

Magma Fractionation and Mixing in Nephelinite Plug Associated with Deccan Magmatism at Murud-Janjira, South of Bombay, India

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Abstract: The nephelinite occurs as a N-S trending plug (500 x 200 m.) intrusive into basalts. The rock is porphyritic and principally composed of complexly zoned phenocrysts of clinopyroxene, Fe-Ti oxide and olivine (<5%) in a fine grained groundmass dominated by clinopyroxene, nepheline and Fe-Ti oxides. Mineralogically and chemically the rocks vary between pyroxene melaneophelinites and nephelinites.

The mineral chemistry implies that the magma has undergone varying degrees of polybaric crystallisation in a subcrustal magma chamber with mixing of more fractionated magma with primitive pulses in which are incorporated disaggregated mantle xenolith phases.

Keywords: Nephelinite, Igneous Petrology, Deccan Traps, Bombay, Maharashtra.

INTRODUCTION

Nephelinites (*sensu lato*) associated with Deccan magmatism have been reported from very few localities in India. Those better known come from Amba Dongar in Gujarat (Viladkar, 1985) along the Narmada-Son mid-continental rift. Recently, however, nephelinites (*sensu lato*) have been described from Murud-Janjira (18° 18' 06" N. and 72° 53' 02" E.) located 70 km south of Bombay, and were tentatively classified as "nephelinites-basanites" (Dessai *et al.*, 1990). Precise classification of these rocks is therefore wanting.

Dessai *et al.*, (1990) deferred their classification because of (i) presence of small quantities of albite - which in fact is secondary and more so its association with pervoskite precludes its primary nature and (ii) lack of specific criteria to distinguish the nephelinites and basanites, both of which have many features in common due to which the nephelinites (the present ones too) plot in the basanite field in the TAS diagram. This latter difficulty has been now overcome (Le Bas, 1989). It is therefore, proposed to (i)

assign these rocks their correct status as per modern schemes of classification failing which, as aptly put by Le Bas, it would lead to "blurring of petrographic distinction" (Le Bas, 1989) and (ii) present modern mineralogical data which are totally lacking. Finally in the light of petrography and rock - and mineral - chemistry, the petrogenesis of these rocks is discussed.

GEOLOGY OF THE AREA

The nephelinite plug occurs as a member of the west coast dyke-swarm (Dessai, 1987; Dessai *et al.*, 1990) which is intrusive into the tholeiitic basalts. The basalts along the coast have been traditionally classified as Upper Traps (Pascoe, 1964). However, as per recent chemostratigraphic work (Bean *et al.*, 1986) these rocks are included under Poladpur and Ambenali Formations of the youngest Wai Sub-group of the Deccan Basalt Group (Subbarao and Hooper, 1988) of late Cretaceous to Eocene age (Mahoney, 1988).

The dyke-swarm is characterised by a variety of alkaline rocks including alkali dolerites, lamprophyres (Dessai, 1985; 1987),

nepheline syenite (Dessai and Bodas, 1984), tephriphonolite (Dessai *et al.*, 1990) quartz-monzonite, melanephelinite among others. The nephelinites are exposed on a bay-beach to the west of Rajpuri village and southeast of Murud (Fig. 1). They occur as a dyke-like intrusive body whose longer axis

trends in N-S direction and can be traced over a distance of about 500 m. The maximum exposed width is about 200 m. The northern and eastern contacts in general, are concealed by beach sands, habitation and cultivation except for a part of northern contact which exhibits 1 m. wide zone traversed by

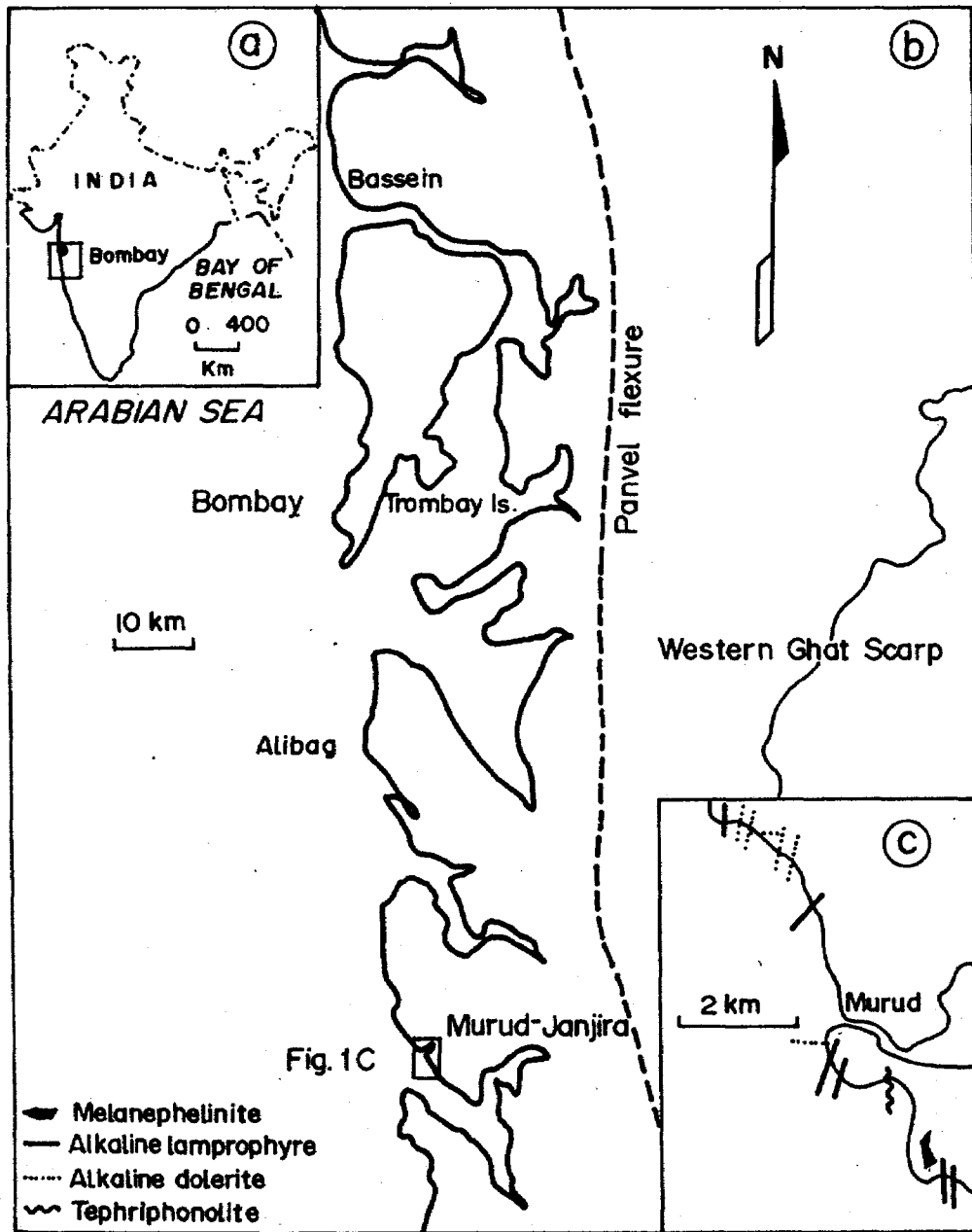


Fig.1. Location map of Murud-Janjira nephelinites (a) Regional context (b) relation of Murud-Janjira to Bombay and Panvel Flexure axis (c) distribution of nephelinites and other dykes at Murud-Janjira.

thin veinlets (< 1 cm.) of calcite. The western and southern contacts are under water. The body therefore, was delineated with the help of aerial photographs on 1 : 45,000 scale.

About 800 m. to the northwest of nephelinite, a multiple intrusion of tephriphonolite trending N-S is exposed. Its maximum exposed width is 10 m., the central portion being 1.5 to 5 m. wide. It appears to be an extension of the nephelinite plug, hence has been included here. Dessai *et al.*, (1990) however, have related the tephriphonolite to camptonite on the basis of quantitative modelling.

PETROGRAPHY

The nephelinites are pale greenish grey to olive green in colour when fresh. They are distinctly porphyritic in hand specimen. Slight variation in grain size is observed between the central part of the body and the borders, the centre being little coarser than the border. The phenocrysts are made up of clinopyroxene crystals which vary in size between 4 and 20 mm.

In microsections the rock is porphyritic with abundant large crystals of clinopyroxene and Fe-Ti oxides with accessory proportions of olivine and perovskite in a fine microcrystalline groundmass dominated by clinopyroxene, nephelene, Fe-Ti oxides, perovskite and sphene. The minerals exhibit alteration to secondary albite and carbonates. Zeolites occur as amygdules with chlorite-smectite intergrowths. The latter at places, replace the clinopyroxene.

Clinopyroxene is the most dominant constituent of the rock. It makes up as much as 46 to 52 per cent of the crystalline phases. It occurs as phenocryst and groundmass constituents. In peripheral samples the groundmass is extremely fine grained. Invariably the phenocrysts have resorbed, corroded, rounded to irregular, green strongly pleochroic xenocrystic cores, mantled by pale green border zones. The boundary between the core and the mantling material is

generally sharply defined. Invariably the boundary zone is studded with fine inclusions of nephelene and iron oxide whereas, the core and the surrounding mantles are essentially free of inclusions. Generally the phenocrysts are complexly zoned (Fig. 2) and are cor-

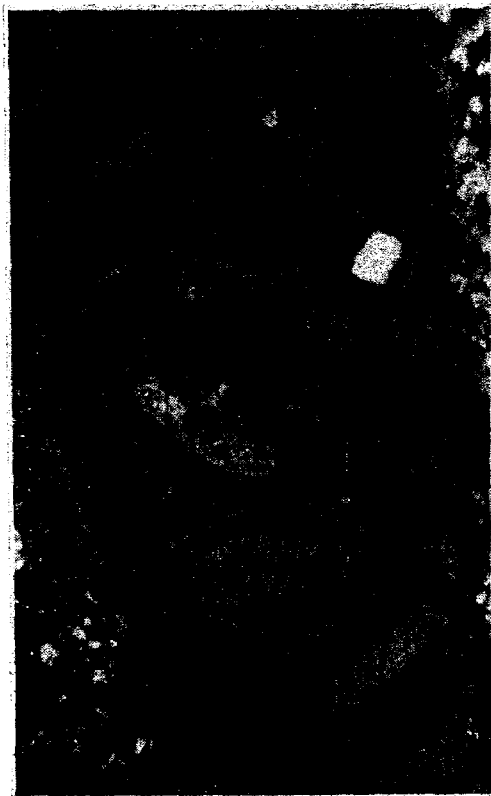


Fig.2. Complexly zoned clinopyroxene phenocryst in nephelinite.

roded and embayed by groundmass constituents. Clinopyroxene phenocrysts also occur devoid of green cores and exhibit idiomorphic square or rhombic shapes with sharply defined outlines. Clinopyroxene is also found included within olivine (Fig. 3). It is unzoned and pale green in colour as compared to the phenocrysts. Olivine occurs as phenocrysts, fresh, resorbed, corroded and embayed by groundmass (Le Bas, 1987). Irregular patches and blebs of calcite are at places seen in the groundmass. Calcite in the veins is associated with clinopyroxene. It is likely therefore, that calcite is of primary



Fig.3. Chrome-diopside inclusion in olivine phenocryst in nephelinite RG 1 (CD - chrome diopside)

magmatic origin. It may be a pointer to the existence of carbonatites in association with nephelinites.

As per recent IUGS recommendations (Le Bas, 1989) these rocks are more specifically identified to vary between pyroxene melanephelinites and nephelinites in difference to nephelinites-basanites of Dessai *et al.*, (1990). However, such unequivocal identification is rarely possible in case of such fine grained rocks in which feldspars may escape identification under the microscope leading to erroneous results. Such instances are documented in literature in case of Cape Verde Island pyroxene melanephelinites which were at one time called 'pyroxenites' and later 'augitites' (Doelter, 1882 in Le Bas, 1989). As a precautionary measure therefore, various parameters based on whole rock chemical data (Le Bas, 1989) have been used to substantiate the modal identification.

The tephriphonolite is greyish in colour. It is porphyritic and is constituted of phenocrysts of plagioclase (deciphered from relicts) altered to an assemblage of albite, sericite and calcite along with clinopyroxene strongly pleochroic in shades of green. The latter forms glomeroporphyritic aggregates along with apatite which at places is included in biotite. The groundmass is made up of acicular green clinopyroxene, albite, sericite, calcite and little apatite and opaques.

WHOLE ROCK GEOCHEMISTRY

Nephelinites were chemically analysed at the Copenhagen University, Denmark and the University of Western Australia. Representative new analyses along with those of Dessai *et al.*, (1990) are presented in Table-I. For comparison analyses of melanephelinite from Amba Dongar, India (Viladkar, 1985) and East African Rift (Le Bas, 1987) are also presented. All samples are nepheline normative and carry < 5% *ab*. In the TAS diagram (Fig. 2 of Dessai *et al.*, 1990) the rocks plot in the basanite/tephrite field instead of foidite field. This prompted Dessai *et al.*, (1990) to suggest that the rocks may have originally carried feldspar. It was cautioned though, that the diagram is recommended for analyses containing < 2% H₂O and < 0.5% CO₂, conditions which the present rocks violate. It has also been shown (Le Bas, 1989) that TAS diagram is unsatisfactory because many nephelinites (mineralogically), particularly those with olivine, plot in the basanite field. Hence several criteria have been suggested to distinguish chemically between nephelinites and basanites.

One of the suggestions is that 5 wt % *ab* is a good discriminator between basanites and melanephelinites, and that 20 wt % *ne* can divide nephelinites from melanephelinites and basanites (Le Bas, 1989). As per these criteria one rock (RG 3) is a melanephelinite whereas others are nephelinites similar to those from Narmada valley and East African Rift. As the analyses contain 10 wt % or more

of MgO and less than 8 wt % (Na₂O + K₂O) the rocks can be classified as pyroxene melanephelinites and nephelinites (Le Bas, 1989).

The analysis of Y1 although appears to be that of a phonotephrite on recalculation to 100 % the rock plots in the tephriphonolite field of the TAS diagram (Dessai *et al.*, 1990).

In order to evaluate the course of crystallisation the major and trace element compositions (Table I) have been plotted in different variation diagrams (Fig. 4 a-k). By and large the observed major and trace element variations correspond to those expected from fractional crystallisation process. The trends (Fig. 4 a,b,d & e) are qualitatively consistent with olivine and clinopyroxene fractionation at the beginning of differentiation. Fig. 4c is indicative of early separation of perovskite or Fe-Ti oxides. Na₂O as expected increases from melanephelinite to nephelinite (Fig. 4f) with fractionation, however, it shows a decrease in tephriphonolite. The behaviour of compatible elements (Fig. 4g & i) confirms early fractionation of olivine and clinopyroxene + spinel. Sympathetic behaviour of V and Fe₂O₃ (Fig. 4k) can be attributed to crystallisation of Fe-Ti oxides. The behaviour of incompatible elements (Fig. 4j & h) appears to be backwards for normal course of fractionation. Trend shown by Zr may be ascribed to its partitioning into sphene and/or spinel (Cox *et al.*, 1979). Decrease of Nb could be attributed to perovskite crystallisation. The trend shown by Ba (Fig. 4h) is again not normal. There is no clear cut relationship between degree of fractionation and Ba content as some low values (300-500ppm) occur in fractionated compositions. Shimizu (1975) has shown that liquids co-existing with clinopyroxene-separates have values between 1000-2300 ppm. The most primitive of present nephelinites (RG 3) shows values of 1077 ppm. However, all values exceeding 740 ppm are restricted to evolved types (Wass, 1980). U (2-5ppm), Th (7-11 ppm), Y (14-17ppm), Pb (7-11 ppm) are all within their

respective primary composition ranges i.e. U (1-7 ppm), Th (6-17 ppm), Y (14-17 ppm) and Pb (7-18 ppm). The anomalies exhibited by the major and trace elements are probably related to the mantle source inhomogeneity as discussed later.

MINERAL CHEMISTRY

The various mineral phases from the nephelinites were analysed for their major element compositions by the standard electron probe technique using an energy dispersive system at the University of Western Australia. Between five and twenty four analyses were made for each mineral phase in each sample and upto nine analyses in each traverse across phenocrysts. Representative analyses of clinopyroxenes, olivines and spinels are presented in Tables II, III & IV respectively.

Clinopyroxene

The analyses of clinopyroxenes in the pyroxene quadrilateral form a cluster near diopside apex (Fig. 5) and show very limited variation in major components Ca-Mg-Fe. This is in contrast to highly complex variation seen within and between grains in minor constituents Na, Al, Ti and Cr. Maximum content of Na₂O is 1.1%, Al₂O₃ - 3.4%, TiO₂ - 1.7% and Cr₂O₃ - 1.1%. Some generalisation is, however, possible as far as Al and Ti distribution is concerned. From core to rim Al decreases at constant or slightly decreasing Ti. Overall the pyroxenes show close similarity to pyroxenes in undersaturated basic rocks (Le Bas, 1987; Rock, 1987). As per IMA terminology the pyroxenes may be identified as sodian, titanian, aluminian and/or chromian diopsides.

On the basis of Cr₂O₃ percentage the pyroxenes belong to two groups. Inclusions within olivine (Analyses 13 & 14 Table I) have Cr₂O₃ >1% with high Mg# [mole % Mg/(Mg + Fe⁺² + Mn)] ~ 0.9, low TiO₂ (0.2 - 0.3%) coupled with octahedrally coordinated Al (as Ca-Tschermak's molecule).

Table-I Whole rock analyses of nephelinites from Murud- Janjira, Amba Dongar and East African Rift.

Major Elements (Wt.%)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|--------------------------------|--------|--------|--------|-------|-------|-------|--------|--------|-------------------------------|--------|-------|
| | RG-3 | RG-1 | RG-5 | RG-7 | RG-2 | Y-1 | 256 | 570 | Olivine-poor (nephelinite) | Sun 6 | Elk 6 |
| SiO ₂ | 40.89 | 42.56 | 43.19 | 43.21 | 44.84 | 49.24 | 43.00 | 43.16 | 41.04 | 43.50 | 42.20 |
| TiO ₂ | 2.21 | 1.32 | 1.20 | 1.23 | 0.89 | 0.30 | 0.70 | 0.72 | 2.08 | 2.03 | 2.48 |
| Al ₂ O ₃ | 10.04 | 11.82 | 11.55 | 11.65 | 13.17 | 18.70 | 14.75 | 12.95 | 11.04 | 10.30 | 12.04 |
| Fe ₂ O ₃ | 12.22 | 10.78 | 7.00 | 7.02 | 7.49 | 4.69 | 6.21 | 8.27 | 7.04 | 15.03 | 13.97 |
| FeO | - | - | 4.15 | 4.20 | - | 1.10 | 3.52 | 2.80 | 6.00 | - | - |
| MnO | 0.24 | 0.21 | 0.21 | 0.20 | 0.14 | 0.20 | 0.15 | n.d. | 0.2 | 0.18 | 0.27 |
| MgO | 10.12 | 10.03 | 9.47 | 9.31 | 8.28 | 1.89 | 2.70 | 3.70 | 8.01 | 19.18 | 6.22 |
| CaO | 12.67 | 12.91 | 12.06 | 12.05 | 11.94 | 6.72 | 10.15 | 10.57 | 13.01 | 16.94 | 15.17 |
| Na ₂ O | 2.82 | 4.99 | 5.95 | 5.72 | 6.50 | 3.86 | 8.94 | 7.00 | 3.07 | 1.26 | 3.93 |
| K ₂ O | 1.97 | 1.13 | 2.16 | 1.98 | 1.31 | 5.87 | 2.08 | 2.98 | 1.08 | 1.68 | 2.54 |
| P ₂ O ₅ | 0.73 | 0.39 | 0.68 | 0.58 | 0.20 | 1.02 | 0.39 | 0.55 | 0.08 | 0.58 | 0.88 |
| H ₂ O | 6.34 | 4.43 | 2.41 | 2.55 | 5.12 | 5.85 | 3.60 | 2.70 | 3.00 | - | - |
| CO ₂ | - | - | - | - | - | - | 4.20 | 5.60 | - | - | - |
| Total | 100.25 | 100.57 | 100.03 | 99.70 | 99.88 | 99.44 | 100.39 | 100.98 | 99.09 | 100.68 | 99.68 |
| CIPW Norms | | | | | | | | | | | |
| cr | 9.76 | 3.32 | - | - | 8.21 | 34.69 | 12.13 | 17.79 | | | |
| ab | - | - | - | - | 2.60 | 12.33 | 12.58 | 15.58 | | | |
| an | 9.57 | 6.82 | - | 0.27 | 3.06 | 16.26 | - | - | | | |
| lc | 2.15 | 2.88 | 10.01 | 9.18 | 0.00 | - | - | - | | | |
| ne | 13.87 | 23.95 | 25.67 | 26.22 | 30.19 | 11.02 | 27.83 | 18.18 | | | |
| ac | - | - | 2.61 | - | - | - | 10.16 | 8.78 | | | |
| di | 41.85 | 45.74 | 34.08 | 40.58 | 46.23 | 8.74 | 17 | 15 | | | |
| ol | 8.89 | 7.18 | 15.94 | 12.82 | 2.83 | 6.11 | 0.00 | - | | | |
| ln | - | - | 4.21 | 1.83 | - | - | - | - | | | |

Table I Continued

| | 1 RG-3 | 2 RG-1 | 3 RG-5 | 4 RG-7 | 5 RG-2 | 6 V-1 | 7 256 | 8 570 | 9 Olivine-poor | 10 Sun 6 | 11 Elk 6 |
|----|-----------|-----------|-----------|-----------|-----------|----------|----------|----------|-------------------|-------------|-------------|
| mt | 7.61 | 6.55 | 0.69 | 2.01 | 4.61 | 1.02 | 3.94 | 6.96 | | | |
| ll | 4.50 | 2.63 | 2.28 | 2.34 | 1.79 | 0.57 | 1.37 | 1.37 | | | |
| ap | 1.82 | 0.95 | 1.58 | 1.34 | 0.49 | 2.34 | 1.01 | 1.34 | | | |
| he | | - | - | - | - | - | - | 0.32 | | | |
| cc | | - | - | - | - | - | 9.50 | 12.50 | | | |

Trace Elements (ppm)

| | | | | | | | | | | | |
|----|------|-----|--|--|-----|--|------|--|--|------|------|
| Sr | 1489 | 675 | | | 486 | | 2246 | | | 1098 | 910 |
| Rb | 61 | 41 | | | 46 | | 30 | | | 31 | 45 |
| Zr | 195 | 78 | | | 59 | | 896 | | | 135 | 193 |
| Nb | 68 | 21 | | | 13 | | 492 | | | 46 | 111 |
| Zn | 108 | 83 | | | 57 | | 208 | | | 92 | 114 |
| Co | 59 | 61 | | | 26 | | 17 | | | - | - |
| Ni | 115 | 75 | | | 51 | | 6 | | | 82 | 29 |
| Ce | 117 | 24 | | | 7 | | 336 | | | 88 | 158 |
| La | 51 | 9 | | | 8 | | 22 | | | 49 | 92 |
| Y | 17 | 15 | | | 14 | | 30 | | | 18 | 25 |
| Cr | 333 | 176 | | | 119 | | 8 | | | - | - |
| Th | 10 | 5 | | | 2 | | 53 | | | 6 | 12 |
| V | 272 | 219 | | | 130 | | - | | | 333 | 211 |
| Ba | 1077 | 786 | | | 132 | | | | | 749 | 1211 |
| Nd | nd | nd | | | nd | | | | | 38 | 57 |
| Cs | 22 | 14 | | | 12 | | | | | | |

Table I Continued

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|----|------|------|------|------|------|-----|-----|-----|--------------|-------|-------|
| | RG-3 | RG-1 | RG-5 | RG-7 | RG-2 | V-1 | 256 | 570 | Olivine-poor | Sun 6 | Elk 6 |
| Pb | 11 | 10 | | | 7 | | | | | | |
| U | 5 | 2 | | | 2 | | | | | | |
| Sc | 31 | 29 | | | 22 | | | | | | |
| Cu | 205 | 105 | | | 58 | | | | | | |

1-: Melanephelinite (analysis of Dessai *et al.*, 1990)

2-5: Nephelinites (analysis 2 and 5 of Dessai *et al.*, 1990; 3 and 4 present study)

6-: Tephriphonolite (Dessai *et al.*, 1990)

7-8: Nephelinites from Amba Dongar (Viladkar, 1984, Table-II)

9-: World average of 97 olivine-poor nephelinites (Le Bas, 1987, Table IV)

10-11: Analysis of melanephelinites from East African Rift (Le Bas, 1987, Table-I)

Table-II Representative microprobe analysis of clinopyroxenes in nephelinites and tephriphonolite from Murud-Janjira.

| | 1 C | 2 R | 3 C | 4 R | 5 C | 6 R | 7 C | 8 R | 9 C | 10 R | 11 G | 12 G | 13 InO | 14 InO | 15 C | 16 R | 17 |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|-----------|-----------|---------|---------|-------|
| SiO ₂ | 51.48 | 51.87 | 51.29 | 53.69 | 51.91 | 54.58 | 52.87 | 54.13 | 52.62 | 52.30 | 53.98 | 54.42 | 53.27 | 53.46 | 51.78 | 52.34 | 53.20 |
| TiO ₂ | 0.58 | 0.49 | 0.80 | 0.67 | 0.79 | 0.51 | 0.25 | 0.46 | 0.47 | 0.33 | 0.46 | 0.89 | 0.36 | 0.22 | 0.31 | 0.32 | 0.45 |
| Al ₂ O ₃ | 2.86 | 2.24 | 3.12 | 0.68 | 2.31 | 0.13 | 1.07 | 0.28 | 2.33 | 2.31 | 0.28 | 0.10 | 1.75 | 1.48 | 1.64 | 1.55 | 1.00 |
| Cr ₂ O ₃ | 0.10 | 0.14 | 0.19 | 0.16 | 0.22 | 0.11 | 0.17 | 0.69 | 0.14 | 0.15 | 0.56 | 0.11 | 1.12 | 1.02 | 0.13 | 0.15 | 0.86 |
| FeO* | 6.60 | 6.89 | 5.56 | 5.00 | 4.85 | 4.22 | 8.44 | 4.65 | 5.69 | 5.32 | 4.52 | 4.75 | 3.59 | 3.41 | 15.39 | 14.78 | 2.93 |
| MnO | 0.11 | 0.11 | 0.11 | 0.11 | 0.10 | 0.11 | 0.11 | 0.11 | 0.00 | 0.00 | 0.11 | 0.13 | 0.00 | 0.00 | 0.30 | 0.21 | 0.06 |
| MgO | 13.75 | 13.91 | 14.79 | 15.24 | 14.96 | 16.17 | 13.51 | 15.92 | 14.65 | 14.79 | 15.91 | 15.02 | 15.78 | 16.02 | 8.71 | 8.61 | 16.85 |
| CaO | 23.46 | 24.12 | 24.57 | 24.18 | 24.52 | 24.63 | 22.44 | 24.29 | 23.44 | 23.30 | 24.29 | 23.94 | 23.99 | 23.81 | 19.60 | 19.30 | 23.43 |
| Na ₂ O | 0.70 | 0.56 | 0.38 | 0.30 | 0.25 | 0.35 | 1.01 | 0.14 | 0.74 | 0.58 | 0.21 | 0.73 | 0.65 | 0.46 | 2.99 | 2.90 | 0.48 |
| Total | 99.64 | 100.33 | 100.81 | 100.03 | 99.91 | 100.88 | 99.87 | 100.67 | 100.08 | 99.08 | 100.32 | 100.09 | 100.51 | 99.94 | 100.85 | 100.12 | 99.33 |
| Cations per formula unit 0 = 6 | | | | | | | | | | | | | | | | | |
| Si | 1.9056 | 1.9264 | 1.8886 | 1.9788 | 1.9194 | 1.9874 | 1.9707 | 1.9807 | 1.9408 | 1.9410 | 1.9836 | 2.002 | 1.9420 | 1.9539 | 1.9788 | 1.9925 | 1.956 |
| Ti | 0.0156 | 0.0134 | 0.0220 | 0.0176 | 0.0199 | 0.0131 | 0.0067 | 0.0109 | 0.0110 | 0.0089 | 0.0110 | 0.0176 | 0.0087 | 0.0065 | 0.0091 | 0.0091 | 0.013 |
| Al | 0.1206 | 0.0940 | 0.1325 | 0.0265 | 0.1020 | 0.0043 | 0.0447 | 0.0087 | 0.1077 | 0.1023 | 0.0088 | 0.0044 | 0.0743 | 0.0614 | 0.0733 | 0.0685 | 0.046 |
| Cr | 0.0268 | 0.0022 | 0.0044 | 0.0044 | 0.0044 | 0.0043 | 0.0044 | 0.0175 | 0.0044 | 0.0044 | 0.0132 | 0.0044 | 0.0306 | 0.0307 | 0.0045 | 0.0046 | 0.025 |
| Fe ⁺³ | 0.0178 | 0.0134 | 0.0088 | 0.0044 | 0.0044 | 0.0087 | 0.0268 | 0.0043 | 0.0177 | 0.0133 | 0.0044 | 0.0176 | 0.0131 | 0.0131 | 0.0733 | 0.0731 | - |
| Fe ⁺² | 0.1854 | 0.1971 | 0.1590 | 0.1437 | 0.1420 | 0.1179 | 0.2371 | 0.1383 | 0.1526 | 0.1491 | 0.1322 | 0.1258 | 0.1006 | 0.0921 | 0.3760 | 0.3815 | 0.090 |
| Mn | 0.0022 | 0.0022 | 0.0022 | 0.0022 | 0.0022 | 0.0021 | 0.0022 | 0.0021 | - | - | 0.0022 | 0.0022 | - | - | 0.0091 | 0.0068 | 0.002 |
| Mg | 0.7617 | 0.7705 | 0.8173 | 0.8423 | 0.8299 | 0.8823 | 0.7561 | 0.8740 | 0.8099 | 0.8236 | 0.8771 | 0.8302 | 0.8638 | 0.8793 | 0.4998 | 0.4912 | 0.924 |
| Ca | 0.9338 | 0.9632 | 0.9675 | 0.9529 | 0.9697 | 0.9587 | 0.8948 | 0.9486 | 0.9228 | 0.9260 | 0.9521 | 0.9406 | 0.9338 | 0.9320 | 0.8025 | 0.7883 | 0.923 |
| Na | 0.0491 | 0.0403 | 0.0220 | 0.0221 | 0.0177 | 0.0218 | 0.0715 | 0.0087 | 0.0486 | 0.0400 | 0.0132 | 0.4850 | 0.0437 | 0.0307 | 0.2155 | 0.2147 | 0.034 |
| Mg | 0.8042 | 0.7963 | 0.8371 | 0.8542 | 0.8538 | 0.8212 | 0.7612 | 0.8633 | 0.8414 | 0.8467 | 0.8690 | 0.8665 | 0.8956 | 0.9051 | 0.5706 | 0.5628 | 0.910 |
| Mg+Fe ²⁺ +Mn | 49.64 | 49.82 | 49.71 | 49.09 | 49.91 | 48.91 | 47.33 | 48.32 | 48.94 | 48.54 | 48.48 | 49.56 | 49.19 | 46.96 | 47.55 | 47.26 | 47.60 |
| Wo | 40.49 | 39.86 | 41.99 | 43.39 | 42.71 | 45.01 | 40.00 | 44.52 | 42.95 | 43.17 | 44.66 | 43.74 | 45.50 | 46.19 | 29.61 | 29.45 | 47.70 |
| Fs | 9.85 | 10.31 | 8.28 | 7.51 | 7.41 | 6.07 | 12.66 | 7.15 | 8.09 | 7.81 | 6.84 | 6.69 | 5.29 | 4.83 | 22.82 | 23.28 | 4.70 |
| Ti/Al | 0.12 | 0.14 | 0.16 | 0.66 | 0.19 | 3.04 | 0.14 | 1.25 | 0.10 | 0.08 | 0.10 | 4.00 | 0.11 | 0.11 | 0.12 | 0.13 | 0.28 |

*Total Fe as FeO

C - Core
R - Rim
InO - Inclusion in Olivine

1-4 : Cpx in RG3
5-8 : Cpx in RG1
9 & 10 : Cpx in RG2

11 & 12 : Cpx in RG1 & RG3 resp.
13 & 14 : Cr - diopside in RG2
15 & 16 : Cpx in Y1

17 : Cr - diopside in olivine
melanephelinite
(analysis 1, Table-IV, Le Bas, 1987).

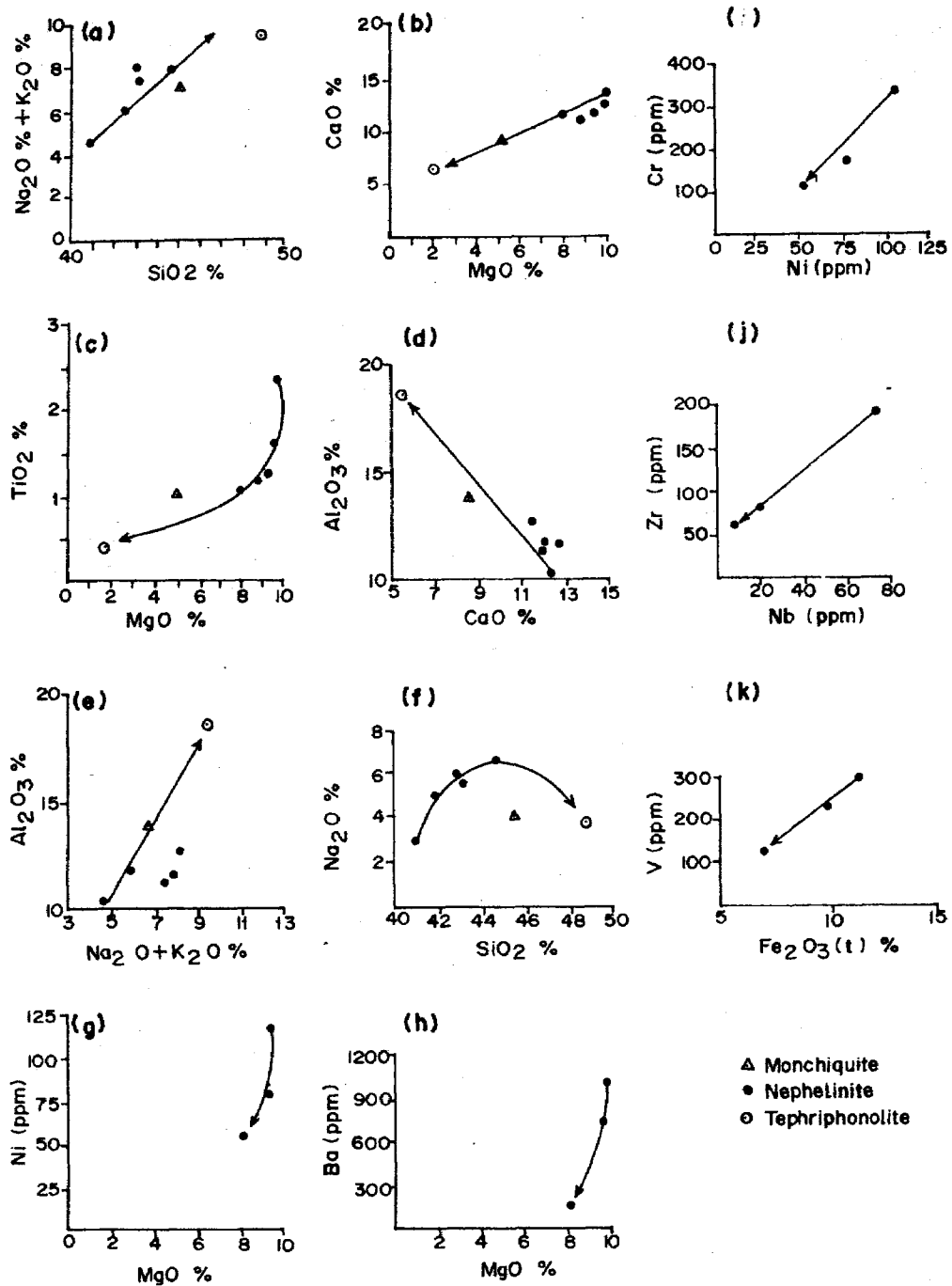


Fig.4. Major element oxide (wt %), compatible - and incompatible- trace element (ppm) variation diagrams to illustrate differentiation (monchiquite: analysis RD 1, Table 2, Dessai *et al.*, 1990).

These can be categorised as chrome diopside (En 45-46 Fs 4-5 Wo 46-49).

The clinopyroxene phenocrysts exhibit a complex variation not only among samples but also within and between grains in the same sample. They exhibit a variety of evolu-

tionary trends. These can be expressed in terms of Mg #, Na_2O , Al_2O_3 , and TiO_2 variations observed across a traverse from core to rim. For the sake of convenience the compositional zoning can be described with reference to rim- and core-composition. Under

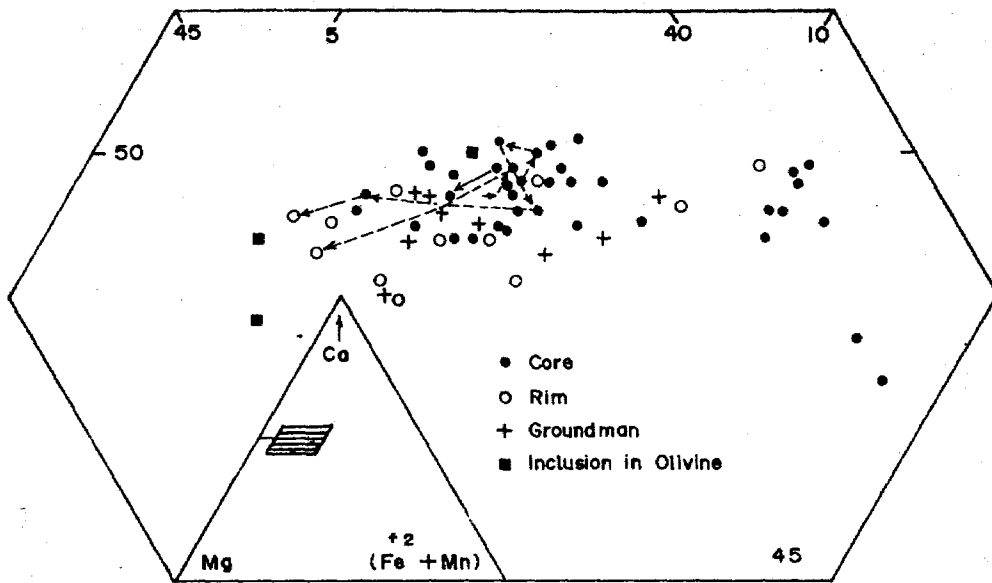


Fig. 5. Ca-Mg-(Fe²⁺ + Mn) plot of clinopyroxenes in nephelinites.

core-composition, the composition of the mantles- the zones in between the core and the rim, will be also described. Representative analysis of clinopyroxenes are listed in Table II and are illustrated in Fig. 6.

The clinopyroxene rims are pale green in colour and exhibit resorption. They can be classified as diopsides and titanian, aluminian diopsides (IMA, 1988). The TiO₂

content varies between 0.33 and 0.67%, and Al₂O₃ between 0.13 and 2.86%. In general rim TiO₂ in least evolved rocks (RG 3, RG 1) is higher than in more evolved rock (RG 2). The converse is true for Al₂O₃. The Ti/Al ratio ranges from 0.8 to 3.0. It is higher in more evolved rocks (RG 2 : 2-2.5) than in least evolved ones (RG 3 & RG 1 : 0.14- 1.5). The rim composition is identical to

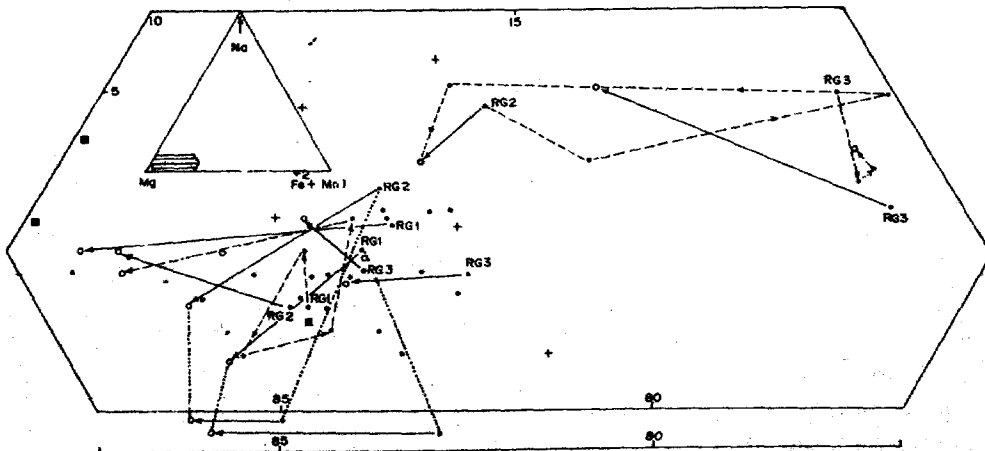


Fig. 6. Na-Mg-(Fe²⁺ + Mn) plot of clinopyroxenes in nephelinites. Dashes connect core to mantles. Dotted tie-lines join olivine and pyroxene from same rock. Bold arrow shows core to rim variation. Symbols as in Fig. 5.

groundmass pyroxene (En 39-45 Fs 7-10 Wo 48-49). The Mg # varies between 0.79 to 0.86, the evolved rocks having highest values.

The cores are deep green and resorbed whereas the mantles are pale green. The cores and the mantles contain higher Al_2O_3 (1.0- 3.1%) and TiO_2 (0.25-0.80%) than the rims. Core Al_2O_3 is higher in least evolved rocks (RG 3, RG 1: 1.7-3.12%) than in more evolved ones (RG 2: 0.9-2.3%). Slight opposite behaviour is shown by TiO_2 (not apparent in Table II). The cores and the mantles have lower Mgs # (0.76-0.86) and higher Na_2O (0.13-0.14%) than the rims. The clinopyroxenes can be classified as aluminian diopsides (IMA, 1988). Their general composition is En 40-43 Fs 7-12 Wo 47-49. Ti/Al ratios (0.12-0.26) are lower than the rims. Ti increases with increasing Fe (Fig. 7), how-

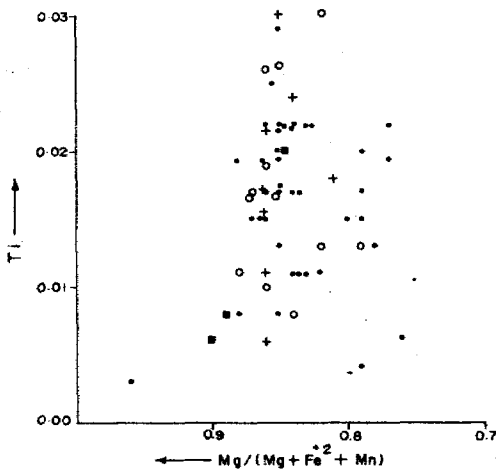


Fig. 7. Atomic proportion Ti versus $\text{Mg}/(\text{Mg} + \text{Fe}^{+2} + \text{Mn})$ plot of clinopyroxenes in nephelinites. Symbols as in Fig. 5.

ever, Al does not show a marked variation unlike the rim composition (Fig. 8). It is also seen from the figure that Al does not show a compositional continuity between core-mantles and the rims.

Majority of phenocrysts are of the type shown in Fig. 2. and exhibit reverse and irregular zoning. Dominant zoning is, however, of the reverse type (Fig. 6). The more primitive of the nephelinites (RG 3, RG 1) has

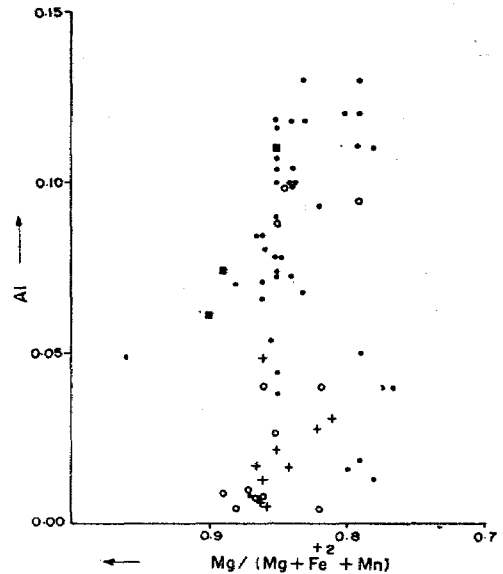


Fig. 8. Atomic proportion Al (total) versus $\text{Mg}/(\text{Mg} + \text{Fe}^{+2} + \text{Mn})$ plot of clinopyroxenes from nephelinites. Symbols as in Fig. 5.

Fe-rich sodic pyroxene cores whereas the more evolved rock (RG 2) has comparatively less sodic cores and more magnesian rims (Fig. 6). The mantles of majority of grains show oscillatory zoning of reverse type. Complex compositional variations in pyroxenes similar to ones under consideration have also been reported from alkaline basaltic rocks from different parts of the world (Frisch and Schminke, 1969; Borley *et al.*, 1971; Girod, 1971; Wilkinson, 1975; Brooks and Prinzlau, 1978; Duda and Schminke, 1985) as also from alkaline lamprophyres from Murud-Janjira (Dessai *et al.*, 1990).

The clinopyroxenes from tephriphonolite can be classified as aegerine augite (IMA, 1988) and have a composition represented by En 27-31 Fs 21-25 Wo 46-47. They show normal zoning with core Mg # varying between 0.53 and 0.60 and rim between 0.52 and 0.55. Core Al_2O_3 is between 1.68 and 3.63 and rim between 1.32 and 3.12 wt %. Ti/Al ratio is higher in the rims (0.09-0.23) than in the cores (0.05-0.12).

Olivine

The olivine phenocrysts have a very

Table-III Representative microprobe analyses of olivines in nephelinite (RG1) from Murud-Janjira.

| | 1 C | 2 R | 3 R |
|--------------------------------|--------|--------|--------|
| SiO ₂ | 39.10 | 39.96 | 39.61 |
| TiO ₂ | 0.10 | 0.09 | 0.10 |
| Al ₂ O ₃ | 0.10 | 0.09 | 0.10 |
| Cr ₂ O ₃ | 0.09 | 0.09 | 0.09 |
| FeO | 16.12 | 12.95 | 15.87 |
| NiO | 0.16 | 0.16 | 0.16 |
| MnO | 0.30 | 0.83 | 0.52 |
| MgO | 43.80 | 45.85 | 43.22 |
| CaO | 0.32 | 0.42 | 0.69 |
| Na ₂ O | 0.17 | 0.17 | 0.17 |
| K ₂ O | 0.05 | 0.05 | 0.05 |
| Total | 100.35 | 100.70 | 100.58 |

Cations per formula unit 0 = 4

| | | | |
|-----------------------------|-------|-------|-------|
| Si | 0.993 | 0.998 | 1.002 |
| Ti | 0.000 | 0.000 | 0.000 |
| Al | 0.000 | 0.000 | 0.000 |
| Cr | 0.000 | 0.000 | 0.000 |
| Fe ⁺² | 0.342 | 0.270 | 0.336 |
| Ni | 0.000 | 0.000 | 0.000 |
| Mn | 0.007 | 0.018 | 0.011 |
| Mg | 1.657 | 1.706 | 1.630 |
| Ca | 0.009 | 0.011 | 0.019 |
| Na | 0.000 | 0.000 | 0.000 |
| K | 0.000 | 0.000 | 0.000 |
| Mg/(Mg + Fe ⁺²) | 0.829 | 0.863 | 0.829 |

C = Cores 1 & 2 : (Dessai *et al.*, 1990, Table-III)

R = Rim

restricted range of composition (Table III) Fo 82-86, about 0.1 % TiO₂ and CaO between 0.13 and 0.74% (Dessai *et al.*, 1990). They are reversely zoned (Fig. 6) with core Fo 82 and rim Fo 86. Olivine in evolved rock (RG 2) is more magnesian than that in least evolved rock (RG 3, RG 1).

Spinel

The spinels occur as phenocrysts, inclusions within olivine and pyroxene and in groundmass. Their general composition is magnetite 67-73 ulvospinel 24-31 spinel 0.6-7.0 and chromite 0.2-4.0 (Table IV). TiO₂ ranges from 8-11 % and MnO from 0.6-1.3 %. They are low in NiO, CaO and ZnO (all < 0.5 wt %). Inclusions in olivine are relatively richer in Cr₂O₃ and poorer in TiO₂ than those in pyroxene. The groundmass spinels

Table-IV Representative microprobe analyses of spinels in nephelinites from Murud-Janjira.

| | RG1 1 In C | RG1 2 In O | RG3 3 G | RG2 4 In O |
|--------------------------------|------------------|------------------|---------------|------------------|
| TiO ₂ | 11.00 | 8.63 | 10.01 | 9.80 |
| Al ₂ O ₃ | 0.83 | 0.27 | 3.34 | 0.54 |
| Cr ₂ O ₃ | 0.10 | 0.90 | 1.19 | 2.45 |
| Fe ₂ O ₃ | 47.87 | 50.58 | 48.70 | 48.89 |
| V ₂ O ₃ | - | - | 0.20 | - |
| FeO | 32.22 | 32.31 | 31.94 | 31.81 |
| NiO | 0.18 | 0.18 | 0.18 | - |
| CaO | - | - | 0.27 | - |
| MnO | 1.40 | 1.39 | 0.67 | 1.12 |
| ZnO | - | - | 0.53 | - |
| MgO | 4.57 | 2.81 | 5.28 | 4.61 |
| Total | 98.16 | 97.06 | 100.32 | 99.23 |

Cations per formula unit 0 = 32

| | | | | |
|---------------------------------|--------|--------|--------|--------|
| Ti | 2.468 | 1.994 | 2.123 | 2.179 |
| Al | 0.292 | 0.098 | 1.110 | 0.188 |
| Cr | 0.024 | 0.219 | 0.265 | 0.573 |
| Fe ⁺³ | 10.748 | 11.695 | 10.334 | 10.880 |
| V | - | - | 0.045 | - |
| Fe ⁺² | 8.039 | 8.301 | 7.532 | 7.867 |
| Ni | 0.043 | 0.044 | 0.041 | - |
| Ca | - | - | 0.061 | - |
| Mn | 0.354 | 0.362 | 0.160 | 0.281 |
| Zn | - | - | 0.110 | - |
| Mg | 2.032 | 1.287 | 2.219 | 2.032 |
| Mg/ (Mg + Fe ⁺²) | 0.202 | 0.134 | 0.228 | 0.205 |
| ulvospinel | 30.85 | 24.93 | 26.53 | 27.24 |
| spinel | 1.82 | 0.61 | 6.94 | 1.18 |
| chromite | 0.15 | 1.37 | 1.66 | 3.58 |
| magnetite | 67.17 | 73.10 | 64.87 | 68.00 |

In C = Inclusion in clinopyroxene

In O = Inclusion in olivine

G = Groundmass

1 : (Dessai *et al.*, 1990, Table-VII)

show compositions between pyroxene-and olivine-inclusions. The phenocrysts in general show compositional resemblance to olivine inclusions, however, they may occur alongside spinels akin to those included within pyroxene. All the spinels in least evolved rocks (RG 3, RG 1) are more ferrous than those in more evolved rock (RG 2, Fig. 9).

DISCUSSION

The petrography, whole rock- and

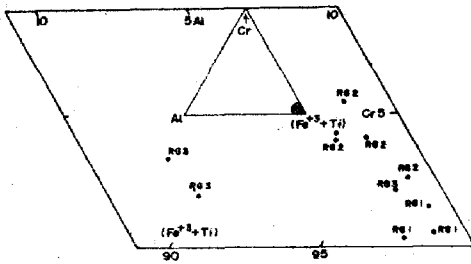


Fig. 9. Cr-Al-(Fe³⁺ + Ti) plot of spinels in nephelinites.

mineral-chemistry enables one to make certain deductions regarding the source, generation and history of magmatic crystallisation. The most primitive of Murud- Janjira nephelinites has Mg # 0.74 and SiO₂ less than 41 %, values that are within the range generally accepted for primary magmas in equilibrium with upper mantle mineralogies (Wilson, 1989). The Cr and Ni contents are, however, lower than accepted values for such magmas. However, from the overall behaviour of major and trace elements, it can be surmised that these magmas were not derived from a normal mantle but from a metasomatised source region, in which case the behaviour of trace elements cannot be strictly held diagnostic. In such cases certain mantle mineral phases may provide valuable clues.

The chrome diopsides with their high Cr represent mantle pressure field phases. Their origin can be sought in disaggregated pegmatitic segregations formed along the conduit wall from flowing nephelinitic magma (Irving, 1980, Fig. 14) prior to its accumulation in a magma reservoir where it underwent further fractionation. Deformed clinopyroxenite xenoliths in lamprophyres which are associated with melanephelinites lend additional support to the above credence.

The complexly zoned clinopyroxene phenocrysts reflect complex crystallisation history under varying but high P-T conditions (Aoki, 1970; Best, 1970; Deer *et al.*, 1978, Le Bas, 1987) in a subcrustal magma reservoir. The reverse zoning of green core pyroxene

phenocrysts is difficult to ascribe to a single mechanism. Lloyd and Bailey (1975) suggest that it is due to loss of alkalis, Fe, Ti, Al, Mn, H₂O and CO₂ from host melt into lherzolite inclusions. However, it is more likely that these phenocrysts have grown in a magma undergoing compositional evolution in a subcrustal magma chamber wherein, a relatively evolved magma undergoing fractional crystallisation was overtaken periodically by more primitive liquids. Mixing between the two, and double diffusive convection believed to operate during magma replenishment (Huppert and Sparks, 1980; Turner and Campbell, 1986) can give rise to resorption and reversely zoned overgrowths. The higher Al content and low Ti/Al ratios are indicative of high pressure environments. Zoning in clinopyroxene phenocrysts wherein the core composition corresponds to the groundmass pyroxene and approximates to that of the tephriphonolite, it can be inferred that the core crystallised from a phonolitic magma and was later incorporated in succeeding pulse/pulses of more primitive nephelinitic magma (Le Bas, 1987). From Figs. 2 and 6 it is clear that there must have been multiple mixing episodes.

The resorbed green cores are overgrown by oscillatory zoned mantles. Three phenocrysts are illustrated in Fig. 6 one each from RG 3, RG 1 and RG 2. RG 3 rim compositions are closer to RG 1 and RG 2 core compositions. The rims of the latter two are much more magnesian. The core in each case is subjected to compositional changes that are reflected in mantles with varying Mg # and Na contents. No satisfactory explanation is, however, available to account for this phenomenon. All that can be said is, it is related to process of growth, dissolution and reaction which in turn reflect changes in bulk liquid chemistry, P-T conditions and redox potential (Shimizu, 1990). Zoning will also be affected by precipitation of other phases preceding pyroxene. In Fig. 7 it is seen that Fe and Ti distribution in mantles and rims is sympathetic. Rimward decrease of Ti seen in

pyroxene is probably due to early separation of Fe-Ti oxides with which the pyroxene had to compete. Al, however, behaves differently. Whereas there is compositional continuity between cores and mantles, there is abrupt drop in Al in the rims (Fig. 8). This may be because Al in clinopyroxene is pressure dependant (Kushiro, 1962; Wass, 1979). Fe and Na show inverse relationship (Table II). The latter is less in the rims than in the cores, suggestive of possible pressure dependence (Dobosi and Fodor, 1992). Pyroxenes whose rim composition corresponds to groundmass pyroxene composition are polybaric cognate phases. They are characteristic of crystallisation in a low pressure environment at shallow crustal levels.

It is now accepted by many that alkaline magmas are generated by low degree of partial melting of mantle that was metasomatically enriched (Lloyd and Bailey, 1975; Menzies and Murthy, 1980; Bailey, 1987). Experimental studies also indicate that as the alkalinity of mafic magma increases, it is more and more unlikely that this magma is derived by partial melting of a normal pyrolite mantle composition (Edgar, 1987). Ryabchikov *et al.*, (1982) pointed out that Na-rich metasomatism at shallower depths of upper mantle would result in Na-rich magmas on partial melting, such as the ones encountered at Murud-Janjira. Drawing an analogy with olivine nephelinite from New South Wales, Australia (Wass, 1980) it may be inferred that 5-12 % melting may have been involved in the magma generation. A mantle origin for these magmas is most likely judged by their higher Mgs # and presence of Cr-diopside inclusions, however, Cr and Ni are lower than the range accepted for primary magmas (Rhodes, 1981).

There is ample evidence from erupted alkaline lavas that fractionation processes are operative at mantle pressures. Magmas ranging in composition from nepheline hawaiite to phonolite which have low Mgs # for derivation as primary melts from a mantle source containing olivine (Fo 86-90) and yet

contain Cr-diopside type inclusions, can be modelled as products of fractional crystallisation of primary basanite liquids within the upper mantle (Irving and Price, 1980). Such magmas may generate at pressures between 15 and 25 kb (Irving, 1980) as evidenced by the presence of clinopyroxene which is the stable phase at these pressures. From a study of clinopyroxene equilibration temperatures in lherzolite inclusions it has been inferred (O'Hara, 1967) that the temperature range 1130-1330°C at 8-21 kb coincides with crystallisation temperature of basaltic magmas. The pressure range approximately corresponds to depths of 30-80 km. The Moho in the vicinity of Bombay occurs at a depth of 31.5 km. (Kaila *et al.*, 1981). These are tentative estimates and should be taken with considerable reservations.

CONCLUSIONS

The available data are consistent with generation of nephelinite magma from a small degree of partial melting of a shallow mantle source which was metasomatically enriched in incompatible elements. The magma underwent flow differentiation by precipitation of Cr-diopside along conduit walls (Irving, 1980). The crystals were subsequently picked up by the magma as it accumulated in a subcrustal magma reservoir where it underwent fractionation with periodic and sudden replenishment and mixing between evolved and primitive pulses prior to rapid ascent to the surface.

Alkaline magmatism both 'dry' nephelinitic and 'wet' lamprophyric along the west coast of India shows a close spatial and temporal association. The west coast magmatism, however, is volumetrically restricted as compared to that in Narmada valley and has a more sodic expression.

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