Petrographical indicators of petrogenesis: Examples from Central Indian Ocean Basin basalts

P.G. Mislankar & S.D. Iyer
National Institute of Oceanography, Dona Paula, Goa 403 004, India

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Petrographical features of the Central Indian Ocean Basin (CIOB) basalts were studied to understand their genetic significance. The fresh basaltic pillows show three textural zones from the top glassy (zone A) through the intermediate (zone B) to the holocrystalline interior (zone C), with each characterised by varying assemblages of plagioclase and olivine that form different textures. Based on the presence and morphotypes of the plagioclase and olivine, the CIOB basalts are classified as aphyric, plagioclase dominant, plagioclase+olivine bearing and rarely plagioclase+olivine+augite bearing. The mineral phases and the textures reflect the magmatic conditions under which the basalts crystallised from a tholeiitic magma.

Materials and Methods

Since the last decade, the NIO has been involved in the exploration and sampling of the CIOB for polymetallic nodules. Tonnes of nodules and encrustations have been recovered during a number of cruises, to help demarcate a first generation mine site for India. In addition to collection of samples, geophysical surveys have also been carried out to help identify the various morpho-tectonic features of the basin. Besides the nodules and encrustations, a number of volcanics were also retrieved. Most of the volcanics are basalts obtained from a depth of 5000 m between lat. 10°-15° S and 72°-84° E (Fig. 1). The samples were selected based on the degree of freshness and by the presence/absence of basaltic glass. About 120 thin sections were examined for the size and morphotype of mineral phases and their textural relation.

Observations and Interpretations

Earlier in a preliminary study the petrological observations of the CIOB volcanics were reported and their origin postulated. Mukherjee & Iyer recently reviewed the volcanics (basalts, ferrobasalts, spilites and pumice) occurring in the CIOB in conjunction with various morpho-tectonic features (seamounts, abyssal hills, fracture zones). It was inferred that a distinct association occurs between the morpho-tectonic forms and the volcanics. Further, two significant volcanic activities were perceived in the CIOB; one occurred during the formation of the near-axis seamounts and the other in an intraplate setting.
The basalts and their variants occur as fragments and pillows, the latter near seamounts and fracture zones, while pumice occurs as clasts of different shapes and sizes. The samples are quite ‘fresh’ to highly altered so much so that they crumble when crushed with the fingers. The pillow basalts sometime typically show radial fractures converging towards the centre. ‘Fresh’ glass selvages (~2 cm thick) are conspicuous in some of the pillow basalts, but are not very common.

The colour of the samples range from shades of gray for the ‘fresh’ fragments, to brown and its variations for the altered ones. In few cases, on slicing the samples, minute rounded to semi-rounded vesicles occur. In well-preserved basalts, three broad textural zones can be noted from the glassy top to the interior (zones A, B and C, respectively). A schematic sketch of the various zones is shown in Fig. 2. Bryan, Scott & Hajash and Banerjee & Iyer identified similar textural zones in oceanic basalts.

The glass (Fig. 3a) commonly hosts plagioclase phenocrysts and rarely olivine and may be altered to form palagonite (Fig. 3b). Many of the basalts have a substantial deposit of ferromanganese oxides that may reach several cm in thickness. Such encrusted basalts form ferromanganese crusts, an investigation of which, amongst others, would throw light on the accretionary processes of the oxides and on the paleoceanographic conditions.

The basalts exhibit typical textures such as holohyaline, glomero-porphyritic, intergranular, intersertal, ophitic, porphyritic and flow. The texture in zone A is composed of sheaflike radial clusters of plagioclase (Fig. 3c) with scattered phenocrysts or microphenocrysts of olivine and plagioclase in the interstices. The transitory zone B with skeletal crystals in glass, grades into the innermost holocrystalline zone C that has intergranular, intersertal and (Fig. 3d) flow (Fig. 3e) textures.

The constituents of the ‘fresh’ basalts are classified into isotropic, yellow-brown glass and well-developed rock-forming minerals. In the latter category are: plagioclase, olivine and rarely pyroxenes and...
From their size, the mineral phases were classified as: laths or groundmass (<0.25 mm), microphenocrysts or tabular (0.25 to 0.50 mm), phenocrysts (0.50 to 1 mm) and megacrysts (>1.0 mm). Observations show that plagioclases predominantly occur as laths and in the groundmass (especially in zone A) followed by their presence as micro-phenocrysts, phenocrysts (Fig. 3f,g) and megacrysts. Olivines, on the other hand, tend to occur as microphenocrysts and rarely as phenocrysts. Augites, if present, occur as minute crystals (<0.25 mm) in the groundmass.

Based on the mineralogy, the CIOB basalts are tentatively grouped into 4 types: aphyric, plagioclase dominant, plagioclase and olivine bearing and rarely plagioclase, olivine and augite bearing. We suggest that the CIOB basalts have similarities to the HPPB and MPPB (i.e., Highly and Moderately Plagioclase Phyric Basalts) of the Mid-Atlantic Ridge (MAR)\textsuperscript{15}. In holocrystalline samples, plagioclases are common in the groundmass, even if it does not appear as a phenocryst; in contrast to olivines, which occur in the groundmass only if they are present as phenocrysts.

**Olivine**—Bryan\textsuperscript{3} has described different morphotypes of olivine in the submarine basalts from the MAR, Red Sea rift and JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) Site 105 in the western Atlantic Ocean. He observed olivines to occur in zone B as euhedral or subhedral microphenocrysts, lattice-like skeletal overgrowths, ornamentation, Maltese cross, lantern-like and swallow-tail, but zone C does not show these many forms of olivine. In the CIOB basalts, olivines, the next dominant mineral after plagioclase, occur as anhedral to euhedral crystals (Fig. 4d) (up to 0.50 mm) that may be fractured and broken. Phenocrysts of olivine are few and unzoned while quenched varieties are uncommon. In one instance, fresh olivine crystals form the sole phase in zone A (Fig. 4e), a feature, termed as “topo-concentrations”\textsuperscript{16}, that suggest a cumulate origin for such early-formed olivines.

**Miscellaneous phases**—Augites are scarce and if present, the crystals are <0.25 mm, anhedral and exhibit typical high extinction angles (38 to 45°). Opaques are mainly stubby crystals of magnetite, reddish-brown hematite and rarely spinel/chrome.
Fig. 3—

(a) Basaltic glass showing flow bands with trails of opaque (×63); (b) glass partly altered to palagonite in which fresh euhedral plagioclases are present (×20); (c) sheaves of plagioclase in a glassy groundmass (×100); (d) medium grained intersertal-intergranular texture (×40); (e) flow/pilotaxitic texture formed by small plagioclase laths (×20); (f) fresh, euhedral plagioclases set in a fine-grained groundmass in zone C (×40); (g) megacrysts of twinned and partly zoned plagioclases (×20); (h) unaltered twinned and zoned plagioclases in a glassy matrix (×20). (a – f are under Plane Polarised Light; g and h are between Crossed Nicols)
Fig. 4—

a) Corroded twinned plagioclase with inclusions ($\times$20); b) another example of corroded plagioclases with ‘fringed’ ends and inclusions of glass ($\times$40); c) highly altered plagioclase with corroded ends projecting into the glassy groundmass ($\times$40); d) partly altered euhedral olivine in a fine-grained matrix ($\times$20); e) fresh, euhedral olivines in zone A depicting a “topo-concentration” ($\times$40); f) coarse grained quartzo-feldspathic rock with granoblastic texture recovered from the base of a seamount ($\times$20); g) coarse grained (dike?) rock with hornblende and pyroxene. Note the expulsion of iron ores adjacent to the pyroxenes ($\times$40); h) transitory texture between zones A and B exhibiting ‘fresh’, unaltered glass (upper left) grading to a zone of alteration consisting of palagonite (bottom right). Small plagioclase crystals form nuclei for blebs of cryptocrystalline materials ($\times$40). (b-e and g, h are under Plane Polarised Light; a and f are between Under Crossed Nicols)
spinel is present. Sometimes, a sprinkling of opaques occur as thin, fine needles forming dendrites and trichites. In case of the ferrobasalts, minute titanomagnetite crystals occur between the plagioclase fibres. Vesicles are few and are usually empty or at times partly filled by cryptocrystalline materials.

Besides the basalts, few other interesting samples were noted. These include a sample collected from a location close to a seamount that has dominantly quartz, feldspars and micaceous minerals and shows a typical granoblastic texture (Fig. 4f). This rock, probably representing a high thermal metamorphic facies, could have resulted by the interaction of the lava with the siliceous sediments in the vicinity of an erupting seamount\(^{18}\). Or else, inter-mingling and assimilation of the surrounding siliceous sediments probably contaminated the basaltic lava and resulted in this type of rock, a view similar to that proposed by Augustithis\(^{16}\). Another sample is a coarse grained, plagioclase-pyroxene-hornblende basalt that was probably dredged from a well-jointed outcrop such as a dyke. Thin section shows partial to complete replacement of pyroxene by hornblende. and expulsion of the excess iron as large sized opaques (Fig. 4g). The hornblende might have formed surrounding the pyroxene and in association with magnetite crystal grains. Such a peculiarity, although uncommon\(^{16}\), has been noted in samples recovered from a pit crater of a seamount in the East Pacific Rise (EPR\(^ {19}\)).

The slightly altered basalts have textures and minerals similar to the fresh ones and in addition show products of alteration. The glassy portions in the groundmass form chloroaracheite, palagonite and smectite with the presence of reddish-brown globular structures (Fig. 4h). This is similar to the “red-feathery alteration” in which small plagioclase crystals form nuclei as described by Baragar et al.\(^ {20}\). Alteration of submarine volcanics is an ubiquitous process and results in the formation of authigenic products and minerals. The process of alteration of the CIOB basaltic glasses was recently examined and it was found that the glasses have been palagonitised but not so severely that the parent rock cannot be recognised\(^ {21}\). This is because the presence of Fe-Mn oxides over the glasses has hindered the progress of palagonitisation.

**Discussion**

In terms of morphology, chemical composition and petrologic characteristics, the CIOB seamounts are analogous to those occurring in the present-day fast spreading EPR and the slow spreading MAR\(^ {22}\). Microprobe analysis of the CIOB basaltic glasses: SiO\(_2\) 50.53%, TiO\(_2\) 1.27%, MgO 7.73%, CaO 12.3%, Na\(_2\)O 2.8% and K\(_2\)O 0.08%. These values are quite similar to those of the EPR (SiO\(_2\) 49.89%, TiO\(_2\) 1.36%, MgO 7.66%, CaO 12.4%, Na\(_2\)O 2.71% and K\(_2\)O 0.10%) and the MAR (SiO\(_2\) 50.10%, TiO\(_2\) 1.25%, MgO 8.13%, CaO 11.45%, Na\(_2\)O 2.79% and K\(_2\)O 0.06%) basaltic glasses\(^ {22}\). The abundance of olivine near glass (Fig. 4e) indicates the magma to be almost certainly magnesium in composition and is evident by the presence of olivine phenocrysts. Confirmation in this regard could come from microprobe analyses in future. The predominance of plagioclases coupled with the presence of small plagioclases and olivines suggests the abyssal tholeiites to be moderately evolved. This observation corroborates the earlier conclusion based on the chemistry of the basalts\(^ {22}\).

Pillow basalts in the CIOB may have formed when hot, fluid basaltic lava chilled rapidly on coming in contact with the cold seawater. During this process, differential cooling of the lava occurred resulting in the formation of three broad textural zones: an outer glassy crust (zone A), beneath which microscopic incipient feathery crystals (zone B) are formed and at still deeper level the pillow is holocrystalline (zone C). The minerals present in the three zones reveal their development and crystallization sequence. Although the phases may vary from sample to sample, a general idea of mineral paragenesis in the CIOB basalts may be inferred.

The mechanism that control the formation of textures in basalts, among others, are the cooling rate, fluid flow, composition of the liquid, nucleation and growth rates, heterogeneous nucleation, and settling or floating of crystals\(^ {23}\). The presence of a variety of plagioclases in the CIOB basalts, may represent different stages in their cooling history but is more likely to be affected by sudden changes in the degree of supercooling\(^ {5}\) (\(\Delta T\)) or in the number of nuclei\(^ {17,23}\). Nucleation occurs more easily if nuclei are already present because of incomplete melting thus, resulting in holocrystalline basalts. The nucleation rate or nucleation density is influenced by the cooling rate that in turn controls the differences in grain size. For instance, low nucleation rate and high growth rate, will produce large crystals (phenocrysts/megacrysts). But if the nucleation rate is high and growth rate remains the same, then microphenocrysts result\(^ {23}\). The
wide range of size of plagioclase in the CIOB basalts could be related to the nature and the number of nuclei per unit volume present in the parent melt. Further, the abundance of smaller crystals (up to 0.50 mm) indicates their formation at a near uniform growth rate at a number of nucleus centres. These observations attest to the fact that nucleation influences the observed textural differences.

Small, equant or tabular crystals (e.g., plagioclase) in glass indicate an early crystallisation prior to extrusion of the magma barely antecedent in composition to the host glass. It has been shown that for equivalent growth conditions, a plagioclase spherulite will grow at a larger ΔT or greater departure from equilibrium than a dendritic or skeletal plagioclase. Further, the growth of a dendritic or skeletal plagioclase occurs at a larger ΔT than a tabular plagioclase. This indicates that differential changes in the cooling temperature could affect the morphology of the resultant crystallising phases. The observed crystal sizes in the CIOB samples could be related to the changes in the ΔT that probably lead to the following crystallisation sequence; spherulites > dendrites/skeletal > tabular.

For a meaningful petrogenetic interpretation of oceanic basalts that host disequilibrium assemblage of minerals, the effects of crystallization kinetics, magma mixing and related processes are also needed to be considered. The properties and extrusion of lava into the seawater are determinative for the formation and morphotypes of the minerals. The formation of sheaf-like radial clusters (Fig. 4c) could have been caused due to rapid spherulitic growth during quenching and/or because of resportion due to disequilibrium with the melt.

Olivine or plagioclase or both may appear in the quenched outer glassy rim (zone A) based on which Miyashiro et al. recognized oceanic basalts to be either ‘plagioclase tholeiite’ and ‘olivine tholeiite,’ depending on the nature of the liquidus phase. Basalts that crystallize both these phases, presumably lie on a cotectic boundary between the plagioclase and olivine fields. The predominance of plagioclase (olivine) and the HPPB/MPPB nature of the CIOB basalts imply a process of fractional crystallisation of a plagioclase-rich magma, an observation that concurs with the other reported oceanic tholeiites.

Crystal growth in zone A and in the outer part of zone B, may occur under a supercooled condition in which the viscosity of the melt significantly reduces diffusion rates. For euhedral crystals to grow, the melt temperature is to be maintained at or just below the liquidus for relatively long periods of time. These conditions coupled with rapid diffusion resulted in crystallization at nearly the same rate around few widely spaced nuclei. The larger plagioclase crystals with hollow cores (belt-buckle) are a growth form allowing a somewhat lower surface to volume ratio, during which stage sector zoning conspicuously develops. The paucity of sector zoned plagioclase phenocrysts in the CIOB basalts, suggest that either a homogeneity in the plagioclase composition was brought about by continued slow growth (perhaps aided by twinning) or that the larger and presumably more slowly grown plagioclase developed more uniformly without passing through a stage of skeletal, sector-zoned crystals.

Variations in the anorthite content of plagioclases (An 32 to 58) might be indicative of the changing composition of the melt during its ascent and on its subsequent crystallization on the seafloor. Although zoned plagioclases occur in the CIOB basalts, their dominance and frequency are less as compared to the ridge basalts. Experiments have demonstrated the rapid growth of large unzoned plagioclase crystals that could grow between 1 to 5 mm per day even for the more anorthite-poor compositions.

We note that the CIOB basalts do not profusely have zoned plagioclases. The factors that might conceivably favour the growth of unzoned crystals from a magma are — very slow cooling or holding at a constant temperature just below the melting temperature; rapid stirring of the magma; large supply of magma so that the bulk composition does not change; growth from a bulk composition of minimum melting temperature; interruption of zoning by settling or floating of uniform crystals that form a compact rock and rapid eruption of a volcanic rock with inhibition of reaction of early formed phenocrysts with the host magma. Other than these conditions, alternatively, extensive mechanical twinning consequent on shearing stress may also result in unzoned plagioclases from zoned plagioclases. It has even been suggested that the amount of zoning could be roughly inversely proportional to the ascent rate of magma and that the size of the magma chamber could also have an effect on the abundance of the zoned crystals. On these tenets, it appears that the magma for the CIOB basalts upwelled rapidly from small chambers with little or no time to form zoned crystals. The present
information does not permit us to pinpoint the causative reason for the near-absence of zoned crystals in our samples, but the textural and mineralogical characteristics seem to imply more than one factor to have been operative that may account for the rarity of zoned plagioclases.

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