

Swath Bathymetric Investigation of the Seamounts Located in the Laxmi Basin, Eastern Arabian Sea

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Multibeam (Hydrosweep) swath bathymetric investigations revealed the presence of a NNW trending linear seamount chain along the axial part of the Laxmi Basin in the eastern Arabian Sea, between 15°N, 70°15'E and 17°20'N, 69°E. This chain consists of three major edifices: RAMAN¹ and PANIKKAR² seamounts and WADIA² guyot. These seamounts are elongated in plan and have heights and basal areas varying between 1068–2240 m and 300–1210 sq km, respectively. Steep lower flanks, flat plateaus, terraces, secondary peaks, and an extensive dendritic gullie pattern are the identified characteristic morphological features of these seamounts. The origin of these seamounts is attributed to anomalous volcanism resulting from the intersection of the Reunion hotspot with an extinct spreading center.

Keywords Arabian Sea, Laxmi Basin, morphology, origin, seamount, swath bathymetry

In the Arabian Sea, along the axial part of the Laxmi Basin, two conspicuous isolated positive bathymetric features (centered around 17°06'N, 69°E and 15°42'N, 70°03'E) were depicted in the published hydrographic chart (chart no. 7705, Indian Naval Hydrographic Office). The existence of a third bathymetric high between these two charted

¹The name is adopted by the GEBCO Subcommittee on Geographical Names and Nomenclature of Ocean Bottom Features (SCGN).

²These names are unofficial, and a proposal to name these undersea features is undergoing review by the appropriate panel.

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features was revealed by a regional bathymetric profile collected during the 50th cruise of R/V *Sagar Kanya* in 1989. Together these three bathymetric features appeared to be a chain of seamounts. Seamounts on the ocean floor are generally assumed to record the passage of the ocean crust over loci of magma generation; therefore, their study can provide important constraints to the evolutionary history of the ocean basins. However, only a few seamounts of the Arabian Sea have been systematically studied, and their significance to the tectonic history of the Arabian Sea remain to be understood. Therefore, to ameliorate this situation, we carried out a detailed bathymetric investigation of these Laxmi Basin seamounts with a swath bathymetric system during the 79th cruise of R/V *Sagar Kanya* in 1992.

In this paper, we present the swath bathymetric map of these seamounts and discuss their main morphological features. To the best of our knowledge, these maps are the first swath bathymetric maps produced for any of the seamounts of the Arabian Sea region. Based on the morphology and spatial distribution pattern of these seamounts, we offer some speculation regarding their probable genesis.

Regional Setting of the Seamounts

The seamount chain is located approximately along the axial part of the Laxmi Basin (Figure 1), extending for about 250 km approximately from 15°N, 70°15'E to 17°20'N, 69°E. More than 100 km southeastward of this chain lies the northern extremity of the Chagos-Laccadive Ridge, and about 100 km westward is the Laxmi Ridge. A number of hypotheses regarding the origin of these ridges have been offered. Naini (1980) and Naini and Talwani (1982) evaluated those hypotheses and, based on additional geophysical data, favored a continental-fragment origin for the Laxmi Ridge and at least for the northern part of the Chagos-Laccadive Ridge. On the other hand, recent findings of the Ocean Drilling Programme (ODP) Leg 115 (Shipboard Scientific Party, 1988) support the postulations of Whitmarsh (1974) and Morgan (1981) that the Chagos-Laccadive Ridge is a linear volcanic feature formed during the northward motion of the Indian Plate over the Reunion hotspot. A divergence of opinion also exists about the nature of the crust over which these seamounts are located. Some authors (Naini, 1980; Naini and Talwani, 1982; Kolla and Coumes, 1990) believed this crust to be transitional in nature, formed by the process of taphrogeny; while others (Biswas and Singh, 1988; Bhattacharya et al., 1994) considered this crust to be oceanic.

Data

A multibeam swath bathymetric system (Hydrosweep) was used to collect the bathymetric data. The positions along the ship's tracks were provided with a GPS (m × 4400), and all three seamounts were primarily covered with predetermined north-south traverses; however, in view of the steep slopes of the edifices, considerable route development was carried out to achieve a 100-percent coverage of the features. The bathymetric data from the individual swaths were postprocessed to generate a grid of depth values that in turn were used to generate the final bathymetric contour maps (Figures 2a-c) and isometric views (Figures 3a-c) of the seamounts. Representative bathymetric cross sections (Figures 4a-c) across each seamount were prepared from the contour maps.

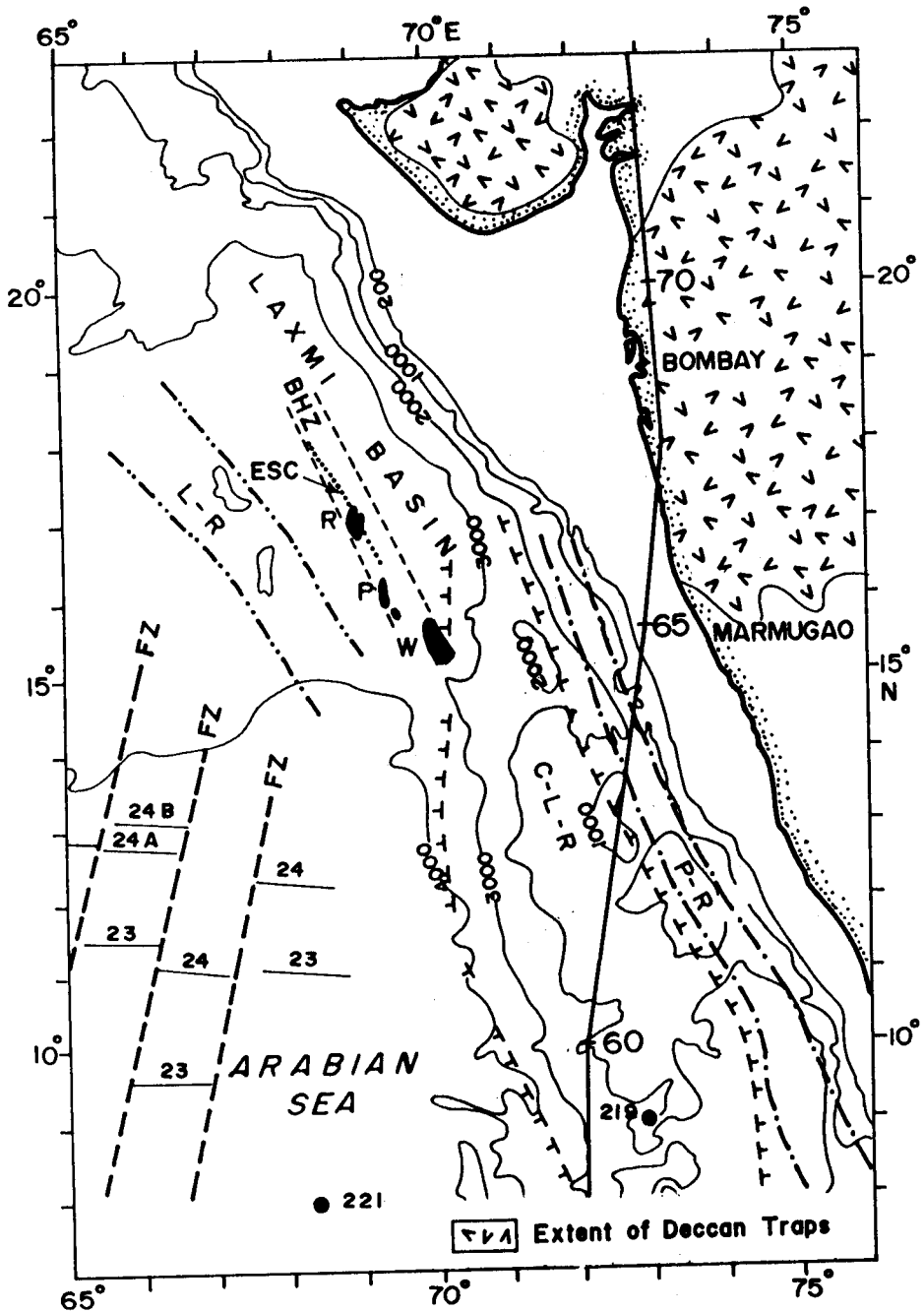


Figure 1. Generalized map of the eastern Arabian Sea, showing main structural features, tectonic elements, and simplified bathymetry (compiled from Naini and Talwani, 1982; Bhattacharya et al., 1992; and Chaubey et al., 1993). Thin lines offset by fracture zones (FZ): magnetic lineations; solid circles: DSDP sites; thick line: computer-modeled Reunion hotspot track. Numbers along the hotspot track are predicted ages in Ma (Shipboard Scientific Party, 1988). R: RAMAN Seamount; P: PANIKKAR Seamount; and W: WADIA Guyot. L-R: Laxmi Ridge; BHZ: suspected basement high zone; ESC: Laxmi Basin extinct spreading center; C-L-R: Chagos-Laccadive Ridge; P-R: Prathap Ridge.

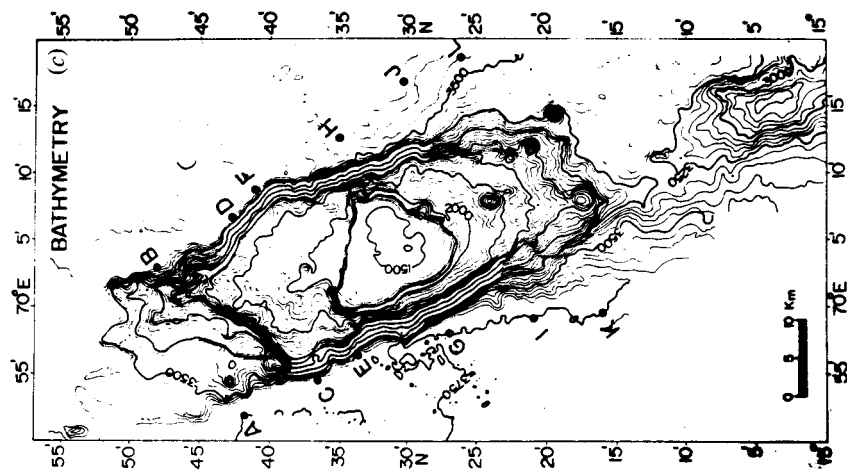
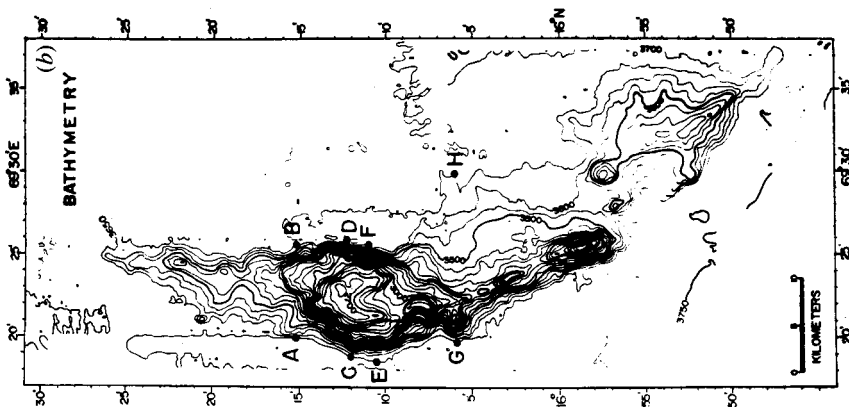
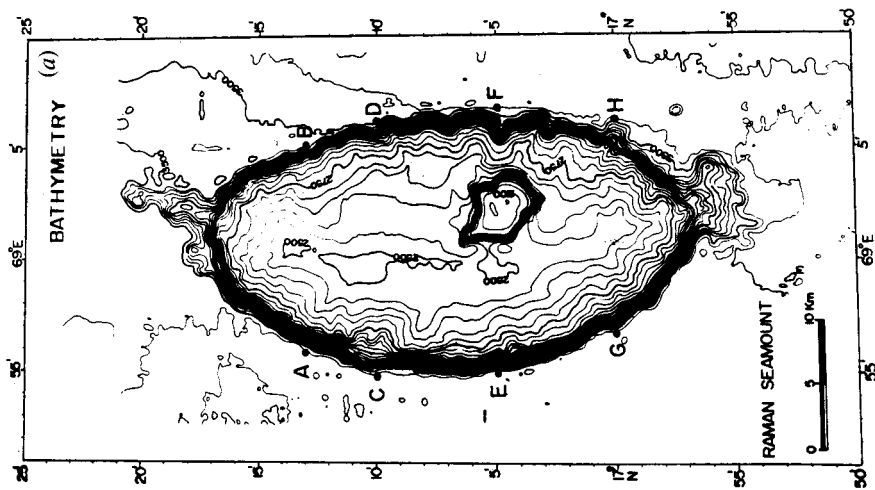


Figure 2. Detailed bathymetric map of the seamounts as derived from the Hydrosweep data. The contour interval is 50 m; labeled dots are locations of the bathymetric cross sections that are shown in Figure 4. (a) RAMAN Seamount (reduced from original 1:110,000 scale map); (b) PANIKKAR Seamount (reduced from original 1:150,000 scale map); (c) WADIA Guyot (reduced from original 1:200,000 scale map).

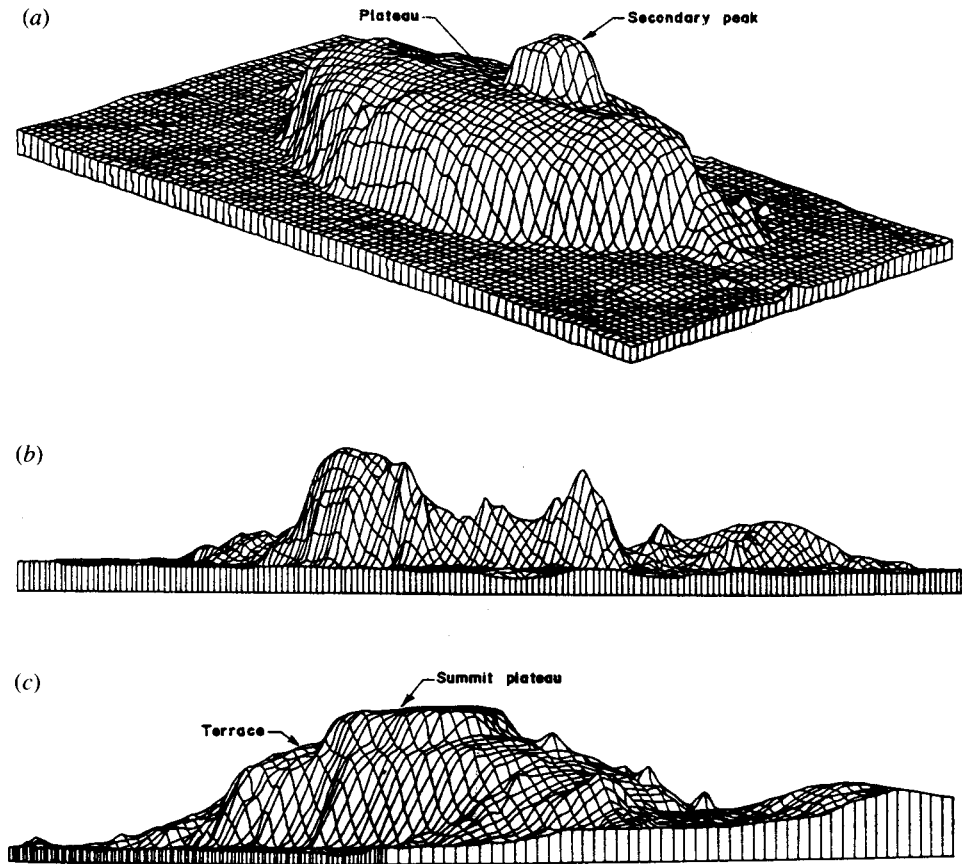


Figure 3. (a) Isometric view of the RAMAN Seamount: view is from south-west to north-east; (b) isometric view of the PANIKKAR Seamount: view is from the south-west to north-east; (c) isometric view of the WADIA Guyot: view is from west-southwest to east-northeast.

Results

In the following sections, we briefly describe the general morphology (Table 1) of these seamounts, which was revealed by the contour maps, isometric views, and the bathymetric cross sections. For convenience we propose the names RAMAN Seamount, PANIKKAR Seamount, and WADIA Guyot consecutively from north to south for the three unnamed seamounts (Figure 5) discussed in this paper.

RAMAN Seamount

The RAMAN Seamount in Figure 5 is the northernmost seamount within our study area. This feature is depicted in the Indian Hydrographic Chart (chart no. 7705) as isolated with a least sounding depth of 2533 m. Earlier we prepared a bathymetric map of this feature (Figure 6) using the single narrow beam echosounder data collected during the 50th cruise of R/V *Sagar Kanya* in 1989. That map indicated that the seamount is located in the surrounding southwestward dipping seafloor. Superimposed on this general decliv-

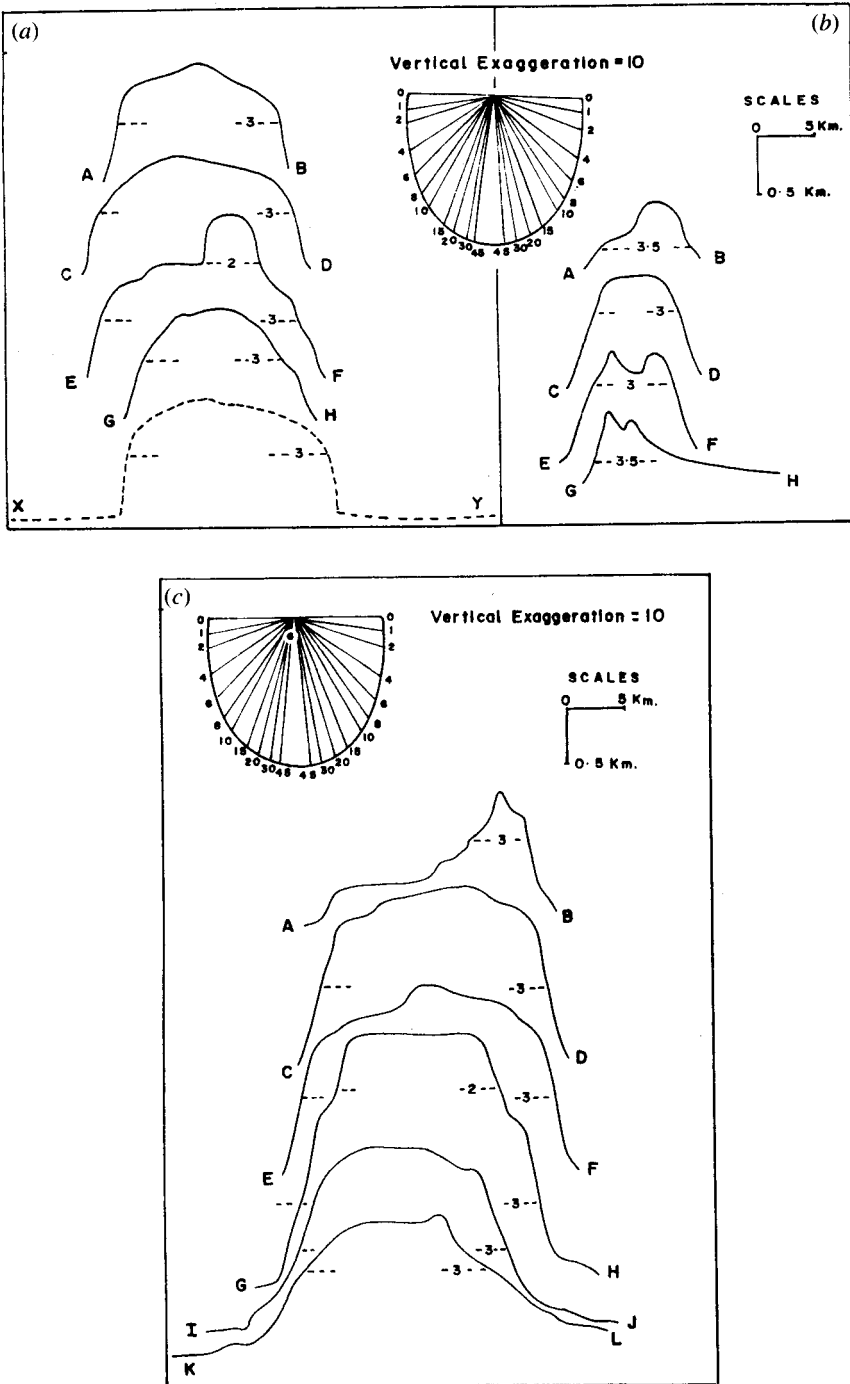


Figure 4. Bathymetric cross sections of the seamounts. The depth levels (in km) are marked on the profiles with thin dashed lines. (a) Across RAMAN Seamount (see Figure 2a for location of the sections; location of section X-Y is shown in Figure 6); (b) across PANIKKAR Seamount (see Figure 2b for location of the sections); (c) across WADIA Guyot (see Figure 2c for location of the sections).

Table 1
General morphological parameters of the seamounts

	RAMAN Seamount	PANIKKAR Seamount	WADIA Guyot
Central position	17°08'N 69°01'E	16°12'N 69°22'E	15°31'N 70°05'E
Least depth encountered	2045 m	2632 m	1461 m
Height of the feature	≈1505 m	≈1068 m	≈2240 m
Basal area	660 km ²	300 km ²	1210 km ²
Average slope of the lower flanks	25°	20°	25°

ity, there is a semiannular-shaped shallow channel around the base of the seamount. This channel shape is relatively pronounced on the northern and western sides of the edifice.

Due to its superior technology, obviously the swath bathymetry-produced map of this seamount (see Figure 2a) is more accurate and detailed. The swath bathymetric map reveals that the seamount is remarkably elliptical in plan view and has a basal area of about 660 sq km. The overall elongation of the feature is approximately NS. From the surrounding flat seafloor (average depth of about 3550 m), the seamount rises (see Figure 4a) with steep ($\approx 25^\circ$) lower flanks up to a depth of about 2950–2800 m. The upper slope region lying approximately between 2800–2550 m is less steep ($\approx 5^\circ$). The areas having water depths shallower than 2550 m are of the form of a relatively flat (gradient $< 2^\circ$) plateau. A secondary peak having a basal area of about 28 sq km is present over this plateau (see Figure 3a). The least depth of 2045 m encountered over this secondary peak gives the total height of the seamount edifice as 1505 m; whereas the relatively flat 2550-m level plateau appears to become gradually shallower, giving rise to a slightly arcuate ridgelike feature (concave side facing toward the east) along the long axis of the seamount. Because our contouring interval is 50 m, we expect the shallowest portion over this ridge to lie somewhere between 2450–2500 m. The cross sections of the seamount (see Figure 4a) indicate that this ridgelike feature is situated slightly toward the western part of the gently arched plateau and, therefore, divides the plateau asymmetrically. Extending this ridge trend from both its extremities, we can possibly trace the extension of the main edifice of the seamount as an uneven seafloor topography for a short distance. The secondary peak depicts subdued spurlike protuberances. The contour map revealed an interesting feature of numerous gullies intersecting the upper and lower flank slopes of the seamount (Figure 7a). Most of these gullies can be traced up to the exposed base of the seamount, and they appear to radiate from the 2550-m level plateau area, which in general appears to be undissected; but some gullies can be traced up to the ridgelike feature or even up to the flanks of the secondary peak, some of which appear to have developed into a dendritic pattern.

PANIKKAR Seamount

As mentioned earlier the PANIKKAR Seamount (see Figure 5) is a newly detected feature. The swath bathymetric map (see Figure 2b) reveals that this seamount is an arcuate elongated feature that contains multiple peaks on a single base and in plan view appears

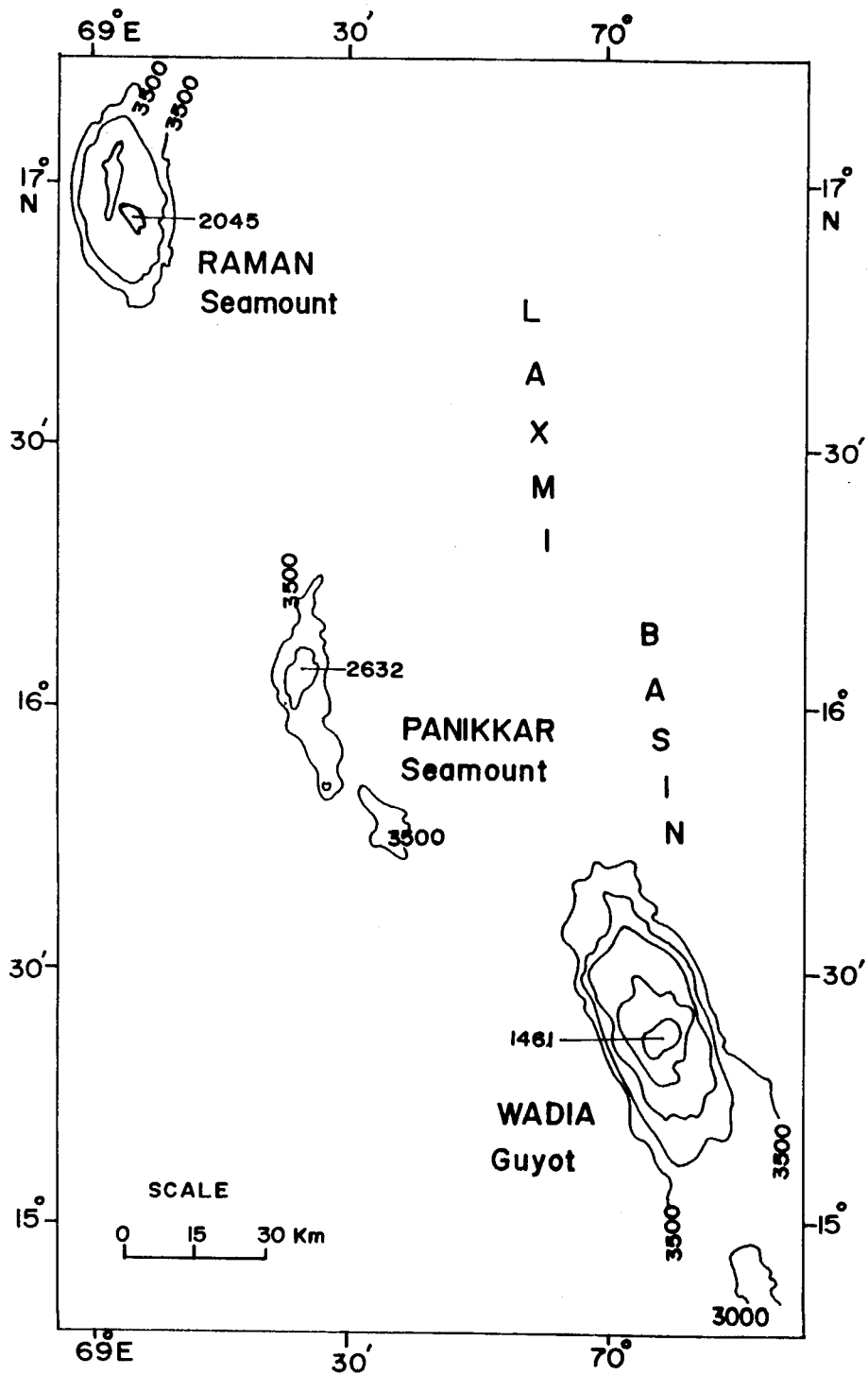


Figure 5. Bathymetric map of the seamount chain (contour interval 500 m) as derived from the Hydrosweep data. Minimum water depth (in meters) recorded over each seamount is labeled.

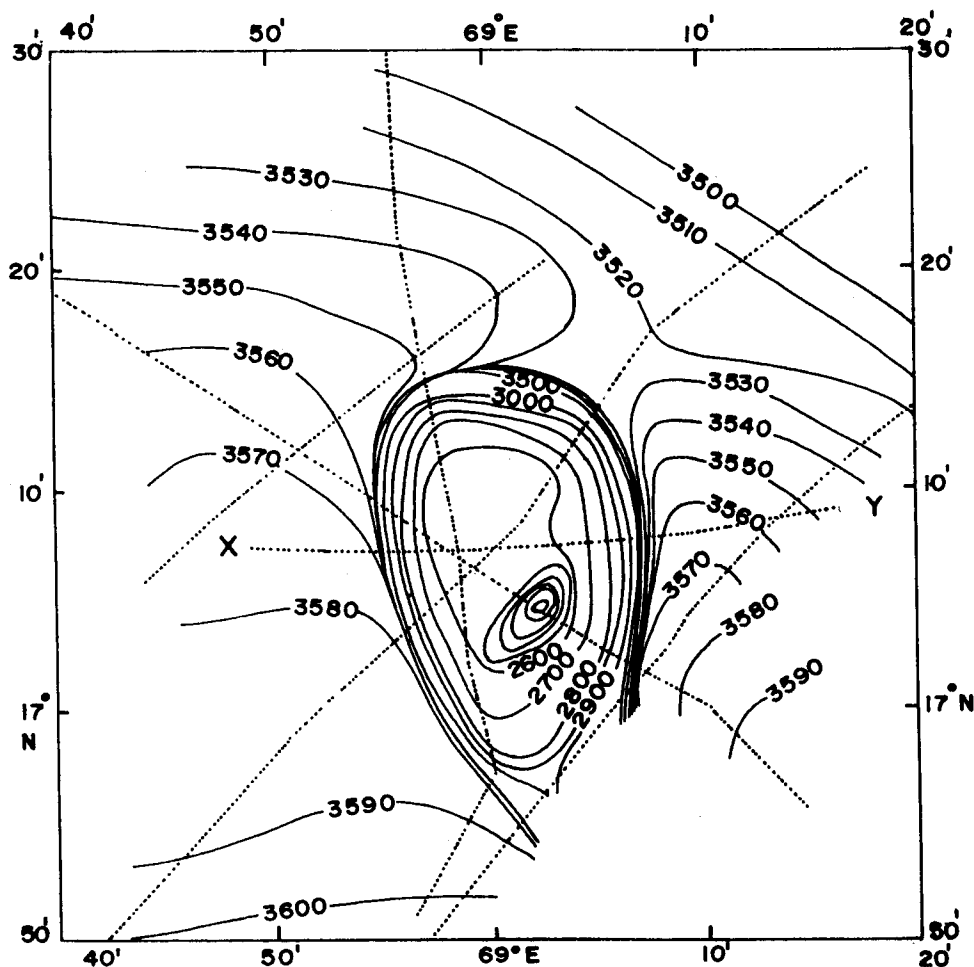


Figure 6. A previously prepared bathymetric map of the RAMAN Seamount based on single-beam echosounder data collected along six traverses (shown by dotted lines) crisscrossing the edifice. Contour intervals: up to 3000 m isobath, 100m; between 3000 and 3500 m isobath, 500 m; afterward, 10 m.

like a curved spindle. The edifice covers a basal area of about 300 sq km. Based on the linear trends of the feature, the edifice can be divided into two segments. Northward of $16^{\circ}7'N$, the feature trends $N10^{\circ}E$, whereas southward its trend is approximately $N24^{\circ}W$. From the surrounding seafloor (average depth of 3700 m) the entire platform base has been built as a single feature approximately up to 3350 m whereupon several individual peaks (see Figure 3b) have formed. The major peak (near $16^{\circ}13'N$) has a relatively flat crescent-shaped summit, whereas the other peaks are conical. The least depth over the largest of the peaks is about 2632 m, which indicates that the maximum height of the PANIKKAR Seamount with respect to the surrounding seafloor is about 1068 m. To the immediate southeast of the seamount there is another smaller hill whose maximum relief is about 350 m. The trend of the smaller feature ($N30^{\circ}W$) is comparable with the trend of the southern portion of the seamount, but it shows a slight offset from its larger

neighbor. No summit plateaulike feature was observed over this seamount. The flank slopes on both the eastern and western sides of the main peak (see Figure 4b) are steepest ($\approx 20^\circ$). The slopes of this seamount also are dissected by numerous gullies (Figure 7b), some of which develop headward into a dendritic pattern. The gullies appear to spread sidewise from a higher axial zone all along the seamount. Most of the gullies can be traced from the highest regions of this axial zone to the base of the seamount. The smaller hill southeast of the PANIKKAR Seamount also indicates the presence of a similar gullie pattern. The open side of the crescent-shaped summit (near $16^\circ 11' \text{N}$) appears to extend downslope as a relatively broad valley.

WADIA Guyot

The WADIA Guyot is the southernmost (see Figure 5) and the largest of the three major edifices investigated in the present study; this is depicted in the Indian Hydrographic Chart (chart no. 7705) as an isolated feature with a least sounding depth of 2284 m. The swath bathymetric map (see Figure 2c) revealed that in plan view the guyot is approximately rhomboid in shape and covers a basal area of about 1210 sq km. Its elongation direction ($\text{N}25^\circ\text{W}$) is almost the same as that of the overall trend of the seamount chain. Along the long axis its length is about 72 km, whereas its maximum width is about 25 km. At the top of the guyot there is a relatively smooth (slope $< 2^\circ$) summit plateau (see Figure 3c) that covers an area of about 108 sq km. The least depth recorded over the summit plateau is 1461 m, which yields the maximum relief of the edifice to be about 2240 m. Below the summit, up to about 2000 m the flanks slope at an average of 20° . From 2000 to about 2500 m, a gently sloping terracelike feature was observed. On the eastern and western sides of the summit plateau the terrace (see Figures 2c and 4c) is relatively narrower and steeper ($\approx 12^\circ$). Toward the northwest and southeast the terrace is relatively wider and with gentler slope ($\approx 4^\circ$). Below 2500 m is the steep ($\approx 25^\circ$) lower flank. The lower flanks are distinct on both the easterly and westerly sides of the edifice. One of the interesting features observed over this guyot is the presence of many small peaks that are evident by closed contours. The most prominent set of these peaks can be noticed (see Figure 2c) in the southeastern slope of the guyot.

Like the other two seamounts of the study area the WADIA Guyot is also dissected by numerous gullies (Figure 7c) that appear to radiate from the central highlands and are present on all the sides of the guyot except the western slope adjacent to the summit plateau. In the western slope, the gullylike features are either absent or very much subtle. Over this guyot also, many of the gullies develop headward into a dendritic pattern and most can be traced from the summit plateau up to the exposed based or even over the apron areas near the base.

Toward the southeast (see Figure 2c) of this guyot another 550-m high small hill-like feature, which trend approximately in the same direction as that of the WADIA Guyot, is present. This small hill is also dissected by gullies and is separated from the WADIA Guyot by a narrow saddelike depression with an approximate maximum water depth of 3250 m.

Discussion

As described earlier, the three edifices are more or less elongated in plan, which probably suggests that they were formed by some sort of linear fissures. Further, even though different edifices have their individual trend, together they form a nearly $\text{N}30^\circ\text{W}$ trending

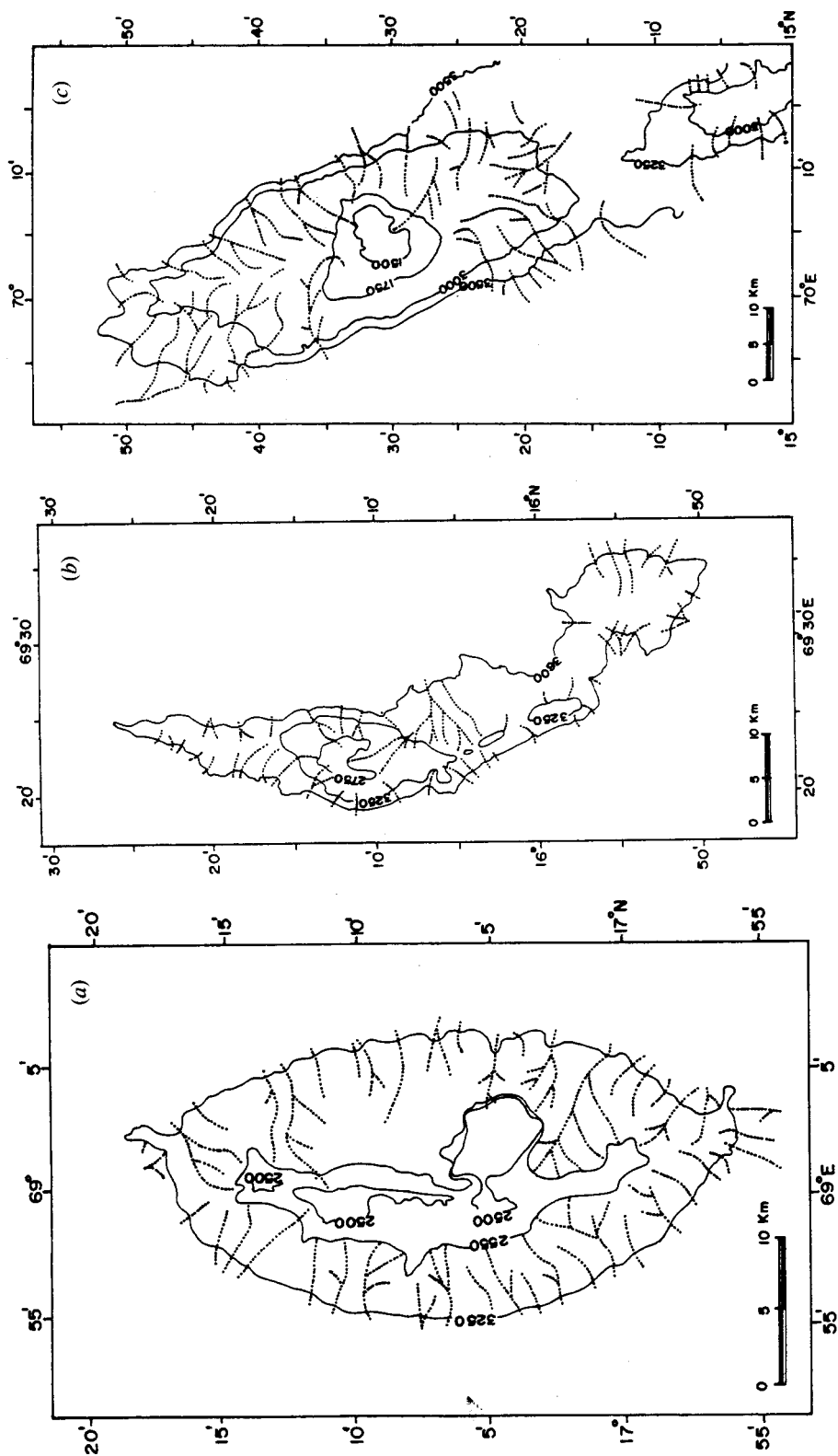


Figure 7. Interpreted gullie pattern (thin dashed line) over: (a) RAMAN Seamount, (b) PANIKKAR Seamount, and (c) WADIA Guyot. Continuous lines represent selected bathymetric contours (in meters).

linear chain (see Figure 5) within a narrow band of about 50 km. This seamount chain is located in the interior of the Indian Plate far removed from the present day spreading centers. Various tectonic processes explaining the formation of linear volcanic chains in the midplate settings have been proposed, such as plate motion over fixed mantle hotspots (Morgan, 1972), volcanism along leaky transform faults or fracture zones (Handschumacher, 1973), interaction of a hotspot with a nearby spreading center or intersection of a hotspot with an active or extinct (still-hot) spreading center (Epp, 1984; Winterer, 1976).

The adjacent Chagos-Laccadive Ridge, which is considered to be the volcanic trace of the Reunion hotspot, has an overall north-south trend; and the computer-modeled track (Shipboard Scientific Party, 1988) of the Reunion hotspot (see Figure 1) also indicates a N-S to NNE-SSW trend. The seamount chain with its N30°W trend, therefore, appears to represent a trend oblique to the evident trend of the main track of the Reunion hotspot in this region. Due to these differing trends, we feel that these seamounts cannot be easily explained as simple time-progressive volcanic chain that formed as a consequence of the movement of the Indian Plate over the Reunion hotspot.

About 300 km southwest of this seamount chain a set of N10°E trending fracture zones are present (see Figure 1), but so far no evidence of their continuity into the Laxmi Basin area has been found. For the sake of argument, if we assume their continuity into the Laxmi Basin, even then the seamount chain cannot be considered as having been formed by these fracture zones because of their obliqueness to the trend of the fracture zones.

The northern part of the seamount chain lies over a linear basement high zone that has been suspected to exist along the axial part of the Laxmi Basin (see Figure 1): Naini (1980) and Gopala Rao et al. (1992) inferred the possible continuity of this basement high zone from the detection of the basement as an isolated outcrop and a subdued subcrop on three widely spaced seismic profiles; however, in the present study, we establish that the outcrops within this zone are not continuous but, rather, are isolated seamounts. Another characteristic that coincides with this basement high zone is an extinct spreading center. Bhattacharya et al. (1994) recently identified this particular NNW trending extinct spreading center (see Figure 1) based on the identification of two-limbed seafloor spreading-type magnetic anomalies on closely spaced profiles between 16°–18°N. In addition, they observed that the RAMAN Seamount lies within this extinct spreading center. Based on these observations we feel that the linear basement high zone represents a composite feature. The places that are expressed as subtle subcrops represent the buried remains of the extinct spreading center. At other places, the relief of this extinct spreading center is covered by anomalous volcanism, which manifest as seamounts.

Now we examine the correlation of the seamount chain with this extinct spreading center. Bhattacharya et al. (1994) inferred that at least the part of the Laxmi Basin where the extinct spreading center is located was created by a pre A-27 episode of seafloor spreading in the Arabian Sea. Since its commencement around 84 Ma (Late Cretaceous), this spreading continued at a very slow rate (<1 cm/yr) until its cessation around 65 Ma (Early Paleocene) when the spreading center jumped west of the Laxmi Ridge. However, the nature of the crust south of 16°N, where the other seamounts of this chain are located, is still obscure. The present bathymetric data indicate that not only the RAMAN Seamount but the entire seamount chain is colinear with the axial zone of this extinct spreading center (see Figure 1). This coincidence surely suggests a genetic correlation between this extinct spreading center and the seamount chain. We are inclined to infer that the axis of the seamount chain represents the continuation of the extinct spreading center southward from 16°N.

It can also be seen (see Figure 1) that the trend of the seamount chain (and thereby the extinct spreading center) intersects the Chagos-Laccadive Ridge (volcanic trail of the Reunion hotspot). Based on the estimated ages of the volcanic rocks, it is believed that the location of the Reunion hotspot was below the Indian mainland around 65–69 Ma (Courtillot et al., 1988) and at the DSDP Site 219 around 58 Ma (Weser, 1974). In view of the spatial and temporal proximity, it appears reasonable to assume that the Reunion hotspot was closer to the Laxmi Basin spreading center during its waning stage or that it might have intersected the spreading center shortly after its extinction. As mentioned earlier, interaction between the hotspot and spreading center in both these conditions can give rise to a linear chain of seamounts. Since in our study area the seamount chain appears to be restricted within the axial zone of the extinct spreading center, we believe they were formed by volcanism due to the intersection of the extinct (still-hot) spreading center and the hotspot.

As mentioned earlier, all the three seamounts of the chain have steep (20–25°) lower slopes. According to Walker (quoted by Epp, 1984), the relief of volcanoes is inversely proportional to the effusion rate of the lavas; steep volcanoes have low rates of effusion. Therefore, we feel that the steep slopes of the Laxmi Basin seamounts indicate a commonality; i.e., all of them were formed by slowly effusive magma.

The bathymetric data indicated the presence of relatively flat surfaces and terraces atop the RAMAN Seamount and WADIA Guyot at various topographic levels. These data also revealed the presence of an extensive pattern of gullylike features on all the three seamounts and their neighboring smaller hills. The flat surfaces over seamounts are believed to have been formed either by erosional wave planation effects or by constructional volcanic processes (Fornari and Ryan, 1984, and references therein). Similarly the origin of the gullylike features over seamounts was ascribed either to subaerial (Barone and Ryan, 1987) or submarine (Kenyon et al., 1978; Lonsdale et al., 1972) erosional processes. The gullies observed over the Laxmi Basin seamounts with their dendritic pattern resembles a relict drainage pattern of subaerial erosional origin. A subaerial erosional origin of these gullies necessitates emergence of the entire edifices above sea level and subsequent subsidence by about 3700 m. A subsidence of this magnitude appears to be anomalously high as compared to the inferred (Whitmarsh et al., 1974) subsidence of only 2075 m of the nearby DSDP Site 219 over the Laccadive Ridge.

While some of the morphological features suggest an emergent stage during history of the development of the edifices, there are some other features that do not support such an inference. For example, if the entire edifices were once above sea level, then the large conical peaks of the PANIKKAR Seamount or small peaks found over the upper slope of the WADIA Guyot could not have escaped truncation at wave base during subsequent submergence. We can reconcile these conflicting observations by assuming that these conical peaks were possibly formed by a postsubsidence episode of volcanism; moreover, it is possible that the secondary peak observed over the RAMAN Seamount also indicates the existence of a later postsubsidence episode of volcanism.

However, based on the bathymetric data alone, we are not able to offer any unequivocal conclusions. In order to understand properly the genesis and subsequent development of these seamounts, geological sampling and near-bottom surveys are required; for that purpose, the data that we present provide the necessary background.

References

- Barone, A. M., and W. B. F. Ryan. 1987. Morphology from subaerial erosion of a Mediterranean Seamount. *Marine Geology* 74: 159–72.

- Biswas, S. K., and N. K. Singh. 1988. Western continental margin of India and hydrocarbon potential of deep-sea basins. In *7th Offshore South East Asia Conference*, Singapore, 170–81.
- Bhattacharya, G. C., A. K. Chaubey, G. P. S. Murty, D. G. Rao, V. S. Scherbakov, V. A. Lygin, A. I. Philipenko, and A. P. Bogomyagkov. 1992. Marine magnetic anomalies in the north-eastern Arabian Sea. In *Oceanography of the Indian Ocean*, ed. B. N. Desai, 503–09. New Delhi: Oxford and IBH.
- Bhattacharya, G. C., A. K. Chaubey, G. P. S. Murty, K. Srinivas, K. V. L. N. S. Sarma, V. Subrahmanyam, and K. S. Krishna. 1994. Evidence for seafloor spreading in the Laxmi Basin, north-eastern Arabian Sea. *Earth Planet. Sci. Letters* (in press).
- Chaubey, A. K., G. C. Bhattacharya, G. P. S. Murty, and Maria Desai. 1993. Spreading history of the Arabian Sea: Some new constraints. *Marine Geology* 112: 343–52.
- Courtillot, V., G. Feraud, H. Maluski, D. Vandamme, M. G. Moreau, and J. Besse. 1988. Deccan flood basalts and the Cretaceous/Tertiary boundary. *Nature* 333: 843–46.
- Epp, D. 1984. Possible perturbations to Hotspot traces and implications for the origin and structure of the Line Islands. *Journal of Geophysical Research* 89(B13): 11273–86.
- Fornari, D. J., and W. B. F. Ryan. 1984. The evolution of craters and calderas on young seamounts: Insight from Sea MARC I and Sea Beam sonar surveys of a small seamount group near the axis of the East Pacific Rise at $\approx 10^\circ\text{N}$. *Journal of Geophysical Research* 89(B13): 11069–83.
- Gopala Rao, D., M. V. Ramana, G. C. Bhattacharya, L. V. Subba Raju, K. A. Kamesh Raju, and T. Ramprasad. 1992. Marine geophysical studies along a transect across the continental margin off Bombay coast, West of India. In *Oceanography of the Indian Ocean*, ed. B. N. Desai, 493–501. New Delhi: Oxford and IBH.
- Handschemacher, D. 1973. Formation of the Emperor Seamount chain. *Nature* 244(5412): 150–52.
- Kenyon, N. H., R. H. Belderson, and A. H. Stride. 1978. Channels, canyons and slump folds on the continental slope between south-west Ireland and Spain. *Oceanologica Acta* 1(3): 369–80.
- Kolla, V., and F. Coumes. 1990. Extension of structural and tectonic trends from the Indian Subcontinent into the Eastern Arabian Sea. *Marine and Petroleum Geology* 7: 188–96.
- Lonsdale, P., W. R. Normark, and W. A. Newman. 1972. Sedimentation and erosion on Horizon Guyot. *Geological Society of America Bulletin* 83: 289–316.
- Morgan, W. J. 1972. Deep Mantle convection plumes and Plate motions. *American Association of Petroleum Geologists Bulletin* 56(2): 203–13.
- Morgari, W. J. 1981. Hotspot tracks and the opening of the Atlantic and Indian Oceans. In *The sea*, Vol. 7, ed. C. Emiliani, 443–87. New York: Wiley-Interscience.
- Naini, B. R. 1980. A geological and geophysical study of the continental margin of Western India, and the adjoining Arabian Sea including the Indus Cone. Ph.D. thesis, Columbia University, New York.
- Naini, B. R., and M. Talwani. 1982. Structural framework and the evolutionary history of the continental margin of Western India. In *Studies in Continental Margin Geology*, eds. J. S. Watkins and C. L. Drake. *American Association of Petroleum Geologists Memoir* 34: 167–91.
- Shipboard Scientific Party. 1988. Site 715. In *Proceedings of Ocean Drilling Program, Initial Reports* eds. J. Backman, R. A. Duncan, et al., 115: 917–46, College Station, Texas.
- Weser, O. E. 1974. Sedimentological aspects of strata encountered on Leg 23 in the northern Arabian Sea. In *Initial Reports of the DSDP*, Vol. 23, eds. R. B. Whitmarsh, O. E. Weser, D. A. Ross, et al., 503–19. Washington, D.C.: U.S. Government Printing Office.
- Whitmarsh, R. B., O. E. Weser, et al. 1974. Sites 219, 220, 221. In *Initial Reports of the DSDP*, Vol. 23, eds. R. B. Whitmarsh, O. E. Weser, D. A. Ross, et al., 35–210. Washington, D.C.: U.S. Government Printing Office.
- Whitmarsh, R. B. 1974. Some aspects of plate tectonics in the Arabian Sea. In *Initial Reports of the DSDP*, Vol. 23, eds. R. B. Whitmarsh, O. E. Weser, D. A. Ross, et al., 527–35. Washington, D.C.: U.S. Government Printing Office.
- Winterer, E. L. 1976. Anomalies in the tectonic evolution of the Pacific. In *The Geophysics of the Pacific Ocean basin and its margin*, eds. G. H. Sutton, M. H. Manghnani, and R. Moberly, *Geophysical Monograph* 19: 269–78. Washington, D.C.: American Geophysical Union.