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MARID-TYPE XENOLITHS IN PROTEROZOIC KIMBERLITES FROM SOUTHERN INDIA: IMPLICATIONS ON MANTLE METASOMATISM

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Introduction

Xenoliths of mica–amphibole–rutile–ilmenite–diopside (MARID) and phlogopite–ilmenite–clinopyroxene (PIC) in kimberlites are alkali-rich, olivine-absent ultramafic rocks derived from the sub-continental lithospheric mantle (SCLM). The origins of these xenoliths have been linked to kimberlitic or lamproitic magmatism, but are still controversial. MARIDs and related assemblages have been inferred to represent metasomatism of mantle wall rock with small-volume alkali melts that migrate through the SCLM, as well as direct crystallisation products of those melts.

Mantle-derived mafic and ultramafic xenoliths in southern Indian kimberlites are of special interest because of the limited inventory of samples. Early studies on the mineralogy of xenoliths in these kimberlites include Ganguly and Bhattacharya (1987) and Nehru and Reddy (1989). Rao et al. (2001) first reported the occurrence of one MARID-type xenolith in a southern Indian kimberlite. In the present study we report on the mineralogy of a few, rare MARID-type xenoliths in southern Indian kimberlites and compare the compositions of their constituent minerals such as phlogopite, diopside and ilmenite with those of discrete macrocrysts of corresponding minerals recovered from heavy mineral concentrates of the kimberlites.

Southern Indian kimberlites and mantle xenoliths

The Eastern Dharwar Craton (EDC), located east of the Chitradurga Boundary fault in southern India, is marked by several occurrences of kimberlites and lamproites (Inset of Fig. 1). The kimberlites are intrusive into the Archaean gneiss–granite–greenstone ensemble, and are distributed in four fields west of the Proterozoic Cuddapah basin: Wajrakarur Kimberlite Field (WKF), Narayanpet Kimberlite Field (NKF), Raichur Kimberlite Field (RKF) and Tungabhadra Kimberlite Field (TKF). In addition, there are three lamproite fields in the EDC, viz. Krishna Lamproite Field (KLF), Nallamalai Lamproite Field (NLF) and Ramadugu Lamproite Field (RLF).

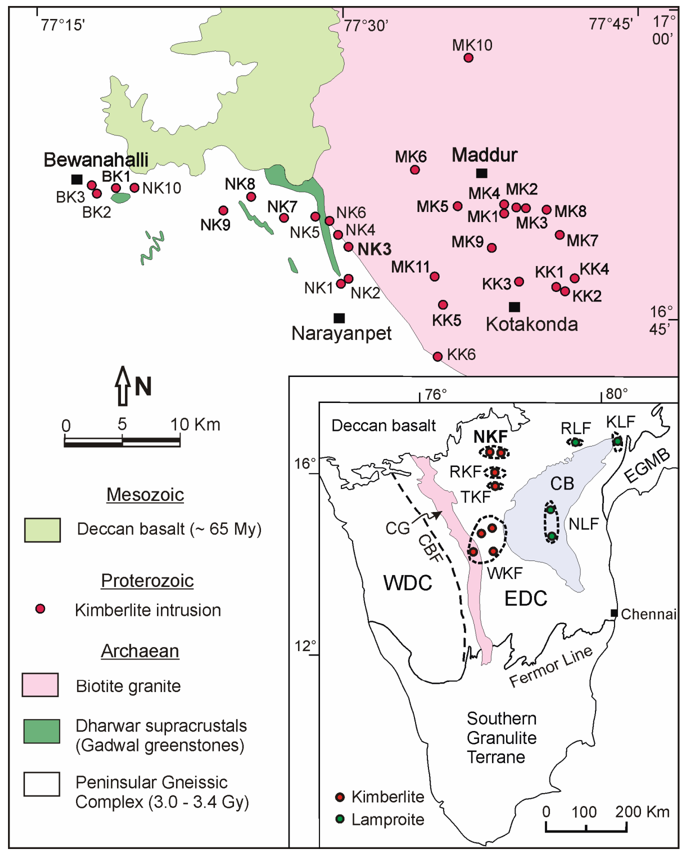

Fig.1. Generalised geological map of Narayanpet Kimberlite Field (NKF). Inset shows kimberlite and lamproite fields of southern India. CB – Cuddapah basin; CG – Closepet Granite; CBF – Chitradurga Boundary Fault; EDC – Eastern Dharwar Craton; EGMB – Eastern Ghats Mobile Belt; KLF – Krishna Lamproite Field; NLF – Nallamalai Lamproite Field; RKF – Raichur Kimberlite Field; RLF – Ramadugu Lamproite Field; TKF – Tungabhadra Kimberlite Field; WDC – Western Dharwar Craton; WKF – Wajrakarur Kimberlite Field.

The WKF has 45 kimberlite bodies, most of which are poorly diamondiferous. On the other hand, the NKF, with 63 intrusions, is an almost barren field except for a few diamonds reported by Lynn (2005) in surface heavy mineral samples from the kimberlites occurring southwest of Bewanahalli (Fig. 1). The RKF contains 6 intrusions (RK1–RK3; SK1–SK3) (Fig. 2), out of which RK1, SK1 and SK2 have been tested for diamond incidence and observed to be barren. The TKF contains 6 intrusions, out of which 4 have been tested for diamond incidence, and 1 has been found to be diamondiferous.

Available age data indicate that the southern Indian kimberlites erupted episodically around 1100 Ma.

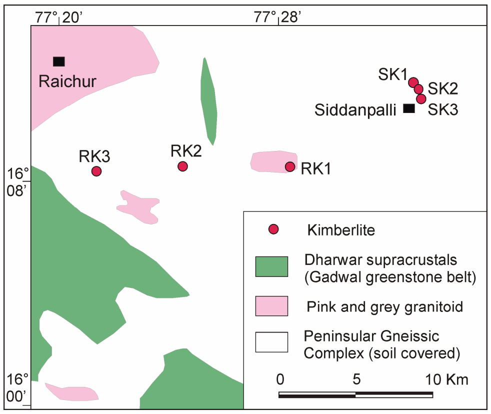

Fig.2. Generalised geological map of Raichur Kimberlite Field.

Mantle xenoliths in the southern Indian kimberlites have been reported from a few intrusions. Ganguly and Bhattacharya (1987) studied 8 samples of ultramafic xenoliths retrieved from drill cores of kimberlites in the WKF. These samples included 7 xenoliths (garnet harzburgite, garnet lherzolite, wehrlite, and olivine clinopyroxenite) from the P3 kimberlite and 1 xenolith (garnet harzburgite) from the P4 kimberlite. Phlogopite was present in most of the samples. Nehru and Reddy (1989) studied 19 samples of xenoliths collected from deep pits which included lherzolite (6), harzburgite (5) and eclogite (7) from the P3 pipe, and harzburgite (1) from the P4 pipe. Patel et al. (2009) described several mineralogical variants of mafic xenoliths in some of the southern Indian kimberlites.

Kimberlite concentrate minerals

Minerals such as pyrope garnet, chrome diopside and ilmenite occur in the heavy mineral suites of kimberlites as discrete, xenocrystic grains disaggregated from mantle xenoliths. Kimberlitic soil from different intrusions of the WKF and NKF was processed by the Geological Survey of India (GSI), Hyderabad, for separation of heavy minerals. The concentrates recovered from the WKF kimberlites include abundant pyrope, Cr-diopside, ilmenite and spinel, whereas those from the NKF are dominated by Cr-diopside with subordinate spinel and ilmenite (Rao et al., 2001). Garnet is strikingly rare or even absent in most of the NKF kimberlites. Appreciable quantities of garnet and phlogopite were recovered only from the NK3 kimberlite of the NKF.

Sastry et al. (2005) analysed the concentrate minerals (macrocrysts, mostly 0.5–5 mm size) from the southern Indian kimberlites using JEOL-JXA-8600M electron microprobe at the GSI, Hyderabad, but did not attempt any interpretation of the data. The compositions of phlogopite, clinopyroxene and ilmenite reported by Sastry et al. (2005) have been used here for comparative study with those of corresponding minerals in the MARID-type xenoliths. Some of the analyses of Sastry et al. (2005) were rejected on stoichiometric ground. The data set from Sastry et al. (2005) used in the present study includes analyses of phlogopite (10 macrocrysts from the NKF), clinopyroxene (85 macrocysts from the WKF and 41 macrocrysts from the NKF, and ilmenite (146 macrocysts from the WKF and 81 macrocrysts from the NKF).

MARID-type xenoliths

The southern Indian MARID-type xenoliths studied here were sampled from the NK3 kimberlite (77^{o} 29′ 15″: 16^{o} 48′ 00″) of the NKF, and RK3 kimberlite (77^{o} 21′ 25″ : 16^{o} 08′ 15″) of the RKF. The surface dimensions of these kimberlites are ~ 120 m × 100 m and ~ 110 m × 80 m for NK3 and RK3, respectively. Both the kimberlites are highly weathered at the surface with calcretic material strewn over the bodies. The xenolith samples include: (i) a few nodules (subrounded mineral aggregates, 2–5 mm across) recovered from heavy mineral concentrates of the kimberlites; and (ii) one hand specimen (4 cm size) collected from a pit in the NK3 kimberlite.

Mineral assemblages in the MARID-type xenoliths include mica–rutile–ilmenite–diopside in the hand specimen, and mica–ilmenite–diopside, mica–ilmenite, mica–diopside and monomineralic aggregate of mica in the nodules. Amphibole (K-richterite) has not been found in any of the samples, and therefore, the xenoliths are referred to as MARID-type rocks rather than strictly MARID rocks. Thin section of the mica–rutile–ilmenite–diopside hand specimen shows the dominance of mica and diopside in the rock, but mica is completely chloritised. However, original cleavage traces are distinctly visible in the altered mica grains and are bent, which indicates that the mineral underwent intracrystalline deformation. The mica–ilmenite–diopside nodule is from the NK3 kimberlite and is dominated by diopside (Fig. 3). Phlogopite in this xenolith occurs as discrete grains as well as fine intergrowth with diopside. Mica–ilmenite nodules from the NK3 kimberlite are dominated by ilmenite. A mica–diopside nodule from the RK3 kimberlite is dominated by diopside. The compositions of phlogopite, clinopyroxene and ilmenite in these xenoliths are outlined below.

Phlogopite

Micas in the southern Indian MARID-type xenoliths are phlogopites with X_{Mg} [= Mg / (Mg + Fe^T)] values in the range of 0.76–0.88. They have TiO_2 content in the range of 4.8–9.4 wt%, which is significantly high compared to that in the phlogopites of South African MARIDs (0.4–3.9 wt% TiO_2) (Dawson and Smith, 1977) and in the phlogopites of NKF and WKF kimberlites (0.3–3.9 wt% TiO_2). However, the phlogopites of KLF lamproites (henceforth referred to as Krishna lamproites) have TiO_2 content in the range of 4.8–8.5 wt% (Reddy et al., 2003; Chalapathi Rao et al., 2010), which is closely comparable to that of the southern Indian MARID-type phlogopites.

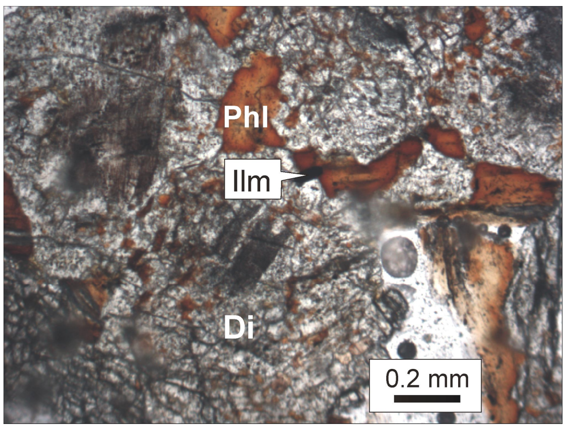

Fig.3. Photomicrograph of a MARID-type nodule from NK3 kimberlite under plane polarized light. Diopside (Di) is intergrown with phlogopite (Phl) and is highly fractured.

On a diagram of Ti versus octahedral site occupancy, the southern Indian MARID-type phlogopites form a distinct linear array which can be attributed to a combination of two substitutional schemes, viz. Ti + $\square^{VI}$ ↔ 2Mg, and Ti + 2Al ↔ Mg + 2Si (Fig. 4). On the same diagram, phlogopites of the Krishna lamproites also form a broad array, but with a different trend than that of the southern Indian MARID-type phlogopites. Stoichiometrically calculated tetraferric iron content is mostly low in the southern Indian MARID-type phlogopites and is comparable to that in the phlogopites of South African MARIDs and Krishna lamproites. This is evident on a diagram of Al^{IV} vs Si where these phlogopites plot close to the line representing Si + Al^{IV} = 8 pfu (Fig. 5). In contrast, all phlogopites in the NKF kimberlites and some phlogopites in the WKF kimberlites have high content of tetraferric iron and plot far off the above line.

Discrete macrocrysts of phlogopite from the NK3 kimberlite of the NKF (Sastry et al., 2005) have similar composition as the phlogopites in southern Indian MARID-type xenoliths, and are therefore treated as MARID-type macrocrysts.

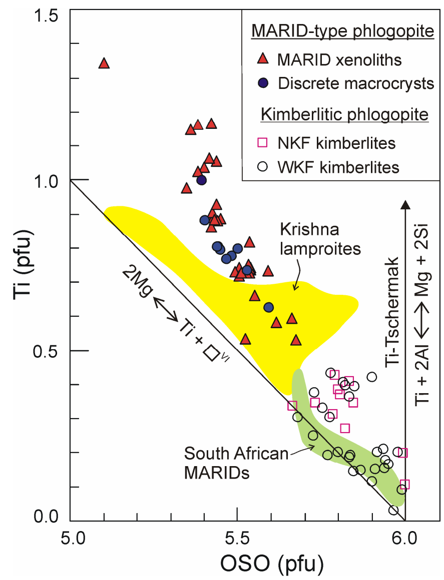

Fig.4. Composition of phlogopite in southern Indian MARID-type xenoliths on Ti vs Octahedral Site Occupancy (OSO) plot. Data on discrete phlogopite macrocrysts (NK3 kimberlite, NKF) from Sastry et al. (2005). Field of phlogopite for Krishna lamproites after Reddy et al. (2003) and Chalapathi Rao et al. (2010), and for South African MARIDs after Dawson and Smith (1977).

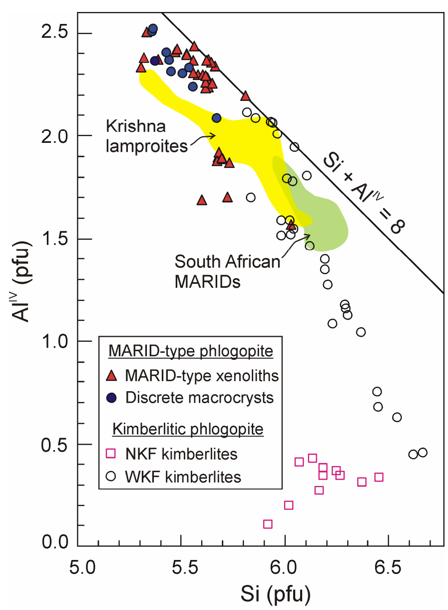

Fig.5. Tetrahedral Al vs Si plot for phlogopite in southern Indian MARID-type xenoliths. Data sources same as in Fig. 4.

Clinopyroxene

Clinopyroxenes in the southern Indian MARID-type xenoliths are diopside to endiopside in composition with Ca/(Ca + Mg + Fe) = 0.38–0.48 and X_{Mg} = 0.81–0.84. They are more aluminous (1.7–5.7 wt% Al_2O_3) than the clinopyroxenes in South African MARIDs (0.1–0.7 wt% Al_2O_3) (Dawson and Smith, 1977). The southern Indian MARID-type clinopyroxenes have low contents of Na_2O (0.7–1.8 wt%) and Cr_2O_3 (0.3–1.7 wt%), which are similar to those in the clinopyroxenes of South African MARIDs.

On a ternary diagram representing atomic proportions of Cr, Al and Na, the southern Indian MARID-type clinopyroxenes fall outside the jadeite ($NaAlSi_2O_6$)–kosmochlor ($NaCrSi_2O_6$) control on the entry of these elements into the mineral structure (Fig. 6). They form a cluster with considerable amounts of jadeite, Ca-tschermak ($CaAlAlSiO_6$) and Cr-Ca-tschermak ($CaAlCrSiO_6$) components. On the same diagram, discrete clinopyroxene macrocrysts from the NKF (Sastry et al., 2005) show two populations, one distributed along the jadeite–kosmochlor join, and the other forming a cluster outside this join. The latter population shows compositional overlap with the southern Indian MARID-type clinopyroxenes. Discrete clinopyroxene macrocrysts from the WKF (Sastry et al., 2005) mostly fall along the jadeite–kosmochlor join.

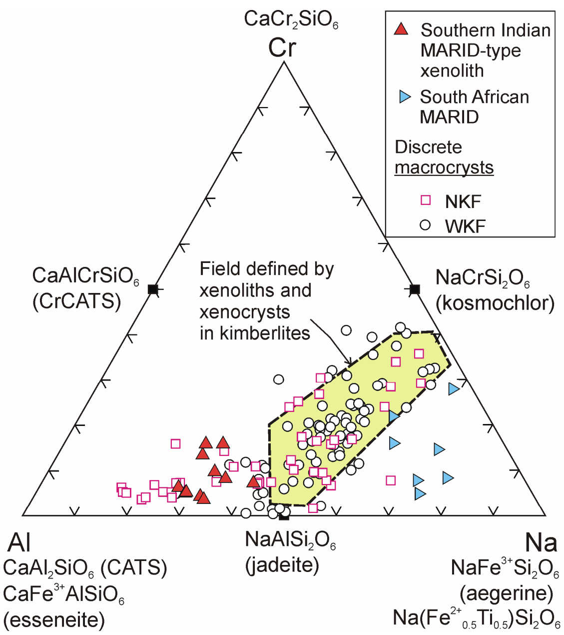

Fig.6. Composition of clinopyroxene in southern Indian MARID-type xenoliths compared with that of clinopyroxene in South African MARIDs (Dawson and Smith, 1977) and discrete clinopyroxene macrocrysts from NKF and WKF kimberlites (Sastry et al., 2005). Field defined by xenoliths and xenocrysts in kimberlites after Morris et al. (2002).

Ilmenite

Ilmenites in the southern Indian MARID-type xenoliths have highly variable contents of MgO and MnO, both falling in the range of 0.2–11.1 wt%, but with a strong negative correlation (R = 0.95) between the two oxides. In general these ilmenites are richer in Mn than the ilmenites in South African MARIDs (0.3–0.5 wt% MnO) (Dawson and Smith, 1977). However, in terms of Cr content the southern Indian MARID-type ilmenites (0.7–1.4 wt% Cr_2O_3) are broadly similar to the ilmenites in South African MARIDs (0.7–1.9 wt% Cr_2O_3). Discrete ilmenite macrocrysts from the NKF kimberlites have Cr_2O_3 content in the range of 0–2.5 wt% (Sastry et al., 2005), which is comparable to that in the southern Indian MARID-type ilmenites, but such macrocrysts from the WKF kimberlites generally have high Cr_2O_3 content (0–6.2 wt% Cr_2O_3). The southern Indian MARID-type ilmenites contain up to 0.5 wt% Nb_2O_5.

On a ternary diagram representing molecular proportions of geikielite ($MgTiO_3$)–ilmenite ($FeTiO_3$)–pyrophanite ($MnTiO_3$), the southern Indian MARID-type ilmenites mostly exhibit a trend consistent with Mg ↔ Mn substitution at constant Fe (Fig. 7). On this plot, ilmenite macrocrysts from the NKF kimberlites (Sastry et al., 2005) show two populations, one that falls along the ilmenite–geikielite join, and the other along the Mg ↔ Mn substitution trend. The latter population is similar in composition to the MARID-type ilmenites. All discrete ilmenite macrocrysts from the WKF kimberlites are distributed along the ilmenite–geikielite join.

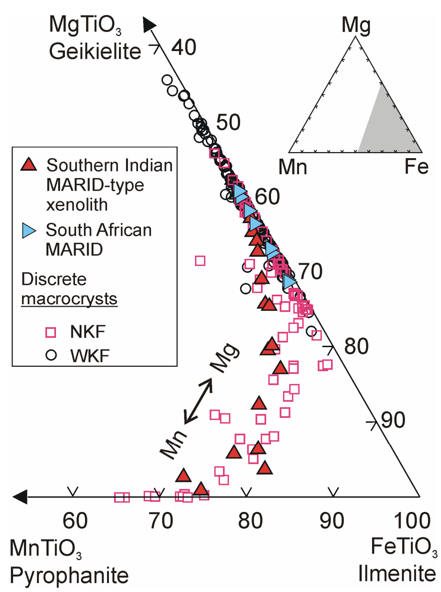

Fig.7. Composition of ilmenite in southern Indian MARID-type xenoliths compared with that of ilmenite in South African MARIDs (Dawson and Smith, 1977) and of discrete ilmenite macrocrysts from NKF and WKF kimberlites (Sastry et al., 205).

Discussion

The whole population of discrete phlogopite macrocrysts from the NK3 kimberlite of the NKF shows similar compositional characteristics as the phologpites in southern Indian MARID-type xenoliths. Sizable proportions of discrete macrocrysts of clinopyroxene and ilmenite from the NKF kimberlites also show close similarity in composition with the respective phases in southern Indian MARID-type xenoliths. These populations of discrete macrocrysts from the NKF are therefore interpreted to have been derived from MARID-type xenoliths. Based on this inference it is suggested that MARID-type rocks are more common in the SCLM beneath the NKF relative to that beneath the WKF.

Mantle metasomatism

Metasomatism of mantle wall rocks have been related to veins defined by concentrations of hydrous K-phases (phlogopite, richterite), clinopyroxene or Mn-rich ilmenite (Erlank et al., 1987). MARIDs, PICs and related suites represent such veins in the SCLM. Occurrences of composite xenoliths of MARID and metasomatised peridotite (phlogopite–K-richterite-bearing) are reported in the literature. Although the precise manner of formation of MARID veins is uncertain, several studies have related the formation of metasomatised peridotites to crystallization of MARID melts in dykes with expulsion of hydrous fluids rich in alkali and incompatible trace elements. This fact and the above inference that MARID-type rocks are relatively common in the SCLM beneath the NKF, lead us to propose that the mantle wall-rocks beneath the NKF have undergone extensive MARID-type metasomatism compared to those beneath the WKF. The almost barren nature of NKF kimberlites vis-à-vis the diamondiferous WKF kimberlites can be attributed to such metasomatism, which was responsible for oxidation and destruction of diamonds in the SCLM beneath the NKF.

Affiliation of MARID-type xenoliths

Gregoire et al. (2002) proposed that PICs and MARIDs are segregations from highly alkaline melts genetically linked to Group I and Group II kimberlite magmas, respectively. However, Waters (1987) suggested that MARID rocks are compositional equivalents of ultrapotassic rocks such as lamproites that crystallized at high pressures. The present study shows that phlogopites in the southern Indian MARID-type xenoliths have similar major element characteristics as those in southern Indian lamproites, while the phlogopites in southern Indian kimberlites are of distinctly different composition. In this respect, the southern Indian MARID-type xenoliths are closer to lamproites than to kimberlites.

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