

Growth constraints of the Indian Ocean Seamounts

RANADHIR MUKHOPADHYAY AND N.H. KHADGE,

National Institute of Oceanography, Dona Paula, Goa - 403004

ABSTRACT

Distribution and morphology of volcanic seamounts from an area of 84572 km² in the Central Indian Ocean basin (CIOB) using multibeam bathymetric system are presented here. The study area is bounded by two NNE-SSW oriented structural lineaments and is infested with about 800 seamounts of various height ranging from 50 m to 1250 m. Statistical analysis suggests that summit height, flatness and volume primarily control shape of seamounts. The remarkable similarity in distribution, flow line parallel orientation, morphology, and lava chemistry between these ancient seamounts in CIOB, and young seamount chains off East Pacific Rise (EPR) in the Pacific Ocean indicate that seamount chains are the fundamental product of fast spreading ridges. Structural and morphological difference at the base and summit in most of these seamounts probably indicates non-uniform growth in response to variable tectonic settings prevailing in the past.

INTRODUCTION

Seamount is a surface manifestation of mantle upwelling. Formation and evolution of a seamount are controlled by tectonic setting, chemical composition of magma, eruptive style, age of the underlying oceanic crust at the time of formation, sediment thickness, conduit geometry and proximate fracture pattern (1-5). A detailed study of seamount, thus carries a better understanding of crustal and mantle processes. Seamount studies from the Indian Ocean are far and few. As far as aerial coverage in the world oceans is concerned, volcanoes and volcanic ridges in the Indian Ocean cover 5.4% of the whole ocean area, compared to only 2.5% and 2.1% coverage in Pacific and Atlantic ocean respectively (6). This indicates that tectono-magmatically Indian ocean has been very active. However, only limited literature is available till date (7-11). Here we describe abundance, distribution and morphology of Indian Ocean seamounts, and discuss the role played by various factors in constraining seamount generation and evolution.

GEOLOGICAL SETTINGS

We traversed the study area (figure 1) along 19 north-south trending lines separated by 10 km -- 9 lines in Sector I covering an area of 56470 km² and 10 lines in sector II occupying an area of 28102 km². Detailed bathymetric map is given elsewhere (Mukhopadhyay et al, communicated). Water depth in study area ranges from 800 m to 5400 m (average 5271 m). The study area is bounded by two structural lineaments - 73° E fracture zone

on the west and Triple Junction Trace on the Indian Plate (TJT-In) along 76°30'E on the east (12,13). The oceanic crust on which these seamounts occur encompasses most important era of the Indian Ocean evolution, such as the India-Eurasia collision period. A profound break in the rate of crustal generation and absolute plate motion is recorded between anomalies A 22 and A 21, i.e. between 49.6 Ma and 47.9 Ma (12,13). During this time spreading rate about Central (CIR) and South Eastern (SEIR) Indian Ridges abruptly reduced from 13.4 to 6.8 cm/yr, and 13.6 to 9.4 cm/yr, respectively. Similarly direction of plate movement also changed from 176° to 214°, and 186° to 182° in case of CIR and SEIR respectively. The break is roughly represented by latitude 14° 30'S. Klootwijk et al (14) paleomagnetically constrained India-Asia contact time as 53 Ma. The fall in spreading rate and change in plate movement direction was caused by the collision of the north bound Indian plate with a much stable Eurasian continent (12-14).

GEOTECTONICS OF SEAMOUNT ABUNDANCE

For abundance in the CIOB, all identifiable seamounts above 50 m in height from a total area of 84572 km² were accounted. We report here the occurrence of 800 seamounts of variable height ranging from 50 m to 1250 m. This figure gives an abundance of about 9460 seamounts/10⁶ km² assuming uniform distribution (Table 1). Seamount abundance in CIOB thus is comparable to that in Atlantic ocean (7000/10⁶ km² [15]), and Pacific Ocean (9000/10⁶ km² [2]).

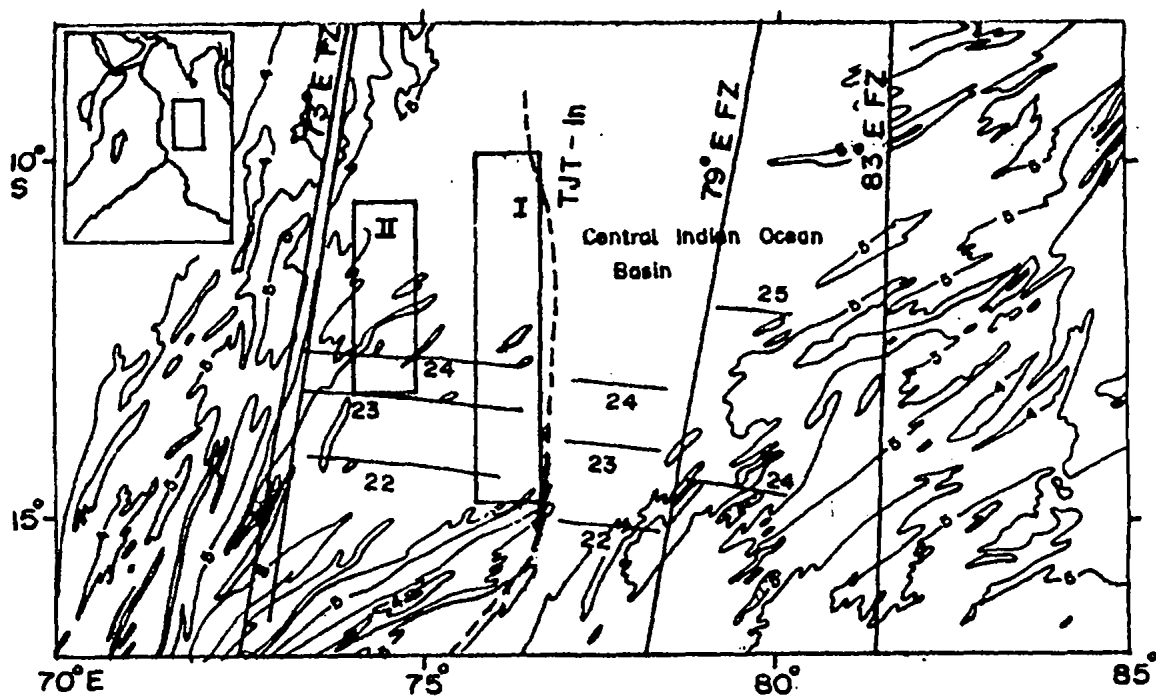


Figure 1: Brief tectonic configuration and structural features of CIOB with study sectors I and II shown in boxes. Bathymetry (numbered thin lines $\times 10^3$ metres), magnetic anomalies (numbered solid lines), fracture zones (NNE-SSW trending solid lines), and ridges (CIR, SWIR, SEIR, inset) are also shown. Triple Junction Trace on the Indian plate (TJT-In) is shown as dashed line. Hotspot generated two aseismic ridges such as Chagos-Laccadive ridge on west and Ninety East ridge on east (not shown) limits the east-west extent of CIOB. Seamounts in discussion are located between the fracture zone at 73°E and TJT-In along $76^\circ 30'\text{E}$.

Tectonic lineaments and seamount abundance : Sector I which is close to TJT-In located along $76^\circ 30'\text{E}$ longitude (Figure 1, Table 1) shows high abundance of about 11387 seamounts/ 10^6 km^2 and density of 1 seamount in every 88^2 km^2 interval. In contrast, sector II, which is close to 73°E fracture zone records low abundance of seamounts (5500 seamounts/ 10^6 km^2) with a density of one seamount in interval of every 192 km^2 . A review of the seamount abundance in these two sectors, as above, suggests that if the influence of fracture zone or any structural weakness on the occurrence and distribution of seamounts (1,2,5,9) is taken into account, the structural lineament along $76^\circ 30'\text{E}$ appear to be magmatically more potential, active and dominating than that along 73°E longitude (Table 1). The fracture zone along 73°E acts as the eastern boundary of the Chagos Ridge, a product of Reunion hotspot activities. Thus 73°E FZ seems to be more of a structural entity (and/or southward continuation of Chagos FZ) probably involved with little magmatic component. In contrast, TJT-In along $76^\circ 30'\text{E}$ (i.e., the trace of the boundary between the crust created from CIR

and SEIR) should possibly be magmatically active zone as it represents the junction point of two ridges. High seamount abundance close to TJT-In (Table 1), thus proves that major crustal weakness along $76^\circ 30'\text{E}$ acts as more efficient conduit of hot magma.

Crustal age and seamount abundance: The underlying crust of the study area was formed at the ridge crest between 49-57 Ma. Minor and small seamounts occur with large abundance in the northern parts of sector I, whereas medium and large seamounts mostly occur south of 12°S latitude, which corresponds roughly to 54 Ma. This variation in distribution of selected type of seamounts on the crust generated roughly before and after 54 Ma is striking. We plan to study this aspect in detail in future after collection of relevant data.

FORMATION AND EVOLUTION OF CIOB SEAMOUNTS

Probable origin: Majority of the seamounts in the study area are formed at the axial ridge crest at CIR/SEIR

simultaneously with the formation of the underlying crust. This is evident from flowline parallel distribution of these seamounts strikingly similar to that of younger seamounts presently forming about fast spreading East Pacific Rise (EPR). Another line of evidence now comes from petrochemistry (glass samples collected from various seamounts and older seafloor, and analysed under microprobe (Mukhopadhyay and Batiza, submitted). The results indicate close affinity of these seamounts to normal mid oceanic ridge basalts (N-MORB) which erupt at the axis. This composition is strikingly related to younger seamounts formed in recent geological time from the fast spreading East Pacific Rise (11).

Measurement of slope angle of a seamount helps to understand the mechanism and mode of lava eruption. Seamounts of hotspot origin record higher slope angles, small base and probably are associated with near violent eruption (1). For the present set of seamounts (Table 2)

gentle slope angles ($3-15^\circ$), wide base and dominant control of the basal area on slope angle are observed indicating non hotspot origin.

A number of seamounts show an extension of their body at the base in direction broadly between $N60^\circ E$ to $E30^\circ S$. One such seamount is shown in figure 2 (extended at the direction $090-270$) which takes an ellipsoidal shape in plan probably because of this east-west extension through addition of mass. Petrology of the rock samples collected from both the central circular main body (CMB) and the later added mass (LAM) at the base of the seamounts reveals some significant facts. Rocks from CMB are profusely weathered, and microprobe analysis of top glass layer shows primitive low fractionated MORB affinity (Mg # 61-67). In contrast, rocks from LAM are relatively fresh, contain several phenocrysts of plagioclase, and chemically suggest their origin from a comparatively fractionated MORB melt (Mg # 50-53). This may suggest

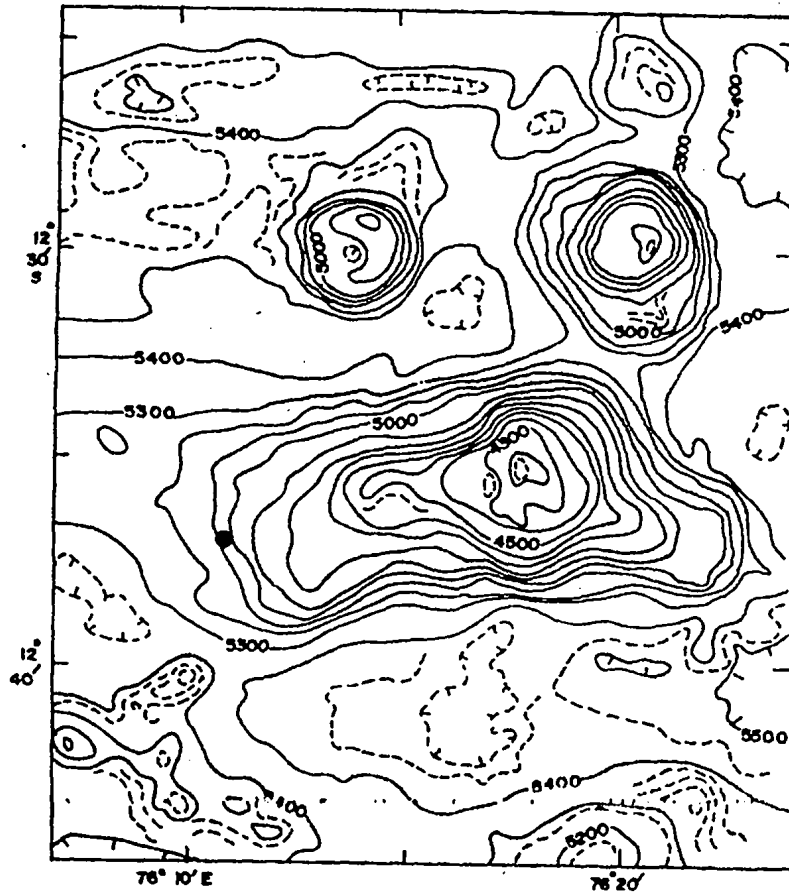


Figure 2 : Detailed bathymetry of a small part of the study area. All three types of seamounts-large, medium and small are shown. Besides, other minor elevations of $< 100m$ height are shown by arrows. Regional bathymetry is flat with numerous lineations (mostly E-W trending) present in the area are inferred normal faults with variable offsets ranging between < 50 and $> 100 m$ (Mukhopadhyay et al. communicated; 11). The dot on western flank of large seamount is the location of one of the rock samples analysed chemically.

that (a) large ellipsoidal seamounts (as in figure 2) had nonuniform accretion in their growth history; and (b) the CMB was formed near the ridge crest simultaneously with the underlying oceanic crust during 49-56 Ma, while the LAM was formed at later times by secondary volcanism triggered by tectonic reactivation (8).

The Growth: Of 800 seamounts (Table 2), occurring in the study area, we have studied detailed morphology of 79 seamounts, representing various size classes (Table 2). It can be seen that height of seamount and total amount of lava used by seamounts increases away from structural lineaments. In large seamounts basal area and volume increase towards these lineaments while in smaller seamounts they increase away from structural lineament. Flatness is a pivotal parameter, and we find that seamounts located away from structural lineaments are pointy or conical than those occurring close to structural lineaments. So it is a clear bias that taller, larger, conical and less abundant seamounts occur away from crustal weak zones; whereas short, wide and flat topped seamounts with more abundance are normally located near the structural lineament. This biasness in seamount formation is probably related to structural lineament which acts as natural conduit for magma to ascend. These are wide and deep, and magma erupted through such elongated fissures normally form short, flattened volcanic swell. In contrast, crust located away from structural lineament would not likely to have wide elongated fissures and cracks. Eruption of magma in such case through narrow openings is likely to produce tall seamounts of pointed summit.

Principal component analysis was performed on seamount data by considering five variables: summit height, flatness, summit diameter, basal diameter, and volume. The first two eigenvectors of the normalised variance-covariance matrix accounts for 83% variance of the data set, which suggests that shape of Indian Ocean seamounts is primarily controlled by two variables - summit height and flatness.

The ratio between the height and the longest diameter at the base of any seamounts is significant (4) to estimate growth consistency of a seamount. Pacific ocean

seamounts record this ratio fairly constant at 1:8 (4). Similar studies in the Indian Ocean from locations outside the study area offer a slightly lower ratio (1:10 [8]); while the seamounts, in the present study area show still lower ratio (1:15). This variation in ratio indicates that seamount generation in the Indian Ocean is not consistent, unlike to that in the Pacific Ocean. Seamount characteristics in the Indian Ocean thus varied with space during their history of growth.

Majority of seamounts studied here show different trend of elongation between their base (BE) and summit (SE), which strikes respectively at 040 and 086 in case of large seamounts, 050 and 115 in case of medium seamounts, and 067 and 073 in case of small seamounts. Variations in orientation of BE and SE reflect on the tectonic stress regime, and available topographic set up prevailing at the time of commencement and completion of seamount formation, respectively. If so, the evolution of seamounts in CIOB seems to be probably nonuniform throughout their formation.

Seamounts in the study area are remarkably more conical compared to equally ancient near axis seamounts in other oceans (2-5). This is unique for any ancient seamounts in the world. This difference suggests formation and evolution of CIOB seamounts under a persistently intense regime of magmatic activity. Such a situation is possible when either processes of seamount erosion and guyot formation in the Indian Ocean are much less active or phenomenon of magma withdrawal from conduits is infrequent. Also the combination of these two is possible. A detailed study of these seamounts with submersibles, gravimeter, seismic section and more petrological and analyses would clarify the relationship between growth of a seamount and tectono-magmatic activities.

ACKNOWLEDGEMENTS

We are thankful to Mr. R.R. Nair, Head GOD for support during various stages of this work, and the participants of the cruise ORV Sagar Kanya 59 for the collection of data. The financial assistance came from DOD (New Delhi).

Table - 1 : Abundance of seamounts in the CIOB

Parameters	sector I	sector II	Total
Geologic setting	close to TJT-In	close to fracture zone	
Area, km ²	56470	28102	84572
Minor seamounts (H = 50 -99 m)	431	90	521
Small seamounts (H = 100 - 499 m)	184	62	246
Medium seamounts (H = 500 - 999 m)	22	04	26
Large seamounts (H > 1000 m)	07	00	07
Total seamount	644	156	800
Abundance, 10 ⁶ km ²	12387	5551	8969
Seamount Density km ² between every SM	88	192	--

Table - 2 : Morphology of CIOB seamounts

Parametres (average)	Sector I	Sector II
Large SM (h > 1000 M), n =7		
Height, m	1123	-
Basal area, Km ²	108	-
Summit area, km ² .	57	-
Slope angle, deg.	14	-
Flatness	.006	-
Volume, km ³	44	-
Lava used for all SM formation, km ³	176	-
Medium SM (h 500 - 999 m), n = 19		
Height, m	688	613
Basal area, km ²	44	28
Summit area, km ²	.49	.29
Slope angle, deg.	14	14
Flatness	.012	.010
Volume, km ³	11	06
Lava used for all SM formation, km ³	175	24
Small Sm (h 100 - 499 m), n = 53		
Height, m	248	257
Basal area, km ²	31	25
Summit area, km ²	.48	1.19
Slope angle, deg.	07	09
Flatness	.016	.048
Volume, km ³	1.15	2.5
Lava used for all SM formation, km ³	106	52

REFERENCES

- Abers, G.A., B.Parsons and J.K.Weissel. Seamount abundance and distributions in the southeast Pacific, *Earth Planet. Sci. Lett.* 87, 137-151, 1988.
- Batiza, R. Abundance, distribution and sizes of volcanoes in the Pacific Ocean and Implications for the origin of non-hotspot volcanoes, *Earth Planet. Sci.Lett.* 60, 195-206, 1982.
- Batiza, R. and D. Vanko. Volcanic development of small oceanic central volcanoes on the flanks of the East Pacific Rise inferred from narrow-beam echo-sounder survey, *Mar.Geol.*54, 53-90, 1983.
- Batiza, R., P.J. Fox, P.R. Vogt, S.C. Cande, N.R. Grindlay, W.G. Melson and T. O'Hearn. Morphology, abundance and chemistry of near-ridge seamounts in the vicinity of the Mid-Atlantic Ridge 26°N, *J. Geol.* 97, 209-220, 1989.
- Dyment, J. Evolution of Indian Ocean Triple Junction between 65-49 Ma (Anomaly 28-21), *J.Geophy.Res.*, 98 13863-13877, 1993.
- Fornari, D.J., R.Batiza and M.A. Luckman. Seamount abundances and distribution near the East Pacific Rise 0-24°N based on sea abeam data, in : *Seamounts, Islands and Atolls*, B.H.Keating et al., eds., *Am.Geophys. Union, Geophys. Monogr.* 43, PP.13-21, 1987.
- Klootjick, C.T., J.S.Gee, J.W.Peirce, G.M.Smith and P.L.McFadden. An early India-Asia contact : Paleomagnetic constraints from Ninetyeast Ridge, *ODP Leg 121, Geology* 20, 395-398, 1992.
- Kodagali, V.N., K.A.K.Raju, T. Ramprasad, P.George and S.Jaishankar. Detailed bathymetric surveys of the Central Indian Basin. *Int. Hydrogr.Rev.* 69, 143-150, 1992.
- Mukhopadhyay, R. and N.H.Khadge. Seamounts in the Indian Ocean : Indicators of the Indian plate movement, *Proc.Ind.Acad.Sc. (Earth Planet. Sci.)*, 99, 357-365, 1990.
- Mukhopadhyay, R. and N.H.Khadge. Tectonic reactivation in the Indian Ocean : Evidences from seamount morphology and manganese nodule characteristics, *J.Geol.Soc.India*, 40, 443-452, 1992.
- Mukhopadhyay, R. and R. Batiza. Small seamounts and seamount chains from fast spreading crust of the Central Indian Ocean Basin, *Mar. Geophys. Res.*, (In Press). *The Ocean basins : Their structure and evolution*, The Open University Program, Pergaman press, PP.172, 1989.
- Patriat, P. and J.Segoufin. Reconstruction of Central Indian Ocean, *Tectonophysics*, 155, 211-234, 1988.
- Raju, K.A.K. Magnetic lineations, fracture zones and seamounts in the Central Indian Basin, *Mar. Geol.* 109, 195-201, 1993.
- Smith, D.K. Shape analysis of Pacific seamounts, *Earth Planet. Sci.Lett.* 90, 457-466, 1988.