Emplacement and Subsidence of Indian Ocean Plateaus and Submarine Ridges

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Ocean Drilling Program, Deep Sea Drilling Project, and industrial borehole results from Indian Ocean plateaus and submarine ridges help to constrain their subsidence histories. I use a simple Airy isostatic model to calculate basement depths at ODP sites in the absence of sediment, and then backtrack these sites using previously determined age-depth relationships for oceanic lithosphere to determine the original depth or elevation of the sites. Resulting subsidence curves for each site were then checked by examining sedimentologic and biostratigraphic evidence for when each site subsided below shelf depths. The analysis suggests that thermal subsidence has been the dominant tectonic process affecting Indian Ocean plateaus and submarine ridges following emplacement. I conclude that large portions of these features were emplaced and began subsiding well above sea level, similar to large igneous provinces (LIPs) worldwide today. This resulted in significant subaerial erosion and redeposition of volcanic material mixed with biogenic sediment, and a gradual development of facies from terrestrial through terrigenous to shallow water and pelagic, resulting in a sedimentary record with both continental and oceanic characteristics.

INTRODUCTION

Voluminous emplacements of mafic igneous rock originating via processes other than "normal" seafloor spreading include continental flood basalt and associated intrusive rock; volcanic passive margins; oceanic plateaus; submarine ridges; ocean basin flood basalts; and seamount groups. These large igneous provinces (LIPs) share many temporal, spatial, and compositional characteristics. The early evolution of LIPs, especially their subsidence history, is not well documented, and oceanic provinces offer an opportunity to study this topic in the simplest possible lithospheric setting.

The Indian Ocean contains a plethora of submarine ridges and oceanic plateaus (Figure 1; Table 1), about which little was known until the advent of deep sea drilling. Since 1972, however, seven of these features have been drilled, and unequivocal igneous basement has been recovered and dated from four - the Chagos-Laccadive Ridge, the Kerguelen Plateau, the Mascarene Plateau, and Ninetyeast Ridge. These drill cores have yielded much information on the features' origin and evolution, especially from stratigraphic, petrologic, geochemical, and geochronologic studies, and they provide essential data for examining their subsidence histories. In this paper I will first briefly summarize our knowledge of four features for which sufficient data are available to study their early development, then analyze their subsidence history, and finally discuss some geologic and geophysical implications of the analysis.

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OCEANIC PLATEAUS AND SUBMARINE RIDGES

Of fourteen known mafic plateaus and ridges in the Indian Ocean (Figure 1; Table 1), reliable dates for drilled, dredged, and subaerially sampled volcanic rock constituting basement are available for six - Broken Ridge, Chagos-Laccadive Ridge, Crozet Plateau, Kerguelen Plateau, Mascarene Plateau, and Ninetyeast Ridge (Table 2). These LIPs range in age from 110 (Kerguelen) to 0 (Crozet) Ma, and geochronologic studies indicate that construction of individual features took from <10 to as many as 44 m.y. Three hotspots are apparently responsible for these six features [Morgan, 1981], the Kerguelen hotspot for the Kerguelen Plateau, Broken Ridge, and Ninetyeast Ridge; the Réunion hotspot for Chagos-Laccadive Ridge and the Mascarene Plateau; and the Crozet hotspot for the Crozet Plateau. The complex tectonic evolution of the Indian Ocean is responsible for one hotspot creating multiple LIPs.

Although basement dates are available for Broken Ridge and the Crozet Plateau (Table 2), the study of subsidence immediately following emplacement of these features is not yet possible. In the case of Broken Ridge, basement samples were dredged, and are thus not reliably located with regard to depth [Duncan, 1991]. Furthermore, Broken Ridge experienced major tectonism prior to and during its breakup with the northern Kerguelen Plateau in Eocene time [Driscoll et al., 1991]. The only basement samples from the Crozet Plateau are from islands, and lack of overlying sediment precludes subsidence analysis.

The Chagos-Laccadive Ridge extends over ~2500 km west and south of India, and its width is ~200 km. Numerous atolls, reefs, banks, and shoals form the subaerial expression of the feature, although no volcanic basement is exposed. The ridge represents part of a hotspot track which also includes the Deccan Traps in India and the Mascarene Plateau [Figure 1; Morgan, 1981; Duncan, 1990]. ODP Leg 115 recovered the first basement samples

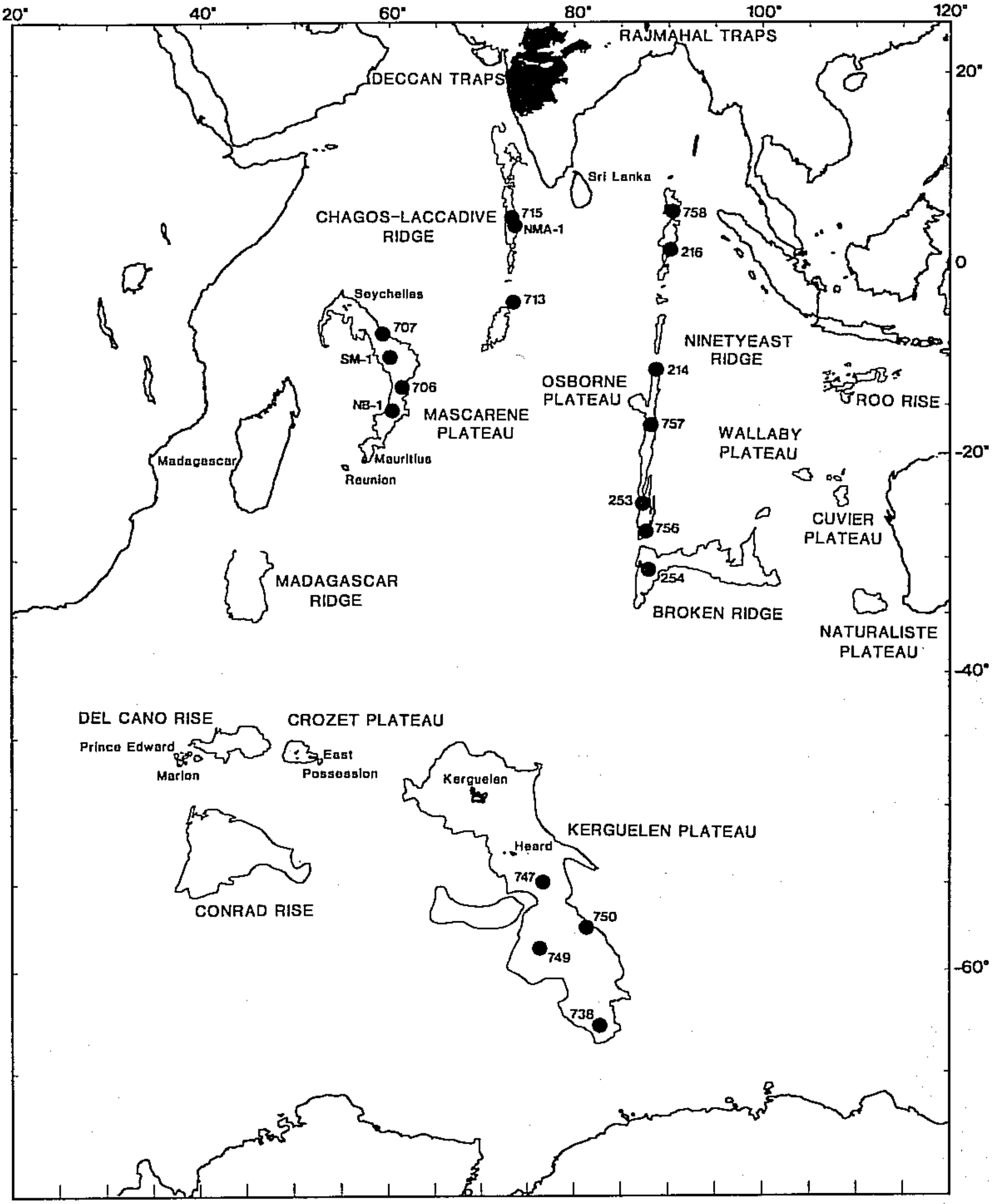

Fig. 1. Indian Ocean plateaus and submarine ridges, and the Deccan and Rajmahal Traps. Locations of DSDP, ODP, and industry volcanic basement sites are indicated by circles (Table 2).

TABLE 1. Indian Ocean Plateaus and Submarine Ridges: DSDP/ODP Sites

LIP	Type§	DSDP/ODP Leg(s)	DSDP/ODP Site(s)	Basement Reached?	Reference(s)
Broken Ridge	SR	26	255	no	Davies, Luyendyk et al., 1974
		121	752	no	Peirce, Weissel et al., 1989;
		121	753	no	Weissel, Peirce, Taylor, Alt et al., 1991
		121	754	no	ibid.
		121	755	no	ibid.
Chagos-Laccadive Ridge	SR	23	219	no	Whitmarsh, Weser, Ross et al., 1974
		115	712	no	Backman, Duncan et al., 1988;
		115	713	yes	Duncan, Backman, Peterson et al., 1990
		115	714	no	ibid.
		115	715	yes	ibid.
		115	716	no	ibid.
Conrad Rise	OP	-	-	-	-
Crozet Plateau	OP	-	-	-	-
Cuvier Plateau	OP	-	-	-	-
Del Caño Rise	OP	-	-	-	-
Kerguelen Plateau	OP	119	736	no	Barron, Larsen et al., 1989;
		119	737	no	Barron, Larsen et al., 1991
		119	738	yes	ibid.
		119	744	no	ibid.
		120	747	yes	Schlich, Wise et al., 1989;
		120	748	no	Wise, Schlich et al., 1992
		120	749	yes	ibid.
		120	750	yes	ibid.
		120	751	no	ibid.
Madagascar Ridge	SR	25	246	no	Simpson, Schlich et al., 1974
		25	247	no	ibid.
Mascarene Plateau	OP	24	237	no	Fisher, Bunce et al., 1974
		115	705	no	Backman, Duncan et al., 1988;
		115	706	yes	Duncan, Backman, Peterson et al., 1990
		115	707	yes	ibid.
Naturaliste Plateau	OP	26	258	no	Davies, Luyendyk et al., 1974
		28	264	?	Hayes, Frakes et al., 1975
Ninetyeast Ridge	SR	22	214	yes	von der Borch, Sclater et al., 1974
		22	215	yes	ibid.
		22	216	yes	ibid.
		22	217	no	ibid.
		26	253	yes	Davies, Luyendyk et al., 1974
		26	254	yes	ibid.
		121	756	yes	Peirce, Weissel et al., 1989;
		121	757	yes	Weissel, Peirce, Taylor, Alt et al., 1991
		121	758	yes	ibid.
Osborn Knoll	OP	-	-	-	-
Roo Rise	OP	-	-	-	-
Wallaby Plateau	OP	-	-	-	-

§OP, oceanic plateau; SR, submarine ridge

from the feature (Figure 1), and reliable dates from two sites are available (Table 2). From these dates, the minimum time for creation of the entire ridge is 8 m.y.

The Kerguelen Plateau, in the south-central Indian Ocean, is ~2500 km long and ~500 km wide. It encompasses an area in excess of 10^6 km^2, making it the second most voluminous LIP yet discovered [Coffin and Eldholm, 1991]. It is suggested to be part of a hotspot track which includes, in chronological order [Davies et al., 1989], the Bunbury Basalt (Australia), Naturaliste Plateau, Rajmahal Traps (India), Kerguelen/Broken Ridge, Ninetyeast Ridge, and the northernmost Kerguelen Plateau (Figure 1). Structural interpretations [Houtz et al., 1977; Coffin et al., 1986] divide the Kerguelen Plateau into two distinct sectors, a northern and a southern, with the boundary at ~54°S (Figure 1), which have experienced differing histories of volcanism. Volcanic basement has been recovered and dated from four ODP sites and one dredge site on the southern Kerguelen Plateau (Figure 1; Tables 1, 2). It formed between 114 and 101 Ma [Whitechurch et al., 1992], with some subsequent alkalic volcanism. Kerguelen and Heard islands on the northern Kerguelen Plateau record volcanism over the past 39 m.y. [Giret and Lameyre, 1983; Clarke et al., 1983], and volcanic basement from its

TABLE 2. Ages of Indian Ocean Plateaus and Submarine Ridges

LIP	Type[1]	DSDP/ODP Leg (s)	Basement Site(s)	Basement Age (Ma)	Reference(s)
Broken Ridge	SR	26, 121	-	-	-
		-	Dredge	88	Duncan, 1991
Chagos-Laccadive Ridge	SR	23, 115	713	49	Duncan & Hargraves, 1990
		115	715	57	ibid.
		-	NMA-1	?	-
Conrad Rise	OP	-	-	?	-
Crozet Plateau	OP	-	Est	0-8	Lameyre & Nougier, 1982
		-	Possession	0-8	Chevallier et al., 1983
Cuvier Plateau	OP	-	-	?	-
Del Caño Rise	OP	-	Marion[2]	0	McDougall, 1971b
		-	Prince Edward[2]	0	ibid.
Kerguelen Plateau	OP	-	Dredge	114	Leclaire et al., 1987
		119	738	? (>91)	Barron, Larsen et al., 1989
		120	747	101-110	Whitechurch et al., 1992
		120	749	110	ibid.
		120	750	101	ibid.
		-	Heard	0-11	Clarke et al., 1983
		-	Kerguelen	0-39	Nougier et al., 1983; Giret & Lameyre, 1983
Madagascar Ridge	SR	25	-	?	Simpson, Schlich et al., 1974
Mascarene Plateau	OP	115	706	33	Duncan & Hargraves, 1990
		115	707	64	ibid.
		-	NB-1	31	ibid.
		-	SM-1	59[3]	ibid.; Meyerhoff & Kamen-Kaye, 1981
		-	Mauritius	1-7	McDougall, 1971a
		-	Reúnion	0-2	ibid.
Naturaliste Plateau	OP	26, 28	264	? (>91)	Hayes, Frakes et al., 1975
Ninetyeast Ridge	SR	22	214	59	Duncan, 1978
		22	216	81	ibid.
		26	253	? (>44)	Davies, Luyendyk et al., 1974
		26	254	38	Duncan, 1978
		121	756	43	Duncan, 1991
		121	757	58	ibid.
		121	758	82	ibid.
Osborn Knoll	OP	-	-	?	-
Roo Rise	OP	-	-	?	-
Wallaby Plateau	OP	-	-	?	-

[1] OP, oceanic plateau; SR, submarine ridge

[2] Marion and Prince Edward islands probably do not represent the age of the bulk of Del Caño Rise - see text for discussion.

[3] the integrated age of Duncan & Hargraves [1990] is used rather than their "best radiometric age estimate," because biostratigraphic evidence in Meyerhoff & Kamen-Kaye [1981] supports the former.

conjugate, Broken Ridge, is dated 88 Ma [Duncan, 1991].

The Mascarene Plateau, east and north of Madagascar, extends for ~2000 km from the continental Seychelles Bank [Baker and Miller, 1963] in the north to Réunion in the south (Figure 1). It consists of several discrete banks, with a maximum width of ~500 km. Volcanic basement crops out on the two youngest portions of the plateau, Réunion and Mauritius; these features formed over the past 7 m.y. (Table 2). Two industry and two ODP sites recovered volcanic basement from the plateau north of the two islands; dates from these rocks indicate that the feature has formed over the past 64 m.y. (Table 2).

Ninetyeast Ridge is one of the longest linear features on the Earth's surface, extending north-south for ~5000 km in the eastern Indian Ocean (Figure 1). It is 150 to 250 km wide. North of 7°S the ridge consists of several discrete blocks; to the south it is continuous to its termination at the western end of Broken Ridge. The feature lacks any subaerial expression, but volcanic basement has been recovered and dated from six DSDP and ODP sites along the ridge (Table 2), documenting a 44 m.y. constructional history [Duncan, 1991].

SUBSIDENCE ANALYSIS

The general subsidence history of oceanic plateaus and submarine ridges has been the focus of only one study to date [Detrick et al., 1977]. A principal conclusion was that subsidence could be attributed to cooling and thickening of the lithospheric plate on which the plateaus and ridges were constructed at rates comparable with those of normal oceanic lithosphere, assuming that emplacement occurred close to sea level. Since that study the age-depth relationship of oceanic lithosphere has been documented further and refined [Parsons and Sclater, 1977; Hayes, 1988]. Below are described the methods and data used to analyze subsidence histories of drill sites on the Chagos-

Laccadive Ridge, Kerguelen Plateau, Mascarene Plateau, and Ninetyeast Ridge.

Methods

The procedure for calculating the subsidence history of oceanic crust has been thoroughly documented [e.g., Parsons and Sclater, 1977], and the most relevant study for the Indian Ocean is that of Hayes [1988], who analyzed data from the Southeast Indian Ocean. The level of emplacement of igneous basement is calculated by the equation,

$$D_0 = D_c - C\ \mathrm{age}^{1/2} \qquad (1)$$

in which D_0 is the original depth or elevation of emplacement of the crust in meters, D_c is the present corrected depth of the crust in meters, C is an empirical constant in meters, and age is in m.y.

Global averages of C have been determined to be 350 m [Parsons and Sclater, 1977] and 300 m [Hayes, 1988]. These averages were determined from Cenozoic age lithosphere; there is no reason to suspect, however, that Mesozoic lithosphere followed different rules of thermal subsidence. I employed the value of 300 m for the Chagos-Laccadive Ridge, Kerguelen Plateau, Mascarene Plateau, and Ninetyeast Ridge in the calculations.

D_c is obtained using to the equation of Crough [1983]:

$$D_c = d_w + t_s(\rho_s - \rho_m/\rho_w - \rho_m) \qquad (2)$$

in which d_w is water depth in meters, t_s is sediment thickness in meters, ρ_s is average sediment density in gcm^{-3} (1.90), ρ_m is upper mantle density in gcm^{-3} (3.22), and ρ_w is water density in gcm^{-3} (1.03).

Detrick et al. [1977] suggest that it is valid to apply age-depth relationships for oceanic lithosphere to oceanic plateaus in the absence of major post-emplacement tectonism which may have resulted in thermal rejuvenation of the lithosphere and/or flexural uplift or subsidence. Evidence for such tectonism is lacking at the majority of drill sites examined [Davies, Luyendyk et al., 1974; von der Borch, Sclater et al., 1974; Backman, Duncan et al., 1988; Peirce, Weissel et al., 1989; Schlich, Wise et al., 1989].

To confirm or deny application of the thermal subsidence model to oceanic plateaus and submarine ridges, facies of the sediment at the various sites were examined, and it was assumed that the end of shallow-water sedimentation occurred at a depth of 200 m. Using basement ages determined by radiometric dating (Table 2), depth to igneous basement at the end of shelf deposition for each site was calculated by the equation:

$$D_{bes} = D_0 + C\ (\mathrm{age}\text{-}\mathrm{age}_{es})^{1/2} \qquad (3)$$

in which D_{bes} is depth of igneous basement at the end of shelf deposition in meters, and age_{es} is age at the end of shelf deposition in m.y. (using time scale of Berggren et al., 1985, and Kent and Gradstein, 1985]. Then depth to seafloor at the end of subaerial and shallow-water deposition was calculated by combining the equations of Hayes (1988) and Crough (1983) as follows:

$$D_{ses} = D_0 + C\ (\mathrm{age}\text{-}\mathrm{age}_{es})^{1/2} - t_{es}(\rho_s - \rho_m/\rho_w - \rho_m) \qquad (4)$$

in which D_{ses} is depth of seafloor at the end of shelf deposition in meters, and t_{es} is sediment thickness at the end of shelf deposition in meters. Various equation parameters, and calculated basement and seafloor depths at the end of shelf deposition are shown in Tables 3 and 4, and calculated basement depths for the various sites are plotted (triangles) on Figure 2.

Another approach to predict levels of emplacement of Indian Ocean plateau and submarine ridge sites would be to use a plate model [e.g., Parker and Oldenburg, 1973; Davis and Lister, 1974; Crough, 1975; Parsons and Sclater, 1977]. Plate model equations, however, contain one variable - temperature at the base of the lithosphere - for which little agreement exists, especially in the case of LIPs such as oceanic plateaus and submarine ridges [e.g., White and McKenzie, 1989; Griffiths and Campbell, 1990; Hill, 1991]. Furthermore, this temperature may vary both spatially, over the ~10^5 to ~10^6 km dimensions, and temporally, over the ~10^5 to ~10^6 yr emplacement phase, of Indian Ocean plateaus and submarine ridges. Calculations of emplacement elevations are extremely sensitive to temperature, and consideration of a plate model in both forward and inverse modeling is beyond the scope of this study.

Data and Results

Fundamental data for this subsidence study are radiometric basement dates, and sedimentology and biostratigraphy of overlying sedimentary rock. Sedimentary facies of rocks provide information on environment of deposition, and macro- and microfossil assemblages can document the depth at which sediment was deposited. Biostratigraphy is used to date the sediment. All of these types of data and accompanying interpretations have errors associated with them, errors which generally increase with age. This study is limited to using the most consistent radiometric age dates (Table 2) for basement; sites for which no or inconsistent dates are available are not included. Combined sedimentary facies, benthic foraminiferal zonation, and biostratigraphic interpretations are used in most cases to estimate when a drill site descended beneath shelf (~200 m) depths; exceptions are noted (Table 4). Changes in sea level and sediment compaction were not considered. At times over the past 120 m.y., eustatic sea level appears to have been as much as ~250 m higher than present [Kominz, 1984; Haq et al., 1987]. This magnitude does not affect the results of the subsidence analysis. Sediment thicknesses at the oceanic plateau and submarine ridge sites examined herein are, with two exceptions, less than 700 m. This amount of overburden does not result in compaction significant enough to alter results of the

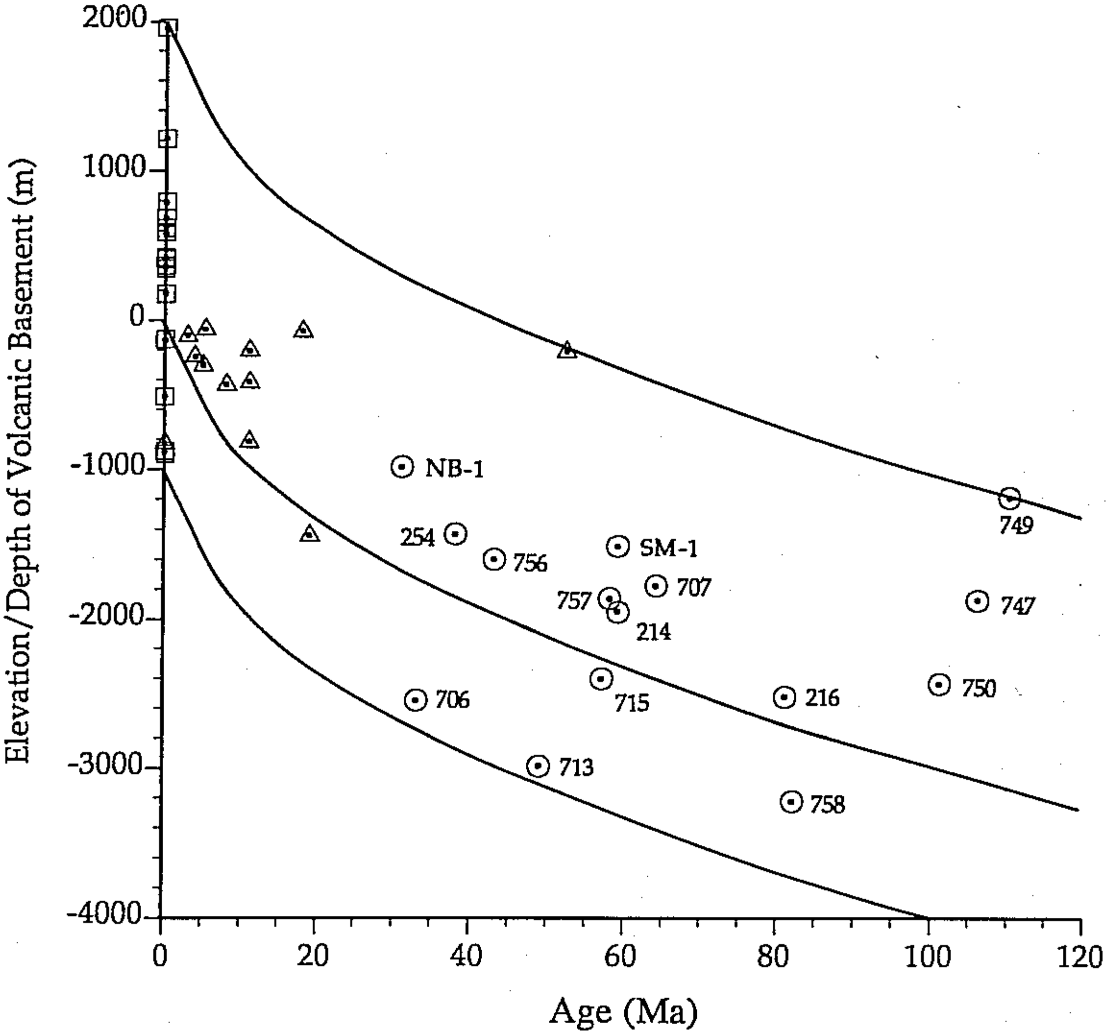

Fig. 2. Age-depth curves for volcanic basement at drill sites listed in Tables 3 and 4. Calculated basement depths (Table 3) for all sites are given for zero age (boxes) and the present (circles); where possible, calculated basement depths at the end of shelf deposition are indicated by triangles. See Table 4 for the corresponding depths to seafloor at the end of shelf deposition. Theoretical subsidence curves according to the equation of Hayes [1988] for crust emplaced 2000 m above sea level and at a depth of 1000 m (C=300) bound all points. Theoretical subsidence curve for crust emplaced at sea level indicates that basement at 11 of 15 sites (circles) was emplaced above sea level.

analysis [Sclater and Christie, 1980]. Below I address limitations of the data and results of the subsidence analysis.

Chagos-Laccadive Ridge. Basement samples from ODP Leg 115 Sites 713 and 715 on the ridge give consistent $^{40}Ar/^{39}Ar$ plateau and isochron ages [Duncan and Hargraves, 1990], and are consistent with plate motion models of the Indian Ocean [e.g., Duncan, 1990]. They are therefore included in the analysis (Tables 3, 4; Figure 2).

Sediment recovered at Site 713 indicates that the site was never shallow enough to experience a shelf depositional regime [Backman, Duncan et al., 1988]; therefore, only the depth of emplacement, 885 m, was calculated (Table 3). Site 715 appears to have been emplaced at shelf depths. The duration of a shallow-water depositional regime at this site, however, is open to question because of a hiatus between upper Eocene shallow-water carbonate and lower Miocene deep-water ooze and chalk. Even using a maximum age for the end of shelf deposition (Table 4), the calculated seafloor depth of 1379 m at the end of shelf deposition is far too great, indicating that something is awry.

Kerguelen Plateau. $^{40}Ar/^{39}Ar$ basement dates from the southern Kerguelen Plateau (Figure 1; Table 2) show fairly wide scatter [Whitechurch et al., 1992]. Basalt from Site 747 yielded plausible dates of 101 to 110 Ma, and a value of 105.5 was used in the subsidence calculations (Tables 3, 4). Site 749 yielded the best documented date, 110 Ma. Plausible dates of 101 Ma were obtained for Site 750 basalt. The only other reported date, 114±1 Ma, was

TABLE 3. Equation parameters and elevations/depths of emplacement (D_0) of drill sites.

LIP	Site	d_w	t_s	D_c	Basement Age (Ma)	D_0
Chagos-Laccadive Ridge	713	-2920.3	107	-2985	49	-885
	715	-2272.8	211	-2400	57	-135
Kerguelen Plateau	747	-1695.2	297	-1874	105.5	1215
	749	-1069.5	202	-1191	110	1955
	750	-2030.5	672	-2435	101	580
Mascarene Plateau	706	-2518.0	48	-2547	33	-824
	707	-1551.9	376	-1779	64	621
	NB-1	-49.7	1556	-988	31	683
	SM-1	-50.9	2432	-1517	59	788
Ninetyeast Ridge	214	-1655	490	-1950	59	354
	216	-2247	457	-2522	81	178
	254	-1253	301	-1434	38	415
	756	-1513.1	145	-1600	43	367
	757	-1643.6	369	-1866	58	419
	758	-2923.6	499	-3224	82	-508

d_w = water depth, in meters.
t_s = sediment thickness, in meters.
D_c = present corrected depth of crust, in meters.
D_0= original depth or elevation of crust emplacement, in meters.

TABLE 4. Equation parameters, calculated basement (D_{bes}), predicted seafloor depths (D_{ses}) , and duration of subaerial/shelf conditions of drill sites.

LIP	Site	age_{es}	D_{bes}	t_{es}	D_{ses}	Duration of Subaerial/Shelf Environments
Chagos-Laccadive Ridge	713[1]	-	-	-	-	0
	715	38[2]	-1443	105	-1379	19[10]
Kerguelen Plateau	747	87.5[3]	-76	1.5	-75	18[11]
	749	57.8[4]	-212	0	-212	52.2[11]
	750	90[5]	-415	52	-384	11[11]
Mascarene Plateau	706	33[6]	-824	0.5	-823	0[10]
	707	58.8[7]	-63	48	-34	5.2[11]
	NB-1[8]	-	-	-	-	31
	SM-1	48	-207	286	-35	11
Ninetyeast Ridge	214	55	-246	167	-145	4
	216	70	-817	109	-752	11
	254	30[9]	-434	92	-378	8
	756	38	-304	15	-295	5
	757	55	-101	157	-6	3
	758[1]	-	-	-1-	0	

age_{es} = age at end of shelf deposition, in m.y.
t_{es} = sediment thickness at end of shelf deposiiton , in meters.

[1] basaltic basement at these sites was emplaced well below shelf depths.

[2] maximum - a hiatus exists between upper Eocene shallow-water carbonate and lower Miocene deep-water ooze and chalk.

[3] minimum - a hiatus exists between 106 Ma basaltic basement and lower Santonian chalk and chert.

[4] minimum - a hiatus exists between 110 Ma basaltic basement and lower Eocene chalk and chert.

[5] minimum - a hiatus exists between Albian claystone and coal, and upper Turonian chalk and marl.

[6] maximum - 33 Ma basaltic basement is overlain by lower Oligocene shallow-water carbonate, which is in turn overlain by lower Oligocene ooze.

[7] minimum - a hiatus exists between upper Paleocene shallow-water and deep-water carbonate.

[8] this site experienced shallow water sediment deposition throughout its history.

[9] detailed age information for this well is not available.

[10] minimum.

[11] maximum.

obtained by the K-Ar method on a plagioclase from a dredged basalt [Leclaire et al., 1987], and no dates have been obtained from the Site 738 basalts. Dates for southern Kerguelen Plateau basalts appear less reliable than those for the other three features studied; more work is clearly needed on dating the cored basalts.

Petrologic analyses [Schlich, Wise et al., 1989] and subsidence calculations [Coffin, 1992] suggest that the three dated basement sites on the southern Kerguelen Plateau were constructed above sea level (Table 3; Figure 2). Sediment recovered from Sites 747 and 749 do not provide information on when the two descended below shelf depths [Schlich, Wise et al., 1989]. At the former, a hiatus exists between basement and lower Santonian chalk and chert; at the latter, between basement and lower Eocene chalk and chert. Using these dates as minimum values in the calculations, however, produces agreement with shelf depths predicted by the thermal subsidence model (Table 4; Figure 2). Site 750 contains the most complete sediment record for subsidence analysis, and again the calculated depths at the end of shelf deposition do not conflict with those interpreted from the sediment (Table 4). The southern Kerguelen Plateau, unlike its northern counterpart, shows no evidence of Tertiary or Quaternary volcanism. This observation and the subsidence analysis suggest that the southern portion has not been thermally rejuvenated. Major normal and possibly transform faults were active on the southern Kerguelen Plateau in Late Cretaceous time [Coffin et al., 1990], but do not appear to have affected the overall subsidence of the feature.

Mascarene Plateau. Two ODP and two industry boreholes on the Mascarene Plateau recovered volcanic basement which was subsequently dated (Table 2). Samples from Leg 115 Sites 706 and 707, and from well NB-1 on the plateau (Figure 1) give consistent $^{40}Ar/^{39}Ar$ plateau and isochron ages [Duncan and Hargraves, 1990], and are consistent with plate motion models of the Indian Ocean [e.g., Duncan, 1990]. The "best radiometric age estimate" of 45 Ma [Duncan and Hargraves, 1990] for volcanic basement at well SM-1, however, contradicts biostratigraphic evidence [Meyerhoff and Kamen-Kaye, 1981]; therefore the integrated age of Duncan and Hargraves [1990] is used (Tables 3, 4; Figure 2).

Petrologic studies [Backman, Duncan et al., 1988] and subsidence analysis indicate that igneous basement at Site 706 was emplaced below sea level. Lower Oligocene shallow-water carbonate overlies basement, and is in turn overlain by lower Oligocene deep-water ooze [Backman, Duncan et al., 1988]. These sedimentologic and biostratigraphic data suggest that the site remained in shallow water only briefly; it was probably emplaced there, and subsided rapidly into deeper water. Because thermal subsidence is of large magnitude immediately following volcanic emplacement, the discrepancy between the predicted seafloor depth at the end of shelf deposition (Table 4) and actual seafloor depth is probably not significant. Interbedded shallow-water limestone and basalt at Site 707 demonstrate shallow water emplacement [Backman, Duncan et al., 1988], although subsidence calculations suggest construction high above sea level (Table 3; Figure 2). A hiatus between upper Paleocene shallow-water and deep-water carbonate suggests rapid initial subsidence. It thus appears that this site was kept elevated by dynamic forces, i.e., thermal or mechanical, after subsiding to deep water in late Paleocene time. Further evidence for this includes the calculated depth to seafloor at the end of shelf deposition, which is less than geologic evidence shows (Table 4). Calculations suggest that volcanic basement at wells NB-1 and SM-1 was constructed well above sea level (Table 3; Figure 2). The calculated depth at the end of shelf deposition for well SM-1 agrees quite well with that interpreted from sediment [Meyerhoff and Kamen-Kaye, 1981; Table 4].

Ninetyeast Ridge. Ninetyeast Ridge basement samples from three DSDP Leg 22 and 26 sites (214, 216, 254) provide K/Ar dates [Duncan, 1978], and samples from three ODP Leg 121 sites (756, 757, 758) on the ridge give consistent $^{40}Ar/^{39}Ar$ plateau and isochron ages [Duncan, 1991]. These dates appear reliable and are consistent with plate motion models of the Indian Ocean [e.g., Duncan, 1990], and are thus included in the analysis (Tables 3, 4; Figure 2).

All basement sites on the Ninetyeast Ridge with the exception of Site 758 backtrack to subaerial levels (Table 3; Figure 2). In all cases subaerial emplacement is consistent with sedimentologic, biostratigraphic, and petrologic interpretations of recovered core material [von der Borch, Sclater et al., 1974; Davies, Luyendyk et al., 1974; Peirce, Weissel et al., 1989]. Calculated depths at the end of shelf deposition for Sites 214, 756, and 757 correlate well with those interpreted from sediment [von der Borch, Sclater et al., 1974; Davies, Luyendyk et al., 1974; Peirce, Weissel et al., 1989]. Detailed biostratigraphic ages for Site 254 sediment are not available [Davies, Luyendyk et al., 1974], so it was impossible to check the calculated versus an observed depth at the end of shelf deposition for this site. Volcanic basement at Site 758, both from backtracking and from geologic evidence [Peirce, Weissel et al., 1989], was emplaced at depths greater than 200 m. Only at Site 216 does the calculated depth to basement at the end of shelf deposition (Table 4; Figure 2) differ markedly from that observed [von der Borch, Sclater et al., 1974]; this site was probably kept elevated by dynamic forces, i.e., thermal or mechanical, for a period after emplacement in the Campanian.

CONCLUDING DISCUSSION

The preceding subsidence analysis confirms that cooling of the lithosphere has been the main factor causing subsidence of the Chagos-Laccadive Ridge, Kerguelen Plateau, Mascarene Plateau, and Ninetyeast Ridge. It also reveals that these features have experienced significant portions of their development subaerially and in shallow water (Figure 3). Progressive development of dominantly

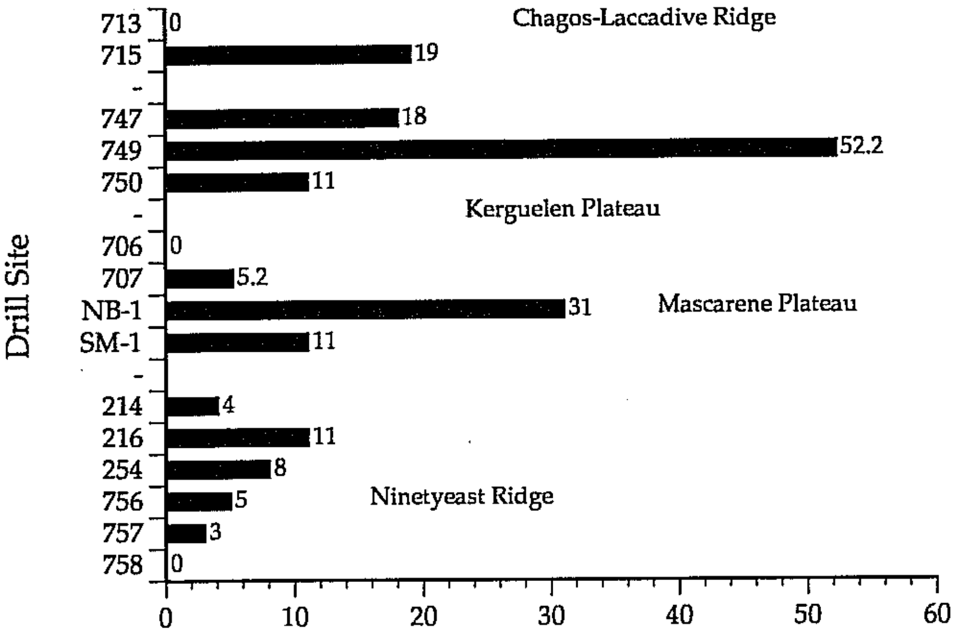

Fig. 3. Duration of subaerial and shelf environments at drill sites on the Chagos-Laccadive Ridge, Kerguelen Plateau, Mascarene Plateau, and Ninetyeast Ridge (Table 4).

terrestrial, then terrigenous, and eventually biogenic shallow-water and pelagic facies sediment in response primarily to thermal subsidence has produced a sedimentary record intermediate between continental margins and open marine.

Long hiatuses at many sites may be explained by their remaining above sea level for as much as ~50 m.y. following emplacement. Two other lines of evidence support this by suggesting that significant erosion of basement is possible. At Site 749 on the Kerguelen Plateau (Figure 1), compressional wave velocities are higher than those determined from samples from other plateau sites [Schlich, Wise et al., 1989], suggesting that deeper levels of the igneous crust were penetrated. At the same site, intermediate zeolite facies [Sevigny et al., 1992] were encountered, indicating higher temperatures and perhaps deeper crustal levels than zeolite facies at Sites 747 and 750.

Present-day, but smaller analogs to the oceanic plateaus and submarine ridges analyzed all suggest that subaerial emplacement and early evolution of such LIPs may be the rule rather than the exception. Table 5 summarizes maximum elevations of some of these provinces, all of which have been active in Quaternary time. These maximum elevations are probably comparable to the original setting of Site 749 on the Kerguelen Plateau (Figure 1), which is now situated on the shallowest part - Banzare Bank - of its southern sector, as well as to sites on other submarine LIPs. Samples obtained from the Naturaliste Plateau [Davies, Luyendyk et al., 1974; Hayes, Frakes et al., 1975; Coleman et al., 1982], Rio Grande Rise [Supko, Perch-Nielsen et al., 1977], and the Iceland-Faeroe Ridge [Talwani, Udinstev et al., 1976] also show strong evidence of subaerial basalt extrusion. Furthermore, at least part of the basaltic seaward-dipping reflector sequences drilled on the Vøring Plateau [Talwani, Udinstev et al., 1976; Eldholm, Thiede, Taylor et al., 1987, 1989] and Rockall Bank [Roberts, Schnitker et al., 1984] was erupted and eroded subaerially.

Following the constructional phase of oceanic plateau and submarine ridge development, erosional processes become the dominant factor in altering plateau morphology if thermal rejuvenation does not keep the feature high-standing. If the plateau or ridge is submarine, erosion of basalt and associated extrusive and intrusive rocks is negligible. However, if the plateau or ridge is subaerial, erosion can be widespread, significantly altering the topography of the feature (e.g., Table 5). Rate of denudation of any rock type is a function of topography and climate. Wood recovered in basal sediment [Francis and Coffin, 1992] and clay mineralogy [Holmes, 1992] at Site 750 on the southern Kerguelen Plateau (Figure 1) suggest a temperate climate. Average denudation rates in temperate climates vary from 10 to 200 m/m.y., depending on the topographic relief [Saunders and Young, 1983]. Evidence from drilling suggests subaerial exposure for up to 50 m.y., allowing 500-10000 m of erosion. Drilling results do not support the latter figure, but several hundred to over a thousand meters of basalt could have been eroded from the Kerguelen Plateau based on compressional wave velocities [Schlich, Wise et al., 1989] and zeolite facies [Sevigny et al., 1992]. This erosional phase of development is marked by the deposition of terrestrial and terrigenous sediment. After the bulk of the feature subsides

TABLE 5. Present maximum elevations of Quaternary Indian Ocean hotspots, Iceland, Hawaii, and their tracks.

Hotspot Track (old→young)	Hotspot Source	Maximum Elevation (m)
Naturaliste Plateau-Kerguelen Plateau/Broken Ridge-Ninetyeast Ridge-northernmost Kerguelen Plateau	Heard Island Kerguelen Island	2745 1849
Chagos-Laccadive Ridge-Mascarene Plateau	Réunion Mauritius	3069 826
Del Caño Rise	Marion[1] Prince Edward[1]	1230 672
Crozet Plateau	Est Possession	1090 934
Iceland/Faeroe-Greenland Ridge	Iceland	2119
Hawaiian-Emperor Seamounts	Hawaii	4169

[1] Marion and Prince Edward islands probably do not represent the age of the bulk of Del Caño Rise - see text for discussion.

below sea level, biogenic shallow-water and pelagic sediment follow.

Why the oceanic plateaus and submarine ridges examined herein, as well as oceanic LIPs in general, are commonly emplaced above sea level and spend a significant portion of their history subaerially exposed or at shallow water depths is probably a combination of two factors. First, the mantle thermal anomaly responsible for LIP emplacement is greater than that for seafloor spreading centers [White and McKenzie, 1989], which results in more decompressional melting, greater thermal expansion of the lithosphere, and a lower surface area-to-volume ratio, meaning less efficient decay of the original thermal anomaly. More melt allows construction of many oceanic LIPs well above sea level, and hotter lithosphere enhances this. Lower surface area-to-volume ratios of LIPs and associated heated lithosphere results in slower decay of the thermal anomaly, i.e., subsidence at a lesser rate. Second, erosion of subaerial oceanic LIPs results in isostatic rebound, which serves to further prolong their anomalous elevation. Emplacement and subsidence analyses of LIPs globally, using both forward and inverse modeling, will help to further constrain and quantify these effects.

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REFERENCES

Backman, J., Duncan, R. A., et al., *Proc. ODP, Init. Repts., 115*, 1085 pp., 1988.

Baker, B. H., and Miller, J. A., Geology and geochronology of the Seychelles Islands and structures of the floor of the Arabian Sea, *Nature, 199*, 346-348, 1963.

Barron, J., Larsen, B. et al., *Proc. ODP, Init. Repts., 119*, 942 pp., 1989.

Barron, J., Larsen, B. et al., *Proc. ODP, Sci. Results, 119*, 1003 pp., 1991.

Berggren, W. A., Kent, D. V., Flynn, J. J., and Van Couvering, J. A., Cenozoic geochronology, *Geol. Soc. Am. Bull., 96*, 1407-1418, 1985.

Chevallier, L., Nougier, J., and Cantagrel, J. M., Volcanology of Possession Island, Crozet Archipelago, in *Antarctic Earth Science*, edited by R. L. Oliver, J. B. Jago, and P. R. James, pp. 652-658, Cambridge Univ. Press, Cambridge, 1983.

Clarke, I., McDougall, I., and Whitford, D. J., Volcanic evolution of Heard and McDonald islands, southern Indian Ocean, in *Antarctic Earth Science*, edited by R. L. Oliver, J. B. Jago, and P. R. James, pp. 631-635, Cambridge Univ. Press, Cambridge, 1983.

Coffin, M. F., Subsidence of the Kerguelen Plateau: the Atlantis concept, *Proc. ODP, Sci. Results, 120*, 945-949, 1992.

Coffin, M. F., Davies, H. L., and Haxby, W. F., Structure of the Kerguelen Plateau province from SEASAT altimetry and seismic reflection data, *Nature, 324*, 134-136, 1986.

Coffin, M. F., Munschy, M., Colwell, J. B., Schlich, R., Davies, H. L., and Li, Z. G., Seismic stratigraphy of the Raggatt Basin, southern Kerguelen Plateau: tectonic and paleoceanographic implications, *Geol. Soc. Am. Bull., 102*, 563-579, 1990.

Coffin, M. F., and Eldholm, O., eds., Large Igneous Provinces: JOI/USSAC Workshop Report, *Univ. Texas at Austin Inst. for Geophys. Tech. Rept. 114*, 79 pp., 1991.

Coleman, P. J., Michael, P. J., and Mutter, J. C., The origin of the Naturaliste Plateau, SE Indian Ocean: implications from dredged basalts, *J. Geol. Soc. Australia, 29*, 457-468, 1982.

Crough, S. T., Thermal model of oceanic lithosphere, *Nature, 256*, 388-390, 1975.

Crough, S. T., The correction for sediment loading on the seafloor, *J. Geophys. Res., 88*, 6449-6454, 1983.

Davies, H. L., Sun, S.- S., Frey, F. A., Gautier, I., McCulloch, M. T., Price, R. C., Bassias, Y., Klootwijk, C. T., and Leclaire, L., Basalt basement from the Kerguelen Plateau and the trail of a Dupal plume, *Contrib. Mineral. Petrol., 103*, 457-469, 1989.

Davies, T. A., Luyendyk, B. P. et al., *Init. Repts. DSDP, 26*, 1129 pp., 1974.

Davis, E. E. and Lister, C. R. B., Fundamentals of ridge crest topography, *Earth Planet. Sci. Lett., 21*, 405-413, 1974.

Detrick, R. S., Sclater, J. G., and Thiede, J., The subsidence of aseismic ridges, *Earth Planet. Sci. Lett., 34*, 185-196, 1977.

Driscoll, N. W., Karner, G. D., and Weissel, J. K., Stratigraphic response of carbonate platforms and terrigenous margins to relative sea-level changes: are they really that different? *Proc. ODP, Sci. Results, 121*, 743-761, 1991.

Duncan, R. A., Geochronology of basalts from the Ninetyeast Ridge and continental dispersion in the eastern Indian Ocean, *J. Volcanol. Geotherm. Res., 4*, 283-305, 1978.

Duncan, R. A., The volcanic record of the Réunion hotspot, *Proc. ODP, Sci. Results, 115*, 3-10, 1990.

Duncan, R. A., Age distribution of volcanism along aseismic ridges in the eastern Indian Ocean, *Proc. ODP, Sci. Results, 121*, 507-517, 1991.

Duncan, R. A., and Hargraves, R. B., ^{40}Ar/^{39}Ar geochronology of basement rocks from the Mascarene Plateau, the Chagos Bank, and the Maldives Ridge, *Proc. ODP, Sci. Results, 115*, 43-51, 1990.

Duncan, R. A., Backman, J., Peterson, L. C. et al., *Proc. ODP, Sci. Results, 115*, 887 pp., 1990.

Eldholm, O., Thiede, J. Taylor, E. et al., *Proc. ODP, Init. Repts., 104*, 783 pp., 1987.

Eldholm, O., Thiede, J. Taylor, E. et al., *Proc. ODP, Sci. Results, 104*, 1141 pp., 1989.

Fisher, R. L., Bunce, E. T. et al., *Init. Repts. DSDP, 24*, 1183 pp., 1974.

Francis, J. E., and Coffin, M. F., Cretaceous fossil wood from the Raggatt Basin, southern Kerguelen Plateau (Site 750), *Proc. ODP, Sci. Results, 120*, 273-280, 1992.

Giret, A., and Lameyre, J., A study of Kerguelen plutonism: petrology, geochronology, and geological implications, in *Antarctic Earth Science* , edited by R. L. Oliver, P. R. James, and J. B. Jago, pp. 646-651, Cambridge Univ. Press, Cambridge, 1983.

Griffiths, R. W., and Campbell, I. H., Stirring and structure in mantle starting plumes, *Earth Planet. Sci. Lett., 99*, 66-78, 1990.

Haq., B. U., Hardenbol, J., and Vail, P. R., Chronology of fluctuating sea levels since the Triassic, *Science, 235*, 1156-1167, 1987.

Hayes, D. E., Age-depth relationships and depth anomalies in the Southeast Indian Ocean and South Atlantic Ocean, *J. Geophys. Res., 93*, 2937-2954, 1988.

Hayes, D. E., Frakes, L. A. et al., *Init. Repts. DSDP, 28*, 1017 pp., 1975.

Hill, R. I., Starting plumes and continental break-up, *Earth Planet. Sci. Lett., 104*, 398-416, 1991.

Holmes, M. A., Cretaceous subtropical weathering followed by cooling at 60°S latitude: the mineral composition of southern Kerguelen Plateau sediment, Leg 120, *Proc. ODP, Sci. Results, 120*, 99-111, 1992.

Houtz, R. E., Hayes, D. E., and Markl, R. G., Kerguelen Plateau bathymetry, sediment distribution, and crustal structure, *Mar. Geol., 25*, 95-130, 1977.

Kent, D. V., and Gradstein, F. M., A Cretaceous and Jurassic geochronology, *Bull. Geol. Soc. Am., 96*, 1419-1427, 1985.

Kominz, M. A., Oceanic ridge volumes and sea-level change - an error analysis, in *Interregional Unconformities and Hydrocarbon Accumulation*, edited by J. S. Schlee, pp. 109-127, Am. Assoc. Petrol. Geol. Mem. 36, Tulsa, OK, 1984.

Lameyre, J., and Nougier, J., Geology of Ile de l'Est, Crozet Archipelago (TAAF), in *Antarctic Geoscience*, edited by C. Craddock, pp. 767-770, Univ. Wisconsin Press, Madison, 1982.

Leclaire, L., Bassias, Y. Denis-Clocchiatti, M. Davies, H. Gautier, I. Gensous, B. Giannesini, P.-J. Patriat, P. Ségoufin, J. Tesson, M., and Wannesson, J., Lower Cretaceous basalt and sediments from the Kerguelen Plateau, *Geomar. Lett., 7*, 169-176, 1987.

McDougall, I., The geochronology and evolution of the young oceanic island of Réunion, Indian Ocean, *Geochim. Cosmochim. Acta, 35*, 261-270, 1971a.

McDougall, I., Geochronology, in *Marion and Prince Edward Islands, Report on the South African Biological and Geological Expedition 1965/66*, edited by E. M. van Zinderen Bakker, J. M. Winterbottom, and R. A. Dyer, pp. 72-77, A.A. Balkema, Cape Town, 1971b.

Meyerhoff, A. A., and Kamen-Kaye, M., Petroleum prospects of Saya de Malha and Nazareth Banks, Indian Ocean, *Am. Assoc. Petrol. Geol. Bull., 65*, 1344-1347, 1981.

Morgan, W. J., Hotspot tracks and the opening of the Atlantic and Indian oceans, in *The Sea, Volume 7, The Oceanic Lithosphere*, edited by C. Emiliani, pp. 443-487, Wiley, New York, 1981.

Nougier, J., Pawlowski, D., and Cantagrel, J. M., Chrono-spatial evolution of the volcanic activity in southeastern Kerguelen (T.A.A.F.), in *Antarctic Earth Science*, edited by R. L. Oliver, J. B. Jago, and P. R. James, pp. 640-645, Cambridge Univ. Press, Cambridge, pp. 640-645, 1983.

Parker, R. L., and Oldenburg, D. W., Thermal model of ocean ridges, *Nature, 242*, 137-139, 1973.

Parsons, B., and Sclater, J. G., An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res., 82*, 803-827, 1977.

Peirce, J. W., Weissel, J. K. et al., *Proc. ODP, Init. Repts., 121*, 1000 pp., 1989.

Roberts, D. G., Schnitker, D. et al., *Init. Repts. DSDP 81*, 923 pp., 1984.

Saunders, I., and Young, A., Rates of surface processes on slopes, slope retreat, and denudation, *Earth Surface Processes Landforms, 8*, 473-501, 1983.

Schlich, R., Wise, S. W., Jr. et al., *Proc. ODP, Init. Repts., 120*, 648 pp., 1989.

Sclater, J. G., and Christie, P. A. F., Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the central North Sea basin, *J. Geophys. Res., 85*, 3711-3739, 1980.

Sevigny, J. H., Whitechurch, H. Storey, M. and Salters, V. J. M., Zeolite-facies metamorphism of central Kerguelen Plateau basalts, *Proc. ODP, Sci. Results, 120*, 63-69, 1992.

Simpson, E. S. W., Schlich, R. et al., *Init. Repts. DSDP, 25*, 884 pp., 1974.

Supko, P. R., Perch-Nielsen, K. et al., *Init. Repts. DSDP, 39*, 1139 pp., 1977.

Talwani, M., Udinstev, G. et al., *Init. Repts. DSDP, 38*, 1256 pp., 1976.

von der Borch, C., Sclater, J. G. et al., *Init. Repts. DSDP, 22*, 890 pp., 1974.

Weissel, J., Peirce, J. Taylor, E. Alt, J. et al., *Proc. ODP, Sci. Results, 121*, 990 pp., 1991.

White, R., and McKenzie, D., Magmatism at rift zones: the generation of volcanic continental margins and flood basalts, *J. Geophys. Res., 94*, 7685-7729, 1989.

Whitechurch, H., Montigny, R. Sevigny, J. Storey, M., and Salters, V., K-Ar and ^{40}Ar-^{39}Ar ages of central Kerguelen Plateau basalts, *Proc. ODP, Sci. Results, 120*, 71-77, 1992.

Whitmarsh, R. B., Weser, O. E. Ross, D. A. et al., *Init Repts. DSDP 23*, 1180 pp., 1974.

Wise, S. W., Jr., Schlich, R. et al., *Proc. ODP, Sci. Results, 120*, 1155 pp., 1992.