Formation of forearc basins by collision between seamounts and accretionary wedges: An example from the New Hebrides subduction zone

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ABSTRACT

Seabeam data reveal two deep subcircular reentrants in the lower arc slope of the New Hebrides island arc that may illustrate two stages in the development of a novel type of forearc basin. The Malekula reentrant lies just south of the partly subducted Bougainville seamount. This proximity, as well as the similarity in morphology between the reentrant and an indentation in the lower arc slope off Japan, suggests that the Malekula reentrant formed by the collision of a seamount with the arc. An arcuate fold-thrust belt has formed across the mouth of the reentrant, forming the toe of a new accretionary wedge. The Efate reentrant may show the next stage in basin development. This reentrant lies landward of a lower-slope ridge that may have begun to form as an arcuate fold-thrust belt across the mouth of a reentrant. This belt may have grown by continued accretion at the toe of the wedge, by underplating beneath the reentrant, and by trapping of sediment shed from the island arc. These processes could result in a roughly circular forearc basin. Basins that may have formed by seamount collision lie within the accretionary wedge adjacent to the Aleutian trenches.

INTRODUCTION

The New Hebrides island arc of the southwestern Pacific Ocean lies within the convergence zone of the Australia-India plate and the oceanic crust under the North Fiji Basin (Fig. 1). Along the trench associated with this arc, Seabeam bathymetry and single-channel seismic reflection data were collected during the Seapso I cruise of the N.O. *Jean Charcot* (Daniel et al., 1986). These data show two deep subcircular reentrants in the lower arc slope west of Malekula and Efate islands (Fig. 1). We propose that these reentrants are scars in the accretionary wedge that were caused by collision and subduction of seamounts and that, in general, such scars could form molds for forearc basins. The two scars appear to be at different stages of healing, and we think that they illustrate successive phases of basin formation. We use the word "seamount" in a generic sense to refer to any submarine mountain, regardless of its genesis.

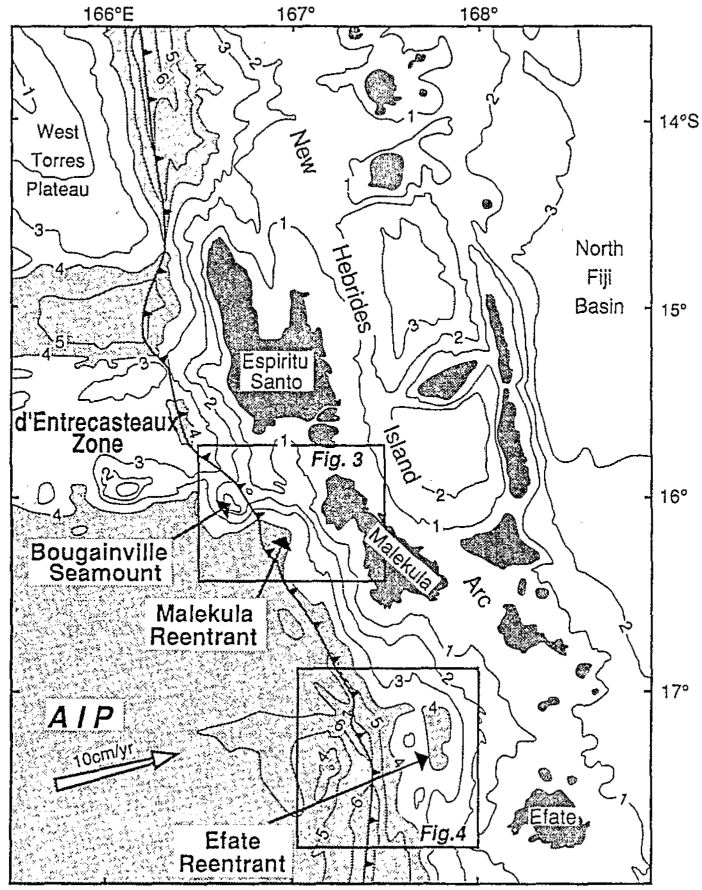

Figure 1. Central New Hebrides island arc. AIP = Australia-India plate. Barbed line shows sea-floor trace of interplate decollement; barbs show downdip direction. Bathymetric contour interval is 1 km.

MORPHOLOGY OF THE LOWER-SLOPE REENTRANTS

West of northern Malekula Island, the subcircular Malekula reentrant indents the lower slope of the New Hebrides arc (Fig. 2). This reentrant is 20 km in diameter and its bottom is about 4300 m below sea level, almost as deep as the abyssal oceanic plain (4500 m). The Malekula reentrant is bounded on the west by the New Hebrides Trench and on its other sides by steep (10°–20°) walls. This reentrant lies just south of the collision zone between the New Hebrides island arc and the d'Entrecasteaux zone (DEZ), a chain of seamounts and linear ridges. This chain includes the Bougainville seamount, which is partly subducted below the accretionary wedge (Fig. 3; Fisher et al., 1986).

Seabeam bathymetric data show that the bottom of the Malekula reentrant is marked by numerous closed highs and lows that have divergent trends (Fig. 2). We divide these closed features into two groups. The first group lies just east of the trench and includes arcuate ridges that are 100–200 m high and range in length from 4 to 10 km. On the southeast, these ridges abut the relatively smooth, north-trending arc slope; toward the north, they curve clockwise, the group narrows overall, and the ridges merge with the east-trending wall of the reentrant. The second group of bottom features forms the highly irregular topography evident at the center of the reentrant. This group also encompasses ridges and lobate bodies (about 50–400 m high) that extend generally inward from the wall of the reentrant.

The wall that encircles the Malekula reentrant varies considerably in morphology. Above 3500 m depth, the north wall near the Bougainville seamount is inclined at 10° and is smooth, but becomes more irregular to the east. Below 3500 m, morphologic irregularities include lobate bodies and small (1–4 km^2) slope terraces that are separated by 100–300-m-high, steep (20°–24°) scarps. Seabeam coverage of the eastern wall of the reentrant is incomplete, but one section of this wall, between 2100 and 2800

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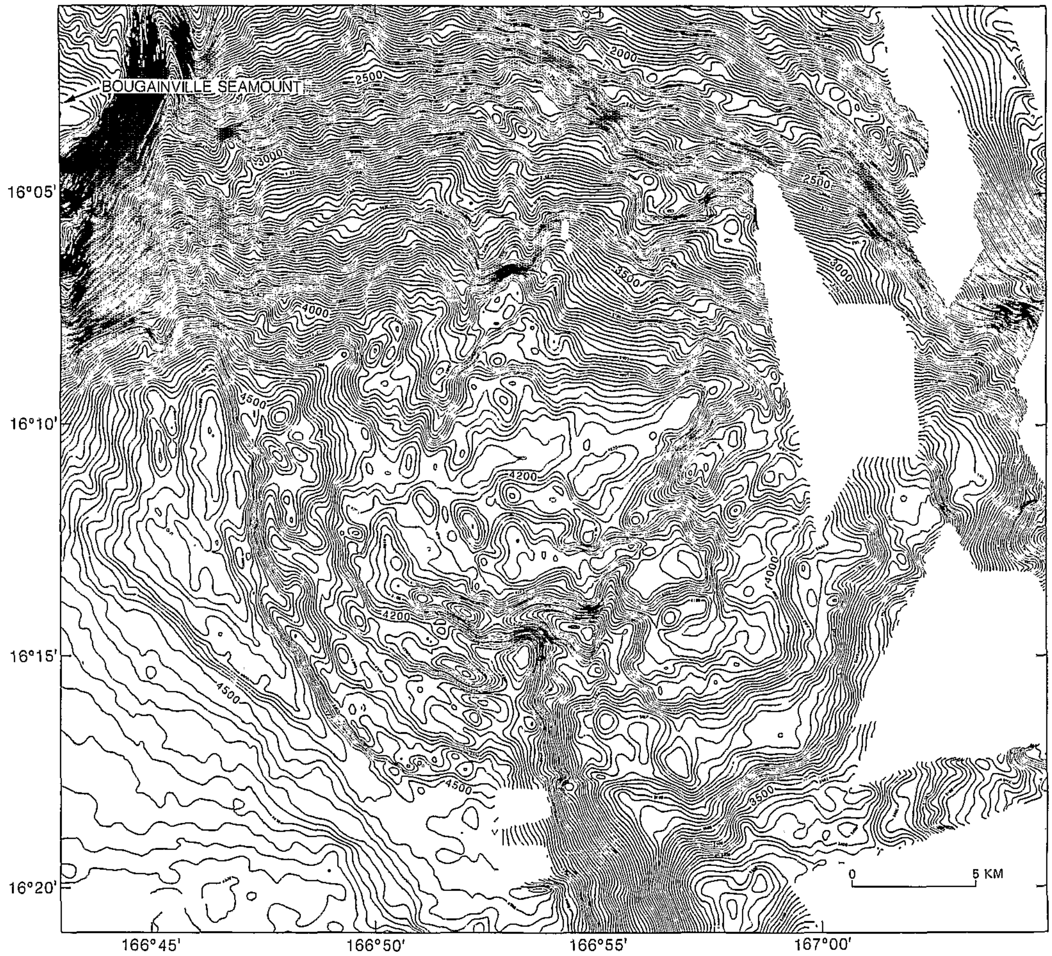
Figure 2. Detailed Seabeam bathymetric map of Malekula reentrant. Bathymetric contour interval is 20 m. Area covered is shown in Figure 3.



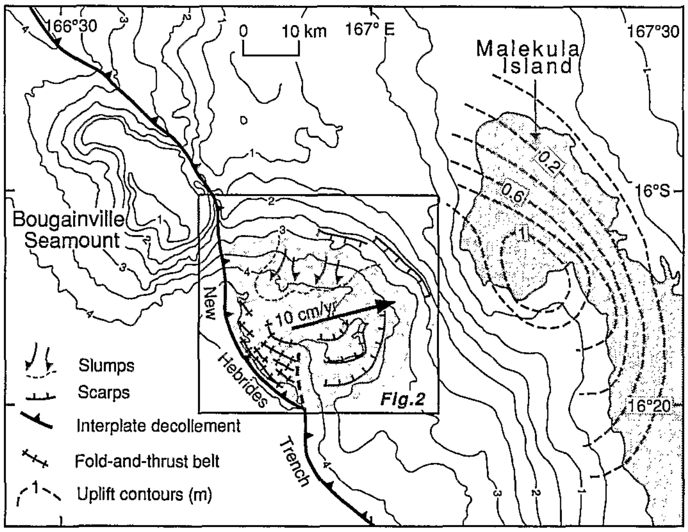


Figure 3. Structural interpretation of morphology of Malekula reentrant, which is outlined by box. Contours on Malekula Island are derived from coral terraces and show magnitude of uplift during 1965 earthquake (Taylor et al., 1980). Malekula reentrant and area of maximum uplift are aligned along plate-convergence vector. Bathymetric contour interval is 500 m.

m, dips steeply (20°–22°). The southeastern quadrant of the reentrant wall includes three narrow terraces that are separated by northwest-facing scarps about 100 to 250 m high. These terraces are concentric with the center of the reentrant and are limited in western extent by the north-trending, smooth arc slope that dips 12° trenchward.

The subcircular Efate reentrant (Figs. 1 and 4) is under water about 4000 m deep and is 40 km in diameter, about twice as large as the Malekula reentrant. A high relief (1–3 km) ridge bridges the mouth of the reentrant and forms the western structural boundary of a basin, which is shown in cross section by single-channel seismic line 1178 (Fig. 5).

DISCUSSION

What Caused the Lower Slope Reentrants?

Morphologic and seismic data that we present can be interpreted in several ways to explain the origin of the reentrants. One possible origin, derived by using the margin off Peru as a guide (von Huene et al., 1989), is that the reentrants are scars of large slumps. In the Efate reentrant, rocks forming the ridge across the mouth of the reentrant could include the allochthonous mass that was modified by accretion and imbrication after slumping. However, for reasons presented below, we believe that seamount-arc collision is a more likely explanation for the reentrants.

The Malekula reentrant appears similar to an indentation in the lower arc slope off Japan, at the junction of the Japan and Kuril trenches (Cadet et al., 1987). The Kuril indentation probably resulted from the collision of a seamount with the continental slope because a seamount has been detected beneath the slope just landward of the indentation, as indicated by modeling of magnetic data (Lallemand and Chamot-Rooke, 1986). Lallemand and Le Pichon (1987) and R. von Huene and S. Lallemand (in prep.) describe general models for the tectonic erosion that accompanies seamount-wedge collision and leads to formation of the indentation. The

Malekula reentrant and the Kuril indentation are similar morphologically in that both are subcircular, about 20 km in diameter, are bounded by steep walls, and are nearly as deep as the oceanic plate seaward of the trench. However, the reentrant and the indentation differ in that the floor of the indentation is smooth, and as yet no arcuate ridges separate this floor from the Japan Trench. Furthermore, the wall of the indentation is steeper than the one around the reentrant.

Our hypothesis that the Malekula reentrant is a scar formed by seamount-wedge collision is difficult to prove because this reentrant has no associated seamount, and the nearby, partly subducted Bougainville seamount has not yet produced a recognizable reentrant. Nevertheless, a seamount that could have caused the scar may still be under the arc slope, as suggested by strong, nearly circular uplift of the northern end of Malekula Island (Fig. 3). Exposed coral terraces indicate that during the major earthquake sequence of 1965, the northern part of the island was uplifted by as much as 1 m (Taylor et al., 1980). A line connecting the approximate center of the uplifted part of the island with the center of the reentrant can be drawn parallel to the vector of relative convergence between the Australia-India plate and the arc (Fig. 3). Therefore, we believe that a seamount forms an asperity in the subduction zone and caused the island uplift as well as the reentrant. The morphologic similarity between the reentrant and the Kuril indentation supports this interpretation, as does the proximity of the reentrant to the collision zone between the Bougainville seamount and the slope of the New Hebrides arc.

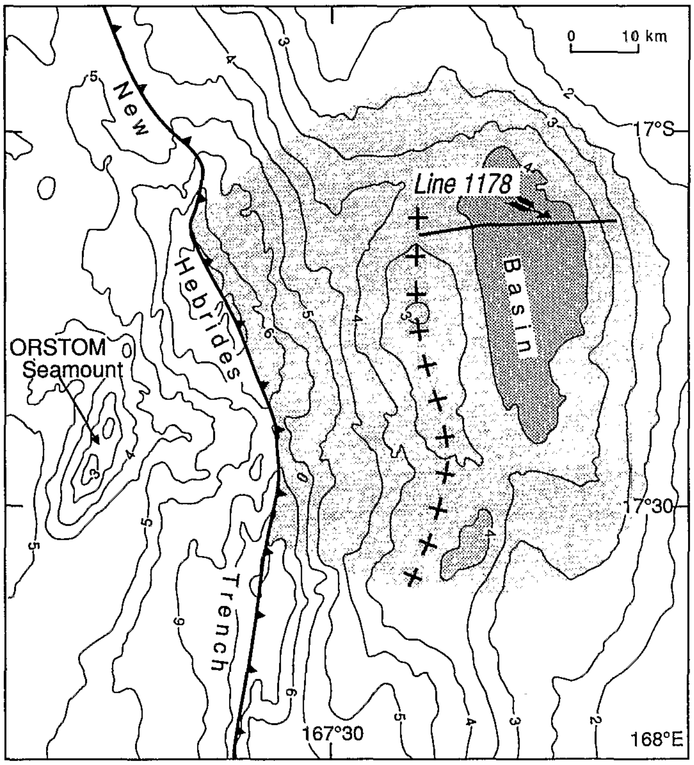


Figure 4. Seabeam bathymetry of Efate reentrant (light gray) and forearc basin (dark gray). Large ridge (crosses) bridges mouth of reentrant and separates forearc basin from trench. Barbed line shows sea-floor trace of interplate decollement; barbs point downdip. Bathymetric contour interval is 500 m.

We interpret the morphology of the Malekula reentrant in the context of seamount-wedge collision. The irregular topography of the reentrant floor probably points to large-scale collapse of the accretionary wedge that occurred as the seamount invaded the subduction zone, uplifting and oversteepening wedge rocks and then withdrawing support for these rocks. Further evidence for collapse includes the concentric terraces that form the southeast quadrant of the reentrant wall (Fig. 3). We interpret the arcuate ridges that separate the New Hebrides Trench from the floor of the reentrant as a newly formed fold-and-thrust belt that formed in oceanic sediment and slumped arc material (Fig. 3). In essence, this belt forms the new and growing toe of the accretionary wedge.

The Efate reentrant could also result from the collision between a seamount and the island arc. As to the Malekula reentrant, however, no oceanic features are evident under the arc slope to prove that collision caused the reentrant and basin. Greene et al. (1988) proposed that this reentrant formed between 8 and 7 Ma and that it resulted from the beginning of the collision between the DEZ and the arc. Subsequently, the oblique angle between the convergence direction and the strike of the DEZ carried the DEZ northward along the trench at about 2.5 cm/yr to its present position. We believe, however, that the Efate reentrant records more recent events because the Orstom seamount lies just west of this reentrant and might mark the tail end of an already subducted sequence of seamounts. In addition, as noted by Isacks et al. (1981) and Chatelain et al. (1986), an intense cluster of earthquakes, the Efate nest, is centered over the southeastern part of the Efate reentrant and reveals a major asperity along the interplate decollement. We propose that this asperity is associated with the subducted feature that collided with the arc slope and caused the reentrant.

Formation of Forearc Basins

Data presented by Lallemand and Le Pichon (1987) show that lower slope reentrants near the Japan Trench are not evident except where a seamount now collides with this slope. Accordingly, they proposed that reentrants heal completely by normal faulting within and collapse of the accretionary wedge as the wedge attempts to reestablish its critical taper. This taper is governed primarily by the internal friction of the accreted rocks; wedges with overcritical tapers collapse and those with undercritical tapers thicken until the critical taper is achieved (Davis et al., 1983). Our data show, however, that deformation associated with reestablishing the critical taper is not confined to collapse of the old wedge; instead, two geographically separated styles of deformation cooperate to reform this taper. One style involves collapse of the wall rock surrounding the reentrant; the second style, not mentioned by Lallemand and Le Pichon (1987), includes the formation of a new accretionary wedge. Differences in deformation style of rocks near the reentrants of the Japan and New Hebrides arcs are probably caused by local geologic conditions, particularly by the

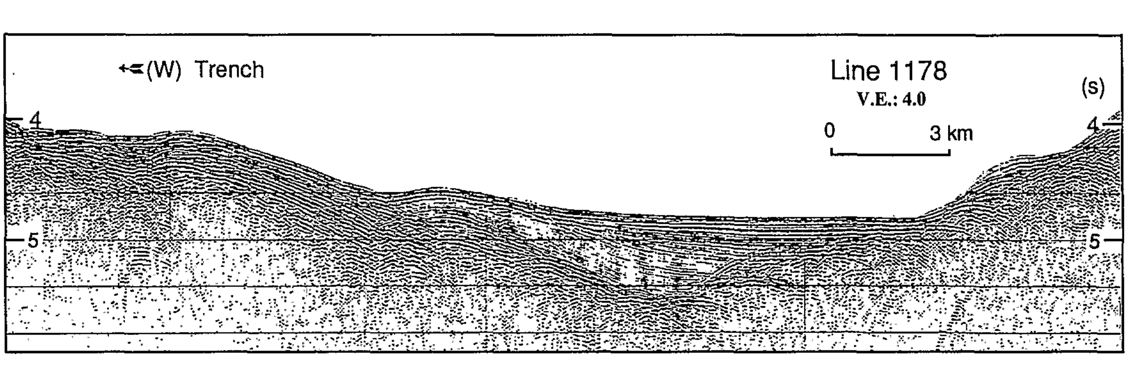


Figure 5. Single-channel seismic line 1178 across Efate reentrant. Strata filling forearc basin show gentle arcward dips and small folds over ridge that bounds basin on west. Basin filling and folding of accreted rocks help restore critical wedge taper.

age of the reentrants, the strength of the wall rocks, and the type of subducting sediment.

We believe that the Malekula reentrant will become a forearc basin as the new accretionary wedge develops across its mouth. This wedge is bounded above by the nearly flat floor of the reentrant, which has such low dip that this wedge most likely has an undercritical taper, so the wedge will thicken. Thickening will involve accreting ocean basin sediment, incorporating slump debris, and filling of the reentrant with sediment shed from the arc. In our view, sediment is typically trapped arcward of the growing toe of the accretionary wedge, forming a subcircular, forearc basin.

If this proposal is correct, then both the basin ensconced within the Efate reentrant and the ridge that bounds the basin on the west formed as the slope reestablished its critical taper. The partly filled basin and large ridge may evince a more mature stage of basin evolution than is evident around the Malekula reentrant. Rocks that form the ridge lie within imbricate thrust slices, as shown by one multichannel seismic line that crosses the arc slope just south of this basin (line 1 in Fisher, 1986). The single-channel seismic section across the basin and ridge shows generally flat-lying basin fill that over the east flank of the ridge is deformed by west-verging folds (Fig. 5). A marked dip discordance occurs within the middle of the fill. The folds and the discordance might reveal progressive, relative uplift of the ridge that is part of the process of reestablishing the critical taper.

A reentrant that heals completely could become a subcircular basin that contains relatively undeformed fill and underlies the slope or shelf of a convergent margin. Possible examples of such basins lie beneath the Gulf of Alaska adjacent to the eastern Aleutian Trench. Five subcircular, Miocene basins (Stevenson, Albatross, Tugidak, Trinity, and Shumagin; Fisher, 1979; Fisher and von Huene, 1980; Bruns et al., 1987, von Huene et al., 1987) have enigmatic origins because of their circular shape in map view and their depth (5–7 km). One possible mechanism to explain basin evolution involves the rotation of blocks of forearc crust during oblique convergence (Geist et al., 1988). According to ideas presented here, however, these basins may have begun to form at the toe of the slope during seamount collision and then were uplifted and isolated from the trench by underplating and seaward growth of the accretionary wedge.

OUTCROP RECOGNITION OF BASINS

Basins that formed by seamount-wedge collision might be recognized in outcrop by their shape and stratigraphy. These basins can be relatively small (20–40 km in diameter) and have a roughly circular outline, which might distinguish them from basins that formed behind the elongated, thrust-fault–bounded ridges of an accretionary complex. The potentially diagnostic stratigraphy includes chaotic debris, slumped from the accretionary wedge, that lies at the bottom of the basin. Rock exotic to the island arc may be scraped from the seamount to coat the reentrant wall or to be mixed in with the slumps. These slumps are overlain by more coherently bedded basin fill, and a substantial break in rock age between the fill and accreted rocks may mark the reentrant wall. Reentrants typically cut downward through the accretionary wedge almost to the level of the abyssal oceanic plain, so the oldest fill could have been deposited at abyssal depth and the coherently bedded basin fill can have substantial thickness.

CONCLUSIONS

Seamounts that collide with accretionary wedges can cause deep, subcircular reentrants that eventually fill to become forearc basins. Reentrants result from tectonic erosion as wedge rocks are oversteepened and jostled aside by the subducting seamount. Subsequent healing of a reentrant involves the formation of an arcuate fold-and-thrust belt that bridges the mouth of the reentrant and forms a new toe of the accretionary wedge. This belt grows vertically to establish the critical wedge taper that is appropriate for newly accreted rocks, and the belt dams sediment that is transported toward the trench. These processes eventually form a basin that could preserve the subcircular outline of the reentrant. Vertical and seaward wedge growth could result in a forearc basin that is preserved at bathyal or shelf depths.

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Reunion hotspot magma chemistry over the past 65 m.y.: Results from Leg 115 of the Ocean Drilling Program

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ABSTRACT

Leg 115 of the Ocean Drilling Program recovered basalts from four locations along the hotspot track that leads from the Deccan flood basalts in India to Reunion Island in the western Indian Ocean (Sites 706, 707, 713, and 715). The drilled basalts range in age from 35 Ma (Site 706) to 64 Ma (Site 707), and including the Deccan basalts (66 to 68 Ma), Mauritius Island (0.2 to 8 Ma), and Reunion Island (0 to 2 Ma), seven sites are provided for sampling the volcanic record of the 5000-km-long hotspot track. Chemical and age comparisons indicate that Site 707 lavas correlate with basalt units near the top of the Deccan flood basalt sequence. The lavas of Site 715 (55 to 60 Ma) are most similar to the islands of Mauritius and Reunion. Site 713 basalts (48 Ma) are similar to the earliest lavas of the Deccan province, and Site 706 basalts are intermediate in chemistry between those of central Indian spreading-ridge basalts and Reunion. Differences in lava compositions along the hotspot track can be related to variable mixing of plume and asthenospheric mantle, depending on the changing position of spreading-ridge segments and the hotspot during the opening of the Indian Ocean. Alternatively, time-dependent changes in the composition of hotspot melts may be due to a decrease in partial melting of a heterogeneous plume or to intrinsic changes in the composition of material supplied by the plume.

INTRODUCTION

Between the Deccan flood basalt province in India and Reunion Island in the western Indian Ocean, the Chagos-Maldive-Laccadive islands, the Saya de Malha–Nazareth Banks, and Mauritius Island mark the 5000 km path of the Indian and African plates over a mantle hotspot currently situated beneath Reunion Island (Fig. 1). The volcanic activity that produced these islands, ridges, and continental flood basalts started about 68 Ma at the Deccan province (Duncan and Pyle, 1988; Courtillot et al., 1988) and continues today at Reunion. The length and duration of this track are similar to the Hawaiian-Emperor chain (5800 km, greater than 74 m.y.; Clague and Dalrymple, 1987) and to the Louisville Ridge (4000 km, 66 m.y.; Watts et al., 1988).

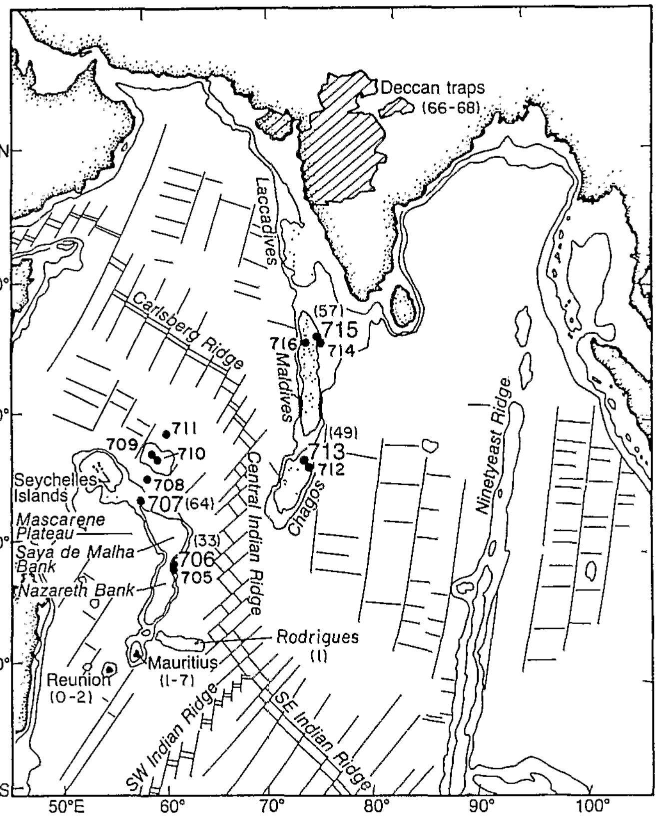

Figure 1. Bathymetric map of western and central Indian Ocean showing major tectonic features, Deccan-Reunion hotspot track, and sites drilled during Leg 115. Large numbers are sites that recovered basalt. Ages of basalts (Ma) along chain are given in parentheses.

The basalts of the Hawaiian-Emperor chain are characterized by a remarkable uniformity in chemistry over the past 70 m.y., but certain isotope ratios and trace-element ratios indicate that subtle changes in the mantle source for the basalts have occurred over the same period (Lanphere et al., 1980; Stille et al., 1986). Basalts from the end points of the Deccan-Reunion chain also suggest there was a change in its mantle source through Tertiary time (Cox and Hawkesworth, 1985; Fisk et al., 1988), but until now there were no data from intervening volcanoes. Leg 115 of the Ocean Drilling Program drilled four sites to basement along the hotspot track (Fig. 1) to determine more precisely the rate of motion of the plates in the western Indian Ocean and to document any changes in basalt compositions through time.

The Leg 115 basalts were recovered from four locations along this ridge (Fig. 1), and age assignments were made from biostratigraphic data from sediments directly overlying or interbedded with the basalts. Ages for oceanic crust underlying the volcanoes are inferred from identified magnetic anomalies (Schlich, 1982). Site 706 drilled 35 Ma basalts that were erupted on young crust at the nascent central Indian spreading ridge (Shipboard Scientific Party, 1989). Site 707 bottomed in 64 Ma basalts that were probably erupted adjacent to the western margin of the Indian

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