions to this rule were made only when back to back specimens showed similar inclinations (within 10°) *and* similar declinations (within 20°).

(2) If two back to back specimens showed discordant directions, both were rejected.

All of the specimens were partially demagnetized at at least three different cleaning fields, usually 100, 150 and 200 Oe. The directions chosen for the palaeolatitude calculations were those which showed the least angular change from the previous direction, and the maximum stability index with respect to the previous magnetic vector ($SI = 1 - (\bar{J}_1 - \bar{J}_2)/\bar{J}_1$, Briden 1972). When these two criteria were not met simultaneously, it was usually because of a large intensity change, and the minimum angular change criterion was given more weight.

The 95 per cent confidence interval for a basalt palaeolatitude is primarily dependent on the number of independent cooling units identified at each site. The identification of cooling unit boundaries is difficult when one only has a core about 6 cm in diameter to work with. In some cases the presence of graded textural changes (glass to vesicular to fine grained to coarse grained) is a clear indication of a cooling unit. Sometimes possible subaerial weathering zones were indicated by oxidized, vesicular flow (?) tops (e.g. Site 216). However, more often, possible cooling unit boundaries are indicated only by chilled margins, and there is no

Table 2. Apparent cooling units, DSDP Site 213.

Unit No.	Top	Bottom	N^1	$\bar{I}$	S.D.[2]	Comments
1	17-1-109	17-2-005	0	—	—	Weathered basalt and glass, not sampled
2	17-2-005	17-2-091	3/4	−40.2	2.4	Weathered basalt bounded by palagonitized glass
3	17-2-091	17-2-130	2/2	−36.7	4.5	Same as unit 2
4	17-2-130	17-3-070	5/6	+ 35.7	6.1	Weathered basalt and glass over partially weathered porphyritic basalt
5	17-3-070	17 cc	4/4	−24.6	2.5	Weathered basalt and glass with 15 cm of partially weathered porphyritic basalt
6	18-1-100	18-2-005	2/2	−20.5	3.3	Partially weathered basalt
7	18-2-005	18-2-055	0	—	—	Zone of alteration and glass; not sampled
8	18-2-055	18-3-005	6/6	+ 35.7	3.7	Weathered glass over partially weathered basalt. One short piece apparently inverted
9	18-3-005	18-3-033	2/2	−34.6	0.6	Weathered basalt
10	18-3-033	18-3-072	3/4	−35.6	3.3	Weathered basalt and glass over partially weathered basalt
11	18-3-072	18-3-101	3/3	−28.7	3.4	Weathered glass over partially weathered basalt
12	18-3-101	18-3-142	2/2	−23.1	1.2	Weathered basalt and glass over partially weathered basalt
13	18-3-142	19-1-135	0	—	—	Weathered basalt and glass over coarse grained basalt (125 cm void); not sampled
14	19-1-135	19-2-010	0	—	—	Weathered basalt and glass over coarse grained basalt; not sampled
15	19-2-010	19-2-150	2/2	−26.1	0.8	Glass over a vesicular zone over coarse grained basalt. One short piece apparently inverted

Units 2–3, 4, 5–6, 8, 9–10, 11, 12–15 are interpreted as being independent.

[1] N as in Table 1.

[2] Standard deviation of inclinations.

way to distinguish whether these represent individual pillows from the same eruption, or whether they represent different cooling units from different eruptions. In Tables 2–5, I have listed the geological evidence suggesting cooling unit boundaries, the palaeomagnetic inclinations associated with each of these units, and my interpretation of which units I considered independent. A more detailed discussion may be found in Peirce (1977).

Table 3. Apparent cooling units, DSDP Site 214.

Unit No.	Top	Bottom	N^1	$\bar{I}$	S.D.[2]	Comments
1	48-1-000	48-2-010	4/4	+ 55.2	2.4	Fine grained over medium grained basalt
2	48-2-010	48-cc	6/6	+ 56.5	1.0	Vesicular over fine grained basalt
3	49-top	51-1-120	6/6	+ 57.1	2.0	Fine grained basalt with chilled bottom
4	51-1-120	53-1-010	0	—	—	Lignite and weathered lapilli tuff; too friable to sample
5	53-1-010	53-1-150	1	−68.0	—	Fine grained, glassy basalt over coarser grained basalt
6	53-2-020	53-cc	0	—	—	Basaltic sand and debris; not sampled
7	54-1-035	54-2-140	10/10	+ 71.5	3.5	Coarse amygdaler basalt over very coarse grained basalt
8	54-2-140	54-3-056	1	−70.0	—	Vesicular over amygdalar basalt
9	54-3-056	54-3-134	2	+ 67.0	—	Vesicular over amygdalar over coarse grained basalt
10	54-3-134	54-cc	1	+ 49.1	—	Vesicular over amygdalar basalt

[1] *N* as in Table 1.

[2] Standard deviation of inclinations.

Units 1–3, 5, 7, 8, 9 and 10 are interpreted as being independent.

Table 4. Apparent cooling units, DSDP Site 215.

Unit No.	Top	Bottom	N^1	$\bar{I}$	S.D.[2]	Comments
1	17-1-110	17 cc	0	—	—	Four small pieces of weathered glass, palagonite and weathered basalt. Bounded by unrecrystallized chalks; not sampled
2	18-1-000	18 cc	6/10	−72.9	4.3	Mostly weathered fine grained basalt; glassy zones occur at 18-1-000, 130, 18-2-055, 068, 140
3	19-1-000	19 cc	5/7	+ 79.0	2.2	Relatively fresh, coarse grained basalt; glassy zones occur at 19-2-050 and 130
4	20-1-070	20 cc	13/17	−72.6	9.8	Mostly weathered fine grained basalt; glassy zones occur at 20-2-73, 130, 20-3-003 (with interbedded limestone), 20-3-042, 100, 20-4-013, 040, 060

Unit 1 may be part of Unit 2. Unit 3 distinguished from units 2 and 4 on the basis of polarity. The three independent units are interpreted as three sets of pillow structures.

[1] *N* as in Table 1.

[2] Standard deviation of inclinations.

Table 5. Apparent cooling units, DSDP Site 216.

Unit No.	Top	Bottom	N^1	$\bar{I}$	S.D.^{2}	Comments
1	36-3-115	36-3-150	0	—	—	Amygdalar basalt; separated from unit 2 by 10 cm of sediment
2	36-4-110	36-4-040	3/3	+ 66.2	4.9	Amygdalar basalt
3	36-4-040	36-4-130	2/2	+ 67.0	6.6	Coarse grained tuff
4	36-4-130	37-3-100	10/10	+ 70.8	1.9	Oxidized, pale red scoriaceous zone over fine grained basalt
5	37-3-100	38-2-030	12/12	+ 71.3	2.3	Oxidized, pale red vesicular zone over fine grained basalt; two alteration zones at 37-4-100-150 and 38-1-30-50
6	38-2-030	38-3-040	6/6	+ 66.5	2.0	Alteration zone with chlorite veins over fresh fine grained basalt. Distinguished from unit 5 on the basis of magnetic inclinations
7	38-3-040	38-4-012	5/5	+ 71.0	1.1	Oxidized, pale red scoriaceous zone over vesicular basalt over fine grained basalt
8	38-4-012	38-4-085	4/4	+ 62.7	4.7	Vesicular basalt over amygdalar basalt over vesicular basalt (cc)

Units 2–3, 4–5, 6, 7, 8 are interpreted as independent.
[1] N as in Table 1.
[2] Standard deviation of inclinations.

The ages of the basalts were assumed to be 0–5 Myr older than the ages of the overlying sediments (von der Borch *et al.* 1974) except for site 214 where the age is more tightly constrained. All ages are based on the Berggren (1972) timescale.

Duncan & McDougall (1976) have reported K/Ar ages for basalts of 57.7 ± 1.2 Myr at site 214 and 61.7 Myr for site 215. An age of 82 Myr was reported for basalt from site 216, but this was not considered reliable.

5 Sediment palaeolatitudes

Palaeolatitudes are calculated from the sediment data at various horizons at site 215, 216 and 217. The palaeolatitudes for sites 216 and 217 show a consistent pattern of northward motion for the Ninetyeast Ridge. At site 215, to the west of the ridge, the sediment palaeolatitude is inconsistent with that of the underlying basalts as well as the results from the Ninetyeast Ridge (Fig. 5). No reliable sediment palaeolatitudes were measured at sites 213 or 214.

The palaeolatitudes and their associated confidence intervals are calculated according to the method developed by Cox (1976), as modified by Peirce (1976) for use with DSDP sediments. Using this method, each sample direction is considered to be an independent sampling of the geomagnetic secular variation. The size of the confidence interval is determined only by the modelled secular variation at the observed palaeolatitude and by the number of samples. The dispersion of the observed directions is not considered because tightly grouped data are usually an indication of inadequate sampling of secular variation. On the other hand, a large amount of dispersion is probably indicative of bad data. Consequently, data are considered reliable only when there are sufficient samples to guarantee some averaging of secular variation and when the standard deviation of the observed inclinations is less than 10° (an empirical cutoff, from Peirce 1976).

Table 6. Sediment palaeolatitudes.

Site	Cores	Horizon[1]		Age (Myr)	N[2]	$\bar{I}$	S.D.[3]	2SM[4]	Corr.[4] P. Lat.	95 per cent C.I.[4]	Rating[4]	Comments
213	16-4	*D. multiradiatus* P5	(N) (F)	54–56	4/4	38.8	26.2	—	—	—	—	Individual specimen directions stable but no grouping. Material probably disturbed by drilling
214	6-2	*D. surculus* *S. pentas* N20	(N) (R) (F)	2.8–3.8 3.8	0/3	—	—	—	—	—	—	$< 1 \times 10^{-6}$
214	22-3, 4	*S. belemnos* N5	(N) (F)	18–21	0/5	—	—	—	—	—	—	$< 1 \times 10^{-6}$
214	32-2, 3 34-6	*C. alatus* to *D. lodoensis* P11 to P7	(N) (F)	46–51	3/6	34.9	10.0	—	—	—	—	Others $< 1 \times 10^{-6}$
214	36-4	*H. kleinpelli* P4	(N) (F)	57–58	1/4	33.6	—	—	—	—	—	Others $< 1 \times 10^{-6}$
214	41-2, 3	*C. robusta* ??	(N)	57–60	0/9	—	—	—	—	—	—	Tuff; thermal demag. used but no stable directions found; generally $< 1 \times 10^{-6}$
214	44-1 46-3	Barren		57–60	5/12	44.9	4.6	(12.8)	(−27.0)	(−13.9) (−40.1)	C°	Inconsistent with basalts
215	15-4, 5 16-1, 4, 5	*H. kleinpelli* P4	(N) (F)	57–58	29/32	56.3	8.7	5.4	−38.5	−33.0 −44.1	B°	Inconsistent with basalts. Inconsistent with Ninetyeast Ridge data
216	5-2 6-3	*S. belemnos* and below *C. virginis* N5-N6	(N) (R) (F)	16–21	3/7	19.2	7.1	—	—	—	—	Others $< 1 \times 10^{-6}$
216	9-1, 2 10-1	*S. ciproensis* *D. ateuchus*	(N) (R)	22–30	9/16	17.8	5.0	9.3	−9.3	+ 0.1 −18.8	B*	All directions in section 9-1 discordant; sections 9-2 and 10-1 concordant; see Fig. 5

Table 6. *Continued.*

Site	Cores	Horizon[1]		Age (Myr)	N^2	$\bar{I}$	S.D.[3]	2SM[4]	Corr.[4] P. Lat.	95 per cent C.I.[4]	Rating[4]	Comments
216	13-1 14-1, 2, 3	*S. distensus* *T. tuberosa* P19-21	(N) (R) (F)	26–34	13/14	23.4	7.2	7.8	−12.6	−4.5 −20.5	B*	See Fig. 5
216	15-3 16-1, 2	*D. barbardiensis* *T. bromia*	(N) (R)	37.5–43	11/16	27.5	8.5	8.5	−15.1	−6.5 −23.8	B*	Five back to back samples unstable and $< 1 \times 10^{-6}$; see Fig. 5
216	21-1 22-1, 2	*D. mohleri* P4	(N) (F)	56–58	8–14	64.0	13.0	—	—	—	—	Others unstable
216	23-2 24-2, 3	*C. danicus* to *N. frequens* Pl to *G. mayaroensis*	(N) (F)	62–67	10/30	56.0	13.0	—	—	—	—	Others unstable
216	34-1, 2 35-2, 3	*N. frequens* or older Maastrichtian	(N) (F)	65–68	3/16	51.4	28.9	—	—	—	—	Mostly $< 1 \times 10^{-6}$ and poor stability
216	36-1, 2	*N. frequens* or older Maastrichtian	(N) (F)	65–68	16/16	68.5	8.9	7.1	−54.7	−46.8 −62.9	B*	See Fig. 5
216	36-3	*N. frequens* or older Maastrichtian	(N)	65–68	0/9	—	—	—	—	—	—	Unstable
217	4-3	*D. neohamatus* *O. antepenultimus* N16	(N) (R) (F)	7–10	1/4	28.5	—	—	—	—	—	Others unstable
217	6-3, 4, 6	*S. heteromorphus* to *S. belemnos* *C. virginis* N5	(N) (R) (F)	15–21	8/20	5.2	9.6	9.9	± 2.7	+ 12.8 −12.8	B*	Others discordant and unstable
217	7-2, 3	*S. ciproensis* *D. ateuchus*	(N) (R)	24–30	3/10	6.5	2.2	—	—	—	—	Others unstable and $< 1 \times 10^{-6}$
217	8-3, 4, 5	*S. distensus* *T. tuberosa* P-21	(N) (R) (F)	26–30	13/17	11.3	8.4	7.8	−5.9	+ 2.0 −13.8	B*	Intensities $< 1 \times 10^{-6}$; directions based on back to back sampling

Table 6. *Continued.*

Site	Cores	Horizon[1]		Age (Myr)	N[2]	$\bar{I}$	S.D.[3]	2SM[4]	Corr.[4] P. Lat.	95 per cent C.I.[4]	Rating[4]	Comments
217	9-2	*S. predistensus* to *D. barbadiensis*	 (N)	30–40	7/8	6.1	9.3	(10.5)	(−3.8)	(+6.7) (−14.6)	C^{0}	$< 1 \times 10^{-6}$; inconsistent with other core 9 data
	9-3, 4, 5, 6	*T. tuberosa* to *T. bromia* P20-16	 (R) (F)	30–40	4/16	27.9	3.1	(15.3)	(−15.0)	(+0.5) (−30.1)	D^{0}	Inconsistent with other core 9 data
217	10-1, 2, 4, 6	*C. alatus* *P. mitra* to *T. triacantha* P11-12	(N) (R) (F)	45.5–48	6/8	16.9	5.5	(11.4)	(−8.8)	(+2.7) (−20.4)	C*	$< 1 \times 10^{-7}$
217	14-1, 5 15-1, 2	*F. tympaniformis* P4	(N) (F)	56–59	12/14	52.0	7.7	8.4	−33.8	−25.2 −42.5	B*	See Fig. 5
217	16-3, 5, 6	*C. helis* P1	(N) (F)	63–65	10/14	13.1	12.2	—	—	—	—	
217	18-2 19-1, 2, 3	*N. frequens* to *L. quadratus* *G. mayaroensis*	 (N) (F)	65–70	13/17	46.0	13.3	—	—	—	—	Wide scatter
217	33-2, 3 34-1	*E. augustus* Companian	(N) (F)	73–76	11/83	25.0	14.7	—	—	—	—	Wide scatter
253	?	*D. tani nodifer*	(N)	46–48	49/55	67.6	10	3.3	−51.9	−48.3 −55.8	A*	See Fig. 5; (Cockerham *et al.* 1975)

[1] Palaeontologic horizons taken from site reports and other palaeontologic studies in the Initial Reports. See text for references. Age correlations from Berggren (1972).

[2] N as in Table 1.

[3] Standard deviation of inclination.

[4] As in Table 1. See Peirce (1976) for definitions.

The palaeolatitudes and their associated statistics are listed in Table 6, and the distributions of the uncorrected palaeolatitudes at each horizon are plotted in Fig. 4. The stereonet plots, normalized intensity curves, and cleaned directions of individual specimens are included in the appendices of Peirce (1977).

A total of 388 sediment samples were measured from DSDP sites 213, 214, 215, 216 and 217. Most of the specimens were drilled from indurated pieces of core, using a diamond rock drill. Relative declinations were preserved when several specimens came from the same piece of core. At sites 213, 215, and the uppermost horizons at sites 214, 216 and 217, specimens were taken using a DSDP plastic sample cutter inserted with a miniature piston core sampling device. The specimens were then capped in the plastic, top and bottom, with an epoxy which cured at room temperature. Measurements were made on the cryogenic magnetometers at the University of Texas (C. E. Helsley) and at the University of Rhode Island (N. D. Watkins). The data from site 253 are from Cockerham, Luyendyk & Jarrard (1975).

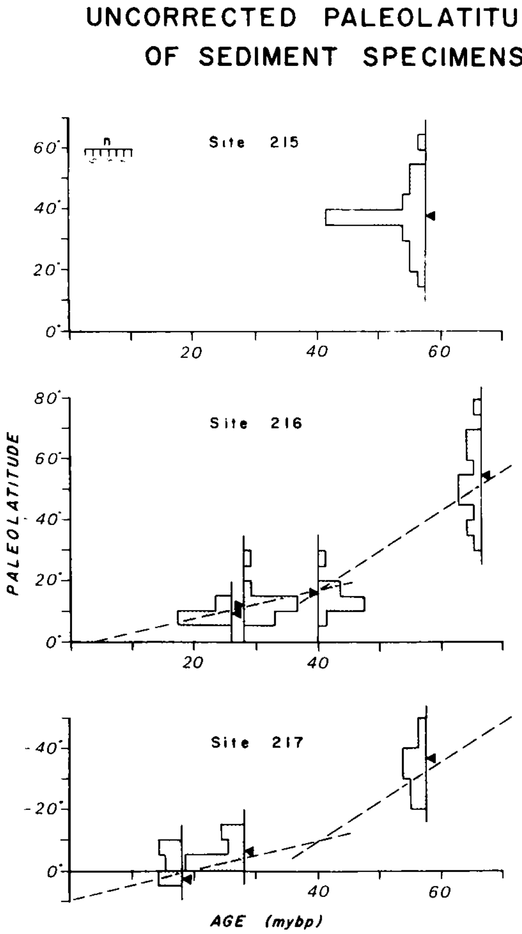

Figure 4. The uncorrected virtual geomagnetic latitudes of the sediment samples from sites 215, 216, and 217 are shown in histogram form. Each baseline is positioned according to age long the horizontal axis. Two histograms in the middle figure are inverted to avoid overlaps. The triangles point to the corrected palaeolatitudes given in Table 6, as a point of comparison. The dashed lines indicate the palaeomotion of the site based on all the palaeomagnetic data (see Fig. 5).

Sixty-one pilot specimens were progressively demagnetized in alternating fields to determine the proper cleaning field. Some specimens were routinely cleaned in fields of 50 or 75 Oe. However, specimens from some horizons subsequently exhibited significant viscous remanent magnetization (VRM) growth which cast doubt on the validity of directions cleaned at only one field. These horizons (at sites 216 and 217) were resampled, and the new set of specimens were all measured at several cleaning fields up to 200 Oe within a few hours of their initial cleaning. Stable directions were selected from these multiple cleanings. None of these specimens exhibited significant VRM growth in this short time interval.

At many of the horizons sampled, the directions which were considered reliable (see discussion of acceptance criteria below) were too scattered or too few to compute a palaeolatitude. In most cases, scattered directions were observed in very weakly magnetized sediments ($< 1 \times 10^{-6}$ emu/cc). However, in core 8 of site 217, sediments with cleaned magnetizations $< 1 \times 10^{-7}$ emu/cc produced very stable, well grouped directions which were confirmed by frequent back to back sampling. It is unclear why some sediments appear to be reliable palaeomagnetic recorders, as characterized by coherent directions in a group of samples, while others of apparently similar lithology and magnetization are not reliable.

Individual specimen directions were rejected as unreliable for several reasons. All specimen directions whose cleaned intensity was $< 1 \times 10^{-6}$ emu/cc were rejected unless that direction could be confirmed in both inclination and declination by a specimen sampled from the same indurated piece of core. This intensity cutoff is not a function of the cryogenic magnetometers, which have a practical sensitivity of about 1×10^{-8} emu/cc, but rather it is based on the empirical observation that most groups of specimens with such low magnetizations do not have well-grouped directions. At only two horizons (cores 8 and 10, site 217) was this poor grouping was not observed. However, in those cases, every direction used in the palaeolatitude calculation was confirmed by at least one other back to back specimen.

Specimen directions were rejected as unreliable when they did not stabilize to less than 10° angular change between successive demagnetization steps unless such a direction was confirmed by that from another back to back specimen. When only one cleaned direction was available, the 10° angular change criterion was not applied.

Palaeolatitudes were calculated only when at least four samples at a given horizon met the direction acceptance criteria. Palaeolatitudes based on less than eight directions are considered marginally reliable, and they are listed in parentheses in Table 6.

The ages assigned in Table 6 are drawn from the site reports in von der Borch *et al.* (1974), as well as the following shipboard and shore laboratory studies: nannofossils, Gartner (1974) and Bukry (1974); foraminifera, McGowran (1974) and Berggren, Lohmann & Poore (1974); and radiolaria, Johnson (1974). The absolute ages of the biostratigraphic horizons are those assigned by Berggren (1972). Generally, all the palaeontological ages agree well except in the lower Oligocene where the radiolaria show discordant ages a few million years older than those from the nannofossils. In these cases, when both the nannofossil and foraminiferal ages are in agreement, I have used them. If no foraminiferal age was available (usually because of dissolution), I have assigned an age range including the nannofossil and the radiolarian ages.

6 Magnetic stability of sediments

The confidence intervals given in Table 6 are a function of the number of samples and the observed palaeolatitude. As such, they cannot reflect certain characteristics of a particular data set which may detract from its reliability as subjectively evaluated. Because such subjective assessments can provide an unquantifiable insight beyond that offered by the statistics in some cases, a brief discussion of the data quality is given below for each site.

SITE 213

The specimens all appeared to be stably magnetized. However, in the absence of observable bedding in the sampled part of the core, I interpret the tremendous scatter of inclinations as an indication of severe disturbance of the mud by the drilling process.

SITE 214

Most of the specimens above the basal section had weak magnetizations ($< 1 \times 10^{-6}$ emu/cc) and the inclinations were very scattered. One pilot specimen from the tuff in core 41 exhibited an extremely high median destructive field (MDF) which extrapolated to > 3000 Oe. Its most stable inclination was 49.3° before thermal cleaning. The entire tuff behaved in an unstable manner when thermally demagnetized.

There were five specimens in the basal section which met the acceptance criteria. Four of these were paired back to back specimens. Four other back to back specimen directions were rejected because of discordant directions. In view of the high rejection percentage (58 per cent) at this horizon and the inconsistency with the basalt palaeolatitude, this palaeolatitude is considered unreliable.

SITE 215

The directions from site 215 were stably magnetized and well grouped. There is no *a priori* reason to disbelieve these data. However, the measured palaeolatitude is inconsistent with that from the basalts which are of similar age. Although the quality of the basalt data is not high, and might be disregarded, the sediment palaeolatitude also radically diverges from the more abundant data from the Ninetyeast Ridge if one assumes that there has been no relative motion between the site and the ridge. One possible explanation is that the palaeolatitude is the result of chemical remanent magnetization (CRM) acquired about 10 Myr after the sediment was deposited. As there is no other evidence to support relative motion between the site and the ridge or the existence of CRM, the sediment palaeolatitude remains a well defined but unexplained anomaly.

SITE 216

The magnetic stability of specimens from site 216 is quite variable from horizon to horizon. The demarcation between stable and unstable zones is usually quite clear, especially between core sections 9–1 and 9–2, and also in core section 16–2. The calculated palaeolatitudes are based on specimens which did not exhibit unstable behaviour. They are self-consistent in the upper part of the hole. The sediment palaeolatitude is 3° further south than the basalt palaeolatitude, but there is good overlap of the 95 per cent confidence intervals (Fig. 5).

In core 16, two adjacent specimens (05-2-82 and 86) had NRM intensities more than two orders of magnitude greater than those of the adjacent specimens. I interpret this sharp intensity change as probably indicating an ash layer which is not visible. The coercivity of these two specimens (Peirce 1977) reveals that over 80 per cent of the total NRM was contained in a narrow coercivity band between 160 and 180 Oe. One explanation for this unusually coherent coercivity distribution is that the remanence is contained in the particles of a very well sorted ash layer where all the magnetic grains are of the same size and mineralogy.

SITE 217

The entire section at Site 217 is calcareous and weakly magnetized. Very few specimens show a high degree of stability, and none of the palaeolatitudes is considered to be of high quality. The palaeolatitudes for zones P-20 to P-16 are not consistent with each other and are considered unreliable. The palaeolatitudes for zones P-21 and P-11-12 are based on weakly magnetized material, and either may be in error. However, the directions at both horizons are based only on specimens oriented with respect to at least one other specimen, and there is good correspondence between adjacent specimens. Therefore, they are interpreted as probably reliable. As the palaeolatitude from zone P-11-12 is based on only six samples, it is considered less reliable than the one from P-21. Most of the specimens from zone P-4 have MDF's < 100 Oe. The directions from back to back specimens are generally concordant, but one pair of discordant directions was observed. The P-4 palaeolatitude is also interpreted as probably reliable.

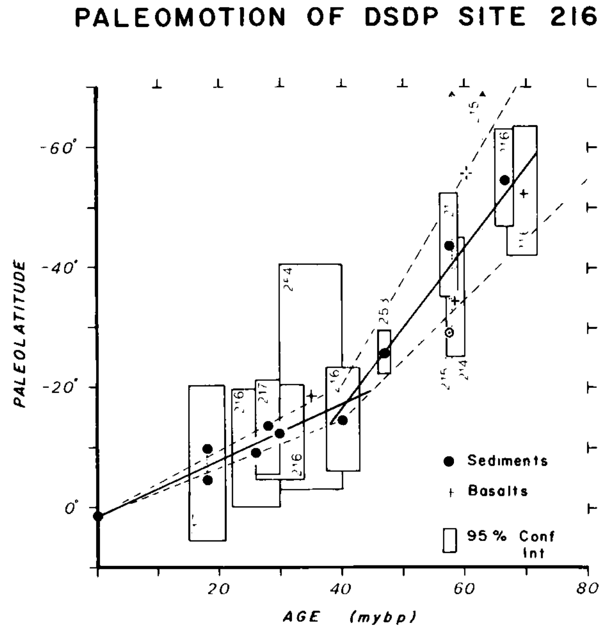

Figure 5. Palaeomotion of DSDP Site 216 based on palaeolatitudes from all the sites on the Ninetyeast Ridge. Boxes indicate the 95 per cent confidence intervals of each palaeolatitude and the best estimate of the associated age. Crosses indicate basalt data; solid circles indicate sediment data; and numbers indicate the site. Only palaeolatitudes based on at least eight samples are plotted. For sites other than 216, a correction equal to the present latitude difference from Site 216 was applied. Site 215 data are not consistent with those from the Ninetyeast Ridge sites and they have been dotted in. The solid lines indicate rates of northward motion of India obtained by weighted least squares linear regression. The dashed lines indicate the 95 per cent confidence region for the position of Site 216, assuming Student t-statistics apply to the rates of motion. The calculated rates are: 0–40 Myr, 5.2 ± 0.8 cm/yr ($N = 6$, through the origin); and 40–70 Myr, 14.9 ± 4.5 cm/yr ($N = 6$).

7 Palaeomotion of the Ninetyeast Ridge

The basalt palaeolatitudes and the sediment palaeolatitudes are combined into one graph of the palaeomotion for the Ninetyeast Ridge in Fig. 5. All the data shown in Fig. 5 are 'reduced' to site 216 by assuming that there has been no relative motion between the sites on the ridge and applying a correction to the palaeolatitudes equal to the present latitude difference between the sites. Thus, the graph can be made applicable to any point on the ridge by the addition of an offset equal to the present latitude difference between that point and site 216.

These palaeolatitudes indicate that the Ninetyeast Ridge and, by implication, the Indian plate were moving northward with respect to the South Pole at 14.9 ±4.5 cm/yr from 70 to 40 Myr. About 40 Myr ago the rate of the northward flight slowed to 5.2 (±0.8) cm/yr. This slowing was most likely a rapid but smooth deceleration, not the abrupt change obtained by the linear regressions in Fig. 5. This slowing of India roughly coincides with the time of spreading reorganization in the Indian Ocean and the beginning of the collision of the Indian subcontinent and Eurasia (Molnar & Tapponnier 1975).

The rates of *absolute* northward motion of India derived from the palaeomagnetic data are in excellent agreement with the *relative* rate of closing between Asia and India calculated

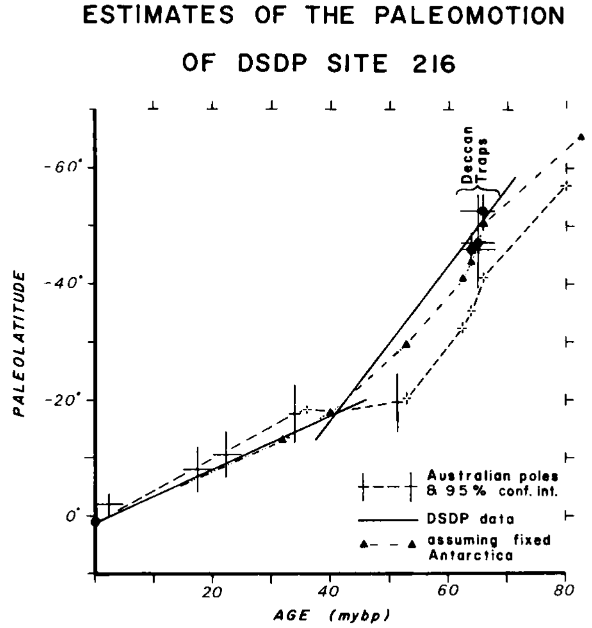

Figure 6. Estimates of the palaeomotion of DSDP Site 216 using different assumptions. The solid lines indicate the rates determined in Fig. 5. The triangles show the positions of Site 216 assuming that Antarctica has remained fixed and using the India/Antarctica poles of relative motion from Table 7. The crosses show the positions of the site based on Australian palaeomagnetic data (Wellman *et al.* 1969) and using the poles of relative motion for India/Antarctica and Australia/Antarctica from Table 7. The size of the crosses indicate the accuracy of the Australian data. The small dashed crosses indicate ages where palaeomagnetic pole positions (no errors calculated) were inferred from the apparent polar wandering path for Australia (McElhinney *et al.* 1974). Also shown are positions of Site 216 based on three palaeomagnetic poles from the Deccan Traps (poles 11.1–11.3, McElhinney 1973; age 65 Myr, Molnar & Francheteau 1975b). Note the discrepancy between the positions of Site 216 indicated by the Australian and Indian plate data sets prior to 40 Myr.

by Molnar & Tapponnier (1975). Using the assumption that Eurasia had negligible absolute motion, they calculated relative closing rates of 10.0–18.4 cm/yr between Eurasia and India for the time period 80–38 Myr. (The range of linear rates is due to the different distances of parts of India from the pole of rotation.) After 38 Myr, their calculated rate is 4.5–6.4 cm/yr. This correlation between the rates of relative and absolute motion implies that the pole of relative motion for Eurasia/India and the pole of absolute motion for India were nearly coincident during this time. Implicit in this coincidence is the conclusion that India had no significant longitudinal component of absolute motion. Such a component is undetectable by palaeomagnetic techniques. The implication of coincident poles is valid only to the extent that the assumption of a nearly stationary Eurasia is correct. However, it is an important point to which I shall return in the discussion of the origin of the Ninetyeast Ridge.

The DSDP data can be compared to the Indian continental palaeomagnetic data by correcting for any relative motion or rotation between the Ninetyeast Ridge and the continental sites. Palaeolatitudes calculated from the palaeomagnetic pole positions for the Deccan Traps (McElhinny 1973; Wensink 1973; Molnar & Francheteau 1975a) lie very close to the best fit line through the Ninetyeast Ridge data (Fig. 6). On the other hand, the lower Siwalik beds of Miocene age indicate a more southerly palaeolatitude (Wensink 1972a, b) than the DSDP data yield. However, the Siwaliks pole is based on a small number of samples and there is some doubt as to its validity (Wensink 1976, private communication).

The palaeomagnetic data from Australia are extensive and well-documented (McElhinny, Embleton & Wellman 1974). One can use the Australian palaeomagnetic poles to predict the motion of site 216 by removing the relative motion components (as estimated from magnetic anomalies), much as Sclater & Fisher (1974) did in their reconstruction maps. To do this for a given age one rotates site 216 (India back to its position relative to Antarctica, Antarctica (and India) back to its position relative to Australia, and Australia (and Antarctica and India) back to its position relative to the South Pole.

The results of such rotations for the ages corresponding to the Australian palaeomagnetic poles are plotted on Fig. 6. Note that the indicated rate of motion for India 70 Myr ago is the same as is indicated by the DSDP data, but the palaeolatitudes disagree by 13°. Furthermore, the use of this method suggests that the northward motion of India came to an abrupt halt about 51 Myr ago before resuming again 17 Myr later at a rate approximately equal to the measured rate. The directly measured motion of India (DSDP data) is less complicated.

The source of this discrepancy must lie either in the palaeomagnetic data or in the relative motion estimates for India/Antarctica and Australia/Antarctica. As both sets of palaeomagnetic data are self-consistent and well defined, and as the Australia/Antarctica motion seems relatively straightforward (Weissel & Hayes 1972), the logical place to look for an error is in the more complicated Indian/Antarctic relative motion (Sclater & Fisher 1974; Schlich 1975).

As a way of checking this possibility, I assumed that the Antarctic plate has remained fixed with respect to the South Pole, and then I calculated the palaeomotion of site 216 by rotating India back to Antarctica using Sclater & Fisher's (1974) poles of rotation. The results (Fig. 6) show good agreement with the measured palaeolatitudes, and, most importantly, they do not show the break in motion which was indicated by using Australia as the reference point. This is an *ad hoc* comparison, but it does provide a useful point of reference.

We are left in a quandary: the position of the Antarctic plate as defined by its motion with respect to India and the absolute motion of India does not agree with its position as defined by its motion with respect to Australia and the absolute motion of Australia. The scale of the mismatch is demonstrated in Fig. 7(a) and (b). Here I have assumed that all the

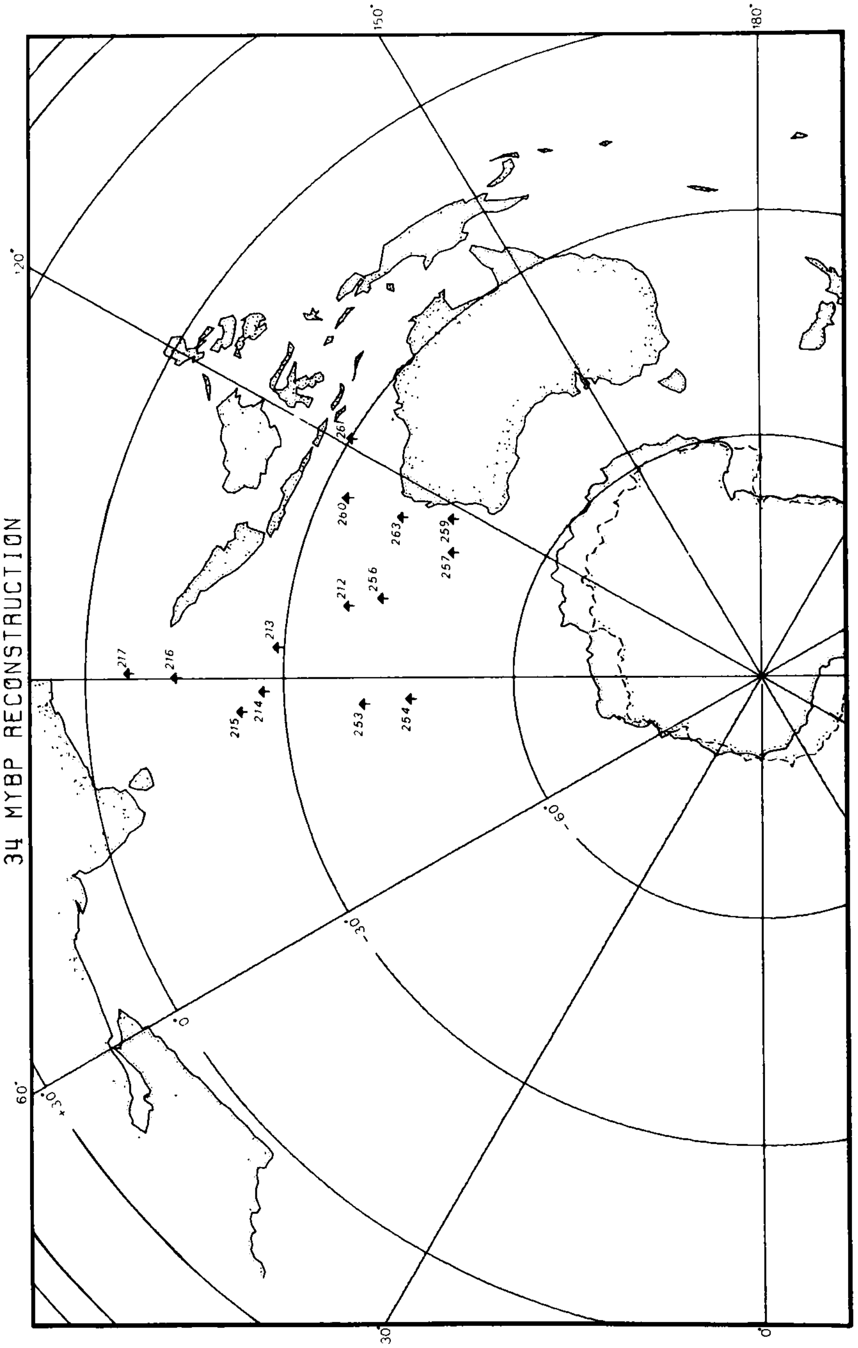
34 MYBP RECONSTRUCTION
150°
180°
120°
60°
30
0
-60°
-30°
0°
-30°
217
216
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Figure 7. (a)

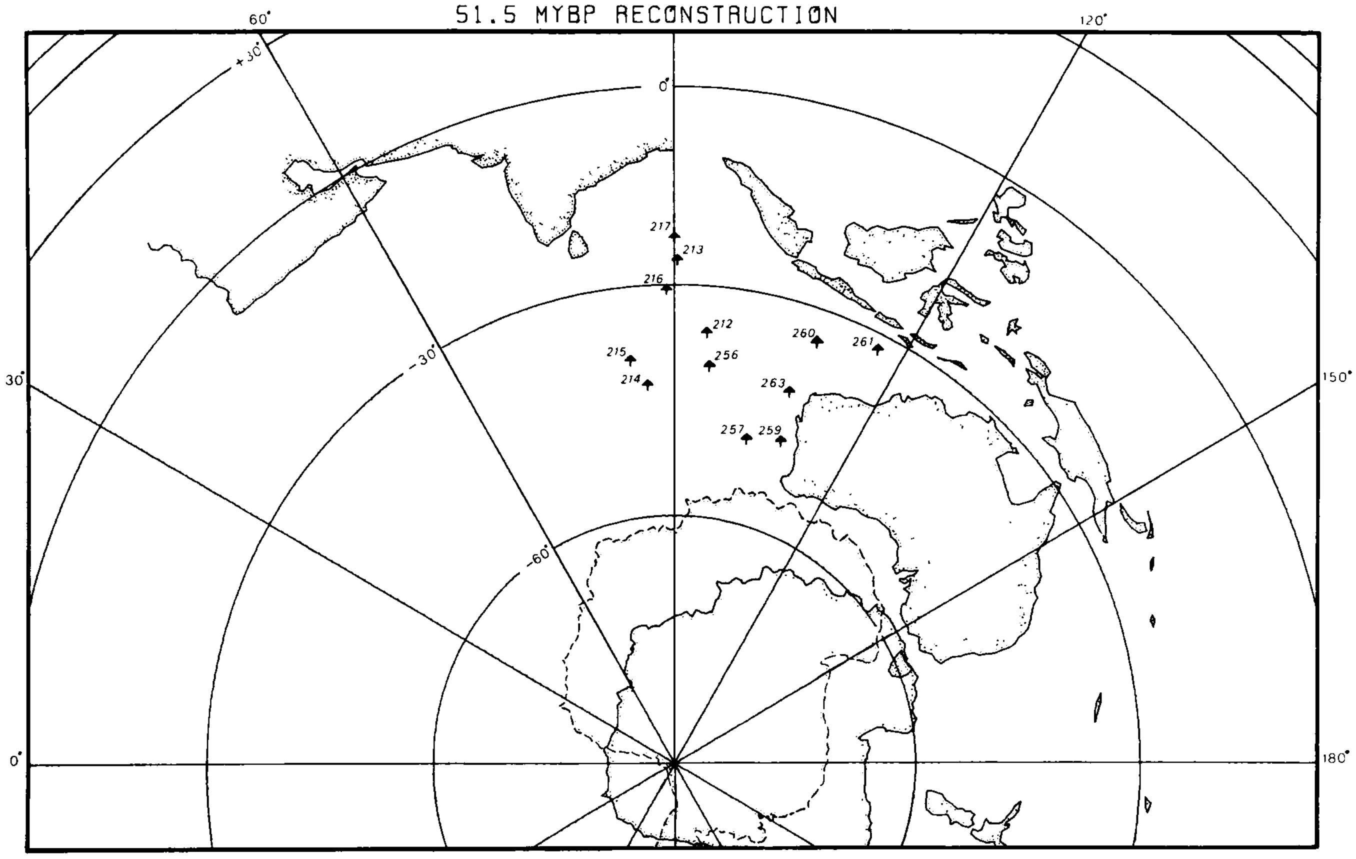

Figure 7. (b)

Figure 7. (a) and (b) Reconstructions of the Indian Ocean for 34 and 51.5 Myr. The position of India and the DSDP sites on the Ninetyeast Ridge relative to the South Pole were computed from the palaeomotion curve for Site 216 in Fig. 6. The positions of Australia and the remaining DSDP sites were computed from the Australian palaeomagnetic data (Wellman *et al.* 1969; McElhinney *et al.* 1974). Two positions are shown for Antarctica to demonstrate the magnitude of the discrepancy noted in Fig. 7. The solid outlines are the positions using the Ninetyeast Ridge palaeomagnetic data and the relative motion poles from Table 7. The dashed outlines are the positions using the Australian palaeomagnetic data and the poles from Table 7. The projections are Lambert equal area, centred at the South Pole.

errors in matching are in the positions of Antarctica, and its positions are plotted with respect to India and to Australia for 34 and 51.5 Myr. The match of the positions is fairly close at 34 Myr, and it is terrible at 51.5 Myr. Longitudinal adjustments might help, but a

Table 7. Poles of relative rotation.

(a) India/Antarctica

Time	Latitude	Longitude	Angle
0–32	4.9	36.4	18.3
32–34	–16.0	27.4	1.28
0–34	3.66	35.62	19.49
32–36	–16.00	27.4	2.56
0–36	2.56	34.93	20.68
32–40	–16.0	27.4	5.11
0–40	0.72	33.78	23.10
40–51.5	–16.0	27.4	11.76
0–51.5	–4.45	30.56	34.48
40–53	–16.0	27.4	13.29
0–53	–4.88	30.28	35.98
53–62.5	4.0	357.0	12.43
0–62.5	–0.10	22.82	46.75
62.5–64	4.0	357.0	3.17
0–64	0.80	21.42	49.61
64–66.5	–2.0	8.0	7.27
0–66.5	1.21	19.65	56.70
66.5–80	–2.0	8.0	17.91
0–80	1.9	16.63	74.30

(b) South Pole/India

Time	Latitude	Longitude	Angle
0–34	1.32	1.92	–18.36
0–36	0.62	6.74	–19.59
0–40	1.83	11.40	–19.63
0–51.5	2.80	25.54	–23.25
0–53	2.81	26.15	–24.29
0–62.5	6.31	24.21	–38.54
0–64	6.74	23.58	–41.99
0–66.5	5.96	22.84	–49.73
0–80	3.46	23.08	–69.5

(c) Australia/Antarctica

Time	Latitude	Longitude	Angle
0–32	4.9	36.4	18.3
32–34	–17.2	51.5	1.21
0–34	3.43	37.07	19.39
32–36	–17.2	51.5	2.43
0–36	2.11	37.67	20.5
36–40	–20.6	42.7	2.83
0–40	–0.67	37.76	23.13
36–51.5	–20.6	42.7	11.29
0–51.5	–6.19	37.93	31.19
36–53	–20.6	42.7	12.38
0–53	–6.70	37.94	32.24

Table 7. *Continued.*

(d) South Pole/Australia

Time	Latitude	Longitude	Angle	
0–5	0	356.3	−3.4	Composite pole
0–17.5	0	336.0	−10.6	Composite pole
0–22.5	0	20.9	−12.6	Composite pole
0–30	0	2.4	−21.1	Composite pole
0–34	0	5.5	−18.9	Liverpool volc.
0–36	0	9.1	−19.0	Inferred
0–40	0	15.8	−19.1	Inferred
0–51.5	0	35.6	−19.5	Barrington volc.
0–53	0	36.7	−20.1	Inferred
0–62.5	0	43.4	−23.7	Inferred
0–64	0	44.5	−24.4	Inferred
0–66.5	0	46.3	−25.4	Inferred
0–80	0	53.0	−29.5	Inferred

Notes:

Australia and India are assumed to be one plate from 0 to 32 Myr. and the rotation pole from Sclater & Fisher (1974) is used. India/Antarctica poles are taken from Sclater & Fisher (1974) with adjustments in the rate of opening to match the observed changes in spreading rate. Australia/Antarctica poles are taken from Weissel & Hayes (1972) except that the ages have been changed to conform to the Sclater *et al.* (1974) timescale.

The South Pole/Australia poles have been calculated from the palaeomagnetic poles for Australia given by McElhinny *et al.* (1974). Inferred poles have been estimated from the apparent polar wandering curve in that paper. The South Pole/India poles have been calculated from the two relative motion poles and the South Pole/Australia poles. See text for method of calculation.

These poles have been used to calculate the palaeolatitude of site 216 with respect to the Australian palaeomagnetic data and with respect to a fixed Antarctica (Fig. 6).

revised fit of Australia in a more westerly position against Antarctica (Norton & Molnar 1977) makes the mismatch even worse. There are undoubtedly some errors in the palaeomagnetic directions, but it is unlikely that these could account for more than about 5° of mismatch. As all of the error occurs between 40 and 50 Myr, and as the indicated rates of motion prior to that time are the same for both data sets, it seems most likely that the age for the 51.5 Myr pole for Australia (Barrington volcano) is in error. If the date is 10 Myr too old then the problem would be resolved. Some younger dates have been reported (Wellman *et al.* 1969), but these were ascribed to argon loss. This interpretation needs to be checked, either with new dates, or new palaeomagnetic poles of similar age.

8 Anomaly identification and skewness

The discussion of Indian Ocean tectonics at the beginning of this paper was based primarily on the anomaly identifications of Sclater & Fisher (1974). Deskewing the anomalies removes the distortions from their shapes and makes them easier to identify (Schouten & McCamy 1972). The deskewed anomalies used for this study are plotted along track in Fig. 8. The observed data are presented in the same format by Sclater & Fisher (1974) for all the tracks except *Pioneer 1964*. My identifications of these anomalies generally agree with those of Sclater & Fisher (1974), and they confirm the overall pattern of spreading rate changes postulated by them.

The *Pioneer 1964* track confirms the previous tentative identification of anomaly 30 (Sclater & Fisher 1974) between 86° E and 90° E, and it clearly establishes the existence of

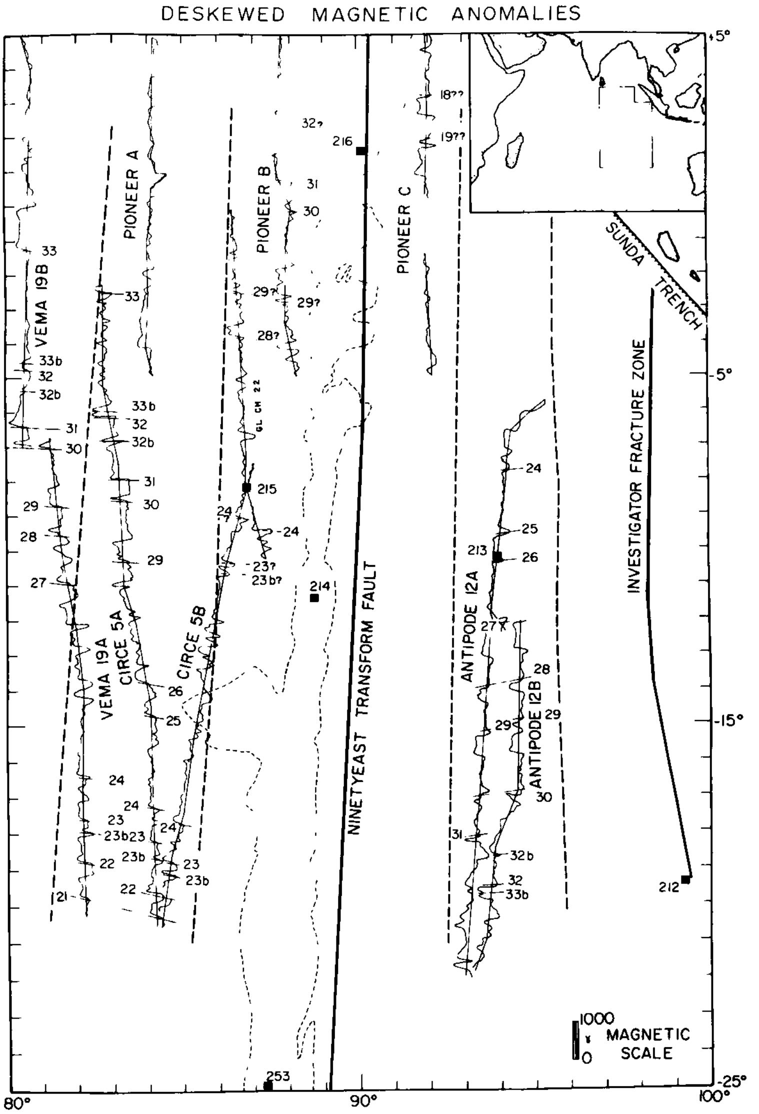

Figure 8. Deskewed magnetic anomalies in the east central Indian Ocean, plotted perpendicular to track. The straight lines are the approximate ship tracks. Representative phaseshifts were chosen for each data set; plots of several different phaseshifts and the original data are given in Peirce (1977). Phaseshifts used: *Antipode 12A*, −65°; *Antipode 12B*, −60°; *Circe 5A*, −75°; *Circe 5B*, 70°; *Glomer Challenger 22*, −80°; *Pioneer A and B*, −80°; *Pioneer C*, −90°; *Vema 19A*, −70°; *Vema 19B*, −80°.

an 8–9° left lateral offset on the 86° E fracture zone for that age. Throughout all the profiles west of the Ninetyeast Ridge, the time between anomalies 24 and 30 is marked by poorly correlatable anomalies. In the slice of crust between 86° E and 90° E the record is by no means straightforward, and it consists of basically one track. Nevertheless, I agree with Sclater & Fisher's (1974) tentative identification of anomaly 24 there, primarily on the basis of its position with respect to anomaly 30. Furthermore, I tentatively identify anomaly 23 on the *Circe 5* track just to the south (Fig. 8).

If these tentative identifications are correct, then the 11° of extra crust between 86° E and the ridge must lie south of site 214. Unfortunately, only east–west tracks cross this area. Sclater *et al.* (1976) identified anomalies 18–22 in the area just north and west of site 253. Although I feel that these anomaly identifications were made on extremely tenuous grounds, the possibility exists that between 11° and 22° S there is a captured portion of the Antarctic plate. However, it is more likely, in my opinion, that some of these tentative anomaly identifications are wrong and that the 11° of extra crust has been broken up into small pieces by a series of small ridge jumps.

To the east of the Ninetyeast Ridge, the *Pioneer 1964* data add coverage between the ridge and 93° E. North of the Equator the anomalies seem clear and distinct. These might be anomalies 18–20, but the track is short and these identifications should be regarded as very tenuous. South of the Equator, the anomalies seem quite different in character and they seem indistinct. Unfortunately, the ship was diverted for a station in the transition between the two anomaly types.

One potential means of checking on the DSDP palaeolatitudes is to estimate the skewness of the magnetic anomalies and then compute a lune of possible palaeomagnetic pole positions (Schouten & Cande 1976). Implicit in the use of this method for the Ninetyeast Ridge is the assumption that there is a negligible difference in the ages and the original latitudes between the Ninetyeast Ridge sites and the anomalies to the west on the Indian plate. All the tracks used for picking the skewness of anomalies run nearly north/south, and the anomalies strike N 95° E. Unfortunately, the quantity of suitable tracks is low, and the variability of the measured skewnesses is usually 10–20° and occasionally more. Consequently the resulting lunes (Peirce 1977) are too wide to be useful.

9 Previous Ninetyeast Ridge models and their predicted palaeolatitudes

There are three models for the origin of the Ninetyeast Ridge which are compatible with the existing data. They are, in chronological order, the hotspot model (Morgan 1972a,b), the migrating spreading centre–transform fault junction model (Sclater & Fisher 1974), and the two hotspot model (Rennick & Luyendyk 1975; Luyendyk & Rennick 1977). Basically, the differences are that the hotspot model predicts a fixed (or nearly fixed) palaeolatitude for the basement rocks along the length of the ridge. The migrating spreading centre–transform junction model assumes that the position of the spreading centre is free to migrate in latitude (and longitude) to keep itself in a median position between India and Antarctica. The two hotspot model assumes that the spreading centre is free to migrate and that it is independent of the position of the Amsterdam–St Paul (AMSP) and Kerguelen (KER) hotspots. It considers the effects of the plate boundary passing back and forth over this pair of hotspots. The predicted palaeolatitudes of each model are discussed in detail below.

9.1 MIGRATING SPREADING CENTRE–TRANSFORM JUNCTION MODEL

This model of Sclater & Fisher (1974) proposes that the Ninetyeast Ridge is the result of excess volcanism at the junction of a spreading centre and a major transform fault. Thus the age of the crust to the west and the age of the ridge are assumed to be nearly identical, and the palaeolatitudes of sites on the Ninetyeast Ridge at various ages can be predicted from the positions of the corresponding anomalies to the west.

According to their model site 217 was formed at 55° S some 80 Myr ago. As the spreading system moved north, the crust at site 216 was formed at about 40° S about 67 Myr ago. Around 58–63 Myr ago, with site 216 near 30° S, site 215 formed west of the Ninetyeast Ridge near 40° S, and site 213 formed east of the ridge near 30° S. Shortly thereafter, site 214 formed on the ridge near 35° S. Thus the difference in palaeolatitudes at the bottom of holes 213 and 214 should indicate the offset of the Ninetyeast Fault plus any offset of a possible minor transform fault at 93° E. This length is that before the spreading centre immediately west of the Ninetyeast Ridge jumped or migrated 11° to the south about 53 Myr ago. The combination of the southerly jump of the spreading centre and the southward motion of the Antarctic plate (according to Australian poles) during the next few million years means that site 253 (age 46–51 Myr) must have formed near 45° S, further south than either 214 or 216. Site 254 (age 30–40 Myr) should have formed still further south if the Sclater & Fisher (1974) model is correct (Fig. 9). An objection to this model is that one would expect some of the excess volcanics to accumulate on the Antarctic plate and to form a 'mirror image' ridge. At the time the model was proposed no such ridge was known (but see model 3 below).

9.2 HOTSPOT MODEL

On the other hand, if Morgan's (1972a, b) hypothesis were correct, namely that the Ninetyeast Ridge formed by a deep seated hotspot fixed with respect to the Earth's spin axis, then the DSDP site palaeolatitudes from the Ninetyeast Ridge should be all the same. If the hotspot were not absolutely fixed, but instead had moved slowly (say 1 cm/yr) with respect to the spin axis, then the ridge palaeolatitudes should show a slow steady change with age. Over a time span of 40 Myr, 1 cm/yr of hotspot motion would produce no more than 4° change in palaeolatitude. Thus, this model predicts that all the basement palaeolatitudes for sites on the Ninetyeast Ridge should lie near 40° S if the Amsterdam–St Paul hotspot formed the ridge, or near 50° S if the Kerguelen hotspot formed the ridge (Fig. 9).

This model, as originally presented, did not predict any age relationship between the Ninetyeast Ridge and the adjacent Indian plate to which it is attached. The results of DSDP Legs 22 and 26 (von der Borch *et al.* 1974; Davies *et al.* 1974) showed that the ridge is of very nearly the same age as the ocean crust just to the west. A further shortcoming is that it offers no explanation for the curious coincidence of the strikes of the Ninetyeast Ridge and the Ninetyeast Transform Fault. This second point is not inconsistent with the hotspot model, it is merely an unlikely coincidence. Bowin (1973) attempted to explain this by suggesting that the volcanic source was not deep seated in the mantle but was in some way being carried along with India, but at a lower rate.

9.3 TWO HOTSPOT MODEL

Luyendyk & Rennick (1977) and Rennick & Luyendyk (1975) favour a two-hotspot model for the origin of the ridge to overcome the shortcomings of the earlier ones. The model considers the effects of a spreading system migrating northwards towards the Kerguelen and Amsterdam/St Paul hotspots, passing over Kerguelen, then jumping south of it when the 11° ridge jump occurred (Sclater & Fisher 1974), and finally passing northwards over it once again. It predicts that basement formed near 40° at sites 216 and 217, and that it formed near 50° S at sites 253 and 254. The predicted palaeolatitude of site 214 is ambiguous, between 40° S and 50° S, because the site may have formed during the 11° ridge jump in their interpretation.

They showed that the Kerguelen–Gaussberg Ridge on the Antarctic plate is the 'mirror image' ridge to the Ninetyeast Ridge *if* the Ninetyeast Ridge is assumed to be a hotspot trace. Broken Ridge, now on the Australian plate, was once part of the Kerguelen–Gaussberg complex. This finding overcomes the previous objection to the migrating spreading centre–transform junction model, but it requires the assumption of a contradictory model to do it! The two-hotspot model explains the age correlation between the Ninetyeast Ridge

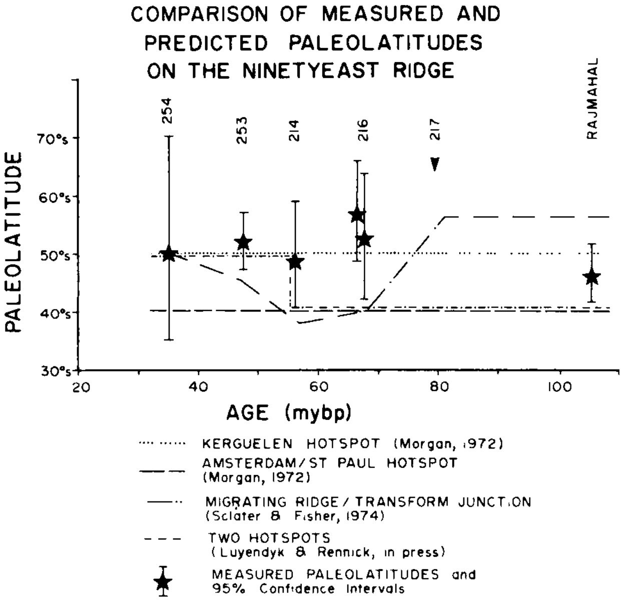

Figure 9. Comparison of the measured and predicted basement palaeolatitudes at the DSDP sites on the Ninetyeast Ridge. The measured palaeolatitudes and 95 per cent confidence intervals (Tables 1 and 6) are shown by the stars and error bars. No basement palaeolatitude is available for Site 217. The palaeolatitudes predicted by various models discussed in the text are shown by the indicated symbols. Note that all the basement palaeolatitudes lie near 50° S and that only the Kerguelen hotspot model predicts all of them.

and the Indian plate because one or the other hotspot is always near the spreading centre. Luyendyk & Rennick (1977) explain the coincident strike of the hotspot traces and the fault by postulating that the transform fault was constrained to follow the line between the two hotspots. This presumed line of weakness has the same strike as that of the Ninetyeast Ridge and the Ninetyeast Transform Fault.

The predicted palaeolatitudes are compared with the measured basal palaeolatitudes in Fig. 9. The only model which fits the measured palaeolatitudes is the Kerguelen hotspot model. It is the only model which predicts a palaeolatitude near 50° S for site 216. As the basalt and sediment palaeolatitudes have 95 per cent confidence intervals which lie wholly south of 40° S, this is strong evidence in favour of the Kerguelen hotspot model. The other basement palaeolatitudes on the Ninetyeast Ridge also lie near 50° S. In addition, the Rajmahal Traps (age 105 Myr), which lie along the strike of the ridge to the north, have palaeolatitudes of 46° S and 48° S (Klootwijk 1971). Thus these data indicate that the volcanic source of the Ninetyeast Ridge was fixed, or nearly fixed, in latitude for 60–70 Myr.

10 The origin of the Ninetyeast Ridge – implications and speculations

The palaeomagnetic evidence strongly supports the hypothesis that the Kerguelen hotspot was the source of the Ninetyeast Ridge. What other geological and geophysical evidence can be cited which is relevant to the fixed volanic source idea? In the discussion below I will show that none of the available geological and geophysical data contradicts the hotspot model as it was originally proposed by Morgan (1972a, b). There is room for other interpretations, but it is this model which best satisfies all of the available data.

A large number of authors have worked on the petrology and the geochemistry of the Ninetyeast Ridge rocks (Hekinian 1974; Frey & Sung 1974; Kempe 1974; Thompson *et al.* 1974; and Frey *et al.* 1977). At the three sites with significant basalt recovery (214, 216 and 254), the basalts were generally enriched with large ion lithophile elements such as Ba, K, Hf, Sr and Zr. They also showed a negative slope in the rare earth pattern, indicating enrichment of the lighter rare earths (Frey & Sung 1974; Fleet & Kempe 1974), although this pattern was not universal (Frey *et al.* 1977). The overall suite of rock types indicated a similarity between the petrogenic processes under oceanic islands and a dissimilarity with 'normal' mid-ocean ridge processes (Frey & Sung 1974), indicating an affinity with the rocks from other hypothesized hotspot traces.

Because the Ninetyeast Ridge has a free air gravity anomaly near zero and no major flanking faults to the west, Bowin (1973) argued that the ridge has always been nearly in isostatic equilibrium. In order to accomplish this and to provide the 7–8 km/s material detected by seismic refraction (Francis & Raitt 1967), he proposed that a mixture of gabbro and serpentized peridotite was emplaced at depth at the same time the volcanic pile was being built near sea level. Such high velocity rocks could provide both the isostatic compensation required by the new gravity data and the observed uplift. He favoured a modification of Morgan's (1972a, b) hotspot model as the mechanism to accomplish this emplacement.

The morphology of the Ninetyeast Ridge can be divided up into three parts: a series of peaks apparently *en échelon* in the north, a long narrow section in the middle, and a wider portion in the south which is bounded by Osborn Knoll at its northern end (Sclater & Fisher 1974, Fig. 1). The single-hotspot explanation cannot directly account for these morphological differences. Variations in spreading rate and small-scale tectonic changes may well be responsible.

Much of the geology, palaeontology, and palynology of the Ninetyeast Ridge indicates that it was once near or above sea level, as discussed above. As the topography of the ridge roughly follows the shape of the age–depth curve (Sclater & Fisher 1974) for oceanic basins, it is reasonable to suppose that the basement at the Ninetyeast Ridge drill sites was formed very close to an active spreading centre. If the Ninetyeast Ridge is a hotspot trace, and if it is slightly younger than the Indian plate to the west, then there should be no 'mirror image' ridge on the Antarctic plate, unless there are two hotspots, as proposed by Luyendyk & Rennick (1977). On the other hand if it is exactly the same age as the Indian plate, then it formed at the Indian–Antarctic plate boundary, and there should be a complementary ridge on the Antarctic plate. The available data cannot resolve this age question.

Luyendyk & Rennick (1977) showed that a 'mirror image' ridge does exist. They did reconstructions of the Indian Ocean using marine magnetic anomalies and the Australian palaeomagnetic data in a manner very similar to that of Sclater & Fisher (1974). They assumed that the Ninetyeast Ridge was a hotspot trace, and therefore they constrained the longitude of their reconstructions to keep the Amsterdam–St Paul hotspot under the Ninetyeast Ridge until 53 Myr. Because the trace of the Ninetyeast Ridge can be approximated by an equatorial pole of rotation, a corollary to this assumption is that India has experienced no absolute longitudinal rotation. The most important result of their work was that they demonstrated that the Kerguelen–Gaussberg/Broken Ridge complex forms a hotspot trace on the Antarctic plate from the Kerguelen hotspot. These two features were subsequently rifted apart during the reorganization of spreading in the Indian Ocean about 40 Myr ago. As none of their assumptions constrain the motion of the Antarctic plate relative to the Kerguelen hotspot, their work demonstrates that there may indeed be a 'mirror image' ridge to the Ninetyeast Ridge. Thus, if one accepts the hypothesis advanced above that the Ninetyeast Ridge is the trace of one fixed volcanic source, Luyendyk & Rennick's reconstructions show that it must have formed at the Indian–Antarctic spreading centre and created traces on both plates.

The existence of a worldwide network of hotspots with little or no relative motion between them remains in doubt. Hey (1975) has shown that the Galapagos hotspot is fixed with respect to Hawaii. Duncan & McDougall (1977) have shown that the Society, Austral, Marquesas, and Pitcairn–Gambier Island chains have rates and trends of volcanic migration which predict the same motion for the Pacific plate as is predicted by the Hawaii–Midway chain. Thus the existence of a Pacific network of hotspots relatively fixed with respect to one another seems probable. Whether or not this network can be extended to include Kerguelen is problematic (Molnar & Atwater 1973). Because the Kerguelen hotspot appears to be essentially fixed in latitude, one would like to infer that it is also fixed with respect to Hawaii. However, there is no conclusive evidence that it is. It is clear that the Atlantic hotspots cannot have remained fixed with respect to the Indian Ocean hotspots if they all created the hotspot traces usually ascribed to them (Molnar & Francheteau 1975a). Relative motions up to 2 cm/yr are required to satisfy all of the available constraints.

Thus the weight of evidence strongly supports the concept that the Ninetyeast Ridge is the volcanic trace of the Kerguelen hotspot which is fixed with respect to latitude (Fig. 10). However, an apparent contradiction exists in the arguments presented above. The volcanic source of the ridge was nearly fixed in latitude, and yet it appears to have remained under the Indian–Antarctic spreading centre from the initial rifting of India and the Antarctic until spreading reorganized in the central India Ocean about 40 Myr ago. Considering that the measured spreading rates during that time (up to 12.0 cm/yr one limb rate – Sclater & Fisher 1974) are among the highest ever observed, it seems to be an artificial constraint to suggest that the spreading centre did not migrate quite freely with respect to latitude. Thus it seems that the spreading centre, if it were spreading symmetrically, must have been migrating rapidly northwards with respect to the South Pole unless Antarctica migrated rapidly southwards at the same time.

In his discussion of the hotspot hypothesis Morgan (1972a) suggests that if one plate of a rifting two-plate system were fixed by forces external to those causing the rifting, a hotspot under the spreading centre might cause asymmetric spreading. I suggest that the Kerguelen hotspot has caused asymmetric accretion (symmetric spreading with repeated spreading centre jumps in the same direction; see Hey (1975) and Hey, Johnson & Lowrie (1977) in

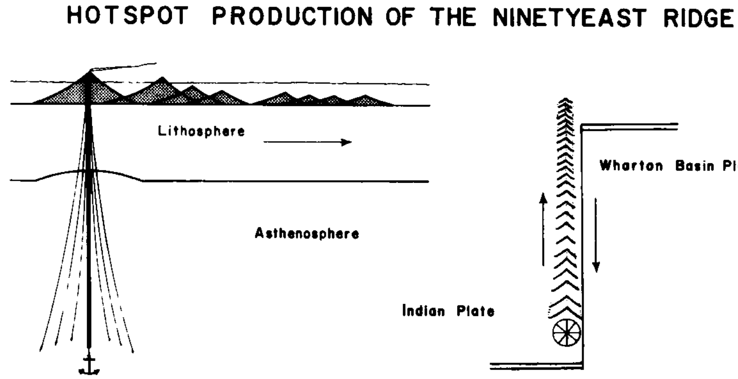

Figure 10. Sketch of the model for the generation of the Ninetyeast Ridge by a fixed volcanic source.

the Indian Ocean, and furthermore that this asymmetric accretion was, at least in part, the cause of the extreme length of the Ninetyeast Transform Fault.

There are no relevant palaeomagnetic data from East Antarctica, but there are several poles of Cretaceous and Lower Tertiary age from West Antarctica and from Australia (McElhinny 1973) which suggest that Antarctica was indeed moving very little with respect to the spin axis of the Earth during the period from the middle Cretaceous to the Palaeocene (also see Sclater & Fisher 1974, Fig. 13; Luyendyk & Rennick 1977, Fig. 8d). Perhaps the geometry of other plate motions held the Antarctic nearly fixed in much the same manner as it appears to be today. Thus if the Ninetyeast Ridge is a hotspot trace we might expect to find asymmetric spreading or asymmetric accretion between the Indian and Antarctic plates for the reasons suggested by Morgan (1972a). Sclater & Fisher (1974) have documented an 11° southerly jump of the spreading centre at the southwestern end of the Ninetyeast Ridge. There is a data gap through the region of the jump, and the equivalent anomalies on the Antarctic plate have not yet been described, so the exact nature of the jump is unknown. Its existence cannot be doubted, however, as anomalies 27–30 are offset 8–9° left laterally and the anomalies younger than anomaly 15 are offset 2–3° right laterally along the same fracture zone. This jump may have occurred as a series of small jumps or as one large jump, but the net effect was to cause asymmetric accretion with the Indian plate growing much faster than the Antarctic plate between the 86° E fracture zone and the Ninetyeast Ridge. It is possible that the Antarctic plate did not grow at all during the time of the jumping and that the integrated effect of this asymmetric accretion process was entirely one sided. This jumping must have predated the reorganization of spreading south of the Ninetyeast Ridge as the crust involved is bounded by the north striking 86° E and 90° E transform faults. Thus it cannot have been caused by the westward migration of the spreading pattern which separated Australia from Antarctica (Bowin 1974).

A very similar process has been documented for the Galapagos spreading system. Hey *et al.* (1977) showed that part of that system has been spreading symmetrically, but accreting asymmetrically. The spreading process itself has been symmetric and continuous, but the ridge has jumped south towards the hotspot at discrete times, making the accretion process discontinuous and asymmetric.

Melosh, Stein & Minster (1976) have suggested that some asymmetric accretion occurs along spreading centres which are migrating with respect to the mantle. Their model predicts that the trailing edge of the spreading centre will accrete more quickly than the leading edge. This sense of asymmetry is opposite to that observed near the Ninetyeast Ridge. The only other major exception to their model is the Galapagos system, and they suggest that the proximity of the hotspot may be the reason.

It is possible that a mantle plume of finite dimensions has a limited effect on the asymmetry of a spreading ridge system. In both the cases of the Ninetyeast Ridge and Galapagos systems, the asymmetries are confined to one segment of the spreading system and they may have occurred only within certain well-defined periods. Hayes (1976) has noted similar scale limitations in asymmetric spreading south of Australia, and he has used a similar model to explain them even though there is no direct evidence for a hotspot south of Australia.

There is no *a priori* reason why the absolute motion vector of a plate should coincide with its relative rotation vector with respect to some other plate. Neither is there any reason why they should not coincide. If the Ninetyeast Ridge is indeed a hotspot trace, then its strike parallel to the Ninetyeast Transform Fault implies that the absolute rotation vector of India and the relative motion vector for Antarctica/India were nearly coincident. As mentioned above, Molnar & Tapponnier's (1975) analysis of the relative motion of Eurasia/India agrees well with the foregoing analysis of India's northward motion. This is independent circumstantial evidence supporting the possibility of coincident absolute and relative motion vectors.

The palaeomagnetic data presented in the beginning of this paper suggested that the Ninetyeast Ridge may be a hotspot trace. The foregoing discussion has shown that there are no other data in conflict with this hypothesis and, indeed, the hypothesis predicts some of the unusual geometric relationships observed. Two hotspots are not needed to explain the presence of both the Ninetyeast Ridge and the Kerguelen–Gaussberg Ridge/Broken Ridge complex if one accepts the palaeomagnetic evidence for an essentially stationary Antarctic plate and the causal relationship between the hotspot position and the position of the spreading centre. Although many will disagree with such a position, the two-hotspot model will not work if Indian palaeomagnetic poles are used instead of Australian poles.

11 Conclusions

Palaeomagnetic data have been presented for several DSDP sites on and near the Ninetyeast Ridge. Several north–south magnetic anomaly profiles in the area have been deskewed, and three old but previously unpublished tracklines near the ridge are presented.

Analysis of these data together with previously published information, leads to the following conclusions:

(1) The Ninetyeast Ridge is attached to the Indian plate and it has moved northwards about 5000 km since the Late Cretaceous. The extent of northward motion is supported by the palaeontological and palynological evidence in the drill holes.

(2) The Ninetyeast Transform Fault, which once separated the Indian plate from the Australian–Wharton Basin plate, was some 3500 km long about 55–60 Myr ago.

(3) The rate of northward motion of India relative to the South Pole was 14.9 ± 4.5 cm/yr from 70 to 40 Myr when it slowed to a rate of 5.2 ± 0.8 cm/yr. This latter rate has continued to the present. The time of slowing roughly corresponds to the time of the collision of India and Asia to the Eocene.

(4) The continental palaeomagnetic poles from the Deccan Traps are in excellent agreement with the Ninetyeast Ridge palaeolatitudes. However, the Australian continental palaeomagnetic poles do not agree with the Indian plate data prior to 40 Myr. The Australian data indicate that India was 10–15° further north at any given time than the Indian plate data imply. In order to compare these various data sets one must correct for the relative motions of the plates via Antarctica. Thus, the source of the error may be in the relative motion estimates for India/Antarctica and Australia/Antarctica as well as in the palaeomagnetic data. At present, there is no explanation for the discrepancy, although an error in the age of the Barrington volcano pole for Australia could explain the problem. The palaeolatitudes on published Indian Ocean reconstructions (Sclater & Fisher 1974; Luyendyk & Rennick 1977) are probably partially in error because they are based on only the Australian palaeomagnetic data.

(5) The identification of magnetic anomalies in the east central Indian Ocean (Sclater & Fisher 1974) is confirmed by deskewing anomaly shapes. In particular, the inference of an 11° southward shift of the position of the spreading centre at the southwestern end of the Ninetyeast Ridge is confirmed.

(6) The basal palaeolatitudes for four DSDP sites on the ridge are all near 50° S, supporting a Kerguelen hotspot model for the origin of the ridge as suggested by Morgan (1972a, b). The Rajmahal Traps in eastern India lie near the Ninetyeast Ridge line, and they formed

between 45° S and 50° S about 105 Myr ago (Klootwijk 1971). Thus, the volcanic source of the Ninetyeast Ridge appears to have been active and nearly fixed in latitude for about 70 Myr, from 105 to 37 Myr (Fig. 10).

(7) The existence of a 'mirror image' ridge on the Antarctic plate (Luyendyk & Renmick 1977) indicates that the volcanic source must have remained very near to the Indian–Antarctic plate boundary. This implication, together with the fixed latitude constraint, implies a causal relationship between the positions of the hotspot and the plate boundary. It is suggested that Antarctica was held relatively fixed by forces external to those controlling the Indian–Antarctic separation, and that, as a result, the hotspot may have caused asymmetric accretion of crust between 86 and 90° E near the southern end of the Ninetyeast Ridge in a manner similar to that predicted by Morgan (1972a) in his original discussion of the hotspot hypothesis. The existence of such asymmetric accretion near the Ninetyeast Ridge is postulated on the basis of an inferred 11° southerly migration or jump of the spreading centre at the southwest end of the ridge. This probably occurred between anomalies 23 and 15 (55–38 Myr). Clearly more detailed magnetic mapping in the region immediately west of the Ninetyeast Ridge is needed to resolve the nature of this 11° migration or jump.

The discrepancy between the Australian and Indian palaeomagnetic data sets is a significant problem which may hinge on the Barrington palaeomagnetic pole for Australia. Although the dating of Barrington volcano appears good (Wellman *et al.* 1969), there is sufficient variability in the dates to cast doubt on their validity. Beyond checking that pole, further detailed magnetic mapping in the Wharton Basin between the Cenozoic anomalies west of the Investigator Fracture zone (Sclater & Fisher 1974) and the Mesozoic anomalies recently mapped by Heirtzler *et al.* (1977, private communication) off northwestern Australia may shed some light on the nature of the motion between India and Australia.

Although the palaeomagnetic data strongly support the Kerguelen hotspot model for the origin of the Ninetyeast Ridge, the major firm conclusion is that the volcanic source which created the ridge was nearly fixed in latitude. To date there has been no mechanism supported by the available evidence which can explain the reason for the existence of rising plumes of hot material from deep in the mantle. As such plumes have been proposed as a plate driving mechanism (Morgan 1971), the proof or disproof of their existence is a major unsolved problem. This paper strongly supports the existence of one such plume, but a plausible mechanism for its existence remains to be demonstrated.

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