

## **Submarine Silicic Volcanism**

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### **Abstract**

The occurrence of submarine silicic volcanics is rare at the mid-oceanic ridges, abyssal depths, seamounts and fracture zones. Hydrothermal processes are active in submarine silicic environments and host ores of Cu, Au, Ag, Pb, Zn, Mo, etc. Here we present the globally occurring submarine silicic volcanisms and associated hydrothermal activities and also discuss the origin of silicic volcanics of the Central Indian Ocean Basin.

### **Keywords**

Marine, silicic volcanics, processes, origin, hydrothermal, CIOB

### **Introduction**

High-silica containing rocks like granites, granodiorites, quartz-diorites, rhyolites, dacites, plagiogranites etc. are associated with seismically active continental margins and with zones of block faulting and extension in the continental crust. In contrast, silicic rocks are rare in the oceans vis-à-vis basalt and its variants. The bimodal distribution of basalt-rhyolite along the mid-ocean ridges (MOR) indicates their extrusion in anorogenic settings during crustal extension and normal faulting (Christiansen and Lipman, 1972). Subaqueous eruptions are abundant and the proportions of those that are explosive, although poorly known, are significant (White et al., 2003). The knowledge of deepwater silicic volcanism comes from inferences based on ancient terrestrial successions. We synthesis the findings of submarine silicic volcanics in terms of petrology, magmatic processes and the associated hydrothermal activities.

### **Underwater eruptions**

Underwater eruptions are either quite or explosive and are determined amongst others, by the depth and pressure of the water column, magma composition, amount of volatiles and extent of interaction between magma and water. The depth at which explosion takes place is called as pressure compensation level (PCL) and occurs due to exsolution of magmatic volatiles

(Fisher and Schmincke, 1984). Silicic magmas being volatile-rich tend to produce violent eruptions. Hence, PCL may exceed 1000 m for silicic and volatile-rich mafic alkali magmas but is less than 500 m for most basaltic magmas (McBirney, 1963).

### **Occurrences of silicic volcanics**

Oceans silicic rocks occur in various tectonic/geomorphic settings such as back arc, ridges, along arcs, abyssal plains, ocean islands/seamounts and fracture zones (Table I, Fig. 1).

## a) Along ridges

Silicic rocks have been recovered, although rarely from MOR, within water depth of 1500 to 1800 m (Christiansen and Lipman, 1972). Some of the examples of occurrences of silicic rocks along the ridges are detailed below.

**Mid-Atlantic Ridge (MAR):** Along the faulted scraps of two seamounts (45° N) granites, granodiorites, granite gneisses, diorites and amphibolites have been recovered from >2000 m water depth (Table 1). The age, isotopic composition, chemistry and physical appearance of the diorites are strong indicators that these occur in situ and are associated with the basalts, metabasalts, serpentinised gabbro and peridotites (Aumento, 1969). The silicic rocks at these seamounts suggest that differentiation progresses farther than is generally thought possible at MOR. Coleman and Peterman (1975) suggested that slow-spreading centres might favour the formation of the oceanic plagiogranites as fractionation is more likely to occur in such situations.

**Pacific-Antarctic Ridge (PAR):** Silicic lavas have been recorded from a 290 km long section to the north of this ridge (Table I) adjacent to the active Foundation plume. A dome (37° 40'S) rising to a depth of 2120 m is cut by a cleft and the lavas from the summit and cleft include aphyric dacites and andesites with >5 mm thick glass crust. Conchoidal fractures along with strongly elongated and flow aligned vesicles characterise these lavas that have a range of SiO<sub>2</sub> at a given Mg and the dustings of MnOx suggest that most of the lower lavas are older (Stoffers et al., 2002).

**Iceland:** Trondhjemites, quartz diorite xenoliths and rhyolites occur in Iceland in association with basalts along Jan Mayen and on many other oceanic islands (Table I). The ice-covered Oraefajokull stratovolcano is composed mainly of sub-glacial pillow lava and hyaloclastite tuff, ranging from basalt, via hawaiite, mugearite, benmorite and trachyte to rhyolite (Prestvik et al., 2001). A plinian eruption produced rhyolitic ash and pumice while an initial phreatomagmatic explosion gave rise to lithic fragments characterised by bomb-like pumice blocks (Selbekk and Tronnes, 2007).

**Galapagos Spreading Centre (GSC):** Rocks ranging from normal-Mid Ocean Ridge Basalts (N-MORB) through Fe-Ti basalts and andesites to rhyolites have been recovered (Table I) on the GSC, Pacific Ocean (Byerly, 1980). The petrological model by Christie and Sinton (1981) showed that when the magma volume was too small and cooling rate too rapid and no eruption was possible, then increased magma supply would result in eruption of initial unfractionated lavas with little or no residence in the crust. Further eruption leads to a decrease in magma supply and this may cause the limited magma to reside in the crust and fractionate in shallow isolated chambers. Extensive fractionation can produce silicic melts in regions where a delicate balance between cooling rates and magma supply rates exists. These authors proposed that if supply rate continues to increase, mixing might occur prior to extreme fractionation and produce heterogeneous magmas.

## b) Along arcs

Silicic volcanism along island arcs is common and not only shallow but also deepwater explosives and effusive eruptions are possible. Studies on Ordovician Bald Mountain (United States) (Table I) volcanic-hosted massive sulphides have distinctive characteristics to recognise silicic products in very deep-water settings wherein fluidal rhyolite may be produced when hydrostatic pressure reduces exsolution of dissolved water in the magma (Busby, 2005). Fluidal rhyolites are enigmatic because rhyolitic magmas are generally considered to be too viscous to fountain or to exhibit other

fluidal behaviours, the exception to this is high-temperature fissure eruptions (McCurry et al., 1997). The Myojin knoll submarine silicic caldera (Table 1) of the Izu-Bonin (Ogasawara) arc at 900-500 m below sea level is a composite volcano of rhyolitic lavas, shallow intrusions, volcanoclastic deposits and rhyolitic pumice (Fiske et al., 2001). Yumul et al. (2003) found that the volcanic center of Central Luzon, Philippines hosts basalts to dacites that formed through partial melting, fractionation, magma mixing and mantle-melt interaction.

### **c) Abyssal**

Silicic volcanism at an off-axis geothermal field in the Mariana Trough resulted in rhyodacitic pumice between 2600 and 3600 m water depth (Table 1). A possible source for the silicic magma was melting of the sea floor sediment, which includes altered volcanoclastic debris from the adjacent island arc and siliceous hemipelagic muds (Lonsdale et al., 1985).

### **d) Ocean islands/Seamounts**

Within oceanic islands two differentiation trends of alkalic magma series were recognised: 1) undersaturated, the ultimate differentiation products being nepheline-bearing phonolites and 2) oversaturated, the final differentiates are quartz-bearing alkali rhyolites (comendite or pantellite) (Wilson, 1989).

The Atlantic islands of Ascension and the Azores are sites of alkalic magmas evolving to quartz-saturated residue (Clague, 1987). Compositionally, the quartz syenite xenoliths and their silica-oversaturated host rocks from the Azores and the Canaries are cognate and the silica-oversaturated host rocks probably derived by differentiation from basaltic melts (Schmincke, 1973).

The Galápagos Islands consist of 19 shield volcanoes of which Alcedo (Table 1) has erupted ~1 km<sup>3</sup> of rhyolite. The crystallisation of anhydrous phases resulted in exsolution, vesiculation and explosive eruption (Geist et al., 1995).

Rhyolitic magmas have formed repeatedly in Iceland (Table 1) and have erupted explosively several times from Hekla volcano (Sigvaldason, 1974). Investigations of Society hot spot region show the Turoi seamount to consist of trachytic lavas with bread crust surface and pumice core. The fragmented pumice flow is coated by indurated hydrothermal crusts and located between 2200 and 2400 m water depth (Binard et al., 1992).

### **e) Fracture zones (FZ)**

Although volcanism occurs in areas of divergence, convergence and hot spots, but those on the Pacific Plate (Table 1) do not belong to any of these categories (Hirano et al., 2006). They proposed that small alkalic volcanoes formed from small amount of melts which originated in the asthenosphere and the eruptions along lithospheric fractures occurred due to plate fracturing during subduction. Hall and Gurnis (2005) suggested that FZ with strengths less than ~10 MPa can evolve into self-sustaining subduction zones e.g., Marianas FZ transitioned into a subduction zone due to polarity changes. The transformation of FZ to subduction zones could lead to silicic eruptions. Probably the type of eruption reported by Hirano et al. (2006) for the Pacific could be the initialisation of such a process. Hey and Vogt (1977) suggested that differentiation of magma ponded against transform faults could give rise to silica enrichment. For instance at the Galapagos Ridge fractionation resulted in enrichment, removal of Fe-Ti by fractionation and subsequently lead to silica enrichment in residual magmas along transform

faults as well as FZ. Hence, a magma ascending through FZ would evolve considerably to produce silica-rich differentiates.

### **Genesis of silicic magmas**

Dacites, rhyodacites, calc-alkalic rhyolites, granodiorites and quartz-diorites commonly occur along the various tectonic settings (Table 1). Of these the first three are more abundant as pyroclasts than as lavas. Processes such as differentiation, fractionation, magma mixing and partial melting have been forwarded for the origin of silicic magmas and these are supported by several experimental studies (Annen et al., 2006). A silicic calc-alkalic magma can form by differentiation from a more mafic parent magma and by crustal anatexis. Several evidences show the origin of some rhyolitic and andesitic magma to be related due to similar tectonic settings.

**Fractional crystallisation:** This process produces a series of residual liquids of variable compositions as compared to their parental magmas and is best explained by the Bowen's reaction principle (Bowen, 1922). Crystal fractionation was suggested as a mechanism for the silicic lavas at PAR (Nielsen and DeLong, 1922). Similarly, the Alcedo's rhyolites of Galapagos Archipelago are the residual liquids derived by ~90% fractionation (by weight) of plagioclase, augite, titanomagnetite, olivine and apatite from the most primitive olivine tholeiite (Geist et al., 1995). The formation of silica-rich residues by crystal-liquid differentiation from tholeiite was also suggested by Dixon and Rutherford (1983). Such crystallisation of abyssal tholeiites forms layered or stratified magma chambers with alkali and volatile enriched silicic melts e.g., in Tonga region (Hawkins, 1985).

**Magma mixing:** Mixing of magmas could explain petrogenetic models of co-genetic suites of igneous rocks formed in different tectonic settings. For example, many of the geochemical and petrographic characteristics of MORB can be explained if the ridge axis magma chambers are periodically refluxed with new pulses of primitive magma, which mix with batches of fractionated magma in the chamber (Dixon and Rutherford, 1983). Turner and Campbell (1986) suggested that the extent of mixing between the inflowing magma and the chamber magma depends on the flow rate and on the relative densities and viscosities of the two magmas. Overturning of a volatile-rich mafic layer into a cooler silicic layer leads to quenching, exsolution of a gas phase and trigger an explosion.

The outer less viscous component (basic magma) offers less resistance to flow as compared to the more viscous component. Hot new magma if injected in sluggish crystal reservoir will act as a lubricant and trigger the rise of high viscosity magma to the surface (Carrigan and Eichelberger, 1989). The silicic lavas from PAR are best explained by mixing between highly fractionated magmas formed at high oxygen fugacity and an unevolved basaltic melt (Stoffers et al., 2002).

**Partial melting:** The partial melting of a silicic crust produces silica-enriched residue (Walker, 1966). Sigurdsson (1977) proposed a model for the Icelandic rhyolites that indicates bimodal volcanism and attributed the rhyolites to the melting of the earlier formed plagiogranites, which had originated from crystallisation of a basaltic magma. The availability of plagiogranite for melting is limited to regions of older crust and probably occurs during an event of rift jump. But since the  $Sr^{87}/Sr^{86}$  ratio of the felsic rocks is indistinguishable from those of basalts, it was concluded that the granophyres, rhyolites and obsidian of Iceland originated from partial melting of the oceanic basalts and not by melting of old sialic rocks under Iceland (O'nions and Gronvold, 1973).

Hydrous partial melting of basaltic crust could be another mechanism for the formation of silicic magmas. Dixon and Rutherford (1983) conducted hydrous and anhydrous experiments on a primitive oceanic tholeiite from GSC (Mg# 0.65 %,  $K_2O=0.06$  %) and on a more evolved oceanic tholeiite from Hawaii (Kilauea: Mg# 0.53 %,  $K_2O=0.44$  %) to characterise the minerals and residual melts present over a range of melting (10-100 %). The residual melt after 90% crystallisation (or 10 % partial melting) was granitic and compositionally akin to the Icelandic rhyolites. They concluded the possibility of producing a natural Icelandic granite from an evolved Kilauea-type basalt under low  $f_{O_2}$ ,  $P_{fluid}=1$  to 2 kb, and  $P_{H_2O} < P_{total}$  conditions, a major factor being the fractionation of Fe-Ti oxides. After the Fe-Ti oxides begin to crystallise,  $Al_2O_3$  shows little change in abundance, MgO and CaO get depleted, and  $SiO_2$ ,  $Na_2O$ ,  $K_2O$  and  $P_2O_5$  are enriched in the residual liquid (Middlemost, 1985). Koepke et al. (2007) model for partial melting of gabbroic rocks in tectonically active areas of the MOR shows that  $TiO_2$  helps to discriminate between different processes.  $TiO_2$  is relatively low in melts generated by anatexis of gabbros which have initial low  $TiO_2$  contents due to their depleted nature of typical cumulate formed in the oceanic crust, whereas  $TiO_2$  is relatively high in the melts generated by MORB differentiation or liquid immiscibility. Since the  $TiO_2$  content of many oceanic plagiogranites is far below than those generated by simple MORB differentiation or immiscibility, hence these may be regarded as products of anatexis. Also this may indicate that partial melting triggered by water-rich fluids are more common in the deep oceanic crust.

### **Hydrothermal activity**

Submarine hydrothermal activity is difficult to be studied due to their location, inaccessibility for direct observations and for sampling. The conditions for hydrothermal activity are: percolation of cold seawater through pores, cracks and crevices in the rocks; a heat source to produce large scale convective circulation; a mechanism to precipitate the sulphides from the fluid were the acidic hydrothermal fluid is injected into cold, alkaline seawater resulting in precipitation of vent deposits and particle rich plumes and; a stable structural environment for sufficient influx of new volcanic or sedimentary material to bury the deposits and protect it from oxidation and erosion (Thompson et al., 1988). At a hydrothermal site, as the vent fluid shoots up in plumes and mixes with the cold sea water, smokers are formed resulting in precipitation of minerals. Two types of smokers are present: black smokers form from fluids with high temperature ( $350-400^\circ C$ ), contain marcasite, pyrite, bornite, sphalerite, wurtzite, anhydrite etc. and, white smokers form from relatively low temperature ( $100-250^\circ C$ ) fluids enriched in silica and sulphides of barium and calcium (Schmincke, 2004).

The felsic volcanic sequences, terrestrial and oceanic, are ideal sites for several valuable ore deposits. The widespread hydrothermal activity and sulphide deposits are associated with silicic volcanism and may reflect the high heat flow available from fractionating magma (Stoffers et al., 2002). They concluded that enhanced magma supply from mantle plumes together with the spreading rate might promote extensive magma fractionation in the crust.

The silicic magmas are mostly associated with metal enrichment processes resulting in ore formation and are common along convergent zones. These host polymetallic sulphide ores of Au, Ag, Cu, Pb, Zn, Mo, base metals and rare metals e.g., sulphide deposits of the Hokuroko district of Japan in felsic calc-alkaline rocks (Halbach, 1989). Opalite and jasper of hydrothermal origin have been reported from the Indian Ocean triple junction, jasper being impregnated and replaced by sphalerite, barite, pyrite and traces of chalcopyrite. The relationship between the mineral-rich and silica-rich phases is explained by different cycles of hydrothermal activity (Halbach et al., 2002).

Gold is most abundant in sulphides associated with immature seafloor rifts, which are dominated by calc-alkaline volcanics including andesites, dacites and rhyolites (e.g., Okinawa Trough, Lau Basin, Manus Basin, Herzig et al. 1993). Hydrothermal precipitates associated with active vents have been observed in andesitic-dacitic rocks from eastern Manus back-arc basin, Papua New Guinea (Moss and Scott, 2001). Large Kuroko-type polymetallic sulphide deposits have been recovered from various subduction zones. A large and actively growing Kuroko-type volcanogenic massive sulphide deposit rich in gold and silver 400 km south of Tokyo in Myojin Knoll submarine silicic caldera (1360 m water depth) has been delineated by manned submersible studies. Several unexplored submarine silicic calderas with similar deposits might hold precious minerals (Iizasa et al., 1999).

The Conical Seamount from Lihir Island Group, New Guinea has high-grade gold and the style of mineralisation indicates the participation of gold-rich magmatic fluids as opposed to circulating sea water (Herzig et al., 1999). The trachybasalts from the crater contain up to 230 ppm gold and native gold as inclusions in sphalerite, galena and amorphous silica. From the above investigations it is noted that silicic rocks can host important minerals of economic importance.

### **Indian Ocean**

Several evidences of silicic volcanism occur in the Indian Ocean. The silicic volcanics in the Central Indian Ocean (CIOB) comprise pumices (Iyer, 2005, Kalangutkar et al., 2011 and references therein) and volcanic shards (Iyer et al., 1997; Sukumaran et al., 1999; Mascarenhas-Pereira et al., 2006). The rhyolitic glass shards in the CIOB were perhaps derived from Toba eruptions in northern Sumatra (Martin-Barajas and Lallier-Verges, 1993), whereas the rhyolitic composition of CIOB pumices cannot be explained solely by the 1883 eruptions of Krakatoa, which produced andesitic to dacitic pyroclastic material (Nishimura et al., 1980). Although Krakatoa as a source cannot be completely precluded, Iyer and Sudhakar (1993) postulated an in situ submarine silicic volcanism as a source of pumice since tectonic unloading and decompression at differentiating magma chambers can justify such occurrences (Binns, 2003). Volcanic rhyolitic ash recovered from sediment cores from the CIOB (Sukumaran et al., 1999) and from a seamount from Rodriguez Triple Junction (Mascarenhas-Pereira et al., 2006) also attests to intraplate silicic volcanism.

Along the Central Indian Ridge system (CIR) the rocks, besides basalts, are lherzolite and minor harzburgite, orthopyroxenite, olivine- and two-pyroxene gabbros, Ti-ferrogabbros, norite and anorthosite. There are also occurrences of diabase intrusions of granophyre that are cut by late-stage dikelets of quartz monzonite and Na-rich trondhjemite (Engel and Fisher, 1975). Plagiogranites from the CIR have also been studied by Morishita et al. (2007).

Rhyolites and trachytes co-occur with basalts in the Deep Sea Drilling Project site 216 along the Ninety East Ridge in the Indian Ocean. According to Reverdatto et al. (1985) the association of silicic and subalkaline intermediate volcanics may be widely distributed and that the silicic melt could have formed due to intense crystal differentiation of basalt.

Submarine eruptions have been recorded from New Zealand and Tonga. Healy a submarine volcano, in New Zealand, lies along the South Kermadec Ridge and exhibits rhyodacitic pumice deposits which mantle the caldera floor and walls, as well as the flanks of the volcano at a water depth of 1150 to 1800 m. The Clark submarine volcano, near the southern end of the Southern Kermadec arc, consists of basaltic and dacitic stratovolcano and displays hydrothermal activity with sulphide chimneys.

The submarine explosive eruptions from Tonga region resulted in large rafts of dacitic pumice covering an area of more than 100 sq km (Wright et al., 2006 and references within).

Lithofacies characteristics of submarine, silicic, syn-eruptive pyroclastic units in the Cambrian Mount Read Volcanics have been recognised from Western Tasmania. The beds are composed of variable proportions of rhyolitic or dacitic pumice, crystals of quartz and feldspar, shards, volcanic lithic clasts and non-volcanic sedimentary clasts indicating submarine explosive silicic volcanism and deposition in deep water (McPhie and Allen, 2003).

The above examples show that other than basaltic eruptions substantial amount of submarine silicic volcanism has occurred in and around the Indian Ocean.

### **Conclusion**

From the several occurrences and from experimental studies oceanic silicic rocks apparently evolve from tholeiites in several tectonic settings and are most common along the convergent margins, followed by MOR and also along aseismic ridges and FZ. Fracture zones if transformed into subduction zone due to polarity changes would generate more silicic rocks. Fractionation and partial melting that play important roles in most cases in the formation of silicic melts along the submarine tectonic settings, would in most cases result in the formation of oceanic plagiogranite. Detailed study involving bathymetry and morphology of the seafloor to locate areas of potential submarine volcanism, sampling and analysis of the submarine silicic rocks are necessary to tap the associated hydrothermal deposits.

### **Acknowledgements**

We thank the Director for permission to publish this paper. NK acknowledges the financial assistance provided under the CSIR (New Delhi) Fellowship scheme. We are grateful to Dr. Scott Bryan, Queensland University of Technology, Australia, for suggestions on an earlier version of the manuscript. This is NIO's contribution # ????.

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**Table I: Examples of tectonic settings and occurrences of silicic rocks in the global oceans.**

<b>Tectonic settings</b>	<b>Rock types</b>	<b>Source</b>
<b>Divergent plates</b>	N-MORB	
South West Indian Ridge	Felsic veins in gabbro plagiogranite	Dick et al. (2000), Morishita et al. (2007)
Mid-Atlantic Ridge (45° N)	Granites, granodiorites, diorites, granite gneisses, amphibolites, serpentinised gabbro	Aumento (1969)
Pacific-Antarctic Ridge	Dacites, andesitic	Nielsen and Delong (1992), Stoffers et al. (2002)
Galapagos Spreading Centre	N-MORB, Fe-Ti basalt, andesites, rhyodacites	Byerly (1980)
<b>Oceanic islands/ Seamounts</b>		
Alcedo, Galapagos	Rhyolites	Geist et al. (1995)
Jan Mayen and Iceland Oraefajokull	Trondhjemites, quartz diorite xenoliths, rhyolites, pillow lavas, hyaloclastites tuff of basalt, hawaiiite, mugearite, benmorite, trachyte, rhyolite	Prestvik (2001)
Hekla volcano	Rhyolite ash, pumice blocks and bombs	Selbekk and Tronnes (2007)
	Granophyres, rhyolites obsidian	O'nions and Gronvold (1973)
	Rhyolite	Sigvaldason (1974)
Ascension and the Azores	Quartz saturated residue	Clague (1987)

Azores and the Canaries	Silica oversaturated	Schmincke (1973)
<b>Convergent plates</b>		
--	Rhyolitic block peprites	Busby (2005)
Myojin knoll caldera, Izu-Bonin Arc Tokyo	Rhyolitic	Fiske et al. (2001)
Central Luzon Philippines	Basalt, andesites, rhyolites	Yumul et al. (2003)
<b>Abyssal plain</b>		
Off axis, Mariana Trough	Rhyodacite pumice	Lonsdale (1985)
<b>Fracture zones</b>		
Pacific	Alkali rocks	Hirano et al. (2006)

Fig.1. USGS Map showing convergent and divergent boundaries ([http:// www.usgs.gov](http://www.usgs.gov)). Silicic volcanic sites mentioned in manuscript are added. S.E. Indian Ridge = South East Indian Ridge.

