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Seamounts – characteristics, formation, mineral deposits and biodiversity

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ABSTRACT

Seamounts represent crust-mantle activities and are areas of petrological deviations, biodiversity, seismicity and hydrothermal events. An estimated ~50 million tons/year of basalts are required to produce seamounts suggesting intense oceanic volcanism. Seamounts either occur as chains perpendicular to the ridge or as isolated entities or in clusters. Seamounts may host basalts, hyaloclastites, gabbros and serpentinites and these variants perhaps evolve from multiple melting domains as a consequence of large-scale thermal structure and mantle lithology. Non-hotspot seamounts on a young, thin and hot lithosphere host tholeiites whereas the plume related ones on thick, older lithosphere may be either tholeiitic or alkaline.

Seamounts may bear hydrothermal deposits (Fe, Mn, Co) rare metals and phosphorites. The resistance of seamounts to subduction could trigger slides; while shearing of seamounts buried in subduction zones leads to seismicity, both of which could cause tsunamis. Seamounts greatly affect the circulation patterns and currents, which in turn influence the surrounding biota. We review here the seamounts in terms of discovery, characteristics, distribution and their influence on the marine environment.

KEYWORDS **Seamounts. Distribution. Origin. Influence on Marine Systems.**

INTRODUCTION

Mid-ocean ridges (MOR), seamounts and deep trenches are the most striking features on the deep sea floor. Slow spreading ridges (full rate <40mm/year) typically have deep-seated earthquakes, major normal faults, a wider neo-volcanic zone (2000-12000m) and host small seamounts, while off-axis seamounts are uncommon. In contrast, the fast spreading ridges (full rate 80-160mm/year) are less seismic, have a narrow neo-volcanic zone (100-200m) and may host off-axis seamounts (*e.g.*, Iyer and Ray, 2003).

Morphology and petrology of seamounts help understand and constrain models of seafloor spreading. The distribution and shape of the seamounts provide evidence for their temporal growth, the role of local tectonics on magma production and the emplacement mechanism. A relation may exist between seamounts and phenomena such as seismicity, hydrothermal deposits, biodiversity and possibly atmospheric oxygen (Iyer, 2009).

Review works pertaining to seamounts independently concern the geological, biological or physical oceanographic aspects (Keating *et al*., 1987; Hekinian *et al*., 2004; Morato and Pauly, 2004; Pitcher *et al*., 2007; Mehta, 2008; Staudigel *et al.*, 2010). Hence, an attempt is made to compile the available disparate information and present an overview of seamounts in relation to their type, formation, significance and influence on the marine environment.

SEAMOUNTS – DEFINITION

The International Hydrographic Organisation (Intergovernmental Oceanographic Commission) defines a seamount as "a discrete (or group of) large isolated elevation(s), greater than 1000m in relief above the sea floor, characteristically of conical form." Since the term "seamount" is variably used by marine scientists, Staudigel *et al*. (2010) proposed that a seamount be defined as "any geographically isolated topographic feature on the seafloor taller than 100m, including ones whose summit regions may temporarily emerge above sea level, but not including features that are located on continental shelves or that are part of other major landmasses." But generically, any conical or steep volcanic feature is referred to as a seamount and these may or may not be volcanically active.

DISCOVERY AND DISTRIBUTION

A comprehensive report on the early discovery of seamounts suggests that the Josephine Bank (north Atlantic) was perhaps the first identified seamount and in 1938, the term "seamount" was first officially given by the US Board of Geographic Names to the Davidson Seamount (Brewin *et al*., 2007). Until 1964, about 2000 seamounts had been discovered, several hundred, surveyed to establish their shape and about 50, dredged (Menard, 1964). Volcanic activity was more intense in the geological past due to plate reorganisation. This is attested by the seamount abundance of the Pacific Ocean that indicates an increase in its number per unit area of the oceanic crust going back to Eocene time (37-43Ma). This implies that either volcanism was particularly active during the Eocene or volcanism was more or less continuous from the Eocene, with the Eocene crust being vulnerable to volcanism for the longest time (Batiza, 1982).

Seamounts occur in groups or in chains or are isolated and distributed in space and time with the majority lying along convergent plates and in areas of vertical tectonic movement. Seamounts also occur at ridge-transform fault intersections, at overlapping spreading centres and at hotspots. Probably 10^4 volcanoes of >1km relief exist in the Pacific (Menard, 1964). Estimations reveal that ~30,000 seamounts (height h>1000m) occur in the Pacific while the rest are mostly in the Atlantic and Indian oceans, and more dominantly in the southern hemisphere (Smith and Jordan, 1988). In the Atlantic, about 810 seamounts occur at the NE with the highest concentration between the Charlie-Gibbs fault zone, the Azores, and North of Madeira (Epp and Smoot, 1989).

The present number of existing seamounts is debatable. Wessel (2001) reported nearly 12,000 seamounts from altimetry data. Based on the ETOPO 2 grid, Kitchingman and Lai (2004) inferred 8,500-14,200 seamounts (including abyssal hills and isolated peaks) to be present while bathymetric data revealed more than 200,000 seamounts (h>100m) (Hillier and Watts, 2007). Later, Kitchingman *et al*. (2007) inferred 14,000 seamounts which they presume is a fraction of a larger global database of 50,000 or more seamounts. A compilation of bathymetric and altimetric data suggested ~125,000 seamounts (h>1000m) but could be between 45,000-350,000; while smaller seamounts (h<100m) could be 25 million (8-80 million) (Wessel *et al*., 2010). Recently, by using global bathymetric data at 30 arc-sec resolution, Yesson *et al*. (2011) identified 33,452 seamounts and 138,412 knolls (height between 200 and 1000m). Therefore, the variability in abundance depends on the techniques used to count the seamounts. Figure 1 presents the global distribution of seamounts based on the revised data of Wessel *et al*. (2010). Seamounts not only characterise modern fast spreading ridge flanks but also ancient fast spreading crust. For instance, the seamounts in the Central Indian Ocean Basin that formed before the Indo-Eurasian collision events are of the latter type (Das *et al*., 2007). Along the East Pacific Rise seamounts mostly occur within 5-15km and rarely further than 50km away from the axis. As new ones form, their number per unit area increases with distance from the MOR. At times, the apparent volcano density decreases due to sediment cover over smaller seamounts. Along slow spreading ridges, the seamounts tend to grow almost exclusively in the central graben except for those along the boundary of oceanic/continental lithosphere, *e.g.* off NW Africa (Schmincke, 2004).

Seamounts may be "on-ridge (near-axis)" or "off-ridge (off-axis)" depending on the elastic thickness (T_e) of the underlying oceanic crust. Koppers and Watts (2006) reported T_e estimates for 9,758 seamounts in the Pacific, Indian and Atlantic oceans and assigned the seamounts as "on-ridge" if the T_e was <12km and "off-ridge" (*i.e.*, intraplate) if the T_e>20km, as occuring in seamounts on older crust. Near-axis seamounts occurring on flanks of inflated ridges have large cross sectional areas, and a profuse supply of magma and the abundance of large ones (h >400m) strongly correlates with the spreading rate. Hillier (2007) forwarded a method to convert the crustal strengths to "date" the seamounts and found the derived ages compared well with those obtained from geochronology.

MAGMA AND HEAT BUDGETS

Divergent plates witness the highest production and eruption of magmas and the largest number of active seamounts while convergent plate margins host active sub-aerial volcanoes above the subduction zones. Even though eruptive volumes of magmas along subduction zones comprise <10% of the global production or about 4km^3 per year, these represent >80% of the roughly 5,350 eruptions recorded in historic times (Schmincke, 2004).

Depending on the nature of seismic layer 3 (gabbros) volcanism at the MOR varies between <5km^3/year and >20km^3/year and contrasts with volumes of 1.5 and 1.7km^3/year computed for hotspot and island arc volcanism, respectively (Schilling *et al.*, 1978). Annually about 75% of the magma which reaches the Earth's surface gets emplaced at the MOR to produce ~3km^3/year of extrusives and ~18km^3/year of intrusives (Crisp, 1984). The apparent volume of extrusions produced by oceanic volcanoes during the last 10^8 years is similar to that erupted by continental volcanoes during $3x10^9$ years, indicating that volcanism has been far more intense in the oceans than on the continents (Menard, 1964). Calculations show that ~50 million tons/year of basalt form seamounts, yet this huge volume of lava is significantly smaller than the amount (60 billion tons/year) formed at MOR (Lisitzin, 1996).

Seamounts contribute a major amount of convective heat loss (Villinger *et al.*, 2002). An assessment of mantle plumes in transporting heat to the base of the lithosphere suggests the total global surface heat flow to be $4.43x10^{13}$W and of this $0.68x10^{13}$W (*i.e.*, 15%) represents radiogenic heat production in the continental crust and $3.75x10^{13}$W (*i.e.*, 85%) the heat loss from the mantle (Malamud and Turcotte, 1999).

SURVEY AND SAMPLING

Since the 19th century seamounts have been explored to some extent (Brewin *et al.*, 2007) but new technologies help to investigate seamounts in more detail. For instance, Bryan and Cooper (1995) deployed a deep ocean-bottom seismometer to record an undersea volcanic event and monitor the seismic events on the summit and flanks of the Loihi Seamount. Systematic deviations in spatial clustering during the initial swarm activity suggested a changing pattern of stress due to magma movement in the crust or deep portions of the edifice.

Satellite altimetry aids in locating and understanding the bathymetry of seamounts (Cazenave *et al.*, 1980; Craig and Sandwell, 1988; Sandwell and Smith, 1997; Wessel, 1997). Gairola *et al.* (1992) derived noise power spectral

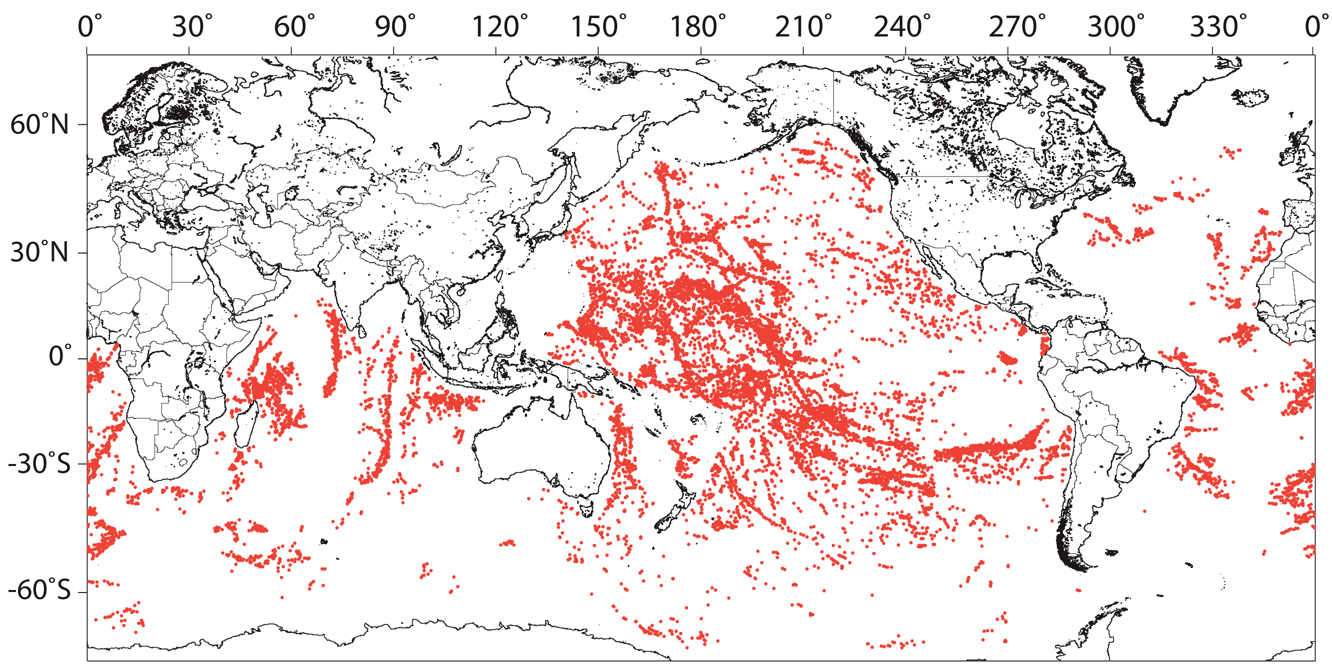

FIGURE 1 | Global distribution of 11882 seamounts (Wessel *et al.*, 2010).

densities by analysing ten seamount-free Geosat tracks in the Indian seas. The model noise power spectral density together with a seamount signature model was used to construct a matched filter and detect the Somali Ridge and the Error Seamount (Arabian Sea) and predict the existence of several uncharted seamounts. This method along with ground truthing detected four seamounts and predicted the presence of six in the Central Indian Ocean Basin (Basu *et al*., 1994).

Submersibles are deployed to gain a better idea of the seamount environment. For example, surveys in the Red Sea showed the presence of marginal seamounts and on flat portions of the slopes (Yastrebov *et al*., 1981). Using a unique sampling strategy involving the cementation of a permanent fluid sampler directly to the seafloor, the fluid volume and heat flux from a diffuse hydrothermal vent was measured on the seafloor over a period of 206 days on the Axial Seamount, Juan de Fuca Ridge (Pruis and Johnson, 2004).

MORPHOLOGY

Seamount morphology is controlled by: 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. Seamounts range from small domes of tens of metres to large edifices of several kilometres in height. Commonly, they have steep outer slopes, flat or nearly flat circular summit areas and collapse features (calderas, pit craters). Seamounts may grow in height when their substructure is intruded by sills and their flanks become steeper and more unstable. Flank collapse and explosive volcanism cause clastic mass flows that enlarge a seamount's base (Staudigel and Schmincke, 1984).

Menard (1964) recognised craters on seamounts and later high resolution sonar data suggested that more than 50% of the thousands of seamounts have craters or calderas while many others may have buried ones (Batiza, 1982; Batiza and Vanko, 1983). The collapse features vary from tiny pits only a few tens or hundreds of metres in diameter to large complex calderas >5km long, *e.g.*, MOK seamount (near the East Pacific Rise) and some in the western Pacific and Phillippine basins (Hollister *et al*., 1978).

Generally, craters and calderas are roughly circular or elliptical. Most craters are single collapse features floored by flat ponded lava flows; some others are more complex and consist of multiple features that may be nested or coalesced in chains while many craters are scalloped by collapse and mass wasting. Most crater walls are vertical and truncate sub-horizontal lava flows. Talus ramps and irregular projecting buttresses occur around the basal margin of the crater (*e.g.*, Batiza and Vanko, 1983).

Seamounts of variable sizes resemble sub-aerial shield volcanoes. Small, young seamounts near the East Pacific Rise are conical domes to truncated cones with summit plateaus or craters (Fornari *et al*., 1984), in addition to more irregular plan-forms controlled by fractures (Fornari *et al*., 1987). The Lamont Seamounts (10°N, East Pacific Rise) suggest an evolutionary trend as they age and move away from the axis (Fornari *et al*., 1984). Initially small conical volcanoes (<1km high) form and subsequent flank activity causes central collapse and the growth of a summit crater or larger caldera. Continued growth may result from eruptions through fractures at the summit and the formation of a summit plateau. Explosive, phreatomagmatic eruptions form bedded (and slumped) hyaloclastites that indicate a waning late stage summit activity (Batiza *et al*., 1984).

The initial growth phase of a seamount is governed by central magma conduits which produce seamounts with a circular base. For instance, several of the seamounts in the Central Indian Ocean Basin either have a circular shape (Fig. 2A; 3) or are elliptical (Fig. 2B). Subsequently, the shape is modified by later growth due to eruptions fed by dykes and these produce a star-shaped base (Geisha Seamount, NW Pacific Basin, Vogt and Smoot, 1984). There are instances of multiple peaks resulting in a seamount complex as to the East of the 79°E fracture zone in the Central Indian Ocean Basin. Although construction rates are very different, this interpretation of the magma plumbing system for the development of large seamounts is similar to sub-aerial edifices (Ryan *et al*., 1981).

Besides the shapes, seamounts may show the presence of flank cones and lava ponds (Fig. 2A; 3). The relationship between seamount gravimetric amplitudes and the age of the seabed implies an upper limit on seamount height that depends on melt availability, magma driving pressure and plate thickness (Clouard *et al*., 2003). Specifically, compressional stresses directly beneath the seamount, as a consequence of the lithosphere's flexural response to loading, may eventually exceed the magma driving pressure and prevent magma from surfacing, thus limiting the growth of the seamount. This is exemplified by the seamounts found in the Central Indian Ocean Basin, wherein regional stress patterns maintained the orientation of the seamount chains while local stress led to magma upwelling and formation of the seamounts (Das *et al*., 2007).

PETROLOGY

Lava eruption is determined by temperature, viscosity, composition and extrusion rate (Bonatti, 1967). These factors produce volcanic forms such as pillow and sheet lavas, lava lakes, "paving-stones" and hyaloclastites. Bonatti and Harrison (1988) investigated the eruption style of MOR and seamount basalts in relation to magma temperature and viscosity and proposed an eruptive style model for seamounts (especially intraplate ones) that involved three stages of eruption style. At the base of the seamount, sheet basalt would form during the early stages of its growth and, as the seamount develops, pillow basalt would be more dominant. During its final growth stage, hyaloclastites would occur at the summit.

Seamounts host hyaloclastites, pillow basalts, alkali basalts and serpentinites that may evolve from multiple melting domains due to the large-scale thermal structure and lithology of the mantle. Axial and seamount lavas have comparable crystal assemblages and chemistry, melt inclusion diversity and a similar range in composition, suggesting that their magmas are formed from a single parent one of a relatively homogenous source. The parent magmas are initially fractionated and mixed but later the magma paths of axial and seamount magma would diverge. Axial lavas continue through the magma chamber, become more fractionated and have more phenocrysts removed while seamount magmas ascend without further significant fractionation and crystal separation (Sours-Page *et al.*, 2002). Therefore, seamounts basalts are enriched in rare earth elements (REE) and incompatible elements vis-à-vis the MORB (*e.g.*, Zindler and Hart, 1986).

Two seamounts (45°N, Mid-Atlantic Ridge) consisting of granites, granodiorites, granite gneisses and diorites are directly related to basalts, metabasalts, serpentinised gabbro and peridotites (Aumento, 1969). The presence of silicic rocks suggests that differentiation progresses farther than was believed possible at the MOR. Seamounts may also host ultramafic and ultrabasic rocks. The gabbros from the Macdonald Seamount probably originated from a plume magma and their texture and mineralogy indicate crystallisation in an undisturbed reservoir, or in an undisturbed part of a magma chamber. Subsequently, alteration resulted due to fracturing during cooling and was enhanced by magma pressure and hydration (Bideau and Hekinian, 2004).

Hyaloclastites from the MOK seamount are flat slabs up to 10cm thick with unusually fresh basalt glass shards loosely cemented in a fine grained matrix. The shapes and compositions of the shards, their sedimentary structures, their occurrence as thin blanket deposits and the abundance of pelagic sediment in the matrix indicate an explosive origin followed by transport in a high density flow (Batiza *et al.*, 1984). The upper flank of Seamount Six (Cocos plate) have sheet- hyaloclastites at a water depth between 2024 and 1723m. Pillow talus, knobbly

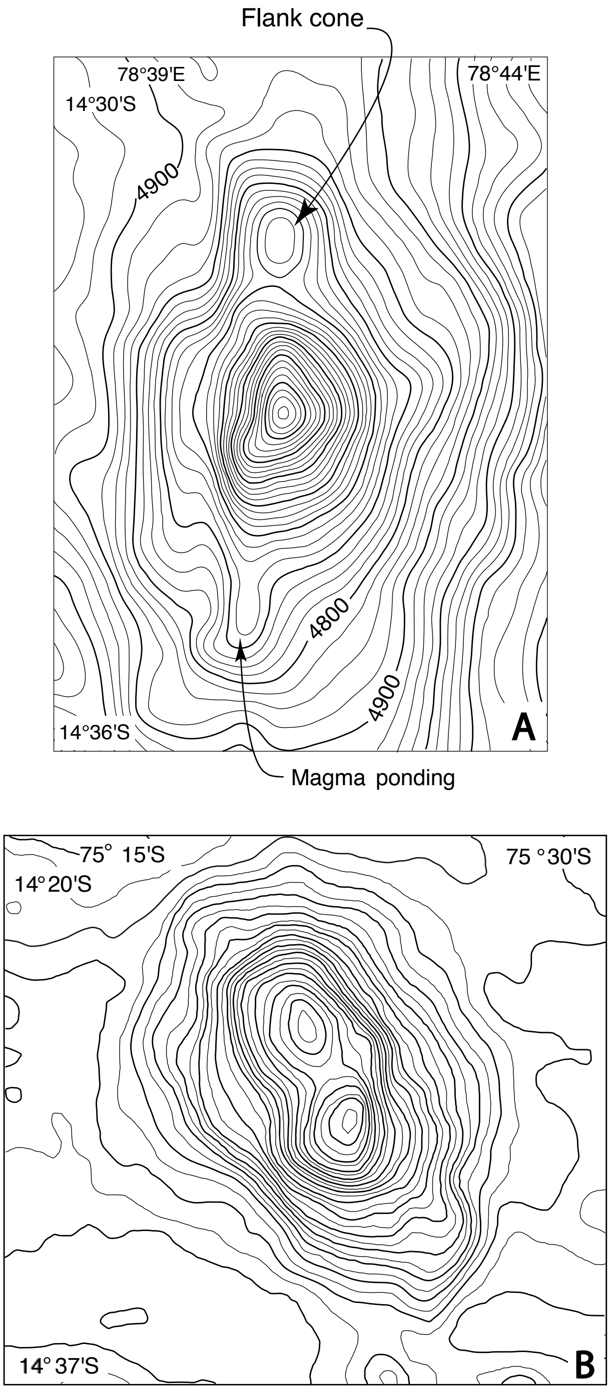

FIGURE 2 | Bathymetry of seamounts from the Central Indian Ocean Basin (Das *et al.*, 2007). A) A conical seamount (h 850m, slope 20°) with an N–S extended base with a cone located on the flank in the north and magma ponding feature in the south. B) A composite seamount of a height of 1200 m and slope angle of 9°.

fist-sized lava fragments and thin sheet lava (<10cm) underlie the hyaloclastites made of sideromelane shards and Limu O'Pele (Maicher *et al*., 2000). Turoi seamount in Society hot spot region has trachytic lavas with bread crust surface and fragmented pumice flow coated in hydrothermal crusts (Binard *et al*., 1992). Apparently, seamounts exhibit a variety of lava forms and could consist of ultrabasic/ ultramafic to silicic rocks in contrast to the MOR where basalt is ubiquitous.

EMPLACEMENT MECHANISM

Volcanoes erupt at fixed hotspots (Wilson, 1963) and on a moving plate. In this latter case volcanoes form a series of seamounts (*e.g.*, Hawaiian-Emperor chain) and the trail of old volcanoes in the chain indicates the direction of plate movement (Morgan, 1972). The use of hotspot produced seamounts in plate tectonic reconstructions has limitations due to the multiple sources of error and ambiguity that constrain radiometric ages. Unless the hotspot has maintained a steady and voluminous flux rate over long periods of time, its exact location is difficult to determine (Wessel and Kroenke, 1998). The Pacific plate is considered to host 14 hotspots but, at most of these hotspots, volcanism does not seem to originate from deep-mantle plumes (Clouard and Bonneville, 2001).

Intraplate seamounts form either from the partial melting of a rising plume, from tensional stresses that fracture the lithosphere and allow magma to ascend or from a combination of these processes. Concrete evidences are unavailable to suggest that intraplate seamounts originate differently (*e.g.*, Batiza, 1982). For instance, the abundance of non-hotspot seamounts may be a function of the age of the lithosphere. In some cases, fracture zones may control the sites of non-hotspot and hotspot seamounts. Furthermore, plume and non-plume intraplate volcanism may define a single population that exhibits chemical systematics and suggest significant intraplate volcanism to originate in the upper mantle (Haase, 1996).

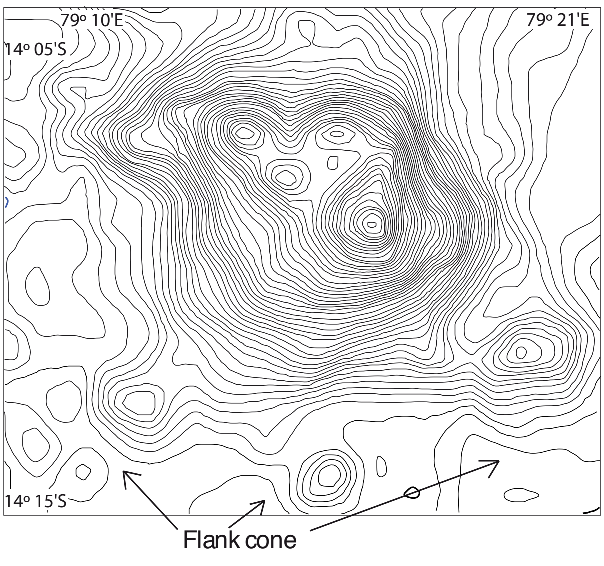

FIGURE 3 | An example of a complex seamount site near the 79°E fracture zone of the Central Indian Ocean Basin (Das *et al*., 2007). Note the presence of multiple peaks and flank cones.

Mantle heterogeneities could produce near-ridge seamounts. This explains the chains trending in the direction of absolute plate motion and possibly the observed asymmetry of distribution on the flanks of some ridges, *e.g.*, the Juan de Fuca Ridge. On the Cocos plate, where the absolute and relative motions differ, most chains are parallel to relative motion and suggest lithospheric movement or convection rolls that are parallel to relative motion that may trigger seamount formation. However, not all near-axis seamount chains run parallel or sub-parallel to relative or absolute plate motion (Batiza, 2001).

On the flanks of the South East Pacific Rise several chains of near-axis seamounts inversely correlate with the seamount volume between adjacent chains suggesting the origin of magma in plume-like sources in the upper mantle and the control on seamounts by melt availability. Perhaps seamounts produced in a narrow zone near the axis correspond to a T_e of 4-8km and being independent of spreading rates indicate the influence of the lithosphere. But the extent to which near-axis seamounts are controlled by magma availability or lithospheric vulnerability, or both, is unknown (Batiza, 2001).

Mixing between plume and ridge mantle sources and plume-ridge inter-action may form a second type of hotspot island chain wherein the linear chain is not parallel to the absolute plate motion for normal plumes, rather it trends intermediate between the absolute and relative plate motions (Morgan, 1978). Most mantle convection models show no upwelling in the intraplate region hence, intraplate non-plume generated seamounts could form by i) secondary upwelling events in intraplate regions, as with Richter and Parsons longitudinal upper mantle convective rolls (Richter, 1973, Richter and Parson, 1975) called "Richter rolls", (*cf.* Batiza, 2001) ii) initiation of localised upward mantle flow into depressions or recesses at the base of the lithosphere, and iii) diffuse regional mantle upwelling generated by a weak mantle plume.

Bonatti and Harrison (1976) proposed that in lieu of hot spots, "hot lines" in the mantle could produce linearly disposed seamounts and volcanic islands. According to these authors, Easter Island (south-eastern Pacific) could be a manifestation of a hot line wherein the mantle convection rolls (Richter-Parsons rolls) or spouts are located parallel to the plate movement. The petrology and geochemistry of the Easter Island basalts also suggest their derivation from a mantle plume (Bonatti *et al*., 1977).

From the above information it is apparent that no single mechanism could account for the production and disposition of seamounts. Several factors influence seamount formation, including mantle upwelling associated with superfast spreading, off-axis mantle heterogeneities, mini plumes and local upwelling and the vulnerability of the lithosphere to magma penetration (*cf.* Scheirer *et al*., 1996).

SIGNIFICANCE OF SEAMOUNTS

Seamounts affect geochemical cycles and mixing processes in the oceans as well as oceanic circulation, thermohaline structure, biological productivity, formation of eddies, etc. The oceanographic effects near a seamount depend on the morphology, the local component of the Earth's rotation rate, local density and turbulence of the sea water, currents and eddies, and the hydrothermal or magmatic activity of the seamount (Lavelle and Mohn, 2010). The dissipation rate of kinetic energy showed that the magnitude of mixing near a shallow seated seamount in the NE Pacific was 100 to 10,000 times greater than at a distance (Lueck and Mudge, 1997).

SEAMOUNTS AND SEISMICITY

Large seamounts may hinder plate subduction, trigger slides and earthquakes and also generate tsunamis (Schmincke, 2004). Newly created lithosphere at the MOR, spreads and ages and the seafloor gradually attains a typical depth of about 5km below the sea level. Eventually the crust would encounter a subduction zone wherein the pressure crushes any void below a depth of 1km. Hence, either the seamounts are sheared off at a shallow depth to make the top of the subducting seafloor smooth, or are covered by sediments (Ruff, 1996). Recently, Staudigel *et al*. (2010) reviewed the several effects caused by subducting seamounts.

On 2nd June 1994, a large subduction thrust earthquake (M_s 7.2) produced a devastating tsunami on Java. The size and timing of the tsunami was explained by using a source model (Abercrombie *et al*., 2001). On 25th January 1998, within the summit caldera of Axial volcano, central Juan de Fuca Ridge, an intense seismic swarm was detected that lasted 11 days and produced 8247 earthquakes. The largest three swarms were located within the caldera and their timings and mechanisms corresponded to the adjustment of the caldera floor as magma withdrew below the summit (Dziak and Fox, 1999).

SEAMOUNTS AND HYDROTHERMAL ACTIVITY

The possibility of hydrothermal activity at MOR was noted by Boström *et al*. (1969) and Corliss (1971) and was confirmed by the discoveries of Fe-Mn rich sediments, black and white smokers (sulphide and oxides, respectively) and methane vents. A survey of 20-25% of the 70,000km of total MOR length has revealed 280 hydrothermal sites of which ~10% are along the Indian Ocean ridges but only two are confirmed (Baker and German, 2004). Although MOR host a majority of hydrothermal deposits, more significant ones occur at subduction related settings, back- and fore-arc basins and seamounts. Relatively young seamounts that form at spreading centres and drift later are particularly congenial for hydrothermal activity.

Alt *et al*. (1987) identified four types of hydrothermal material at seamount sites: massive sulphides, material containing opal-barite-atacamite, Fe-Mn oxides and clays. At 21°N East Pacific Rise the Green Volcano hosts sulphide chimneys and mound deposits, Fe-Mn sediments and crusts and massive deposits of opal-barite while the Red Volcano has Fe-Mn red-orange muds, crusts, nontronite and talc within its caldera. Sulphides replaced by Fe oxyhydroxides occur with jarosite, natrojarosite and opal intergrown with barite and atacamite, in fractures, pores and surfaces. The non-sulphides form either by oxidation of sulphides or are low-temperature (170-30°C) hydrothermal precipitates.

Along a north-south fissure on the Axial Seamount (Juan de Fuca Ridge) fluids are discharged at low temperatures (~29-35°C) and extrapolation to the end-member primary fluid gives a high value (532°C). A few chimneys consist of sulphides, amorphous silica and barite (Pirajno, 1992). The Loihi Seamount consists of precipitates of yellow-brown goethite-Fe-montmorillonite-nontronite that are alteration products of high-temperature sulphides (Pirajno, 1992). In the crater of Palinuro Seamount (Tyrrhenian Sea) massive sulphides occur (tennantite-tetrahedrite, luzonite) and in addition, pyrite, barite, native Ag, bismuthinite and stibnite, an assemblage resembling the high level areas of the porphyry systems are also observed (Minniti and Bonavia, 1984). The Manji Seamount, northeastern margin of the Philippine Sea plate, hosts porphyry copper outcrops at a water depth of 700m (Ishizuka *et al*., 2002).

Wheat *et al*. (2000) collected fluids at two sites to monitor the crustal and hydrothermal conditions after an event in October 1996. An eruption (25th January 1998) at the summit of Axial volcano resulted in extensive and vigorous hydrothermal discharge and a temperature increase (0.6°C) up to 115m above the seafloor (Baker *et al*., 1999). Submersible investigations near the 13°N East Pacific Rise hydrothermal field, close to a pit-crater at the top of a young seamount, showed a large sulphide mound (70m high, 200m diametre) formed at a fast spreading ridge (Fouquet *et al*., 1996). The authors suggested that off-axial volcanoes close to the ridge are first order targets to discover active or inactive large deposits along fast- to medium-spreading ridges.

Recently, Hein *et al*. (2010) suggested six types of metal-rich deposits to occur on seamounts: hydrogenous ferromanganese (FeMn) crusts, hydrothermal iron oxides, hydrothermal manganese oxides, hydrothermal sulphide, sulphate and sulphur deposits, phosphorite deposits and hydrogenetic FeMn nodules. According to those authors, due to the slow growth rate, high surface area and high porosity of FeMn crusts make these conducive to adsorb rare 'high tech' metals like tellurium, cobalt, bismuth, zirconium, niobium, tungsten, molybdenum, platinum, titanium and thorium. For instance, platinum group elements and gold are of significance in the Co-rich ferromanganese crust of the Afanasiy–Nikitin Seamount in the Indo-Australian Basin (Banakar *et al*., 2007). These "high tech" minerals are of commercial interest to the manufacturers of solar cells, computer chips and hydrogen fuel cells (Hein *et al*., 2010). Trachybasalt of the Conical Seamount south of Lihir Island, Papua New Guinea contains up to 230ppm gold and native gold as inclusions in sphalerite, galena and amorphous silica (Herzig *et al*., 1999).

Volatile metal and metalloid elements could indicate significant degassing of magmatic vapours during submarine eruptions leading to the net transfer of chemical elements to seawater in addition to that arising from seafloor hydrothermal systems. A model predicted that exit fluxes, formed due to degassing, have the highest volatility and their content in the main group and transition elements is up to 10^2-10^3 greater at seamounts than at MOR hydrothermal sites (Rubin, 1997). Some of the seamounts in the western Pacific discharge elemental sulphur in liquid form (Embley *et al*., 2007) and liquid carbon dioxide (Lupton *et al*., 2006).

Phosphorites (P_2O_5 up to 33%) recovered from the crests of three subsided seamounts in the Eastern Atlantic (6°N-9°N) were formed from the replacement of the shallow water reef limestones of Middle Eocene age (Jones *et al*., 2002). Analysis of laminated crusts and massive slabs of phosphorites from Error Seamount (NW Arabian Sea) indicated that microbes played a vital role during early diagenesis of the phosphorites when the seamount was subaerially exposed (Rao *et al*., 1992). The above investigations suggest that seamounts are favourable sites for the formation of a variety of hydrothermal deposits.

SEAMOUNTS AND BIODIVERSITY

Some seamounts have enhanced biodiversity, unique biological communities and high levels of endemic species and act as regional centres of speciation, stepping stones for dispersal across the oceans and shelter for species with a shrinking range (Emmett Duffy, 2008). In the early 1960s, Russia initiated studies of seamounts mainly to establish new deep-sea fishing grounds. A review of seamount biota and biogeography indicated a total of 597 invertebrate species occur at seamounts. Only five seamounts of the estimated more than 30,000 seamounts accounted for 72% of the species recorded and only 15% of the species were seamount endemic (Wilson and Kaufmann, 1987).

The distribution pattern of biological communities with little or no overlap at even a few kilometres apart supports Johannesson's hypothesis that many taxa adapted to seamount environs have limited dispersal so as to maintain their populations. This may be due to the small size of seamounts, the distance between them and the prevalent conditions (de Forges *et al*., 2000).

Fujioka *et al*. (2002) proposed the existence of the "Serpentinite biosphere" and suggested that serpentinites act as a receptacle of the deep biosphere. Investigations of the Chamorro seamount (Mariana forearc) revealed serpentinite flows that provide hydrogen gas and methane, which supply energy for the extremophile life and induces buoyant rise of serpentinite diapirs. These diapirs capture and transport portions of the deep biosphere during their ascent. Submersible recoveries at the Nishi-Jolyo back-arc seamount included basaltic andesite and celadonite hosting bacteria-like fossils, implying microbial activity and selective concentration of Fe (Ishizuka *et al*., 1998). Interestingly, the presence of new organisms and microbes at seamounts has been noticed (Emerson and Moyer, 2010).

Current-topography interactions on seamounts include semi-stationary eddies (Taylor columns), internal wave reflection, tidally induced currents and eddies, trapped waves and eddies shed downstream. Currents measured up to 48cm/second over seamounts could enhance upwelling and production of plankton biomass and this may lead to increased predators (Emmett Duffy, 2008). Sorokin (1987) measured high primary production (0.3-0.8g C/m^2 per day) near the Western Indian Ocean seamounts, in areas located in the trade wind current above the Fred and Farquhar seamounts and near the Nossi Be island, Madagascar (0.5-2.0g C/m^2 per day). Circulation cells near the seamounts help recruit biological species (*e.g.*, Mullineaux and Mills, 1997).

Since seamounts provide habitats and spawning grounds, a variety of marine mammals, sharks and cephalopods and sea birds are more abundant near shallow seamounts (Emmett Duffy, 2008). Reportedly, the avifauna at the Fieberling guyot, NE Pacific Ocean, changed from small procellariiformes away from the seamount to an assemblage dominated by larger tubenoses. Compared to adjacent waters, sea bird density and biomass, within a 30km radius from the seamount summit, were 2.4 to 8 times higher, respectively. Individual sea bird taxa were 2 to 40 times more abundant at the Central North Pacific seamounts (Haney *et al*., 1995). Near seamounts, the most dominant organisms are suspension feeders, *e.g.* corals, in contrast to the typical deep-sea deposit-feeding animals. Sediments on seamounts host polychaetes, oligochaetes and gastropods while xenophyophores may be dominant (Emmett Duffy, 2008). A study of core and grab samples revealed about 82 species of macrofauna near the Central Indian Ocean Basin seamounts (Ingole and Iyer, 2006).

Seamounts may retain fossils in centimetre deep pockets present in the bed rocks and when the sediments are eroded the oldest fossils are exposed hence, most of the early palaeontological dates from the oceans have come from seamounts (Menard, 1964).

The United Nations in its 2002 General Assembly urged researchers to urgently "consider 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 United Nations Convention on the Law of the Sea". Gianni (2003) discussed a strategy for a large-scale system of marine reserves for seamounts, deep-sea ridges and plateaus. Some of the examples of seamount conservation are those in the Exclusive Economic Zone of New Zealand, the Azores, Gulf of Alaska and New England seamounts (North Atlantic). Fishery and related activities are banned near these seamounts while the Condor Seamount (the Azores) is a marine observatory (Morato *et al*., 2010). Ecological conservation and prevention of fisheries at seamounts near the coast could get a boost by the cooperation of the local fishery community.

SEAMOUNTS AND ATMOSPHERIC OXYGEN

The time and source of oxygen on Earth is not known yet. Kump *et al*. reported that prior to 2.5 billion years, the Earth lacked oxygen (Science Daily, 2007). Interestingly, biomarkers in rocks 200Ma older than that period show oxygen-producing cyanobacteria that released oxygen at the same levels as today, oxidised the soils and formed red beds. However, such occurrences were negligible during the Archaean. Hence, the ancient Earth should have had an oxygen-rich atmosphere but paradoxically, the oxygen was reduced and removed from the atmosphere. Kump *et al*. suggested that submarine volcanoes produced a reducing mixture of gases and lavas that effectively removed oxygen from the atmosphere and this was bound to minerals.

The above postulation was tested by examining the geologic record from the Archaean and the Palaeo-Proterozoic for evidences of volcanoes. Professors Kump and M.E. Barley found that during the Archaean there were hardly any terrestrial volcanoes in contrast to a high population of submarine ones, while during the Palaeo-Proterozoic abundant terrestrial and submarine volcanism occurred. Although sub-aerial volcanoes increased after 2.5 billion years, these did not reduce the atmospheric oxygen. The authors studied the ratio of submarine to subaerial volcanoes in relation to the geologic time and proposed that because submarine volcanoes erupt at lower temperatures than terrestrial volcanoes, they are more reducing. Hence, as long as the reducing ability of the submarine volcanoes was larger than the amounts of oxygen created, the atmosphere had no oxygen.

To recapitulate, it is recognized that seamounts are unique and important features that not only affect the crustal structure but also play a key role in influencing the marine ecosystem. Some of these factors are represented in Figure 4 which illustrates the construction and evolution of seamounts, the associated processes (volcanism, hydrothermal activities) and products (lava flows, shards) and their ultimate subduction and destruction, amongst others. The figure also represents the influence of the seamounts on the biological and oceanographic parametres and the co-existence of diverse biodiversity.

Globally less than 400 seamounts have been sampled and hardly 100 have been intensively sampled (Stocks, 2009) hence, seamounts have not yet been studied in detail. Investigations of seamounts would also help to answer questions such as: Does a casual or causal connection exist between seamount morphology and volcanism? What controls the production of seamounts of variable dimensions? Why do some seamounts display a suite of rocks while others are petrologically monotonous? Are seamounts affected by thermal structure and composition? Do seamounts represent slow evolution of the mantle with time? Why are some seamounts congenial sites for hydrothermal activities? (Iyer and Das, 2005).

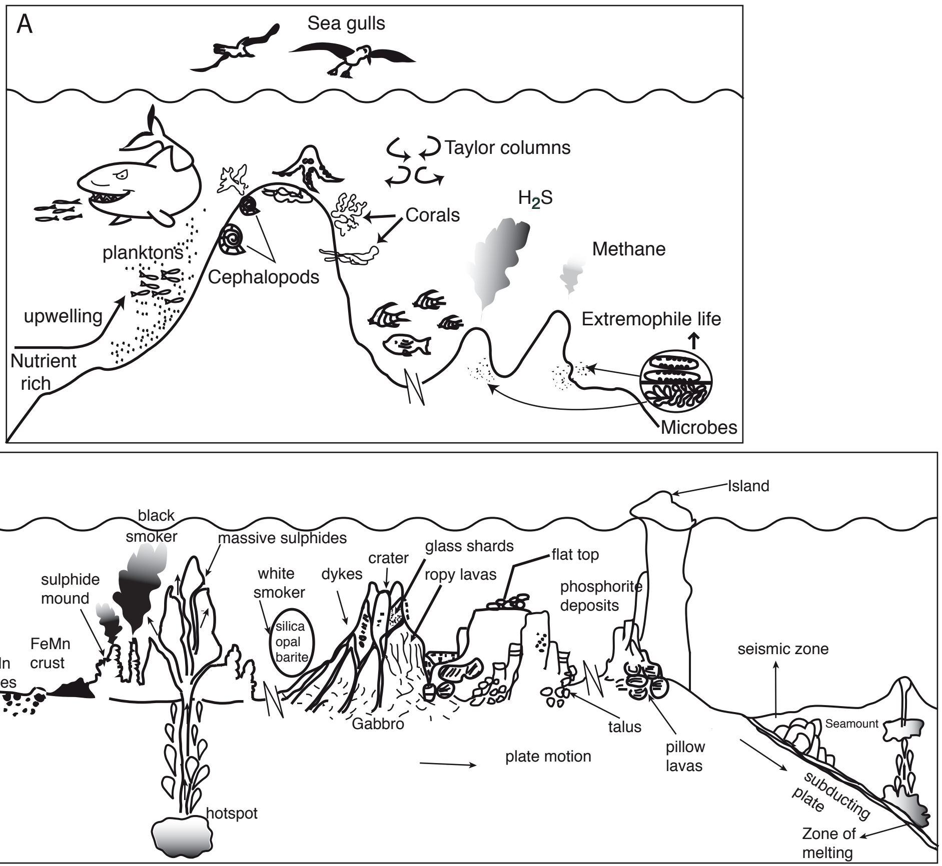

FIGURE 4 | Cartoons to show the production of seamounts and their significant role in the marine environment. A) The figure shows the influence of the seamounts on oceanographic parametres and the existence of a diverse biological community. B) The figure depicts the two types of seamounts (intraplate and hot-spot), their "decay and death" in a subduction zone. The associated features and processes at the seamounts are also portrayed.

CONCLUSIONS

Several theories and processes have been proposed to understand the formation of seamounts. For instance, propagative fracture, off-axis production, hotspot-ridge interaction, off volcanism, magma density and viscosity, depth of the magma chamber, subsidence, caldera collapse, explosive or re-active volcanism, amongst others. Based on the available data we consider that a single unique process can not explain the variations in the abundance and emplacement mechanisms of the seamounts. The major characteristics of a seamount's morphology are its height, base width, slope angle and summit types. But these features could be controlled by local and regional tectonic settings, sediment cover, physico-thermal properties of the lithosphere, conduit geometry, chemical composition and magma dynamics.

Our studies indicate that the seamounts could considerably influence several oceanographic parametres and the marine life in their vicinity. Additionally, seamounts are congenial locales for hydrothermal activities that could result in the formation and concentration of economically viable sulphide and ferromanganese oxide deposits. It is suggested that stringent regulations and measures could help save the unique environment prevalent at seamount sites.

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