Seamounts – windows of opportunities and the Indian scenario

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Seamounts are manifestations of crustal tectonics and volcanism, and are also sites of biodiversity and hydrothermal events. Although the population of seamounts is estimated to be in thousands, a large number of these have not been thoroughly studied. Globally, several seamounts are being exploited by the fishery industries, whereas a few have been demarcated for conservation and serve as underwater observatories. We provide a summary of the seamounts related to their discovery, distribution, nature and influence in the marine environment. In addition, we review the findings of seamounts in the Indian Ocean and the need to have a multi-disciplinary approach to explore them.

Keywords: Crustal tectonics, exploration, seamounts, volcanism.

A TRAVERSE perpendicular to the coast into the sea would reveal, amongst others, continental shelves and margins, abyssal plain, mid-ocean ridges (MORs), plateaus and seamounts that may emerge to form islands. Studies of seamounts help understand their petrological and morphological variations, which in turn shed light on their growth and the role of tectonics and volcanism. A fundamental relation may exist between seamounts and phenomena such as seismicity, hydrothermal deposits, biodiversity and possibly atmospheric oxygen[1–3]. We present information on the globally distributed seamounts and of some Indian Ocean seamounts. A case is made to explore and exploit (if feasible) some of the Indian Ocean seamounts.

Background

Prior to delving into the topic, the definition, discovery, distribution, genesis and petrology of the seamounts are warranted.

Menard[4] defined a seamount as a volcanic feature rising to more than 1000 m from the seafloor, whereas the International Hydrographic Organisation (Intergovernmental Oceanographic Commission) defines a seamount as ‘a discrete (or group of large isolated elevation(s)), greater than 1000 m in relief above the seafloor, characteristically of conical form’. Since the term ‘seamount’ is used in various ways by marine scientists, Staudigel *et al.*[5] proposed that a seamount is ‘any geographically isolated topographic feature on the seafloor taller than 100 m, including ones whose summit regions may temporarily emerge above sea level, but not including features that are located on continental shelves or that part of other major landmasses’. Generically, any conical or steep volcanic feature is referred to as a seamount and these may or may not be volcanically active.

Brewin *et al.*[6] has provided details concerning the early discovery and the history of seamount research. Till 1964, about 2000 seamounts had been discovered, several hundreds were surveyed and about 50 were dredged[4]. The seamount abundance of the Pacific Ocean indicated an increase in their number per unit area of the seafloor going back to the Eocene, implying that either volcanism was particularly active during the Eocene, or was more or less continuous since the Eocene due to the vulnerability of the crust[7].

Seamounts occur at the ridge-transform fault intersection, at overlapping spreading centres, in intraplate regions and at hotspots. Menard[4] postulated 10,000 volcanoes (> 1000 m high) in the Pacific, whereas Smith and Jordan[8] estimated ~30,000 seamounts (> 1000 m high) in the Pacific. Using ETOPO 2 grid, 8,500–14,200 seamounts (including abyssal hills and isolated peaks) have been inferred[9], while bathymetric data revealed greater than 200,000 seamounts ($h > 100$ m)[10]. Later, Kitchingman *et al.*[11] reported 14,000 seamounts which they presume is a fraction of a larger global database of 50,000 or more seamounts. Wessel *et al.*[12] compiled bathymetric and altimetry data and suggested the occurrence of ~ 125,000 seamounts ($h > 1000$ m). The abundance ranged between 45,000 and 350,000, and smaller seamounts ($h < 100$ m) could be 25 million (8–80 million). Using global bathymetric data at 30 arcsec resolution, Yesson *et al.*[13]

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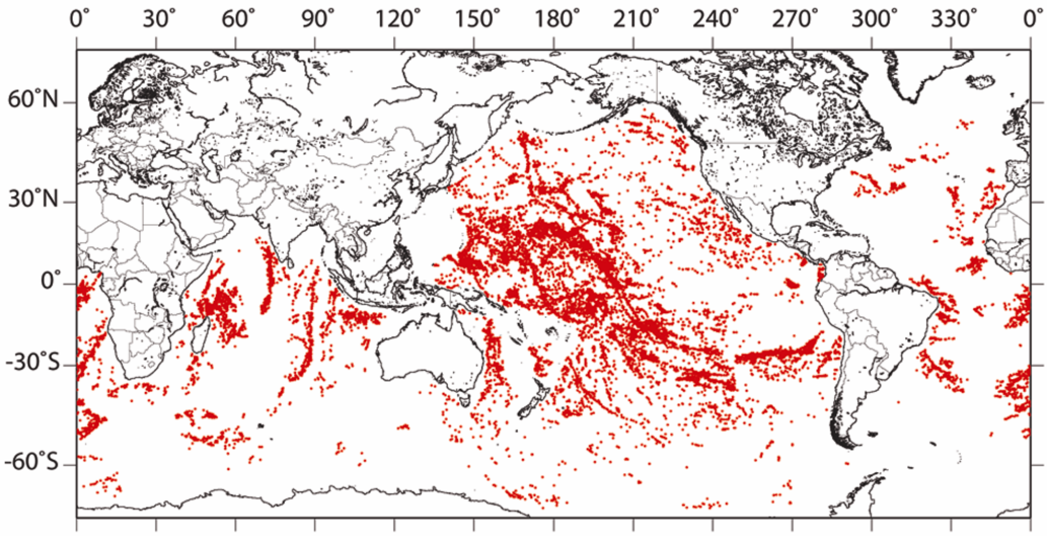

Figure 1. Global distribution of seamounts based on satellite altimetry data[14]. The map is produced using GMT software.

identified 33,452 seamounts and 138,412 knolls (*h* 200–1000 m), of which 4023 seamounts and 19,909 knolls are in the Indian Ocean. Therefore, it is noted that the abundance varies depending on the techniques used to count the seamounts. Figure 1 shows the distribution of seamounts based on the data of gridded Geosat/ERS-1 altimetry[14].

The volume of extrusions produced by oceanic volcanoes during the last 10^8 years perhaps equals that erupted by continental ones during 3×10^9 years, indicating the former to have been more intense[4]. Calculations show ~ 50 million tonnes/year of basalts form seamounts, yet these are several orders of magnitude lower than the Mid-Ocean Ridge Basalt (MORB, 60 billion tonnes/year)[15].

Seamounts add volcanic mass and also lead to significant convective heat loss of the ageing oceanic lithosphere[16]. The transport of heat to the base of the lithosphere by mantle plumes suggests the total global surface heat flow to be 4.43×10^{13} W, and that 15% of this (0.68×10^{13} W) is due to radiogenic heat production in the continental crust and 85% (3.75×10^{13} W) due to heat loss from the mantle[17].

While seamounts have been dredged since the 19th century, in the last few decades several have been sufficiently sampled (rocks, sediments, water and biota) utilizing manned or unmanned submersibles. Seafloor mapping and satellite altimetry have helped locate and map the seamounts[14,18–20]. Using noise power spectral densities from the analysis of ten seamount-free Geosat tracks in the Indian seas, Gairola *et al.*[21] detected the Somali Ridge and the Error Seamount (Arabian Sea), and predicted the existence of several uncharted seamounts. This method coupled with detection and verification of ground truth data helped locate four and forecast the presence of six seamounts in the Central Indian Ocean Basin (CIOB)[22].

Seamounts may occur as chains perpendicular to the axis at or near the crest, in clusters or in isolation, and depict variable morphology due to local and regional tectonic settings, sediment cover, physico-thermal properties of the lithosphere, conduit geometry, chemical composition and physical properties (viscosity, flow rate, gravity pull) of the magma. Commonly, seamounts have steep outer slopes, flat or nearly flat, circular, summit areas, calderas and craters[4,7,23].

Morphologically, seamounts of variable sizes resemble sub-aerial volcanoes. Small, young seamounts near the East Pacific Rise (EPR) range from domes to truncated cones with summit plateaus or craters[24], in addition to more irregular ones controlled by fractures[25]. Initially small, conical volcanoes (< 1 km high) form on the seafloor by summit eruptions, and subsequent flank activity leads to central collapse and the growth of a summit crater or larger caldera. The growth may be hindered by vent eruptions from ring fractures at the summit and the growth of a summit plateau. The Geisha guyots (NW Pacific Basin) range from small-volume, circular seamounts to large, irregular, star-shaped (in plan view) ones that may represent an evolutionary sequence with intermediate morphologies attesting to an arrested stage in their growth[26].

Seamounts host tholeiites, alkali basalts, transitional basalts, highly undersaturated basanites and nephelinites, trachybasalts, trachyte and even pumiceous flows[3]. Two seamounts (45°N, Mid-Atlantic Ridge (MAR)) consist of granites, granodiorites, granite gneisses, diorites, basalts, metabasalts, serpentinized gabbro and peridotites[27], whereas gabbros have been dredged from the Macdonald Seamount[28]. Explosive, phreatomagmatic eruptions are common and produce hyaloclastites within the craters during a period of waning volcanic activity[29].

The emplacement of seamounts from either hotspots or from small or shared (either with one another or with the MOR) magma chambers depends on physico-chemical conditions, ascension rate of the magma and location of the magmatic melt, amongst others. The parent magmas are initially fractionated and mixed, but later the axial and seamount magma paths diverge. Axial lavas continue through the axial magma chamber, become more fractionated and have more phenocrysts removed (possibly in the upper melt lens), whereas seamount magmas ascend without further significant fractionation and crystal separation[30]. Several factors and mechanisms that influence seamount formation include mantle upwelling associated with superfast spreading, off-axis mantle heterogeneities, mini plumes and local upwelling, and the resistance of the lithosphere to penetration by the magma[31].

Intraplate non-plume activities could also generate volcanoes by mantle upwelling coupled with melting that could probably be brought about by secondary upwelling in intraplate regions in the form of longitudinal upper mantle convective rolls called ‘Richter rolls’[32], localized upward mantle flow into depressions or recesses at the base of the lithosphere, and diffuse regional mantle upwelling that may be generated by a weak mantle plume. Melting may also be caused by an influx of volatiles that ascend from the low-velocity zone of the asthenosphere[33].

Significance of seamounts

Seamounts indicate the rate and direction of plate movement, contribute to basinal volcanism, provide information about crustal processes, and influence the formation and distribution of mineral deposits (Iyer *et al.*[3] and reference therein). The oceanographic effects adjacent to a seamount depend on the height and morphology of the seamount, the local component of the Earth’s rotation rate determined by its latitude, local density stratification of the sea water, currents and eddies, local turbulence, and the hydrothermal or magmatic activity of the seamount[34]. These factors could affect the geochemical cycles, mixing processes, biological productivity, etc. Large seamounts could impede a subducting plate and trigger slides along the slope and earthquakes, and may generate tsunamis[35].

A survey of 20–25% of the 70,000 km long MOR showed 280 hydrothermal sites of which ~ 10% is along the Indian Ocean ridges, but only two are confirmed[36]. Although the MOR is the major area of hydrothermal deposits, seamounts, especially young ones that form at the MOR and later drift are also candidate sites. According to Fouquet *et al.*[37], off-axial volcanoes near the ridge are first-order targets to discover active or inactive large deposits along fast- to medium-spreading ridges.

Some sites of seamount hydrothermalism where sulphide deposits and copper porphyry occur are at 21°N EPR, Juan de Fuca Ridge, in the Hawaiian chain, Manji Seamount (Philippine Sea) and in the Tyrrhenian Sea[38–40]. Hein *et al.*[41] classified the seamount ore deposits into six types: hydrogenous ferromanganese (FeMn) crusts, hydrothermal iron oxides, hydrothermal manganese oxides, hydrothermal sulphide, sulphate and sulphur deposits, phosphorite deposits and hydrogenetic FeMn nodules. Phosphorites (P_2O_5 up to 33%) collected from the crests of three subsided seamounts in the Eastern Atlantic (6°–9°N) indicate their formation by the replacement of the shallow-water reef limestones of the middle Eocene[42]. The influence of microbes in the formation of laminated crusts and massive slabs of phosphorites of the Error Seamount (NW Arabian Sea) has been reported[43].

Some seamounts have enhanced biodiversity, unique biological communities and high levels of endemic species. In the 1960–70s, the erstwhile Soviet Union initiated seamount exploration in the Atlantic, Pacific and Indian oceans to establish deep-sea fishing grounds. Seamounts not only provide shelter and food for large fishes and mammals but are also sites for reproduction of bacteria[44]. Data from the Chamorro Seamount (Mariana forearc) reveal that serpentinite flows provide hydrogen and methane that supply energy to the extremophile life[45].

A review of seamount biota and distribution shows the presence of 597 invertebrate species. Only five seamounts (of the estimated more than 30,000) account for 72% of the species recorded and ~ 15% was endemic[46]. The size and distance between seamounts aid many taxa to adapt to such an environment and show limited dispersal[47]. Due to strong localized currents and upwellings, the plankton biomass is enhanced over seamounts and the easy availability of food leads to increased predators like fishes, birds and mammals[48].

The biota of the Indian Ocean seamounts is poorly known. In the CIOB most of the macrobenthic data obtained were from core and grab samples and about 82 species were identified, whereas megabenthic data were based on still and video photographs and dredged samples[49].

The UN has asked the research community to ‘consider urgently ways to integrate and improve on a scientific basis the management of risk to marine biodiversity of seamounts and certain other underwater features within the framework of the UN Convention on the Law of the Sea’. Gianni[50] discussed a strategy to achieve a global agreement for a large-scale system of marine reserves for seamounts, deep-sea ridges and plateaus by considering fisheries, marine biodiversity and a ban on fishing near seamounts.

The time and source of oxygen on the Earth are enigmatic. L. R. Kump and his group reported that prior to 2.5 billion years ago, the earth lacked oxygen[51]. Interestingly, biomarkers in rocks older than 200 Ma show oxygen-producing cyanobacteria that released oxygen (at the same levels as today), oxidized the soils and formed red beds, but these were negligible during the Archaean. The suggested mechanism was that submarine volcanoes erupted at lower temperatures than terrestrial ones and produced a reducing mixture of gases and lavas, which effectively removed oxygen from the atmosphere and bound these to the minerals.

Indian Ocean seamounts

In contrast to the detailed multi-disciplinary studies being carried out on the Pacific and Atlantic seamounts (Figure 1), similar ones are sparse in the Indian Ocean and more so in the Arabian Sea and the Bay of Bengal. We synthesize the results of the Indian Ocean seamounts and stress the need to detail and sample them (Table 1).

Central Indian Ocean Basin

The CIOB (Figure 2) has fracture zones (FZs), the trace of an ancient triple junction and hosts several seamounts[52,53]. Seamounts of variable dimensions occur in chains, isolation and clusters. For instance, near the 79° FZ the seamounts are less conical in shape, have steep flanks and most have an elongated base, whereas some seamounts have twin summits. In contrast, seamounts present at the centre of the basin are more conical, symmetrical and with gentle flanks (Figure 3). In general, the elongated base of some seamounts could be accounted by later addition of volcanic material after the seamounts were emplaced. Seamounts within 20 km of FZs have moderate to high basal area, slope angle and volume in contrast to those between 20 and 50 km across FZs, which generally are the tallest, most conical and largest. The seamounts between 50 and 100 km from FZs have no definite trend and vary in height, volume, basal area and slope angle. The normalized abundance of the CIOB seamount is 976 seamounts/10^6 km^2, but on a finer scale this value varies from 500 to 1600 seamounts/10^6 km^2, which is less than the seamount concentrations of the Pacific and Atlantic oceans (9000–16,000 seamounts/10^6 km^2). Principle component analysis showed that summit height and flatness influence the morphology[54].

Four types of relations between the flatness and slope angle have been identified for the CIOB seamounts[53]. Type 1: low height-width (HW) ratio < 0.08 indicates low slope angle ($< 10°$) and low flatness (< 0.12); type 2: HW ratio of 0.081–0.16 shows variable slope angle (6°–15°) and flatness (0.08–0.3); type 3: an intermediate HW ratio of 0.161–0.23 shows high slope angle ($> 10°$) and high flatness (> 0.2) and type 4: high HW ratio > 0.23 points to a high slope angle ($>10°$) and low to moderate flatness (< 0.2). Type 3 represents older seamounts with collapse summits that formed through fissure eruption, type 4 indicates a point source of magma eruption, type 1 indicates point source with flow of magma along the seamount slope and type 2 seamount complex indicates subsequent eruption (Figure 3). The large seamounts with low flatness and high slope angle indicate narrow conduits; most of the small seamounts with high flatness and low slope angle indicate fissure type of eruption, whereas the medium seamounts with a wide range of flatness and slope angle denote both point and fissure type of opening[53].

A majority of these flow-line parallel, N–S trending, ancient (age > 50 Ma) CIOB seamounts are similar in terms of distribution, petrology and origin to the younger ones formed at the EPR (age < 10 Ma)[55]. Based on the morphology, mechanisms were proposed for the emplacement of single-peaked, multi-peaked and composite seamounts. Irrespective of size, single-peaked seamounts are dominant (89%), multi-peaked are less (8%) and composite ones are rare (3%). Since seamounts are manifestations of magmatic and tectonic activities at spreading ridges the overall style suggests: (i) a majority of the CIOB seamounts formed near the ridges, and their abundance depends on availability of magma; (ii) their disposition and morphology are spreading rate-dependent; (iii) a few seamounts show multi-stage of growth and (iv) local intraplate secondary eruptions, facilitated by tectonic reactivation, enlarged the dimensions of the pre-existing seamounts[53–55].

The CIOB seamounts seem to have controlled the distribution of FeMn nodules by providing rock fragments as nucleus, whereas seamount slope needs to be considered for demarcating unfavourable areas for mining[56]. Signatures of hydrothermal events occur near the seamounts as evident from the magnetite spherules, Fe–Si-rich sediment, Al-rich grains and spherules, and FeMn crusts (Iyer *et al.*[57,58] and references therein). Therefore, it would be prudent to sample some of the CIOB seamounts to discover elusive, fossil or active, hydrothermal vents.

Other seamount sites

Several reports provide data concerning the Indian Ocean seamounts (Table 1). Remote sensing and bathymetric studies of the western Indian Ocean revealed a seamount at Madagascar[59]. Engel *et al.*[60] examined vesicular tholeiite, dredged from the lower flank of a seamount near the Central Indian Ridge that had higher concentrations of potassium and titanium and slightly lower silica and calcium than the MORB. A study of the Owen FZ and the northern end of the Carlsberg Ridge (CR) showed the presence of large seamounts[61]. A reconnaissance survey of Murray Ridge (Gulf of Oman) showed elongated, weakly magnetized seamounts, suggesting the CR to be contiguous with the Owen FZ[62]. The Darshak Seamount, south of the Indus Canyon, rises from a depth of about 1,500 m to approximately 450 m towards the surface.

Table 1. Location and characteristics of a few seamounts reported in the Indian Ocean

Serial no.	Seamount	Latitude	Longitude	Description	Reference
1	Sagar Kanya Seamount[#]	9°15′N	71°00′E	Height 2464 m, summit width ~ 1 km, base 33 km, summit depth 1686–1700 m, flank slope ~ 30°. The seamount formed during Oligocene.	69
2	Error Seamount	10°20′N	56°05′E	Height 3850 m, flat-topped guyot, strikes ENE–WSW, more or less parallel to 10°N, summit depth 377 m. Age 45 Ma.	43, 64, 84
3	Prathap Ridge Seamount, the continental rise, southwest coast of India[#]	8°–15′N	72°30′–75°23′E	NW–SE to NNW–SSE, similar to the trend of the present western Indian margin, the Ridge is mostly buried below Tertiary sediments, Extends for about 1000 km in a NW–SE direction between 8°F and 15°E.	85
4	Wadia Guyot[#]	15°31′N	70°05′E	Height 2240 m, basal area 1210 sq. km, average slope 25°. Elongated in N–S direction.	71
5	Panikar Seamount[@,#]	16°12′N	69°22′N	Height 1068 m, basal area 300 sq. km, average slope 20°. Elongated in NS direction.	71
6	Genista Bank, Centre of Arabian Sea	16°33′N	53°28′E	Water depth 200 m. A well-defined, roughly elliptical bank, gentle slope to the east and comparatively steeper southern and western faces. It rises from depths of 20–25 m in the north, to a least depth of 5 m at the summit. 900 fathoms in the south.	86
7	Raman Seamount[@,#]	17°08′N	69°01′E	Height 1505 m, basal area 660 sq. km, average slope 25°, secondary peak and flat plateau, basal area 28 sq. km, N–S elongation.	71
8	Laxmi Basin Seamount chain[#]	15°–17°20′N	69°–70°15′E	Height 1068–2240 m, basal area 300–1210 sq. km, Extension of the chain is around 250 km. The chain consists of Raman and Panikar seamounts and Wadia guyots.	71
9	Murray Ridge, NW Arabian Sea	21°45′N	61°50′E	420 km long, ~ 20–50 km wide, water depth ~ 400 m.	62
10	Darshak Seamount, NE Arabian Sea[#]	22°N	66°E	Mean base depth 1500 m, height 450 m. The steep scarp indicates ancient volcanoes and fractures.	63
11	SM1, SM2	2°N and 2°30′N	83°30′E and 86°30′E	Height 800 m, width 10–35 km, presence of abandoned major channels with levees and fan. Positive magnetic anomaly (~ 400 nT) and gravity high (45 mGal), Seafloor age is middle to late Cretaceous.	80
12	Cratered Seamount, CSM[#]	7°55′N	94°02′E	Located in Nicobar earthquake swarm area at water depth is between 373 and 671 m, crater is 160 m deep. Seamount is conical, has steep slope and hard, rocky substratum. The highest abundance of megabenthic communities, species richness and diversity occur on the flank.	87
13	Sewell Seamount[#]	9°25′N	94°45′E	Pleistocene volcanic episode, distinct magnetic anomalies. Size and relief similar to Alcock Seamount.	73, 88
14	SM2[#]	10°N	94°E	A flat-topped and part of the arc-parallel seamounts chain in the Andaman Sea. Dominated by cobbles and fine sediment. Water depth in area 1290–1424 m.	87
15	Alcock Seamount[#]	12°30′N	94°40′E	270 km long and 100 km wide. Maximum relief 2400 m. Slope > 3°. Massive slabs of unaltered intergranular basalt. Pre-Pleistocene age, distinct magnetic anomalies.	74, 88
16	Afanasy Nikitin Seamount	3°S	83°E	Average height ~ 4750 m, N–S extension, for about 500 km. Subsidence rate of the seamount ~ 50 mm/Ma. The seamount was emplaced during ~ 75 Ma. Bimodal volcanism, occurrence of cobalt-rich ferromanganese crusts.	76, 78, 79, 89–91

(*Contd*)

Table 1. (*Contd*)

Serial no.	Seamount	Latitude	Longitude	Description	Reference
17	Boomerang Seamount	37°43′S	77°49′E	Base to summit height 950–1350 m, Volume ~ 300 km^3, seafloor age 700 kyr. Summit has a 2 km wide caldera with a nearly constant 200 m depth and a volume of 0.63 km^3. The steep slopes (> 45°) of the caldera walls suggest an origin by faulting and subsequent mass-wasting.	67
18	Kainan Maru	65°15′S	34°15′E	Height 3500 m, oval summit, NW elongation. The northern and eastern sides are steeper than the southern and western sides. The seamount is ~ 60 km wide and 120 km long, with the long axis oriented NNW–SSE. It is a remnant of continental crust left behind when Madagascar and India separated from Antarctica through strike–slip motions. The eastern flank of the seamount is steep (> 30°). Distinct asymmetrical flanks. The seamount rotated clockwise during the break-up of Gondwana land as India–Sri Lanka–Madagascar moved north.	68

@, These three seamounts are a part of the Laxmi Basin seamount chain. #, Seamounts in the Exclusive Economic Zone of India.

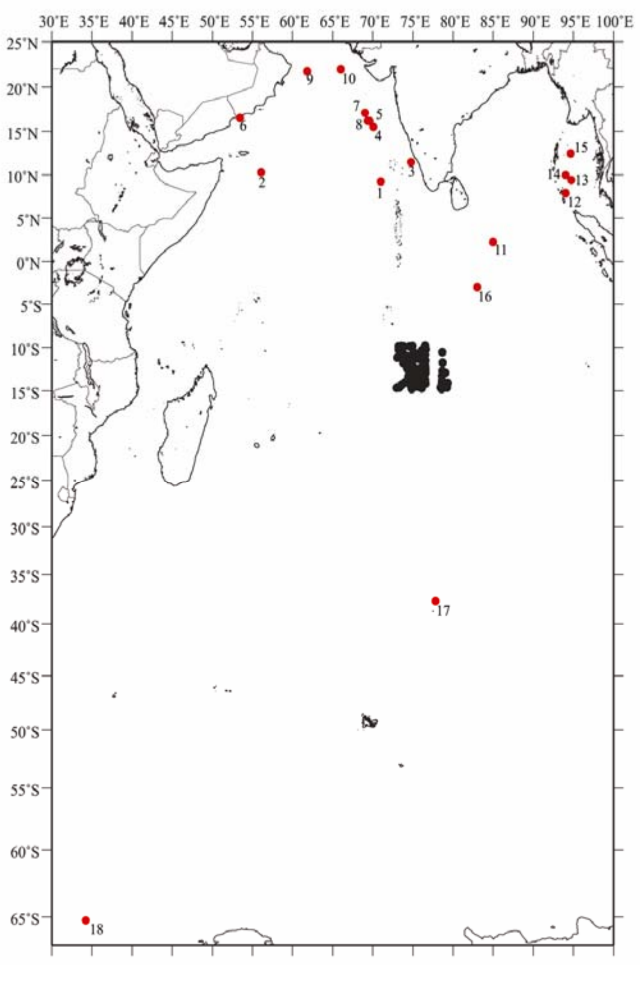

Figure 2. Location of seamounts in the Indian Ocean. The numbered seamounts correspond to those detailed in Table 1. The block of solid dots represents > 200 seamounts in the Central Indian Ocean Basin[53]. Source: see text and Table 1.

Similar hills and seamounts indicate volcanism related to the Deccan Traps[63].

Surveys of the Mount Error (NW Indian Ocean) indicated a 330 m thick sediment cover on the summit and 880 m in the valley, whereas the basement has a thin sill of lamprophyre[64]. High-resolution bathymetric data revealed 523 seamounts located in the axial valley of the southwest Indian Ridge, between the Atlantis 2 FZ (57°E) and the Rodriguez Triple Junction (70°E). Mendel and Sauter[65] proposed that cooler mantle temperatures resulted in the formation of taller and fewer seamounts between 62°E and 70°E. Gravity model indicated that the on-axis Styx volcano (20–30 km diameter, 2500 m height) located at the axis of the Wharton fossil spreading centre (NE Indian Ocean), was emplaced on a weak lithosphere during the final phase of seafloor spreading and consists of alkaline rocks derived from an enriched mantle source[66]. The 1100 m tall, volcanically active Boomerang Seamount (Amsterdam-St Paul Plateau) shows enhanced water column temperature (1.7°C) and turbidity (0.3 V) within the caldera that suggests hydrothermal activity[67].

The Kainan Maru Seamount (~ 15 km north of the Gunnerus Ridge, east Antarctica) rises 3500 m from the seafloor, has an oval shape (~ 60 km wide and 120 km long) and a gently sloping summit. The northern and eastern sides are steeper and have erosional channels, whereas the more gently sloping western side shows evidence of large sediment slides. This seamount was detached and rotated clockwise away from the ridge during the Gondwanaland break-up[68].

A 2464 m high seamount in the Arabian Sea extends for 1 km beneath the seafloor and is locally isostatically compensated. With a reversibly magnetized upper part and normally magnetized base, the seamount probably formed by at least two volcanic episodes. The base was formed during the late Paleocene during the movement of the Indian plate over the Reunion hotspot, whereas the summit formed during a renewed period of volcanism, contemporaneous with the major changes in direction of the Indian plate motion during the early Oligocene[69].

Off the Karnataka coast (water depth 40–2300 m, Arabian Sea) four seamounts occur between Karwar and south of Mangalore. The two in the north are close to each other, trend NW–SE and mark the southern tip of Prathap Ridge. One seamount (1200 m tall) is small, steep and has a pointed cone shape, whereas the other (> 1500 m) has a moderate slope and a flat top[70].

A NNW chain along the axial part of the Laxmi Basin (eastern Arabian Sea) consists of three elongated features, Raman and Panikar seamounts and Wadia guyot, of variable height (1068–2240 m) and basal area (300–1210 km^2) and has steep lower flanks, flat plateaus, terraces, secondary peaks and an extensive dendritic gully pattern. Volcanism at the intersection of the Reunion hotspot and an extinct spreading centre produced these seamounts[71].

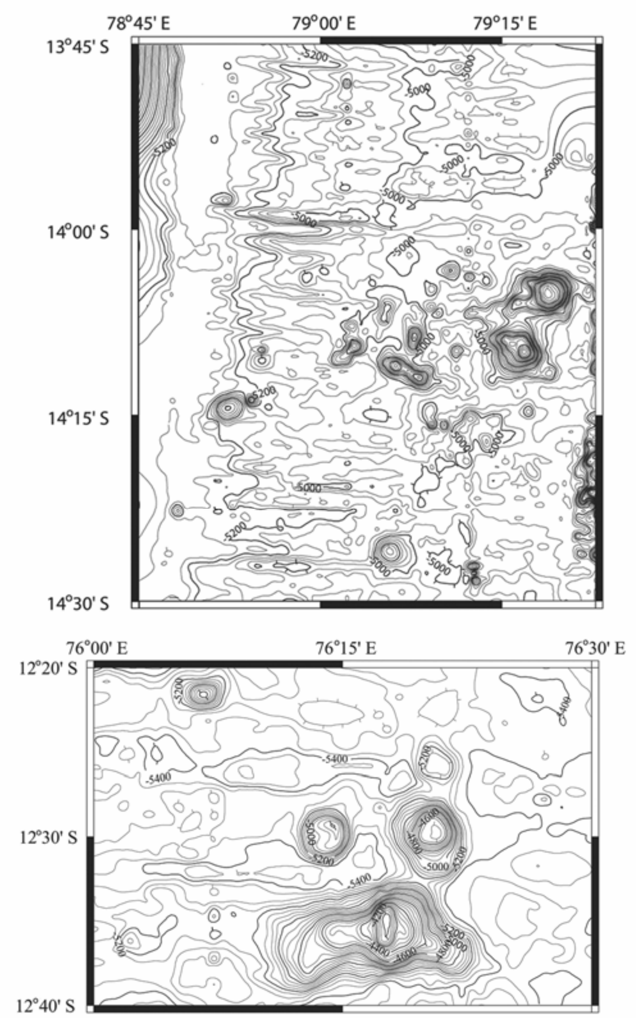

Figure 3. Bathymetry of seamounts of variable morphology located in CIOB. (Upper panel) Seamounts near the 79° fracture zone that are less conical and have an elongated base. (Lower panel) Mostly conical seamounts, except for one which has a significant E–W trending base. See text for details.

Bathymetric survey of the southwest Great Nicobar shows an eastern undulatory and craggy bottom with calcareous ooze, a central smooth and gently sloping, elongated trough with foraminiferal ooze mixed with terrigenous and volcanic material, and an undulatory, hummocky feature with a possible buried seamount[72].

The Sewell Seamount (Andaman back-arc basin) marks the Pleistocene volcanic episode[73]. Magnetic anomaly over the Sewell and Alcock seamounts (Andaman Sea) shows distinct patterns over the Sewell Seamount, and side-scan images of the Alcock Seamount depict imprints of penetrative movements and a pre-Pleistocene age in contrast to the possibly younger Sewell Seamount[74]. Banerji *et al.*[75] evaluated the sulphide mineralization, volcanism, bathymetric and magnetic data around Barren Island and Alcock Seamount. The isobath map showed a 2–6 km wide, southerly sloping valley separating the Narcondam Island and the nearby volcanic ridges from a northeasterly trending sedimentary ridge to its west. The seamount in the Car-Nicobar–Tillanchang Dwip has a fairly uneven topography with several conical hills and central depressions suggestive of caldera collapse.

The Afanasy Nikitin Seamount (ANS) complex, extending north–south for 500 km from the Bay of Bengal to 7°S–8°S in the Indo-Australian Basin, rising 3500 m from the seafloor, has been subjected to repeated uplift and subsidence and probably formed through bimodal volcanism (basic and acidic lavas)[76]. Geophysical data show the ANS joining the 85°E Ridge through isolated buried hills and intervening subsurface structures. The gravity signatures of the ridge change from negative to positive (south of 5°N) and probably coincide with termination of pre-collision continental sediments in the Bay of Bengal. An 8 km thick, deep crustal body of magmatic rocks underlies the ANS, while beneath other structures the crust is down-flexed up to 2.5 km. The hotspot that formed the 85°E Ridge reactivated the ANS during the Palaeocene and exposed it to the sea surface, and later the ANS eroded and subsided[77].

The ANS consists of late Cretaceous effusive rocks such as olivine picrite-basalt, trachybasalt and trachyte that erupted near a spreading centre. Conglomerates from the upper slope indicate emergence of the volcano in the Palaeocene and subsidence in the Eocene[78]. There is a significant presence of platinum group elements and gold in the cobalt-rich FeMn crusts[79].

The distal Bengal Fan (around 2°N lat.) has two seamounts (SM1 and SM2) that rise 800 m from the seafloor (4400 m water depth) with large-amplitude magnetic and gravity anomalies[80]. Magnetic model suggests that one seamount evolved along with the crust during isochron

A32 (similar to 72 Ma), whereas the other formed over the Cretaceous magnetic quiet-zone crust with reversed polarity.

Summarizing the above reports it is apparent that although several seamounts of different geological ages in the Indian Ocean have been studied, no single mechanism can explain the production and emplacement of these seamounts (Table 1). The available information though useful, is not 'all inclusive', since no single seamount has been thoroughly examined in relation to their geological, biological, physical and chemical parameters. Therefore, a comprehensive programme to locate, map, sample and create a database of the seamounts adjacent to India would be a welcome step. Perhaps it would be prudent to earmark for investigations some of the seamounts that lie in the Exclusive Economic Zone of India (EEZ, Table 1). Such studies should consider the international rules and regulations that govern the exploration and exploitation of seamounts. In the event the seamounts within the EEZ are not exploitable, perhaps these could be demarcated as marine observatories similar to the Condor Seamount (the Azores)[81].

Worldwide, less than 400 seamounts have been sampled and of these hardly 100 have been sampled in detail[82]. It would be pertinent to systematically gather data on the seamounts, at least of those that lie in the Indian waters. Investigations of seamounts would help answer several questions relating to the morphology of and volcanism at seamounts, crustal structure and plate movement, occurrence of hydrothermal activities and influence of the seamounts on the marine environment[83]. Marine scientists always find it exciting to either discover a seamount or unravel newer aspects of existing ones.

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