

IMPORTANCE OF PLAGIOCLASE MORPHOLOGY AND COMPOSITION IN MAGMAGENESIS OF THE CARLSBERG RIDGE BASALTS

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ABSTRACT

In this paper we examine the morphology and chemical composition of more than 200 plagioclase crystals in the Carlsberg Ridge basalts (3° 35' and 3° 41' N) in relation to the magmagenesis of the basalts. The results indicate that the different morphotypes together with their significant compositional characteristics attest to magmatic processes such as fractional crystallisation and mixing. Our study tends to present a rational interpretation for the occurrence and usefulness of plagioclase in relation to the magmatic regimes.

1 INTRODUCTION

Rock - forming minerals such as feldspars, olivine, pyroxenes and amphiboles, among others, tend to exhibit different morphological and compositional variations which manifest in the form of zoned and twinned crystals. The importance of such crystals lies in the fact for example, zoned crystals are indicators of magmatic processes, by their incorporation of the major and minor elements within them. Thus, these crystals are potential recorders of the different aspects of their growth and of the magmatic conditions (Pearce 1994). Plagioclase crystals have been widely recognised to show different types of zoning viz., normal, reverse, patchy, oscillatory and sector - type. One or all of these types may be identified even within a single slide. Zoned plagioclases can be used as 'mineral stratigraphy' because they offer a viable record of the environmental changes during crystallisation (Allegre et al. 1981). The fact that plagioclases are neutrally buoyant in basaltic magmas and does not re-equilibrate rapidly (Grove et al. 1984) make them an excellent recorder of the pre-eruptive history of magma batches since the compositional zones record variation in the compositions, temperature and storage depth of magma as well as variations in the volatile pressure and hydraulic pressure (e.g., Kuo & Kirkpatrick 1982). It has been suggested that the amount of zoning in minerals 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 (Fisk 1984). All such parameters must be considered when interpreting compositional zoning in plagioclase.

The phenomenon of zoning has been explained through a kinetic mathematical model of crystal growth from the melt and in this, the functional surface composi-

tion and the transport of material within the melt are explicitly considered (Haase et al. 1980). In contradiction to this model, Allegre et al. (1981) argued that the growth rate can not be simply some function of the supersaturation. On the contrary, they proposed that the interface kinetics is sensitive to concentration changes in the melt and that the crystal growth rate responds with a definite delay time to such changes.

Another common feature of the rock - forming minerals, especially in plagioclase, is the presence of twinning. Different categories of twinning in plagioclase have been identified such as Manebach, Baveno (rare), Carlsbad (most common), Ala, Ab - Carlsbad, etc. (Deer et al. 1967).

Besides zoned and twinned crystals, a study of plagioclase accumulation becomes pertinent when investigating the ocean - floor basalts. Flower (1980) found that the basalts of the slow - spreading Mid - Atlantic Ridge (MAR) have a widespread accumulation of calcic plagioclase (Anorthite, An 70 - 90), while such a phenomenon is absent in basalts found at fast - spreading ridges such as the East Pacific Rise (EPR).

Thus, it is observed that plagioclase feldspars that form a simple reaction series with Ca and Na at either ends, are very good pointers of the crystallisation history of a rock. In this backdrop we discuss the morphological and compositional significance of plagioclase occurring in the Carlsberg Ridge (CR) basalts and relate these with the possible magmatic processes such as fractional crystallisation and magma mixing.

2 BACKGROUND

The CR forms an active oceanic ridge at the northern re-

gion of the Central Indian Ridge (CIR) system and has a slow - spreading rate of 1.2 to 1.3 mm/yr (half - rate, Ramana et al. 1993). Since the classical work of Vine & Matthew (1963) on the origin of seafloor magnetic anomalies from observations made on the CR, this ridge has been intensively investigated. Petrological studies have revealed the presence of ultrabasics, gabbros, dolerites, spilites and metamorphosed effusives besides basalts along the different segments of the CR. (Banerjee & Iyer, 1991 and references therein).

The pillow basalts recovered through dredging from a segment of the CR at 3° 35' - 3° 41' N and 64° 05' - 64° 07' E (average water depth = 3750 m) are now detailed. The basalts are fresh and have a thin veneer of glass (1 - 3 mm) with phenocrysts mostly of plagioclase and rarely of olivine. Texturally, the outermost zone is vitrophyric, followed by variolitic to hypocrySTALLINE and leading to a holocrystalline interior with intergranular and subophitic textures. The mineral phases are dominated by plagioclase, followed by olivine and few pyroxene (Banerjee & Iyer, 1989) while the opaques are mainly of pyrite, chalcopyrite and magnetite (Banerjee & Iyer 1993). The textural and mineral assemblages indicate these basalts to be akin to the moderately phyric plagioclase basalts (MPPB) as reported from the MAR. Based on the petrographical and petrochemical characteristics (Banerjee & Iyer 1991) and the mineral chemistry (Iyer & Banerjee 1993) it was reported that these are transitional basalts that formed largely through processes of fractional crystallisation and magma mixing.

3 MINERAL CHEMISTRY

Mineral analyses were carried out with a Camebax Micro - 571 microanalyser operating at 15 kV and 10 to 20 mA sample current. Silicate and oxide standards were used for calibration and the data were corrected for the ZAF effects. Totally 283 crystals of plagioclase of different morphotypes (41 phenocrysts, 21 laths, 7 zoned and 14 twinned) were analysed. Representative analyses together with the molecular norm (Or, Ab and An in mole %) and the cation distribution are presented in tables 1A to 1D.

Plagioclase occurs as euhedral to subhedral crystals of varying dimensions forming phenocrysts, microphenocrysts and laths (Fig. 1). The phenocrysts and microphenocrysts are calcic (Table 1A, An range 82 - 87, average 85 mole %) and are characterised by low K₂O (0.02 to 0.29 %; average 0.06 %); whilst the laths show An 67 - 79 mole % (Table 1B; average 74 mole %) and K₂O (range 0.03 ; average 0.10 %). Some of the plagioclase phenocrysts show both normal and reverse zoning (Table 1C). The twinned plagioclases show a distinct enrichment

of Na₂O (upto 2.84 %) for one part of the twin in comparison to the other within a single crystal (Table 1D).

Melt inclusions, locally devitrified, are prominent in the groundmass and in the plagioclase phenocryst (Fig. 2). Such plagioclase crystals are relatively rich in Na₂O, possibly indicating exchange between the host feldspar and the melt inclusions. Melt composition within some plagioclase and the basaltic matrix have a range of orthoclase (Or) component from 0.48 to 9.63 mole % and 1.08 to 5.82 mole %, respectively. This may probably account for some of the K₂O enrichment noticed earlier in these basalts (Banerjee & Iyer 1991). In the absence of detailed studies of these inclusions, presently it is difficult to decipher whether the melts were trapped during the growth of the plagioclase or they represent corrosion of the plagioclase (cf. Allan et al. 1987).

4 DISCUSSION

Tectonic and petrological segmentations along the CIR reveal the occurrence of different rock types, the principal rocks are basalts (pillows and sheet flows) and ultramafics (serpentinised peridotites, talc-anthophyllite and lherzolites) and thus reflect compositional diversity along this ridge system (Mukhopadhyay & Iyer 1993). The ultramafics occur in regions with large offsets and vertical displacements while basalts are common in areas of low offsets and in rift valleys. No single magmatic process can solely account for the occurrence of such a diverse suite of rocks, which may be brought about by mixing of cogenetic basaltic magmas coupled with subsequent fractional crystallisation (Rhodes et al. 1979; Walker et al. 1979) or alternatively be the result of low but variable amounts of melting of a heterogeneous mantle source (Batiza & Johnson 1980; Hart 1988). The factors that conceivably control the compositions of plagioclase are the mantle compositions, temperature, pressure, crystal growth rate and interface kinetics (Smith & Brown 1988) and partial melting (Parsons 1994). In addition, volatile content is also considered as another important parameter since higher water contents could promote crystallisation of more calcic plagioclase (Ku & Weill 1970).

Plagioclase fractionation and accumulation: The MPPB characteristic of the CR basalts can be explained as a result of the separation of plagioclase from a basaltic magma at a slower rate than the co - crystallising olivine and/or pyroxenes, due to density differences between plagioclase and the basaltic magma (Elthon 1984) or a high pressure effect (Flower 1980). Plagioclase phenocrysts with An - rich zone and corroded rims (Fig. 3) occur which indicate their non-equilibrium state with the cooling lava. Such non-equilibrium conditions could lead to variations

Importance of Plagioclase morphology and composition in
magmagenesis of the Carlsberg Ridge basalts

(A)

	1	2	3	4	5	6
SiO ₂	46.56	48.13	47.38	46.44	48.96	51.21
Al ₂ O ₃	30.96	30.59	31.29	31.56	30.09	29.63
CaO	19.20	18.05	19.73	21.04	18.48	17.63
Na ₂ O	1.87	1.97	1.78	1.78	2.13	2.02
K ₂ O	0.02	0.06	0.05	0.03	0.06	0.04
Or	0.11	0.33	0.26	0.15	0.32	0.22
An	84.95	83.26	85.76	86.62	82.50	82.67
Ab	14.95	16.41	13.98	13.24	17.18	17.11
Si	2.188	2.244	2.193	2.154	2.266	2.335
Al	1.714	1.679	1.704	1.709	1.638	1.586
Ca	0.967	0.901	0.977	1.047	0.916	0.861
Na	0.169	0.179	0.161	0.161	0.189	0.180
K	0.001	0.003	0.002	0.001	0.003	0.002

(B)

	1	2	3	4	5	6
SiO ₂	50.16	52.94	51.78	51.77	50.61	53.10
Al ₂ O ₃	28.16	27.45	27.98	28.67	27.64	27.34
CaO	16.37	17.11	15.65	16.41	17.15	15.27
Na ₂ O	3.03	2.64	3.65	2.68	2.60	3.87
K ₂ O	0.18	0.10	0.11	0.07	0.03	0.05
Or	0.97	0.54	0.59	0.39	0.16	0.27
An	74.21	77.78	69.95	76.92	78.37	68.41
Ab	24.81	21.68	29.47	22.69	21.46	31.32
Si	2.354	2.417	2.392	2.374	2.371	2.434
Al	1.554	1.474	1.519	1.548	1.519	1.474
Ca	0.822	0.835	0.773	0.807	0.860	0.748
Na	0.270	0.230	0.321	0.236	0.230	0.341
K	0.005	0.005	0.005	0.002	0.001	0.002

Table 1: Representative microprobe analyses of plagioclases from the Carlsberg Ridge basalts. (A): Phenocrysts; & (B): Laths. The molecular norms and the cation calculations (based on 8 oxygen) are also included.

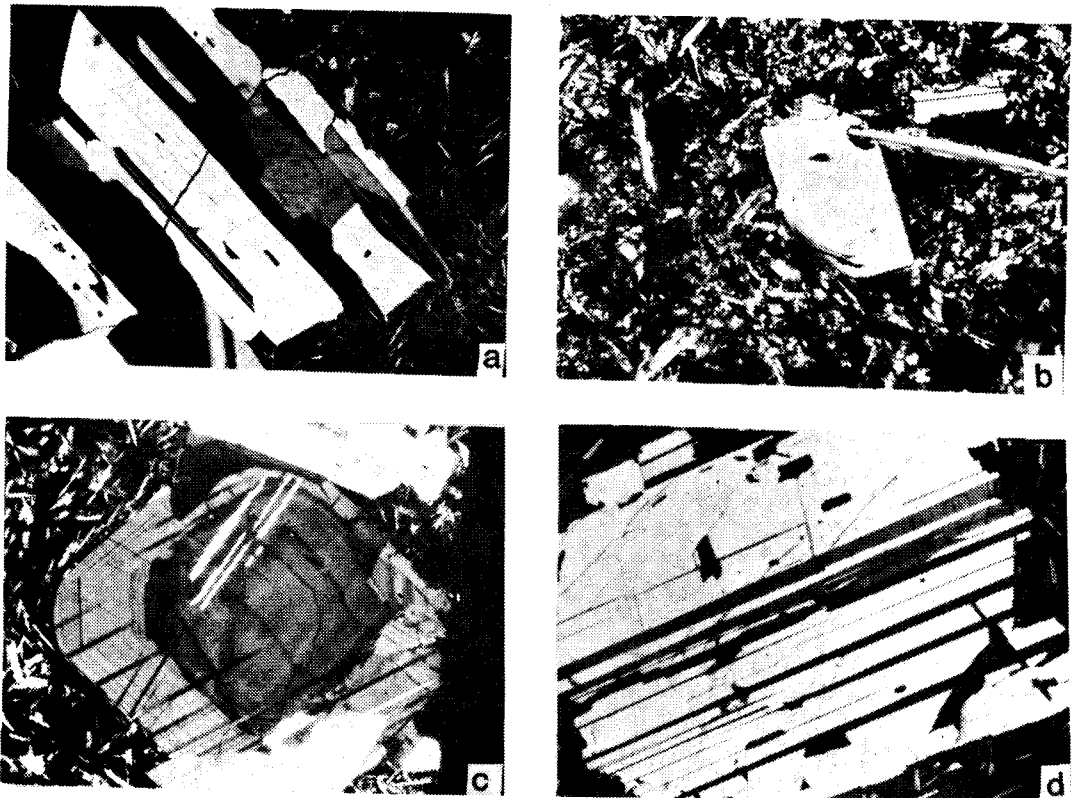


Figure 1. Photomicrographs of the different plagioclase crystal shapes and zone morphologies: a) Phenocryst, b) laths, c) zoned, d) twinned grains (nicols crossed, x40).

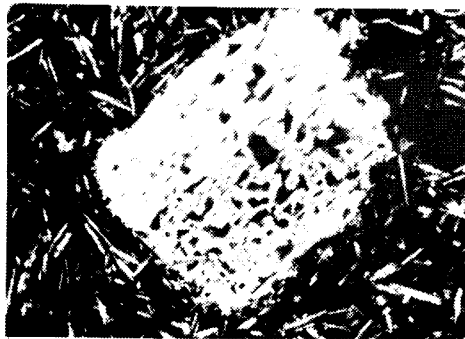


Figure 2. Melt inclusion in plagioclase phenocryst (nicols crossed, x40).

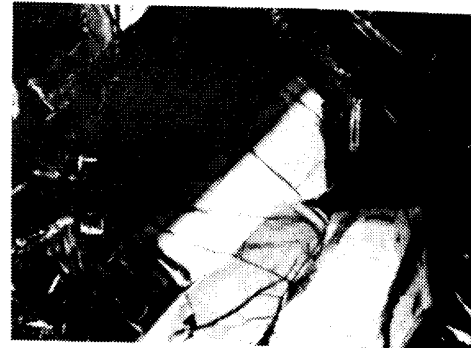


Figure 3. A zoned plagioclase phenocryst with corroded rims (nicols crossed, x40).

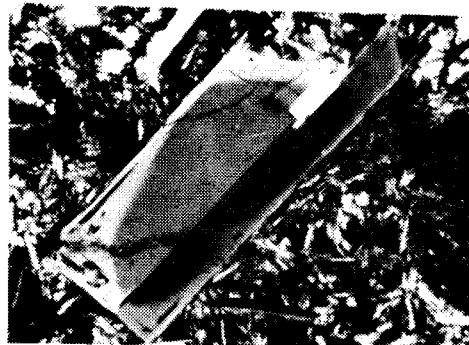


Figure 4. Plagioclase phenocryst showing partial elimination of zones due to the effect of twinning (nicols crossed, x100).

	R			N			R			N		
	a	b	c	a	b	c	a	b	c	a	b	c
SiO ₂	49.44	47.87	48.41	52.05	51.21	52.62	48.33	49.42	48.06	49.41	48.93	47.41
Al ₂ O ₃	29.52	28.24	29.34	30.17	29.80	31.01	31.37	29.67	30.62	30.40	31.82	30.39
CaO	19.58	19.80	20.11	17.50	17.68	17.55	19.69	18.63	19.88	18.88	20.24	19.32
Na ₂ O	1.56	1.78	1.63	1.55	1.22	1.75	1.58	1.93	1.58	2.49	1.26	2.22
K ₂ O	0.04	0.31	0.16	0.08	0.03	0.05	0.05	0.08	0.05	0.03	0.05	0.03
Or	0.21	1.58	0.82	0.47	0.18	0.29	0.26	0.43	0.26	0.15	0.26	0.15
An	87.23	84.67	86.51	85.80	88.76	84.49	87.11	83.87	87.22	80.64	89.65	82.68
Ab	12.56	13.75	12.67	13.73	11.06	15.22	12.63	15.70	12.52	19.21	10.08	17.16
Si	2.281	2.272	2.255	2.345	2.339	2.332	2.214	2.286	2.221	2.256	2.214	2.216
Al	1.600	1.573	1.606	1.596	1.602	1.617	1.689	1.611	1.664	1.634	1.689	1.666
Ca	0.966	1.006	1.004	0.844	0.864	0.832	0.866	0.922	0.945	0.924	0.980	0.967
Na	0.138	0.159	0.145	0.135	0.104	0.148	0.137	0.172	0.138	0.219	0.108	0.196
K	0.002	0.017	0.005	0.002	0.001	0.002	0.002	0.002	0.002	0.001	0.002	0.001

R= Reverse zoning, N= Normal zoning; a and c are at the margin and b is at the center of the grain.

Table 1C: Representative microprobe analyses of plagioclases from the Carlsberg Ridge basalts. (C) Zoned crystals. (D) Twinned Crystals. The molecular norms and the cation calculations (based on 8 oxygen) are also included.

	1		2		3		4	
	a	b	a	b	a	b	a	b
SiO ₂	51.99	52.90	48.67	51.01	51.54	50.98	49.63	49.71
Al ₂ O ₃	28.87	29.52	28.25	29.30	27.92	28.35	29.08	28.36
CaO	15.99	16.24	20.05	17.02	17.71	16.76	17.52	17.60
Na ₂ O	3.11	3.10	1.57	1.95	2.30	1.95	3.85	5.20
K ₂ O	0.05	0.05	0.10	0.08	0.10	0.11	0.09	0.09
Or	0.27	0.27	0.52	0.46	0.54	0.64	0.44	0.40
An	73.80	74.16	87.15	82.47	80.56	82.10	71.27	64.94
Ab	25.93	25.57	12.33	17.07	18.90	17.26	28.29	34.66
Si	2.374	2.372	2.289	2.348	2.375	2.373	2.294	2.292
Al	1.552	1.556	1.561	1.585	1.509	1.551	1.581	1.539
Ca	0.781	0.781	1.010	0.837	0.873	0.835	0.865	0.869
Na	0.274	0.269	0.141	0.171	0.204	0.173	0.343	0.462
K	0.002	0.002	0.005	0.002	0.005	0.005	0.002	0.002

a and b are twin lamellae within individual crystals.

Table 1D: Representative microprobe analyses of plagioclases from the Carlsberg Ridge basalts. (D) Twinned crystals. The molecular norms and the cation calculations (based on 8 oxygen) are also included.

in the An content of the plagioclase of different morphologies, as also observed earlier (Banerjee & Iyer 1989). The crystallisation of such An - rich plagioclases could be from a more 'primitive' calcic melts prior to their incorporation in the phyric basaltic magma (Rhodes et al. 1979).

The plagioclase microphenocrysts in the CR basalts depict them to be components of equilibrium phases. Laboratory simulation experiments of aphyric basalts have revealed plagioclase to occur on the liquidus over a considerable temperature interval (Walker et al. 1979). Hence, it is likely that some of our samples could represent a liquid composition that precipitated plagioclase to reach the cotectic. Such a liquid composition might occur through mixing and/or resorption of cumulate plagioclase in a normal cotectic liquid (Bryan et al. 1981).

The various crystal shapes and zone morphologies of the plagioclase (Fig.1) suggest different crystal growth

rates due to differential cooling rates or varying degrees of supercooling of the liquid in which they grew. It has been experimentally shown that the shape of plagioclase changes progressively from tabular to elongate skeletal to dendritic to spherulitic with increasing degree of supercooling from 40° C to 350° C below the liquidus or with increasing cooling rates from 2° C / hour to 130° C /hour (Lofgren 1980).

Implications of zoned and twinned plagioclase crystals: According to Fisk (1984) the cause of the different degrees of zoning in minerals occurring in ocean floor and ocean - island basalts is probably one of kinetics because the amount of zoning will be roughly inversely proportional to the rate of ascent. Magmas that are brought to the surface quickly and without cooling should show no zoning, while those that arise slowly are more likely to cool extensively and have zoned phenocrysts. Further, the size of the magma chambers could also have an effect in that

magmas erupting from a large, thermally heterogeneous and actively mixing chamber are likely to show signs of zoning vis-a-vis lavas from small, unzoned magma chamber. Alternatively, removal of the residual host liquid prior to its complete crystallisation could also result in unzoned minerals. Diversity in zoning patterns and compositions is a common feature of MAR basalts and has been interpreted as evidence for magma mixing (e.g. Bryan & Moore 1977; Dungan et al. 1978; Shibata et al. 1979; Kuo & Kirkpatrick 1982).

We note the presence of both normal and reverse zoned plagioclase crystals (Table 1C) in the CR basalts. This suggests changing physico-chemical conditions of the melt during the crystallisation of such plagioclase crystals. According to Rhodes et al. (1979) the upwelled mantle material ('Primitive' magma) is repeatedly injected into the magma chamber containing a more evolved, consanguineous fractionated basalts of earlier episode of injection and mixing. The injected magma may be a primary melt with olivine on the liquidus or it may have fractionated somewhat during ascent and saturated with both olivine and plagioclase. Each episode of injection and mixing is followed by a quiescent period while the mixed magma fractionates to a more evolved composition. It has been reported that widespread accumulation of calcic plagioclase is due to a process of polybaric fractionation and is more characteristic of slow spreading than of fast spreading ridges (Flower 1980). The observed accumulation of calcic plagioclase and the slow spreading rate of the CR supports this contention.

The twinned plagioclase crystals (Table 1D) at times show distinct enrichment of Na_2O for even the adjacent lamellae. According to Emmons & Mann (1953), twinning forms late in the history of the crystal and updates zoning and that twinning could cause the obliteration of the zones. This fact is reflected by the compositional differences in contiguous twin lamellae which in part at least substitutes for the compositional differences occurring in zoned plagioclases. Further, it has been proposed that Na-rich plagioclase may crystallise from a mixed magma that had a low $\text{CaO}/\text{Na}_2\text{O}$ value (Elthon 1984; Johnson et al. 1985). Such sodic rimmed plagioclases may also represent low-pressure growth of plagioclase during or immediately prior to eruption (Batiza & Vanko 1984; Allan et al. 1987). In the present samples, the reverse zoned (Table 1C) and twinned (Table 1D) plagioclase crystals with a distinct soda enrichment, probably attest to their low-pressure crystallisation from a mixed magma.

In addition to the changes in the contiguous twin lamellae, as mentioned above, Emmons & Mann (1953)

suggested that zoned plagioclase reflects the conditions of the crystal growth, and that the spacing of twin lamellae in turn may reflect the nature of the zoning in part and hence the growth conditions of the crystals. A twinned crystal may enlarge with zonal growth subsequent to twinning. Some of these observations are in fact noted in the CR basalts. For example, figure 4 shows the part elimination of zones due to the effect of the twinning.

Magma Mixing : Compositional changes in a cooling melt may be brought about by normal liquid differentiation due to crystallisation or by mixing of melts of different compositions. Magma mixing is a direct consequence of the episodic nature and intermittent replenishing of magmatic system at MOR (e.g., Dungan et al. 1978). The occurrence of mixed assemblages of plagioclase crystals observed in the FAMOUS region (Hekinian et al. 1976; Bryan et al. 1979), Iceland (Meyer et al. 1985) and Hole 504B on the Costa Rica rift (Natland et al. 1988); suggest that such assemblages could be the product of magma mixing process, which is a widespread phenomenon at slow-spreading to intermediate spreading MORs. There are certain definite petrological criteria that are highly suggestive of magma mixing. In case of the CR basalts few such signatures of magma mixing have been noted as follows:

1. Presence of plagioclase phenocrysts with An-rich core (Table 1A) and corroded margins (Fig. 3). The anomalously An-rich compositions of some plagioclase megacrysts in oceanic basalt may be related to the increasing Na_2O contents produced by magma mixing (Elthon, 1984). Hekinian et al. (1976) report that the composition of plagioclase megacrysts in the FAMOUS area range from An 89 to An 92, whereas the phenocrysts range from An 86 to An 89. Donaldson & Brown (1977) also report very calcic megacrysts (upto An 91.5) in oceanic basalts from the MAR and suggested that these very calcic plagioclase megacrysts indicate that the parental magmas for some, if not many, oceanic basalts are Na-poor ($\pm 1.5\% \text{Na}_2\text{O}$).
2. Coexistence of calcic plagioclase and olivine with minor compositional variations of the latter (range Fo 83-91 mole %; average 88 mole %; Iyer & Banerjee 1993). This may be due to short time interval of olivine crystallisation or due to magma mixing (Rhodes et al. 1979).
3. Presence of twinned sodic plagioclase and/or reversely zoned plagioclase (Tables 1C, D). Similar occurrences have been noted in the basalts of Site 648 on the MAR (Meyer & Shibata, 1990).

4. Low CaO/Al₂O₃ ratio in the bulk composition of these rocks and typical absence of clinopyroxene (Banerjee & Iyer 1991).
5. Hyperbolic relation of the ratio - ratio plots of trace elements and the variable range of TiO₂ at a given FeO*/MgO in the bulk rocks (Banerjee & Iyer 1991).
6. Rare presence of high forsteritic (Fo upto 91 mole %: Iyer & Banerjee 1993) olivine phenocrysts also suggest that the Mg # of the melt must have been lower than the whole rock Mg# due to a process of magma mixing (cf. Rhodes et al. 1979).

The above evidences imply magma mixing to have occurred beneath the slow - spreading ridge CR in the area of investigation. Geophysical studies in the same area seem to indicate shallowing and narrowing of the CR axis in the middle (Ramana et al. 1993). According to them, this perhaps facilitated the excess outpouring of magma at the wider opening of the valley and perhaps gave rise to a large amplitude magnetic anomaly. Further, it was postulated that this segment of the CR is a probable location for segmentation in the future.

The observed variations in the texture and mineral chemistry of the CR basalts may have been influenced by the tectonic setting in which they formed. We note that the present samples lie within a zone of a down-faulted segment bounded by two transform faults (Geological World Atlas, 1976). Ramana et al. (1993) noted that in the NW part of the study area, the free-air gravity is low and appears to be offset left-laterally by a transform fault which is also depicted in the bathymetric map. The nature of this transform fault and the magnitude of ridge offsets might have resulted in congenial conditions for the eruption of basaltic flows. Langmuir & Bender (1984) opined that cooler, thermal environments, such as large offsets transform faults on slow spreading ridges, there is a decrease in the extent of melting and with alkalic volcanism being an extreme manifestation of the transform fault effect (TFE). The TFE together with the concept of a spreading cell (Langmuir et al. 1986) could help explain the differential extent of partial melting coupled with depth of magma generation beneath the CR. Under these conditions, different degrees of cooling, fractionation and segregation of the magmatic melts could have brought about the resultant changes in the texture and mineral composition in the CR basalts.

Thus, we infer that the different morphologies and composition of the plagioclase in the CR basalts can be explicable as due to partial polybaric re-equilibration of crystals formed at higher pressure during the storage of

the magma at low pressure (cf. Fisk 1982). Further, the present observations generally testify to a process of fractional crystallisation in tandem with magma mixing to have occurred in a large, shallow - seated ephemeral magma chamber/s, findings which reaffirm our earlier conclusions.

ACKNOWLEDGEMENTS

We thank Dr. E. Desa, Director, N.I.O. for the facilities provided during the course of this work and Mr. U. Shirsat for printing the photomicrographs. We acknowledge Dr. P.R. Reddy (editor) and the two reviewers for encouragement and suggestions. This is NIO contribution #2548.

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