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11. PALEOMAGNETISM OF LEG 115 BASEMENT ROCKS AND LATITUDINAL EVOLUTION OF THE RÉUNION HOTSPOT[1]

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ABSTRACT

Paleomagnetic measurements were performed on basement cores from four Leg 115 sites (706, 707, 713, and 715). Although results have on average a good paleomagnetic quality, their interpretation is made difficult by the lack of declination control, and in some cases by insufficient averaging of secular variation, and by subsequent tectonic tilting, all of which cannot generally be corrected for. Sites 707 (64 Ma) and 715 (55–60 Ma) yield paleolatitudes that are consistent with those predicted by the hotspot motion models of Duncan and Morgan, and with the new synthetic apparent polar wander paths of Besse and Courtillot. The Site 707 results are also fully consistent with those of the Deccan Traps, as predicted by Courtillot et al. (1986). On the other hand, Sites 706 (48 Ma) and 713 (36 Ma) yield discrepant results that can be interpreted in terms of emplacement close to a ridge and subsequent tectonic tilting. Results from sediments of Site 706 studied by Schneider and Kent can fortunately be added to the two reliable basement sites to yield the latitude evolution of the hotspot from its inception at the Deccan to its present position at Réunion Island. This motion is consistent with the Morgan model and amounts to northward drift at a mean rate of about 8 mm/yr.

INTRODUCTION

One of the aims of Ocean Drilling Program (ODP) Leg 115 was to test proposed hotspot models of the formation of the composite Laccadive-Maldive-Chagos-Mascarene ridge system. Indeed, Morgan (1983) and Duncan (1981) have proposed that this system was generated by the hotspot now located in the vicinity of Réunion Island, and that the hotspot underwent a violent birth leading to the formation of the Deccan Traps in India (Courtillot et al., 1986). Morgan (1983) also proposed that hotspots are rather stationary relative to each other and to the mantle. These ideas can be tested with paleomagnetism by studying the paleolatitudes of lavas generated by the hotspot from its inception to its present location.

In this brief report, we recall the geographic and age distributions of sites that were drilled through basaltic basement. We then discuss the statistical methods that can be used on this inclination-only data set and describe the paleomagnetic results for each site in detail, with emphasis on problems related to the sampling of secular variation by flow sequences. Paleomagnetic results from overlying sediments are available for only one site (706) and are included in the final discussion, in which data and hotspot models are compared; some limitations of paleomagnetic measurements of seafloor basement are emphasized.

BASEMENT SITES

The *JOIDES Resolution* drilled the basement of the ridge system four times (Fig. 1). The first two sites (706 and 707) were on the African Plate and the last two (713 and 715) on the Indian Plate. The principal characteristics of these sites are given in Table 1. The petrologic units were defined on board using texture and composition of basalts and identifying chilled boundaries (see "Basement Rocks" sections in Backman, Duncan, et al., 1988, pp. 146–149, 261–265, 751–756, and 928–936). Basement ages given in Table 1 were obtained by biostratigraphic dating (Berggren et al., 1985a, 1985b) from interstratified sediments for Sites 706 and 713 or from sediments overlying basement for Sites 707 and 715 (see "Biostratigraphy" sections in Backman, Duncan, et al., 1988, pp. 244–252 and 922–925).

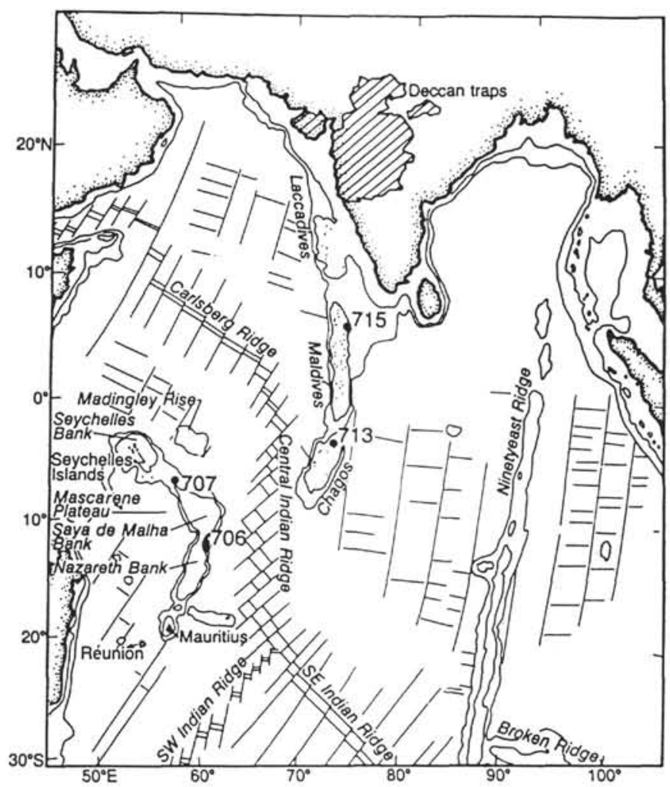

Figure 1. Bathymetric map of the western and central Indian Ocean showing 2- and 4-km depth contours. Leg 115 drilled into basaltic basement at Sites 706, 707, 713, and 715.

The age estimates were further constrained by the determination of the magnetic polarity of basement sequences in Sites 707 and 713 (see "Principal Results" sections in Backman, Duncan, et al., 1988, pp. 233–237 and 733–734). The best example of age

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Table 1. Characteristics of Leg 115 basement sites studied.

Site	Position	Sediment thickness (m)	Penetration in basalt (m)	Mean petrologic unit thickness[a] (m)	Total number of petrologic units	Number of petrologic units sampled for paleomagnetism	Biostratigraphic dating (Ma)
706	13°06.84′S 61°22.26′E	44.8	77.4	0.6	32	20	34.9-36.7
707	07°32.72′S 59°01.01′E	375.6	63.1	7.3	5	5	63.5–64.3
713	04°11.68′S 73°23.65′E	107.0	84.7	1.0	35	34	46.2–48.8
715	05°04.89′N 73°49.88′E	211.3	76.5	1.3	21	12	55–60

[a] Mean petrologic unit thickness is given in meters of recovered core.

estimate is the case of the Site 713 basement because of the presence of two entire cores of sediments sandwiched between two basalt sequences: the location of the CP13b/CP13c boundary in Section 115-713A-16R-1 gives an age of 47 Ma (Berggren et al., 1985a) for the top of the sedimentary interstratification. The reverse polarity of the complete basalt sequence places it in Chron 20R. Thus, the upper and lower parts of the basement are dated at 46.2–47 Ma and 47–48.8 Ma, respectively (using the reversal time scale of Berggren et al., 1985a).

PALEOMAGNETIC STUDY

The remanent magnetization of all basement minicores recovered during Leg 115 were measured with a Molspin spinner magnetometer, either shipboard or in the laboratory at the Institut de Physique du Globe de Paris. Standard alternating-field and thermal techniques were used for demagnetization, and characteristic directions of components were determined by means of vector diagrams and least-squares techniques.

It was impossible, of course, to determine declination because of the rotation of basalt pieces during drilling. Therefore, only inclinations could be obtained; these inclination-only data, which are listed in Tables 2–5 (one per site), cannot be processed by classical statistical techniques. Two specifically adapted methods have been proposed, one by McFadden and Reid (1982), the other by Cox and Gordon (1984).

The McFadden and Reid technique provides maximum likelihood estimates of the mean inclination I (and latitude λ_i) and of the 2-D Fisherian precision parameter k, from which the observed population of inclinations is supposed to have been drawn. Unit weight is given to each cooling unit. A misprint in equation (40) of McFadden and Reid (1982) has been corrected for (the unhatted value of q should be used, rather than the hatted one written in the equation; D. Schneider, pers. comm., 1988). Another possible error, namely an erroneous sign in the bias correction term, has been mentioned by R. Gordon upon review of a first version of this paper, but we do not recognize this error (neither does D. Schneider, pers. comm., 1989).

The Cox and Gordon technique starts with the arithmetic mean colatitude ($\theta_a = \pi/2 - \lambda_a$). This is corrected for a bias that is a function of colatitude and is based on the paleosecular variation (PSV) model of Harrison (1980). The standard deviation of the colatitude can be corrected for the internal standard deviation of each cooling unit and also for systematic errors, such as regional tectonics and the deviation of the borehole from the vertical or nonaxial dipole field.

Cox and Gordon (1984) also point out that successive cooling units can be regarded as providing statistically independent data only if their age difference is greater than the coherency time of the geomagnetic field (i.e., greater than about 10^4 yr). It is clear from the discussion in Cox and Gordon (1984), and in particular from figure 8 in their article, that it is quite difficult to define the number of statistically independent data in a sequential-result set. Such is indeed the case with the data presented here, where the contact between petrologic units is rather clearly characterized by chilled glassy surfaces, by oxidation zones, or, in certain cases, by sedimentary deposits, but where we have no means to estimate, even roughly, the time interval between two units. In the absence of complementary information, we consider the results from each cooling unit as statistically independent data. When the standard deviation between flows S_{bf} is significantly less than predicted by the PSV model (S_o), we have reasons to doubt that secular variation has been averaged out properly, but the uncertainty $\delta\lambda_{cg}$ on the latitude λ_{cg} is not underestimated because it is calculated as $S_o/n^{1/2}$ (n being the number of petrologic units).

Similarly, in the McFadden and Reid technique, the angular standard deviation of field directions σ_d can be simply estimated from the Fisher precision parameter k as $\sigma_d = 81°/k^{1/2}$ and then compared to an appropriate PSV model. We have selected the updated F model of McFadden and McElhinny (1984), which predicts an angular standard deviation σ'_d for the appropriate time-paleolatitude window (see McFadden and McElhinny, 1984, table 2 and figs. 8 and 9). Whenever σ_d is much smaller than σ'_d, there is reason to believe that secular variation has not been properly averaged out.

All of these statistics are listed in Table 6 for the four sites. In the application of the McFadden and Reid (1982) technique, unit weight is given to each basaltic petrologic unit as well as each ash layer. The estimated k is used to determine the confidence angle α_{95} and the uncertainty of inclination δI, which is asymmetrical and equal to a bias-corrected α_{95}. The uncertainty on latitude $\delta\lambda_i$ is then derived as $\delta I(1 + 3\sin^2\lambda)/2$, and is also asymmetrical. The differences between the latitude estimates λ_i, λ_a, and λ_{cg} are always less than 1°, which is much less than the associated uncertainties $\delta\lambda_i$ and $\delta\lambda_{cg}$ that range from 3° to 9°. This difference is primarily related to the assumption of a Fisherian distribution for inclinations vs. virtual geomagnetic poles and is small because of the rather low paleolatitudes (10°–25°) that are involved. The uncertainties on λ_i and λ_{cg} are quite similar for Sites 706, 713, and 715.

Site 707 is the only case in which both techniques clearly demonstrate that secular variation has not been averaged out properly and that the flow directions are not statistically independent. The Cox and Gordon technique shows that the standard deviation between flows is three times less than expected from the Harrison (1980) PSV model; the McFadden and Reid standard deviation of field directions is also about three times less than expected from the F model for PSV. One way to estimate a more reliable confidence interval for the inclination and paleolatitude data may be to note that the observed and predicted angular standard deviations of field directions are in the ratio of 5.8° to 13°–16°. The uncertainties can be divided by this ratio, leading to a $\delta\lambda_i$ on the order of 10° rather than 4°, that is essentially the value found in the Cox and Gordon technique (Table 6).

Finally, the two techniques provide very similar and consistent results. Because the McFadden and Reid (1982) technique does not rest on a particular (built-in) PSV model that allows us to introduce an updated PSV model, we have selected it in Tables 2–5 and in the following discussion. Clearly, this does not make much difference and will not have any significant impact on our conclusions. A short description of the results for each individual site follows.

Site 706

All samples were demagnetized by alternating-field (AF) demagnetization. Each one shows a clear high-coercivity component (above 20 mT) that is revealed after removal of a scattered overprint. All these high-coercivity directions (Table 2) have a negative, though still rather scattered, inclination; this part of the basement was formed, therefore, during a normal chron. Furthermore, the estimated angular standard deviation σ'_d for Site 706 is 25.4°, which is consistent with the range of values predicted by the McFadden and McElhinny PSV model. Thus, we find no reason to doubt that secular variation was properly sampled by the flow sequence. The paleoinclination of Site 706 basement would then seem to be −24.2° +12.1°/−9.5°, leading to a paleolatitude of 12.7°S +5.4°/−6.9°.

On the other hand, the overlying sediments also displayed good magnetic behavior (Schneider and Kent, this volume), with a well-defined high-coercivity direction (above 5–10 mT) in spite of a large-amplitude, low-coercivity component caused by a strong vertical magnetization of the core barrel (see "The Core Barrel Remagnetization Effect," in Backman, Duncan, et al., 1988, pp. 475–476). The mean inclination for 32 samples is −36.3° ± 5.1°, corresponding to a paleolatitude of 20.2°S ± 2.8°. The difference between the basement and sediment results (8.3° ± 6.7°) will be discussed in the final section.

Table 2. Basement inclination for petrologic units, Site 706.

Unit	N	I (°)	λ (°)
1	1	−12.2	−6.2
2	1	−5.1	−2.6
4	1	−34.5	−19.0
5	1	−0.8	−0.4
6	1	−11.1	−5.6
10	1	−15.1	−7.7
12	3	−20.9	−10.8
14	1	−38.1	−21.4
15	1	−5.2	−2.6
17	1	−57.9	−38.6
18	1	−47.5	−28.6
19	1	−24.7	−13.0
20	2	−58.5	−39.2
21	1	−42.8	−24.8
26	1	−5.4	−2.7
27	1	−19.4	−10.0
28	1	−10.2	−5.1
29	1	−2.0	−1.0
31	1	−25.1	−13.2
32	1	−24.9	−13.1

Note: N = number of samples per unit, I = arithmetic mean inclination, and λ = paleolatitude determined from I.

Site 707

The five units of this site were inhomogeneously sampled: 2, 1, 6, 41, and 6 samples per unit, respectively (Table 3). Although petrographic study was not able to subdivide the 32-m-thick Unit 4, which was therefore considered to represent a single flow, we attempted dense paleomagnetic sampling in the hope of being able to reveal a subdivision based on inclination data. However, no really separate data groups could be defined in this way.

We demagnetized 30 samples with the AF method and 26 with the thermal (in Units 3, 4, and 5). The primary component was easily isolated after 15-mT treatment or 300°C heating (Table 3), in spite of the presence of a low blocking temperature component. The McFadden and Reid maximum likelihood algorithm yields a mean inclination of 43.3° +5.4°/−5.6°, which corresponds to a paleolatitude of 25.2°S +4.2°/−4.3° (Table 6).

For the age of this site (around 64 Ma), the F model predicts a time-averaged standard deviation between 13° and 16°; the standard deviation obtained from the five units of Site 707 is much smaller than this (5.8°). Therefore, we have reason to believe that secular variation has not been averaged out, as has been discussed above. The corrected uncertainty $\delta\lambda_i$ is on the order of 10°.

Site 713

All samples (from 27 basaltic units and 7 ash layers) were demagnetized with the AF method. Two samples (115-713-16R-2, 117–119 cm, and 115-713-17R-4, 26–28 cm) were removed from the final analysis because of unstable magnetic behavior and difficulty in determining a reliable primary component. However, the mean inclination and confidence intervals (for 27 basaltic units and 5 ash layers) do not change significantly from the results published in the "Site 713" chapter (Backman, Duncan, et al., 1988) (Table 6).

We have used each ash layer as a petrologic unit for calculations because of their very fast sedimentation rates that imply "instantaneous" recordings of the magnetic field. Basalts as well as ashes display a well-defined, high-coercivity component after 15-mT treatment (Table 4). With these 32 units, we obtain a mean inclination of 23.6° +4.5°/−5.5°, and we deduce a paleolatitude of 12.3°S +2.6°/−3.1° for Site 713 basement.

Petrologic studies (see "Basement Rocks" section, in Backman, Duncan, et al., 1988, pp. 751–756) indicate that we could consider the sequence from Units 12 to 26 as a composite single unit (therefore reducing the total number of independent units

Table 3. Basement inclination for petrologic units, Site 707.

Unit	N	I (°)	k	α_{95} (°)	λ (°)
1	2	50.3	—	—	−31.1
2	1	42.0	—	—	−24.2
3	6	40.6	58.2	8.2	−23.0
4	41	40.9	72.2	2.6	−23.2
5	6	42.8	251.0	3.9	−24.8

Note: N = number of samples per unit, I = arithmetic mean inclination for Unit 1 and maximum likelihood estimate of inclination for Units 3–5, k = maximum likelihood estimate of precision parameter, α_{95} = 95% confidence interval, and λ = paleolatitude determined from I.

Table 4. Basement inclination for petrologic units, Site 713.

Unit	N	I (°)	λ (°)
A	1	34.7	−19.1
1	2	23.0	−12.0
3	3	15.0	−7.6
4	2	32.9	−17.9
5	2	24.7	−13.0
A	1	18.1	−9.3
A	1	56.3	−36.9
A	1	33.8	−18.5
A	1	27.2	−14.4
6	1	42.5	−24.6
7	2	4.6	−2.3
8	2	26.5	−14.0
10	2	13.6	−6.9
11	1	18.9	−9.7
12	1	29.6	−15.9
13	1	28.5	−15.2
14	1	31.5	−17.0
15	1	18.5	−9.5
16	1	20.1	−10.4
18	1	5.7	−2.9
20	1	35.5	−19.6
21	1	23.0	−12.0
22	1	21.4	−11.1
23	1	12.4	−6.3
25	1	25.4	−13.4
26	1	23.1	−12.0
12–26	12	22.9	−11.9
27	1	5.0	−2.5
28	1	19.3	−9.9
31	1	11.0	−5.6
33	1	18.3	−9.4
34	1	30.5	−16.4
35	1	9.2	−4.6

Note: A = ash layer, 12–26 = Units 12–26 are considered as a single flow, N = number of samples per unit, I = arithmetic mean inclination, and λ = paleolatitude determined from I.

Table 5. Basement inclination for peologic units, Site 715.

Unit	N	I (°)	λ (°)
4	1	43.7	−25.5
5	1	−12.9	−6.5
7	3	−24.2	−12.7
9	2	−33.0	−18.0
10	2	−32.6	−17.7
12	2	−46.5	−27.8
13	2	−49.5	−30.4
15	2	−48.0	−29.0
16	2	−49.7	−30.5
17	1	−43.4	−25.3
20	2	−50.8	−31.5
21	3	−45.4	−26.9

Note: N = number of samples per unit, I = arithmetic mean inclination, and λ = paleolatitude determined from I

to 21 that still include the 5 ash layers). Indeed, these basaltic units have a similar petrologic composition and structure, apparently a pillow lava sequence resulting from a single eruption. In this case, the mean inclination becomes 23.8° +6.5°/−7.7° and the associated paleolatitude is 12.7°S +3.7°/−4.4°.

It is difficult to choose between the two lithostratigraphies proposed by petrologists (32 vs. 20 units). In any case, mean paleomagnetic results are very similar, except for somewhat larger confidence intervals in the latter case. The inclination variation between Units 12 and 26 amounts to 30°, which seems quite large for a single flow. Therefore, we prefer the 32-unit option for our final discussion. The estimated and predicted angular standard deviations range from 16° to 18° and 14° to 19°, respectively, and are therefore not significantly different, regardless of which mean is used (Table 6).

Site 715

All demagnetizations were done with alternating fields, and, in general, 15–20-mT treatment was sufficient to remove the low-coercivity overprint (Table 5). The uppermost part of the drilled basement seemed to indicate the presence of a reversal: Unit 4, the uppermost sampled unit, shows a positive inclination that is opposite to all the others. Unfortunately, this small unit was sampled only once, and the first three drilled units were unusable (basalt breccia), as were the overlying sediments. Therefore, it was difficult to ascertain the polarity of this unit unless one considered the intermediate inclination and the anomalously low natural remanent magnetization (NRM) intensity of Unit 5 (see Backman, Duncan, et al., 1988, table 2, p. 927) as indicating a polarity transition. Despite the lack of information from layers surrounding these thin units, we assumed that a transitional unit was indeed sampled, and we removed Unit 5, therefore, from our statistical calculations. Considering only 11 units, then, the mean inclination is 43.0° +7.5°/−6.5° and the associated paleolatitude is 25.0°S +5.0°/−5.8° (Table 6).

The estimated standard deviation is slightly smaller than the value predicted by the F model: 12.2° compared with 13°–16°. However, this difference appears to be marginal in view of the assumptions involved in estimating statistics for inclination-only data and in using one of several PSV models (McFadden and Reid, 1982; McFadden and McElhinny, 1984).

DISCUSSION

Table 6 sums up the statistics of basement results with different possible interpretations for some sites. In this section, we discuss only those results that we consider to be the most reliable following the interpretation of paleomagnetic data of previous sections (see footnote to Table 6).

Paleomagnetic analysis indicates a correct magnetic behavior of all basement sites. However, PSV may not have been averaged out in Site 707, and an alternate uncertainty was proposed above. All results are presented in Figure 2 with their age and paleolatitude uncertainties. The present latitude of Réunion Island is also indicated. The position of the hotspot at the time of eruption of the Deccan Traps is determined as follows. Presently, the traps cover about 9° of latitude. Regarding eruptive source locations, Mahoney (1988) concluded that "there is in any case abundant circumstantial evidence placing the major eruptive sources in the western part of the province, roughly between Bombay and Cambay area." The position of this formerly active zone under the Deccan lies between present latitudes of 19°N and 22°N, with a longitude of 72.5°E. A new review of Deccan paleomagnetic results (Vandamme et al., 1989, following Courtillot et al., 1986) gives a mean virtual geomagnetic pole (VGP) located at 37.3°N, 281.1°E, with an α_{95} of 2.4° (Vandamme et al., 1989). Therefore, the paleolatitude of the Deccan Traps eruptive source is in the interval 22.5°–30°S.

Table 6. Paleomagnetic results of basement sites from Leg 115.

		McFadden and Reid method								Cox and Gordon method			
Site	N	I (°)	δI (°)	k	σ_d	σ'_d	λ_i	$\delta\lambda_i$	λ_a	λ_{cg}	$\delta\lambda_{cg}$	S_{bf}	S_o
706	[a]20	−24.2	+12.1 −9.5	10.2	25.4	24–26	−12.7	+6.9 −5.4	−13.3	−13.5	4.2	11.2	9.45
707	[a]5	43.3	+5.4 −5.6	195.2	5.8	13–16	−25.2	+4.3 −4.2	−25.3	−25.8	9.4	3.3	10.5
(1)			(13)		(14)			(10)					
713	34	24.0	+4.5 −5.3	26.7	15.7		−12.6	+3.0 −2.6	−12.8	−13.0	3.2	6.9	9.4
(2)	[a]32	23.6	+4.5 −5.5	26.3	15.8	14–19	−12.3	+3.1 −2.6	−12.5	−12.7	3.3	7.0	9.4
(3)	21	23.8	+6.5 −7.7	21.1	17.6		−12.4	+4.4 −3.7	−12.7	−12.9	4.1	8.0	9.4
715	12	−41.1	+10.2 −8.2	23.4	16.8		−23.6	+7.6 −6.1	−23.5	−23.9	5.9	8.0	10.3
(4)	[a]11	−43.0	+7.5 −6.5	43.8	12.2	13–16	−25.0	+5.8 −5.0	−25.0	−25.5	6.3	6.2	10.5

Note: N = number of petrologic units, I = arithmetic mean inclination, and k = precision parameter. Statistics derived using the maximum likelihood estimates of McFadden and Reid (1982): δI = inclination uncertainty (95% confidence), σ_d = observed angular standard deviation of field directions $(81/k^{1/2}/2)$; σ'_d = angular standard deviation of field directions predicted by F model, λ_i = paleolatitude, and $\delta\lambda_i$ = paleolatitude uncertainty (based on inclination statistics). λ_a = arithmetic mean of latitude. Statistics derived using the method of Cox and Gordon (1984): λ_{cg} = mean paleolatitude, $\delta\lambda_{cg}$ = paleolatitude error (95% confidence), S_{bf} = standard deviation between flows; and S_o = angular standard deviation of paleolatitude predicted by Harrison (1980) PSV model.

(1) = Statistical values based on secular variation model are given between parentheses.
(2) = Site 713 without two samples is considered as doubtful.
(3) = Same but considering Units 12–26 as a single flow.
(4) = Site 715 without Unit 5 considered as transitional.
[a] Indicates preferred results discussed in last section.

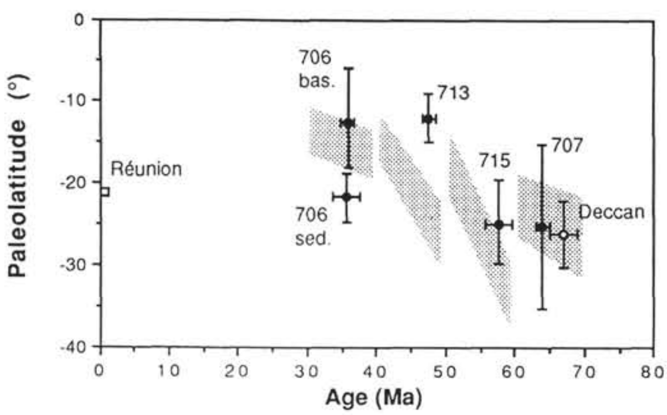

Figure 2. Paleolatitudes of Leg 115 basement sites and Deccan Traps with their α_{95} and age uncertainties. The shaded areas are the paleolatitude-age windows determined from the apparent polar wander paths of the African and Indian plates (see text).

Accurate estimates of the age of this event, based on new $^{40}Ar/^{39}Ar$ dating (Duncan and Pyle, 1988; Courtillot et al., 1988), place the bulk of volcanism in the interval from 65 to 69 Ma.

Besse and Courtillot (in press, see also 1988) recently reviewed data from plates surrounding the Indian Ocean and proposed synthetic apparent polar-wander paths (APWPs) for these plates, including the African and Indian, on which the Leg 115 sites were drilled. These are available as averages every 10 Ma, with a 20-m.y. averaging window. These synthetic paths (and their associated uncertainties) can be used to estimate the expected paleolatitudes of Sites 706, 707, 713, and 715 at the time of lava eruptions. For each site, we calculate the paleolatitude and the associated uncertainty of the two successive 10-Ma averages that bracket the age relevant for the site. The four shaded areas shown on Figure 2 are the interpolated paleolatitude-time domains where each site is expected to lie. We note that results for Sites 707 and 715 (i.e., the two oldest sites) are in agreement with these estimates. On the other hand, the result for Site 713 lies significantly outside its expected range. In the case of Site 706, the paleolatitude estimated from the APWP of Africa seems to be in better agreement with results from the basalt than those from the sediments.

Although various explanations can be invoked to account for these discrepancies, tectonic observations appear to provide the best insight. The paleomagnetic inclinations plotted on Figure 2 are based on the assumption that basement flows were deposited, and still are, in a horizontal position. Any tectonic rotation following cooling and magnetization would invalidate these inclination results.

In spite of occasional normal faulting, seismic lines surrounding Site 707 display a fairly stable and flat-lying platform structure (see "Seismic Stratigraphy" section in Backman, Duncan, et al., 1988, pp. 272–274). No fault has been detected close to the drilling site. The same applies to Site 715 (see "Seismic Stratigraphy" section in Backman, Duncan, et al., 1988, pp. 937–938); evidence of faulting was noted only about 50 km to the west of this site. Furthermore, Site 715 lavas are similar to those of intraplate volcanoes (and, in particular, to the islands of Réunion or Mauritius; Fisk et al., 1989), and it appears that they were erupted in a tectonically stable area.

In contrast, lavas of Sites 706 and 713 appear to be mixed with Mid-Ocean Ridge basalts (Fisk et al., 1989). They were probably erupted close to the spreading ridge. As is well known, the vicinity of ridges is characterized by normal faulting and block tilting. This phenomenon can be seen at a very small scale in the sediments that overlie the basalts of Sites 706 and 713 (see

"Lithostratigraphy" sections in Backman, Duncan, et al., 1988, pp. 130–132 and 737–740). Furthermore, bed tilt can be noticed in the Site 706 and 713 sedimentary sequences (see Backman, Duncan, et al., 1988, pp. 168–178 and 777–788).

At Site 706, bed dips were estimated by measurements on two core faces cut perpendicular to one another (Schneider and Kent, this volume). With this method, cores from Hole 706A were found to dip between 10° and 20°, whereas sediments from Hole 706B appeared horizontal. No measurement was possible in the sediments of Hole 706C, the only one to reach basement, because this hole was washed down to the level of the sediment/basalt boundary.

We have noted that there was an apparent discrepancy of 8.3° ± 6.7° between the paleolatitudes derived from the basement and sediments. The age ranges of these sediments (30.2–33.8 Ma) and basalts (34.9–36.7 Ma) can be used to estimate the paleolatitude evolution of Site 706 by means of the synthetic APWP of Africa (Besse and Courtillot, in press). The expected difference in paleolatitudes for this age separation is 1.5° ± 1°, a value much smaller than the observed one and in the wrong sense. The discrepancy is better understood if the basement results of Hole 706C were affected by tectonic tilting of some 15°. The reliable paleolatitude for Site 706 is likely to be that of the sediments from Holes 706A and 706B, where tilting was indeed observed and corrected for (i.e., a sort of positive fold test; Schneider and Kent, this volume). To estimate basement paleolatitude, this value is corrected for the observed age difference by 1.5° ± 1°, yielding 21.7°S ± 2.9°.

No measurement of bed dip was done on sediments of Site 713. In this case, however, the tectonic effect was far more obvious on seismic lines than at Site 706: "the basement reflector appears as a series of discrete steps" (see "Seismic Stratigraphy" section in Backman, Duncan, et al., 1988, pp. 758–759). The offset of normal faults, which is estimated to be around 100 m, is sufficient to yield large bed tilts and, in particular, the 20° tilt necessary to move the paleolatitude from the observed value to the expected range (Fig. 2). However, no accurate value of this tilt can be obtained. Moreover, the difference between the observed paleolatitude of Site 713 and that predicted by the APWP of Africa is such that it would require an error of at least 6 m.y. in age or 5° in paleolatitude (and more likely 10 m.y. and 10°, respectively) to reconcile them. Such large errors appear improbable.

It is interesting to note that there are strong hints of significant tectonic disruption and tilting in precisely the two sites that yield apparently puzzling inclination results (Site 713) or inconsistency in basalt and sediment results (Site 706). It should be recalled, however, that there is no purely paleomagnetic argument that can be used to disregard these data.

HOTSPOT MODELS AND DATA

A number of difficulties and limitations plagued the paleomagnetic results from basement flows sampled during Leg 115. Among those, we have noted the lack of declination control, the sometimes insufficient averaging out of paleosecular variation, and the possibility of undetected (or at least noncorrectible) tectonic tilting. Despite this, discussion of various kinds of data (paleomagnetic data from basalts and sediments, seismic results, microstructure in the cores, and petrologic observations) yield three apparently reliable estimates of the paleolatitude of the Réunion hotspot: at the time of the opening of the Arabian Sea (Site 707, 64 Ma); when the volcanism had become truly intraoceanic plate (Site 715, about 57 Ma) about 10 m.y. after the Deccan basalt eruption; and when it reached and then crossed beneath the Central Indian Ridge (Site 706, 36 Ma).

These three estimates of the paleolatitude of the Réunion hotspot are plotted in Figure 3, together with the position of the hotspot at present (Réunion Island) and at its inception as the Deccan Traps (Courtillot et al., 1986). We note that Courtillot et al. (1986) suggested that the ODP should drill to the northwest of the Saya de Malha Bank and predicted that an extension of the Deccan flows would be encountered. We note an excellent correspondence of the age and paleomagnetic characteristics of the Deccan Traps and Site 707 basement, which is further confirmed by geochemical arguments (Fisk et al., 1989).

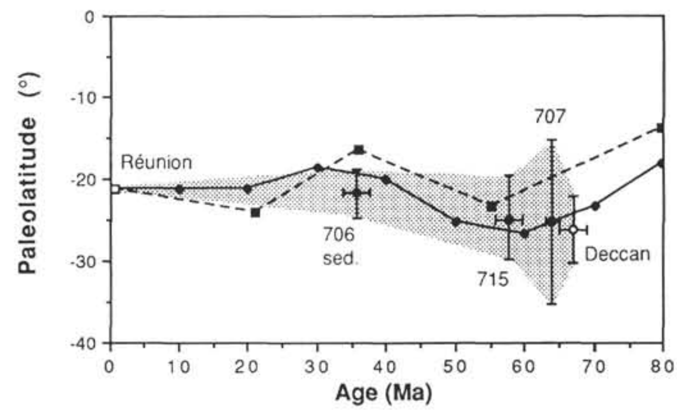

Figure 3. The three paleolatitudes of the Leg 115 sites that we consider as reliable and those of the Deccan Traps with their α_{95} and age uncertainties. The shaded area, which links these paleolatitude uncertainties, represents the latitudinal motion of the Réunion hotspot constrained by paleomagnetic data. The lines show the latitudinal motion of the Réunion hotspot predicted by models (full line and diamonds: Morgan, 1983; dashed line and squares: Duncan, 1981).

The shaded area in Figure 3 connects these points and illustrates our best determination of the paleolatitude evolution of the Réunion hotspot. We see that, in the first place, this has remained roughly constant. Secondly, a slight northward drift of about 5° in 65 Ma, or about 8 mm/yr, can be seen. There is an indication (statistically nonrobust) that this drift might have been accomplished mostly from 65 to 35 Ma, when the Réunion hotspot would have attained its present latitude.

The data can also be tested against the hotspot models of Duncan (1981) and Morgan (1983). To do this, the position of the hotspot with respect to Africa at the appropriate age is first determined from the Duncan (respectively, Morgan) model, and the paleogeographic position of Africa is then restored using the synthetic paleomagnetic poles of Africa derived by Besse and Courtillot (in press). The paleolatitudes of the hotspot found in this way are shown in Figure 3 as a full line for the Morgan model and a dashed line for the Duncan model. We note that in the case of the Morgan model, this is simply a latitude projection of the true polar wander curve determined by Courtillot and Besse (1987). Figure 3 demonstrates the excellent agreement of the data with the model of Morgan (1983).

Agreement is also good for the Duncan (1981) model, although the prediction at 35 Ma is outside and to the north of the Site 706 results. Paradoxically, and we believe by chance only, the Duncan prediction happens to be in better agreement with the basement results (thought to be erroneous because of tectonic tilting) and with the paleolatitudes predicted directly from the African APWP (Fig. 2). However, we have to recall that the hotspot latitudinal motions expected from models are made with the same APWP and, even then, are not completely independent of the predicted paleolatitudes. Further data would be needed to advance this problem, and it is a pity that two other planned drillings on the Nazareth Bank had to be cancelled.

In conclusion, the reliable basement paleomagnetic data provided by Leg 115 tend to validate proposed models of evolution of the Réunion hotspot and in particular that of Morgan (1983). Small northward motion is indicated (8 mm/yr) since the onset of the hotspot at the Deccan Traps. However, the small number of data and the size of uncertainties preclude finer and firmer conclusions.

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