

Are Majhgawan–Hinota pipe rocks truly group-I kimberlite?

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The diamond bearing pipe rocks in Majhgawan–Hinota (more than four pipes) occur as intrusives in sandstones of Kaimur Group. These Proterozoic (974 ± 30 – 1170 ± 20 Ma) intrusive rocks, occupying the southeastern margin of Aravalli craton, were called as ‘micaceous kimberlite’ in tune with the reported kimberlite occurrences from other parts of the world. Judging from the definition of kimberlite, as approved by the IUGS Subcommittee on Systematics of Igneous Rocks, it is not justified to call these rocks as ‘micaceous kimberlite’. Rather the mineralogical assemblages such as absence of typomorphic mineral monticellite (primary), abundance of phlogopite cognate, frequent presence of barite and primary carbonate mostly as calcite coupled with ultrapotassic and volatile-rich (dominantly H_2O) nature and high concentration of incompatible elements (such as Ba, Zr, Th, U), low Th/U ratios, low REE and no Eu-anomaly clearly indicate a close similarity with that of South African orangeites. Thus orangeites of Proterozoic age occur outside the Kaapvaal craton of South Africa which are much younger (200 Ma to 110 Ma) in age.

1. Introduction

The diamond-bearing intrusive rocks near Majhgawan–Hinota are emplaced as pipes in sandstones of Kaimur Group. The occurrence of diamond has long been known also in areas such as Wajrakarur and Lattavaram in southern India. These pipe rocks are restricted to the cratonic areas of India – Majhgawan–Hinota at the southeastern margin of the Aravalli–craton and Wajrakarur–Lattavaram at the core of the Dharwar craton (figure 1). In conformity with Wagner’s classification (1914) and in tune with the reported occurrences of kimberlite from different parts of the world, the pipe rocks from central and southern India were also called kimberlite by a number of workers, an excellent bibliography of which is available in Indian Minerals (1979, 1980). While the Majhgawan–Hinota rocks are designated as ‘micaceous kimberlite’ (or Group II kimberlite of Skinner 1989), the Wajrakarur–Lattavaram rocks are called ‘basaltic kimberlite’ (Paul *et al* 1975a,b, 1977; Rock and Paul 1989; Halder and Ghosh 1978, 1981). Although the first major revision of Wagner’s (1914) classification

scheme was made by Mitchell (1970), who argued that the term ‘basaltic kimberlite’ be abandoned because the kimberlites do not contain feldspars (plagioclase) and are neither mineralogically nor genetically related to basalts, yet the term ‘basaltic kimberlite’ was preferred for Indian pipe rocks.

The data available on the mineralogy and chemistry of pipe rocks from Majhgawan–Hinota require thorough reassessment and modification in their nomenclature, in the light of modern advancement on ‘kimberlite geology’. This is the focus of our discussion.

2. Kimberlite nomenclature – present status

It is not within the purview of our present discussion to present a bibliographical account of kimberlites, a wealth of benchmark papers and books (Kornprobst 1984; vol. I and II) are available to geoscientists working in this interesting field. Smith (1983) had demonstrated that monticellite-calcite-serpentine kimberlite and phlogopite-kimberlite from Kaapvaal

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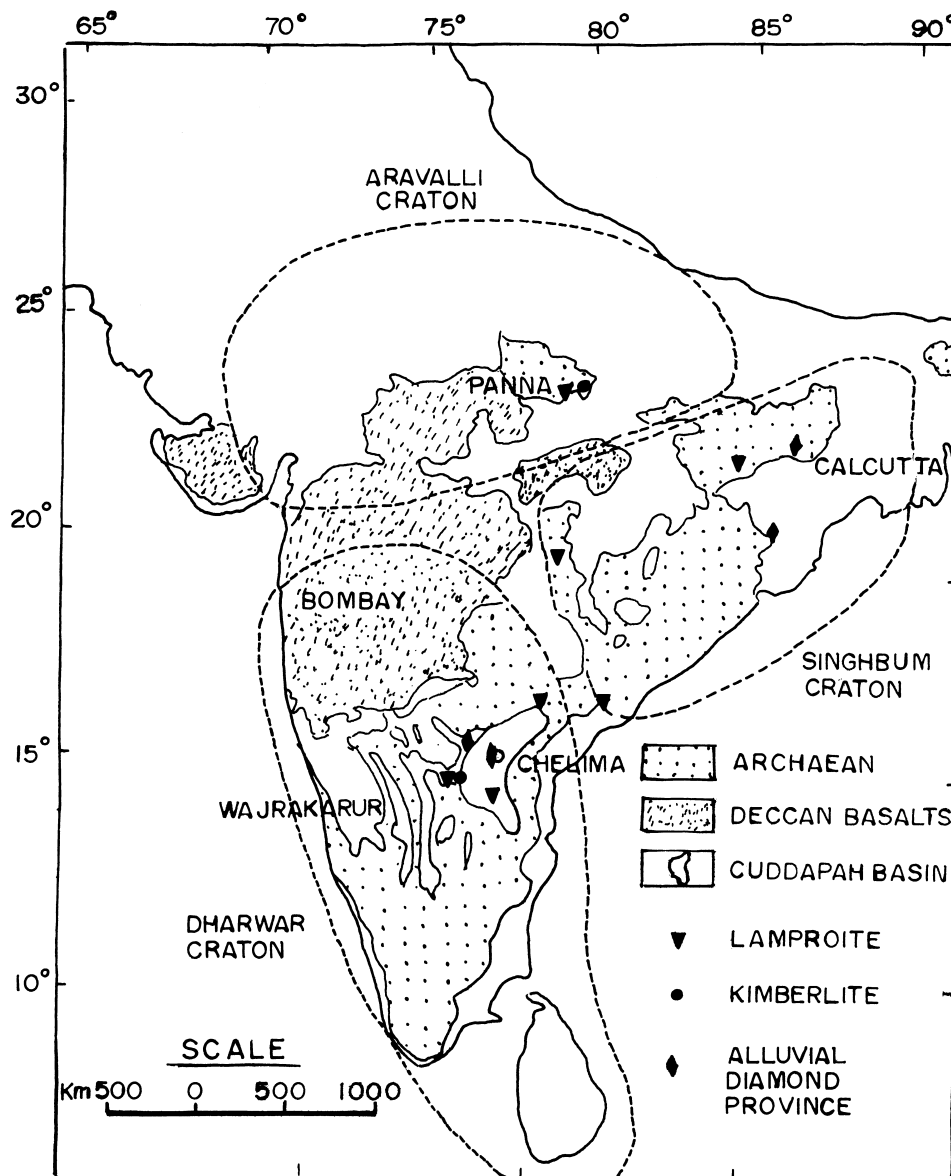


Figure 1. Simplified geological map of India showing the three Archean cratons and the distributions of lamproites, kimberlites and alluvial diamond provinces (adopted from Bergman 1987).

craton (South Africa) possess distinctive Sr and Nd isotopic compositions. As a consequence of these isotopic studies, Skinner (1989) proposed that kimberlites can be divided into two distinct groups, I and II on the basis of differences in their distribution, age, petrography, content of mantle-derived xenocrysts, xenoliths and megacrysts, isotopic character and whole rock chemistry. Interestingly, Skinner's (1989) group II kimberlite corresponds to 'micaceous kimberlite' of Wagner (1928).

Subsequent to the recognition of group II kimberlites there has been an interest in characterising the mineralogy and geochemistry of group II rocks (Fraser *et al* 1985; Dawson 1987; Mitchell and Meyer 1989;

Skinner 1989; Mitchell 1991; Fraser and Hawkesworth 1992; Skinner *et al* 1994; Tainton and McKenzie 1994; Mitchell 1994). From these studies it has become evident that the group I and II kimberlites are mineralogically and geochemically distinct and that group II rocks have closer affinities to 'lamproites' than to group I kimberlites. These distinctive characteristics led Mitchell (1994) to suggest that the rocks are derived from genetically different parent magmas, and that group II rocks should not be treated as a variety of kimberlites but as rocks belonging to an entirely different petrological lineage. This difference between group I and II kimberlites has been recognised on principle by the IUGS Subcommis-

sion on Systematics of Igneous Rocks (Woolley *et al* 1996). While the definition of group I kimberlite is endorsed by IUGS Subcommission, the same for group II rocks is neither rejected nor accepted by the Subcommission but kept in abeyance for want of more data on similar rocks from other parts of the world (Woolley *et al* 1996).

The definition of kimberlite, as approved by the IUGS (Woolley *et al* 1996), states that they are a group of volatile-rich (dominantly CO₂), potassic ultrabasic rocks commonly exhibiting a distinctive inequigranular texture resulting from the presence of macrocryst (and in some instances megacryst), set in a fine grained matrix. The mega/macro-crystal assemblages consist of abundant crystals of olivine, magnesian ilmenite, chromium-poor titanium pyrope, diopside (commonly subcalcic), phlogopite, enstatite and Ti-poor chromite. The matrix contains the second generation of primary, euhedral to subhedral olivine which occurs together with one or more of the following primary minerals: monticellite, phlogopite, perovskite, spinel (magnesian ulvospinel–Mg chromite–ulvospinel–magnetite solid solution), apatite and serpentine. This definition of kimberlite excludes the mineralogical characteristics of group II kimberlite or “orangeite” which were earlier included in it (Clement *et al* 1984; Mitchell 1979, 1986). Looking into the historical work of Wagner (1928) who coined the term “orangeite” for a group of micaceous kimberlites, the term did not find wide acceptance among the researchers on kimberlite until Mitchell (1989, 1991, 1994); Mitchell and Meyer (1989); and Mitchell and Bergman (1991) proposed the revival of the original term “orangeite” as a potential name for micaceous or group II kimberlites. However, in an exhaustive work Mitchell (1995) defined orangeite as a clan of ultrapotassic, peralkaline, volatile-rich (dominantly H₂O) rocks characterised by the presence of phlogopite macrocrysts and microphenocrysts together with groundmass micas which vary in composition from phlogopite to tetraferriphlogopite. The strict mineralogical conditions for naming a rock as group I kimberlite or simply kimberlite (Mitchell 1995) and orangeite have been kept in mind while examining mineralogical assemblages of Majhgawan–Hinota rocks in an endeavour to derive the most appropriate name in conformity with Mitchell (1995).

3. Majhgawan–Hinota pipe rocks – mineralogical and geochemical features

The late Meso-Proterozoic kimberlitic rocks of Majhgawan–Hinota (974 ± 30–1170 ± 20 Ma; K–Ar age; Paul *et al* 1975b) were studied extensively by the Geological Survey of India, but the results are contained mostly in the unpublished progress reports and a few

published accounts (Dubey and Merh 1949; Mathur and Singh 1971; Paul *et al* 1975a,b, 1977; Rock and Paul 1989; Halder and Ghosh 1978, 1981; Singh 1992; Singh *et al* 1992; Soni *et al* 1992; Singh *et al* 1993; Tiwari *et al* 1994 and Soni *et al* 1994; Bhattacharyya and Srivastava 1995; Pimprikar and Srivastava 1996; Soni *et al* 1996; Tiwari *et al* 1997). It is interesting to note that the different workers described the mineralogy (essential information for rock nomenclature) from optical mineralogy and XRD and there was hardly any attempt at investigating the chemistry of mineral constituents (see Halder and Ghosh 1981). Further, synthesis of published data reveals that a systematic study on groundmass mineralogy is lacking – which poses serious constraints on rock nomenclature following IUGS recommendations (Woolley 1996). At this juncture, we believe that there exists ample scope to re-study the central Indian occurrences for a meaningful understanding on macrocrysts/phenocrysts/groundmass mineralogy coupled with detailed geochemistry (including mineral chemistry of essential and accessory constituents) and isotope systematics which will lead to an improved understanding of the cratonised mobile belt (Aravalli craton) of India.

The mineralogical assemblages of pipe rocks from Majhgawan–Hinota, when compared with the typical mineralogical conditions of kimberlites and orangeites (table 1) clearly reveal that:

- The absence of typomorphic mineral monticellite (primary).
- Abundance of phlogopite macrocrysts, in contrast to the mineral being minor as macrocrysts, rare as microphenocrysts and common in groundmass of kimberlite.
- Common ilmenite, magnetite and rare perovskite as microphenocrysts; minor magnetite, chromespinels and rare titanomagnetite in the groundmass.
- Frequent presence of barite which is absent in kimberlite *sensu stricto*.
- Presence of primary carbonates, mostly calcite with minor dolomite, apatite and granular serpentine in the groundmass.

The mineralogical assemblages as listed in table 1, led the earlier workers (Paul *et al* 1975a,b; 1977; Rock and Paul 1989; Halder and Ghosh 1978, 1981) to designate the rocks as micaceous kimberlite/basaltic kimberlite and kimberlite breccia. Kent *et al* (1998) preferred to call the pipe rocks as ‘lamproite’, but significantly these rocks never contain sanidine, leucite and K-richterite (primary mineralogical condition in lamproite; see Bergman 1987), rather they have the adequate presence of carbonates (rare in lamproite), apatite, etc. Hence the mineralogical characteristics of the pipe rocks coupled with their geochemistry (discussed later) have led us to desig-

Table 1. *Mineralogical assemblages of Majhgawan-Hinota pipe-rocks and comparison with kimberlites and orangeites.*

| Mineralogy | Kimberlite* | Orangeite* | Majhgawan--Hinota** |
|------------------------|---|---|--|
| Olivine Macrocrysts | Abundant—principally xenocrysts | Common to rare—principally xenocrysts | Common, intensely altered to serpentine |
| Phenocrysts | Common (Fo ₈₇₋₉₀), subhedral/euhedral | Minor (Fo ₉₁₋₉₃), subhedral/euhedral/dog's tooth | Minor |
| Mica Macrocrysts | Minor, phlogopite- cryptogenic | Common, phlogopite, cognate | Abundant phlogopite Cognate |
| Microphenocrysts | Rare, phlogopite | Common, phlogopite | Common, phlogopite |
| Groundmass | Common, phlogopite- knoshitalite reticulate laths | Common, phlogopite, tetraferriphlogopite poikilitic laths | Common, phlogopite |
| Spinel | Abundant, large (0.01-0.1mm). Typically Mg-chromite zoned to Mg-ulvospinel. Atoll spinels very common. Trend 2 spinels rare, only in varieties with macrocrystal micas. | Minor to rare, small (< 0.01-0.02 mm). Euhedral Mg-chromite common, rarely zoned to Ti-magnetite (Trend 2). Atoll spinels rare, Mg-ulvospinel absent. | Minor, microphenocrystal magnetite, rare chrome spinel in groundmass |
| Monticellite | Common, may be pseudomorphed by carbonate and— or serpentine. | Typically absent | Absent |
| Diopside | Primary diopside absent, may occur in contaminated groundmass | Microphenocrysts, common to rare. Commonly resorbed, zoned to Ti-augite. | Pyroxene common, phenocrystal, altered to talc-tremolite-chlorite |
| Perovskite | Common, rounded to euhedral. SrO (< 1 wt%) and (REE) ₂ O ₃ — poor (< 7 wt%). | Rare, subhedral to poikilitic. SrO (< 1–6 wt%) and (REE) ₂ O ₃ —rich (3–16 wt%). | Rare as microphenocrysts and in groundmass |
| Apatite | Common to rare, euhedral prisms or acicular radiating aggregates in serpentine—calcite segregations. SrO (< 1 wt%) and (REE) ₂ O ₃ —poor (< 1 wt%). | Common, euhedral prisms and poikilitic plates. SrO (3–22 wt%) and (REE) ₂ O ₃ —rich (< 1–10 wt%). | Common, groundmass |
| Serpentine | Abundant, secondary and common primary in segregations | Common, secondary | Common, secondary, minor granular in groundmass |
| Sanidine | Typically absent | Common, secondary | Absent |
| K-richterite | Typically absent | Rare, groundmass | Absent |
| Mn-ilmenite | Rare | Common | Common, macrocrystal and microphenocrystal ilmenite peripherally altered to leucoxene and rarely to perovskite |
| Zr-silicate | Very rare, only in evolved types | Common | Not found |
| K-Ba hollandite | Very rare, only in evolved types | Common | Not found |
| Leucite | Absent | Rare, pseudomorphed in poikilitic mica | Absent |

Table 1. (Continued)

| Mineralogy | Kimberlite* | Orangeite* | Majhgawan Hinota** |
|----------------|--|---|--------------------------------|
| REE-phosphates | Absent | Minor, monazite, daqingshinite, Sr-REE-phosphates | Minor monazite [†] |
| Carbonates | Simple assemblages, common calcite, rare Sr-REE carbonates in very evolved types | Common, calcite, common Sr-Mn-Fe dolomites, minor witherite, ancylite, strontianite, norsethite | Common calcite, minor dolomite |
| Barite | Rare | Common | Common, groundmass |
| Quartz | Absent | Minor, groundmass | Minor, groundmass |

Source: *Mitchell (1995).

**Halder and Ghosh (1981).

[†]Ravi Shanker and Nag (in preparation).

nate them more appropriately as ‘orangeite’ (following Mitchell 1995) instead.

Comparison of average major-element compositions of the rocks from Majhgawan–Hinota with that of typical kimberlites and orangeites are presented in table 2. A consideration of the chemical data on these rocks (sl. nos. 1–5) clearly indicates that the peralkaline and perpotassic indices are always < 1 ; a similar behaviour is observed in orangeites (114–113 Ma) from Damodar Valley, eastern India (Kent *et al* 1998). The majority of the rocks from Majhgawan–Hinota have ultrapotassic index > 3 . In general, the rocks do not show significantly higher contents of K_2O over Na_2O , as prescribed for typical orangeites (table 2), but the K_2O/Na_2O ratios of these rocks are always > 1 ; they are ultrapotassic and also volatile-rich (dominantly H_2O).

When oxides such as SiO_2 , TiO_2 , P_2O_5 and Al_2O_3 are plotted against MgO (figure 2), it is clear that the typical South African kimberlites and orangeites describe separate fields with minor overlap. These plots show that the South African kimberlites are distinctly MgO -rich as compared to orangeites (with intermediate values). The Majhgawan–Hinota rocks never approach MgO -values similar to South African kimberlites and they possess abnormally high TiO_2 because of the presence of modal rutile. Although the nature of silica variation plots (figure 2a) does not reveal any major difference in abundance (wt%) between central and South African kimberlites, yet the intermediate MgO values similar to orangeites, allow the pipe rocks to be grouped with orangeites in field II. A similar behaviour is observed with respect to TiO_2 (2b), Al_2O_3 (2c) and P_2O_5 (2d). Since major element chemistry is largely dependent on constituent minerals, particularly the groundmass mineralogy plus exotic minerals, if any, the major oxide variations

can hardly be used with confidence, except the high ultrapotassic nature, distinctive MgO -content, high volatiles (either H_2O -rich or CO_2 -rich), K_2O and P_2O_5 content.

A comparison of behaviour of incompatible trace elements (Ba, Zr, Hf, Th, U) and rare earths of the rocks under discussion (orangeites as discussed before) with that of typical South African kimberlites and orangeites is presented in table 3. On close scrutiny of bulk of the data, it is clear that the average Ba-content is close to that of average orangeites and are appreciably higher than that of the type kimberlites of South Africa. Abundant phlogopite and late stage barite primarily host the high concentration of Ba in the Majhgawan–Hinota orangeites. Concentration of Zr and Hf in these rocks (sl. nos. 1–3) corresponds closely to that of unevolved orangeites of South Africa, particularly of Swartruggens, New Elands, Sover North and Newlands. Zr and Hf are said to be concentrated in the groundmass of orangeites and hosted primarily by late crystallising Zr-silicates (Mitchell 1995). Although Zr-silicates are not reported so far from the Majhgawan–Hinota areas (table 1), significant Zr-contents indicate that they are concentrated in rutile (1.11–2.77 wt% ZrO_2 ; Ravi Shanker and Nag, in preparation).

Abundance of Th and U suggests that they are probably concentrated in the groundmass apatites and perovskites. The average Th and U contents (18–29ppm and 3–3.28ppm respectively) of Majhgawan–Hinota are comparable with that of typical unevolved orangeites and kimberlites of South Africa. While Mitchell (1995) has shown that the Th/U ratios of orangeites (6–11) are greater than those of kimberlites (3–7); Gurney and Hobbs (1973), Paul *et al* (1977) have demonstrated that the ratios may exceed 10 as in the case of south Indian kimberlites ($Th/U = > 13$ in

Table 2. Comparison of major element compositions (wt%) of pipe rocks from Majhgawan–Hinota with selected average values of kimberlites, orangeites and lamproites.

| Sl. Nos | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|--------------------------------|-------|-------|-------|-------|--------|-------|-------|-------|-------|--------|-------|
| SiO ₂ | 35.63 | 33.69 | 34.39 | 33.13 | 33.78 | 30.00 | 31.99 | 34.37 | 37.48 | 33.86 | 33.92 |
| TiO ₂ | 4.75 | 6.04 | 6.00 | 8.82 | 8.17 | 1.72 | 2.32 | 0.74 | 0.38 | 1.77 | 1.46 |
| Al ₂ O ₃ | 3.90 | 3.28 | 2.53 | 3.58 | 4.55 | 1.99 | 2.68 | 1.04 | 2.31 | 3.88 | 4.26 |
| Fe ₂ O ₃ | 5.32 | – | 6.53 | 3.27 | 9.27 | 5.23 | 5.64 | 4.12 | 3.88 | 10.48 | 8.27 |
| FeO | 3.11 | 10.98 | 3.08 | 4.26 | 5.77 | 3.32 | 3.24 | 3.56 | 3.40 | – | – |
| MnO | 0.16 | 0.11 | 0.11 | 0.16 | 0.10 | 0.16 | 0.16 | 0.13 | 0.11 | 0.17 | 0.16 |
| MgO | 25.69 | 24.40 | 24.72 | 17.11 | 14.41 | 32.49 | 32.44 | 38.55 | 34.43 | 30.67 | 21.93 |
| CaO | 3.44 | 3.78 | 5.37 | 12.40 | 6.29 | 10.90 | 6.71 | 7.03 | 2.13 | 8.64 | 14.60 |
| Na ₂ O | 0.12 | 0.11 | 0.15 | 0.07 | 0.10 | 0.19 | 0.05 | 0.19 | 0.03 | 0.24 | 1.00 |
| K ₂ O | 0.85 | 0.86 | 0.68 | 0.51 | 1.70 | 0.70 | 1.11 | 0.80 | 0.65 | 0.86 | 2.92 |
| H ₂ Ot | 14.08 | 8.12 | 12.45 | 7.78 | 9.35 | – | – | – | – | – | – |
| P ₂ O ₅ | 2.11 | 2.65 | 2.34 | 0.68 | 2.90 | 1.89 | 1.51 | 1.70 | 0.21 | 0.80 | 1.43 |
| CO ₂ | 0.46 | – | 0.76 | 7.31 | 4.28 | – | – | – | – | – | – |
| LOI | – | – | – | – | – | 10.71 | 11.51 | 7.42 | 13.87 | 8.94 | 9.56 |
| Total | 99.58 | 94.02 | 99.11 | 99.08 | 100.67 | 99.30 | 99.36 | 99.65 | 98.88 | 100.31 | 99.51 |
| CI | 1.49 | 1.47 | 1.46 | 2.09 | 2.38 | 0.97 | 1.03 | 0.90 | 1.13 | 1.20 | 1.58 |
| PI | 0.29 | 0.34 | 0.39 | 0.19 | 0.44 | 0.54 | 0.48 | 1.14 | 0.32 | 0.34 | 1.13 |
| PPI | 0.24 | 0.28 | 0.29 | 0.15 | 0.40 | 0.38 | 0.45 | 0.83 | 0.31 | 0.24 | 0.74 |
| UPI | 4.68 | 5.16 | 2.99 | 4.80 | 11.23 | 2.39 | 14.75 | 2.74 | 13.80 | 2.33 | 1.93 |

| Sl. Nos | 12 | 13 | 14 | 15 | 16 | 17 |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|
| SiO ₂ | 36.44 ± 2.98 | 37.53 ± 3.13 | 33.02 ± 1.89 | 35.09 ± 1.72 | 33.52 ± 1.85 | 36.64 ± 0.09 |
| TiO ₂ | 1.58 ± 0.30 | 0.88 ± 0.20 | 0.74 ± 0.13 | 1.06 ± 0.29 | 0.62 ± 0.13 | 1.32 ± 0.16 |
| Al ₂ O ₃ | 4.02 ± 0.87 | 3.34 ± 0.90 | 1.64 ± 0.38 | 2.55 ± 0.70 | 1.71 ± 0.32 | 4.23 ± 0.27 |
| Fe ₂ O ₃ | 8.15 ± 0.85 | 7.99 ± 0.75 | 7.77 ± 0.37 | 7.78 ± 0.47 | 7.36 ± 0.25 | 7.30 ± 1.45 |
| FeO | – | – | – | – | – | – |
| MnO | 0.16 ± 0.03 | 0.17 ± 0.07 | 0.16 ± 0.24 | 0.15 ± 0.03 | 0.14 ± 0.02 | 0.31 ± 0.20 |
| MgO | 21.25 ± 4.25 | 28.18 ± 5.09 | 31.40 ± 4.27 | 29.02 ± 4.53 | 34.08 ± 3.21 | 20.86 ± 5.79 |
| CaO | 8.39 ± 3.75 | 6.54 ± 4.48 | 6.61 ± 2.07 | 6.49 ± 2.46 | 6.12 ± 1.64 | 10.18 ± 5.71 |
| Na ₂ O | 0.24 ± 0.10 | 0.21 ± 0.18 | 0.12 ± 0.06 | 0.18 ± 0.10 | 0.11 ± 0.05 | 0.19 ± 0.05 |
| K ₂ O | 4.65 ± 1.00 | 3.14 ± 0.76 | 1.72 ± 0.55 | 2.91 ± 1.32 | 1.02 ± 0.36 | 4.73 ± 0.36 |
| H ₂ Ot | – | – | – | – | – | – |
| P ₂ O ₅ | 1.34 ± 0.44 | 0.61 ± 0.19 | 1.41 ± 0.52 | 0.68 ± 0.42 | 1.13 ± 0.24 | 1.22 ± 0.16 |
| CO ₂ | – | – | – | – | – | – |
| LOI | 10.45 ± 2.26 | 9.90 ± 3.71 | 12.99 ± 2.14 | 11.76 ± 1.42 | 12.42 ± 2.19 | 11.43 ± 2.86 |
| Total | 96.67 | 98.99 | 97.58 | 97.67 | 98.23 | 98.98 |
| CI | 1.57 | 1.31 | 1.05 | 1.18 | 1.01 | 1.60 |
| PI | 1.35 | 1.12 | 1.26 | 1.35 | 0.75 | 1.28 |
| PPI | 1.25 | 1.02 | 1.14 | 1.24 | 0.65 | 1.21 |
| UPI | 12.75 | 9.84 | 9.43 | 10.64 | 6.10 | 16.38 |

Table 2. (Continued)

| Sl. Nos | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|--------------------------------|--------------|-------|-------|-------|-------|-------|-------|-------|
| SiO ₂ | 34.01 ± 1.09 | 43.75 | 44.87 | 42.51 | 41.01 | 44.27 | 40.08 | 32.85 |
| TiO ₂ | 1.27 ± 0.18 | 1.87 | 1.29 | 1.18 | 1.24 | 1.91 | 5.21 | 4.20 |
| Al ₂ O ₃ | 2.79 ± 0.47 | 5.75 | 7.41 | 4.08 | 6.43 | 6.26 | 3.99 | 4.15 |
| Fe ₂ O ₃ | 8.59 ± 0.60 | 8.20 | 8.80 | 8.26 | 7.67 | 6.26 | -- | 1.37 |
| FeO | -- | -- | -- | -- | -- | -- | 9.76 | 7.95 |
| MnO | 0.26 ± 0.14 | 0.12 | 0.17 | 0.13 | 0.11 | 0.14 | 0.11 | 0.14 |
| MgO | 25.34 ± 5.66 | 20.92 | 14.89 | 27.99 | 20.40 | 18.23 | 15.93 | 18.13 |
| CaO | 7.92 ± 2.65 | 4.86 | 10.38 | 4.04 | 6.15 | 7.02 | 7.51 | 9.78 |
| Na ₂ O | 0.17 ± 0.10 | 1.12 | 0.83 | 0.60 | 0.36 | 0.68 | 0.06 | 0.22 |
| K ₂ O | 2.95 ± 0.27 | 4.07 | 5.52 | 4.31 | 3.17 | 3.70 | 2.41 | 1.93 |
| H ₂ Ot | -- | -- | -- | -- | -- | -- | 1.94 | -- |
| P ₂ O ₅ | 0.82 ± 0.23 | 0.78 | 0.71 | 0.43 | 1.06 | 1.09 | 1.41 | 1.65 |
| CO ₂ | -- | -- | -- | -- | -- | -- | -- | -- |
| LOI | 12.89 ± 2.99 | 4.25 | 3.29 | 4.26 | 8.42 | 5.51 | -- | 15.49 |
| Total | 97.01 | 97.64 | 98.14 | 97.79 | 96.02 | 97.19 | 98.41 | 97.30 |
| CI | 1.31 | 2.03 | 2.60 | 1.46 | 2.03 | 2.33 | 2.41 | 1.85 |
| PI | 1.24 | 1.06 | 0.99 | 1.39 | 0.63 | 0.82 | 0.68 | 0.59 |
| PPI | 1.14 | 0.77 | 0.81 | 1.14 | 0.53 | 0.64 | 0.66 | 0.50 |
| UPI | 11.42 | 2.39 | 4.38 | 4.73 | 5.79 | 3.58 | 26.43 | 5.79 |

| Sl. Nos | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 |
|--------------------------------|--------------|--------------|-------|------|------|------|------|------|-------|
| SiO ₂ | 42.31 ± 2.21 | 45.47 ± 1.15 | 39.91 | 41.1 | 44.5 | 51.2 | 51.6 | 52.2 | 52.5 |
| TiO ₂ | 3.75 ± 0.82 | 2.34 ± 0.32 | 2.89 | 6.4 | 4.5 | 3.3 | 5.0 | 3.5 | 5.9 |
| Al ₂ O ₃ | 3.92 ± 0.87 | 8.82 ± 0.67 | 3.86 | 5.2 | 6.5 | 8.9 | 8.9 | 10.1 | 8.6 |
| Fe ₂ O ₃ | -- | -- | 8.71 | -- | -- | -- | -- | -- | -- |
| FeO | 8.27 ± 0.54 | 5.99 ± 0.27 | -- | 9.3 | 9.7 | 6.2 | 8.1 | 6.1 | 7.2 |
| MnO | -- | -- | 0.13 | 0.10 | 0.15 | 0.10 | 0.11 | 0.09 | 0.01 |
| MgO | 24.42 ± 3.56 | 11.15 ± 0.94 | 27.17 | 20.7 | 15.5 | 8.0 | 5.8 | 8.2 | 10.2 |
| CaO | 5.00 ± 0.95 | 11.84 ± 1.79 | 5.16 | 11.5 | 12.1 | 5.1 | 4.5 | 4.7 | 2.1 |
| Na ₂ O | 0.50 ± 0.25 | 0.83 ± 0.15 | 0.32 | 0.2 | 0.6 | 1.1 | 1.9 | 1.7 | 0.2 |
| K ₂ O | 4.01 ± 1.09 | 7.75 ± 1.49 | 2.69 | 2.9 | 5.8 | 8.8 | 9.2 | 11.9 | 10.4 |
| H ₂ Ot | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| P ₂ O ₅ | 1.59 ± 0.48 | 2.08 ± 0.66 | 0.35 | 2.2 | 0.7 | 3.1 | 1.8 | 1.5 | 2.1 |
| CO ₂ | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| LOI | 6.07 ± 1.88 | 3.49 ± 1.19 | 8.63 | -- | -- | -- | -- | -- | -- |
| Total | 99.84 | 99.83 | 99.78 | -- | -- | -- | -- | -- | -- |
| CI | 1.64 | 2.92 | 1.40 | 1.97 | 2.42 | 3.64 | 4.16 | 3.18 | 2.98 |
| PI | 1.33 | 1.11 | 0.89 | 0.67 | 1.12 | 1.28 | 1.47 | 1.55 | 1.35 |
| PPI | 1.11 | 0.75 | 0.75 | 0.60 | 0.97 | 1.07 | 1.12 | 1.28 | 1.31 |
| UPI | 5.27 | 6.15 | 5.54 | 9.58 | 6.38 | 5.28 | 3.19 | 4.62 | 34.36 |

Table 2 (Continued.)

H₂O_t = Total water.

Data source: Mitchell (1995) and references therein (sl. nos. 6–23 and 26–28).

Bergman (1987) and references therein (sl. nos. 29–34; the analyses are given on volatile-free basis).

CI = Contamination Index = $(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Na}_2\text{O})/(\text{MgO} + \text{K}_2\text{O})$; wt%.

PI = Peralkaline index = $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$; mol. propn.

PPI = Perpotassic index = $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$; mol. propn.

UPI = Ultrapotassic index = $\text{K}_2\text{O}/\text{Na}_2\text{O}$; mol. propn.

1: Average (4 analyses) micaceous kimberlite from Majhgawan, central India (Paul *et al* 1975a).

2: Micaceous kimberlite from Majhgawan, central India (Rock and Paul 1989).

3: Average (10 analyses) kimberlite from Majhgawan, central India (Halder and Ghosh 1981).

4: Average (3 analyses) kimberlite from Hinota, central India (Halder and Ghosh 1981).

5: Average (3 analyses) micaceous kimberlite from Hinota, central India (Paul *et al* 1975a).

6–9: On-Craton kimberlite (6: DeBeers, 7: Wesselton, 8: Dutoitspan, 9: Jagersfontein).

10–11: Off-Craton kimberlite (10: Berseba Reserve, 11: Anis Kubub).

12–18: Unevolved orangeites (12: Swartruggens, 13: Finsch, 14: Bellsbank, 15: Sover, 16: Newlands, 17: New Elands, 18: Star).

19–23: Evolved orangeites (19: Sover North, 20: Postmasburg, 21: Pniel, 22: Brandewynskuil and 23: Slypsteen).

24: Lamprite from Chelima, South India (Rock and Paul 1989).

25: Lamproite (micaceous kimberlitic dyke) from Chelima, south India (Bhaskar Rao 1976).

26: Average (105 analyses) Ellendale Olivine lamproite.

27: Average (6 analyses) Leucite Hill madupitic lamproite.

28: Olivine madupitic lamproite, Prairie Creek, Arizona.

29: Average (2 analyses) lamproite from Chelima, south India (with $\text{H}_2\text{O} = 3.1$ and $\text{CO}_2 = 10.0$ in original analysis).

30: Average (4 analyses) lamproite, Gondwana coalfields (Craton-margin), eastern India (with $\text{H}_2\text{O} = 2.8$ and $\text{CO}_2 = 4.8$ in original analysis).

31: Average (4 analyses) phlogopite – sanidine – amphibole lamproite (Archean craton-margin) from Priestley Peak, Antarctica (with $\text{H}_2\text{O} = 0.8$ and $\text{CO}_2 = 0.1$ in original analysis).

32: Average (2 analyses) sanidine – amphibole lamproite (Archean Craton – margin) from Mount Bayliss, Antarctica (with $\text{H}_2\text{O} = 1.0$ and $\text{CO}_2 = 0.8$ in original analysis).

33: Average (11 analyses) leucite – olivine lamproite (Archean Craton – margin) from Gaussberg, Antarctica (with $\text{H}_2\text{O} = 1.2$ and $\text{CO}_2 = 0.1$ in original analysis).

34: Lamproite from Bobi and Segnola (Stable craton), Ivory Coast (with $\text{H}_2\text{O} = 1.9$ in original analysis).

two samples from Wajrakarur). The Th/U ratios (8.07 to 9.74) of M–H rocks are well within the suggested values of orangeites (6–11, Mitchell 1995). The logarithmic plots of Th versus U do not show any positive correlation as can be verified from figure 3.

The Majhgawan intrusion with high La/Yb ratios (average 122.1, table 3) and REE abundances closely correspond to that of Swartruggens orangeites whereas the Hinota rocks with low La/Yb ratios (average 63.8) are more or less similar to those of Finsch (average 86.11). Studies on orangeites from Kaapvaal craton led Mitchell (1995) to conclude that the La/Yb ratios and REE abundances vary widely within and between intrusions and the high La/Yb ratios can not be considered as unique discriminating criteria between kimberlites and orangeites.

Paul *et al* (1975a) have discussed at length the behaviour of La/Yb ratios and REE abundances of

pipe rocks from Majhgawan–Hinota. They observed that the REE abundances are linear with a strong tendency of enrichment of LREE and show no Eu anomaly. The enrichment of La/Yb ratios and the range of variations within two intrusions can be attributed to varying degrees of partial melting (Paul *et al* 1975a) from a hydrous garnet peridotite mantle source. Mitchell and Brunfelt (1975) and Cullers *et al* (1982) had similar views while explaining the high La/Yb ratios of kimberlites. Recent experimental studies and geodynamic models (for details see Mitchell 1995) have suggested that partial melting of carbonated garnet lherzolite and carbonated garnetite sources in the lower parts of asthenospheric mantle or the transition zone might be the rational mechanism for generation of kimberlites. Contrary to earlier views, it has been pointed out that kimberlites are unlikely to be lithospheric magmas (Bailey 1980, 1983, 1992; Foley 1988; Skinner 1989; Wyllie 1980,

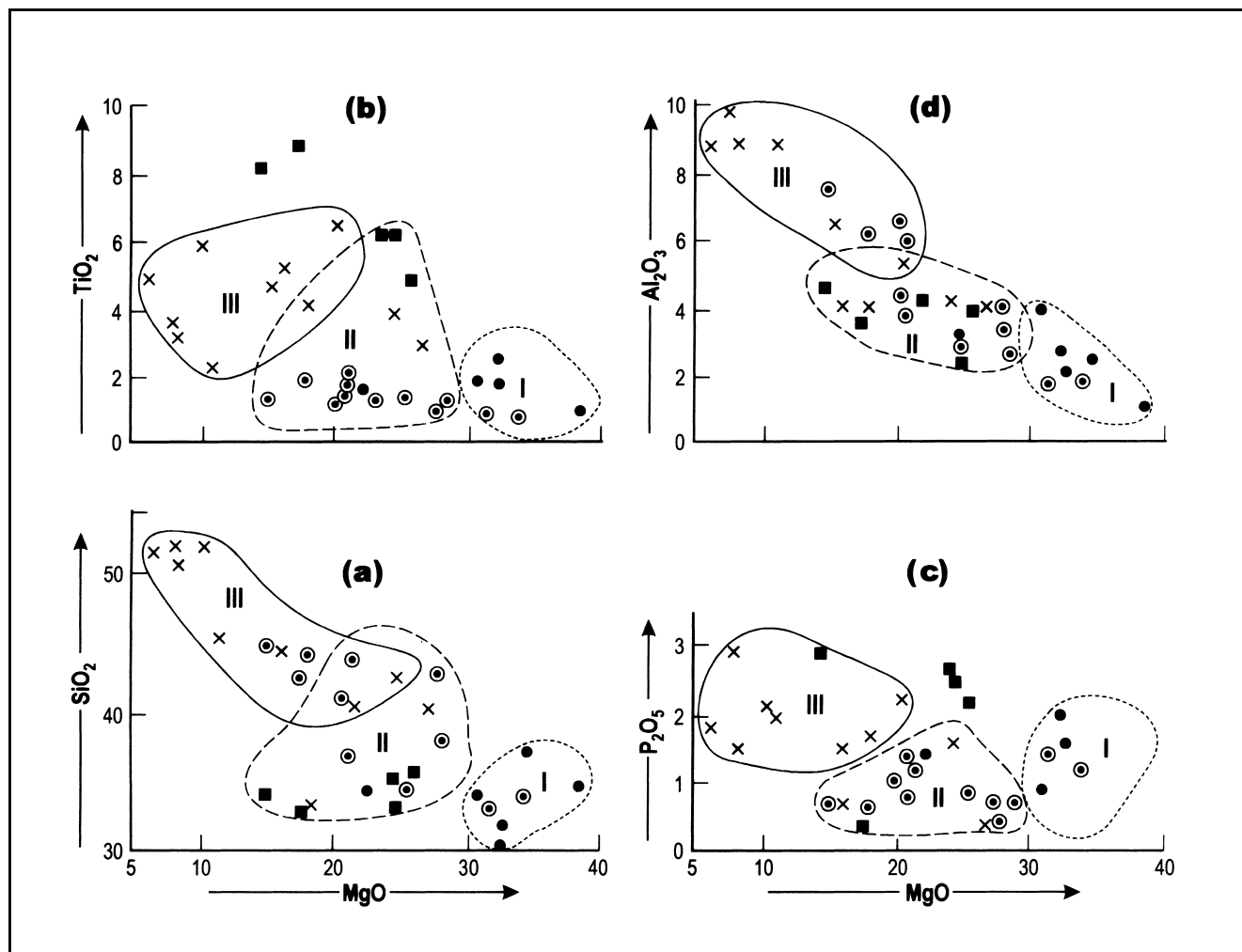


Figure 2. Diagram showing variations of different oxides as a function of MgO for the orangeites of Majhgawan–Hinota along with the typical kimberlites, orangeites and lamproites. Solid squares: Majhgawan–Hinota; solid circles: type kimberlites; centred circles: type orangeites; crosses: lamproites.

1987, 1989) as the isotopic abundances of archetypal kimberlites (Smith 1983) are similar to that of a wide variety of oceanic magmas (Zindler and Hart 1986) which are undoubtedly derived from asthenospheric sources. Recent Sr–Nd isotopic studies on xenoliths in kimberlites of Africa have led Macdougall and Haggerty (1999) to conclude that these ultradeep xenoliths have a complex history and are generated in the upper mantle, in the vicinity of the transition zone (400 kms).

Figure 4 illustrates the nature of plots of the Majhgawan–Hinota rocks in comparison with Finsch orangeites. While the Sm/Nd ratios of rocks from Majhgawan have close similarity with that of Swartuggens and Finsch, the La/Nd ratios are lower as compared to the South African orangeites (cf. table 3). The Hinota rocks, on the other hand, have too low La/Nd ratios and comparatively higher Sm/Nd ratios. Fraser and Hawkesworth (1992) have suggested that

small degrees of partial melting can generate low Sm/Nd ratios in the melt as compared to the source while La/Nd ratios increase. This observation led them to conclude that the melt must have been derived from peridotite with Sm/Nd ratios of 0.25, as compared to the proposed entrained peridotite with Sm/Nd ratios of 0.2. Tainton (1992 in Mitchell 1995), however, argued that the correlation between La/Nd and Sm/Nd, as observed for Finsch orangeites, is because of the low abundances of these elements in the parent magmas; also they were more susceptible to mixing processes (hybridization). In his opinion the initial La/Nd ratios were considerably higher than those now found.

World-wide studies of diatreme facies rocks have shown that they are particularly prone to contamination and alteration. The Majhgawan–Hinota pipe rocks, according to Paul *et al* (1975a), have suffered small degrees of crustal contamination as they were

Table 3. *Selected trace and REE compositions (in ppm) of pipe rocks from Majhgawan–Hinota with average values of kimberlite, orangeite and lamproite.*

| Sl. No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|--------|-------|-------|-----|-------|------|-------|-------|
| Ba | 4765 | 2127 | -- | 850 | 973 | 833 | 5183 | 1467 |
| Zr | 2112 | -- | 1845 | 385 | 125 | 279 | 401 | 184 |
| Hf | 21.07 | 27.7 | -- | -- | 3 | 6 | 10 | 5 |
| Ta | 13.85 | 13.8 | -- | -- | 14 | 9 | 8 | 3 |
| Th | 29.40 | 18.13 | 26.06 | 27 | 15 | 19 | 26 | 9 |
| U | 3.02 | -- | 3.28 | 6 | 3 | -- | 7 | 3 |
| La | 171 | 134 | -- | -- | -- | -- | 218 | 62 |
| Ce | 421.4 | 329.3 | -- | -- | -- | -- | 429 | 132 |
| Nd | 191.8 | 164.4 | -- | -- | -- | -- | 158 | 55 |
| Sm | 27.5 | 32 | -- | -- | -- | -- | 20 | 7.7 |
| Eu | 5.8 | 7.4 | -- | -- | -- | -- | 5.03 | 1.80 |
| Gd | 13.1 | 14.4 | -- | -- | -- | -- | -- | -- |
| Tb | 1.78 | 2.30 | -- | -- | -- | -- | 1.65 | 0.52 |
| Yb | 1.40 | 1.99 | -- | -- | -- | -- | 2.07 | 0.72 |
| Lu | 0.16 | 0.16 | -- | -- | -- | -- | -- | -- |
| Zr/Hf | 100.24 | -- | -- | -- | -- | -- | 40.10 | 36.80 |
| Th/U | 9.74 | -- | 8.07 | 4.5 | 41.66 | 46.5 | 3.71 | 3.00 |
| Sm/Eu | 4.74 | 4.30 | -- | -- | 5.0 | -- | 3.97 | 4.20 |
| Ce/Yb | 301 | 171.5 | -- | -- | -- | -- | 207.2 | 183.3 |
| La/Yb | 122.1 | 63.8 | -- | -- | -- | -- | 105.3 | 86.11 |
| Sm/Nd | 0.14 | 0.19 | -- | -- | -- | -- | 0.13 | 0.14 |
| La/Nd | 0.89 | 0.81 | -- | -- | -- | -- | 1.36 | 1.13 |

| Sl. No. | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------|-------|-------|-------|-------|-------|-------|------|------|
| Ba | 3439 | 2442 | 3351 | 1895 | 4370 | 2234 | 2002 | 1354 |
| Zr | 291 | 214 | 193 | 400 | 194 | 554 | 305 | 171 |
| Hf | 8 | 5 | 4 | 12 | 7 | 19 | -- | -- |
| Ta | 14 | 9 | 9 | 7 | 10 | 5 | 4 | 2 |
| Th | 45 | 30 | 33 | 27 | 28 | 17 | 8 | 4 |
| U | 7 | 3 | 5 | 5 | -- | 3 | 1 | 2 |
| La | 252 | 168 | 203 | 247 | 192 | 149 | -- | -- |
| Ce | 464 | 324 | 346 | 439 | 332 | 288 | -- | -- |
| Nd | 163 | 115 | 120 | 174 | -- | 113 | -- | -- |
| Sm | 17 | 12.6 | 11.3 | 21.4 | 15 | 15.1 | -- | -- |
| Eu | 3.93 | 3 | 2.69 | 5.95 | 3.16 | 3.58 | -- | -- |
| Gd | 13.2 | 9.51 | 8.43 | -- | -- | 10.5 | -- | -- |
| Tb | 1.05 | 0.82 | 0.63 | 1.36 | 0.69 | 1.07 | -- | -- |
| Yb | 1.13 | 0.99 | 0.76 | 1.72 | 0.72 | 1.17 | -- | -- |
| Lu | 0.14 | 0.13 | 0.11 | -- | -- | 0.14 | -- | -- |
| Zr/Hf | 36.37 | 42.80 | 48.25 | 33.33 | 27.21 | 29.15 | -- | -- |
| Th/U | 6.42 | 10.00 | 6.60 | 5.40 | -- | 5.5 | 8.0 | 2.0 |
| Sm/Eu | 4.32 | 4.20 | 4.20 | 3.59 | 4.74 | 4.21 | -- | -- |
| Ce/Yb | 410.6 | 327.2 | 455.2 | 255.2 | 461.1 | 246.1 | -- | -- |
| La/Yb | 223.0 | 164.6 | 267.1 | 143.6 | 266.6 | 127.3 | -- | -- |
| Sm/Nd | 0.10 | 0.11 | 0.09 | 0.12 | 0.13 | -- | -- | 0.15 |
| La/Nd | 1.55 | 1.46 | 1.69 | 1.42 | 1.32 | -- | -- | 1.45 |

Table 3. (continued)

| Sl. No. | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---------|-------|------|-------|-------|------|--------|------|
| Ba | 10584 | 9831 | 1971 | 2120 | 4860 | 5550 | 8370 |
| Zr | 1167 | 1302 | 718 | 865 | 1160 | 1000 | 1580 |
| Hf | 38 | 42 | 17 | 35 | -- | -- | -- |
| Ta | 10 | 6 | 6 | 14 | -- | -- | -- |
| Th | 57 | 37 | 12 | 27 | 46 | 30 | 20 |
| U | 2 | 9 | 3 | 3.8 | -- | 2.5 | 5.8 |
| La | -- | -- | -- | 322 | 629 | 230 | 159 |
| Ce | -- | -- | -- | 600 | 1060 | 420 | 286 |
| Nd | -- | -- | -- | 239 | 501 | 150 | -- |
| Sm | -- | -- | -- | 36 | -- | 19 | -- |
| Eu | -- | -- | -- | 7.3 | -- | 4.5 | -- |
| Gd | -- | -- | -- | -- | -- | 9.8 | -- |
| Tb | -- | -- | -- | 2.5 | -- | -- | -- |
| Yb | -- | -- | -- | 2.5 | -- | 0.45 | -- |
| Lu | -- | -- | -- | 0.33 | -- | -- | -- |
| Zr/Hf | 30.71 | 42.0 | 42.23 | 24.71 | -- | -- | -- |
| Th/U | 28.5 | 4.11 | 4.0 | 7.10 | -- | 12.00 | 3.46 |
| Sm/Eu | -- | -- | -- | 4.93 | -- | 4.22 | -- |
| Ce/Yb | -- | -- | -- | 240.0 | -- | 933.33 | -- |
| La/Yb | -- | -- | -- | 128.8 | -- | 511.11 | -- |
| Sm/Nd | -- | -- | -- | 0.15 | -- | 0.13 | -- |
| La/Nd | -- | -- | -- | 1.35 | 1.25 | 1.53 | -- |

Data source: Mitchell (1995) and references therein (sl. nos. 04–16). Mitchell and Bergman (1991) (sl. nos. 17–19). Bergman (1987) and references therein (sl. nos. 20–23).

1: Average (4 analyses) micaceous kimberlite from Majhgawan (Paul *et al* 1975a).

2: Average (3 analyses) micaceous kimberlite from Hinota (Paul *et al* 1975a).

3: Average (2 analyses) micaceous kimberlite from Majhgawan (Paul *et al* 1977).

4: Average (10 analyses) South African kimberlites.

5: Average (23 analyses) Zaire kimberlites.

6: Average Kimberly Group kimberlite.

7–13: Average values of unevolved orangeites (7: Swartruggens, 8: Finsch, 9: Bellsbank, 10: Sover, 11: Newlands, 12: NewElands, 13: Star).

14–16: Average values of evolved orangeites (14: Sover North, 15: Postmasburg, 16: Pniel).

17: Average lamproite, West Kimberly.

18: Average lamproite, Leucite Hills, Wyoming.

19: Average lamproite, Prairie Creek, Arizona.

20: Average lamproite, Chelima, south India.

21: Average lamproite, Gondwana coalfields, eastern India.

22: Average leucite-olivine lamproite, Gaussberg, Antarctica.

23: Average sanidine-amphibole lamproite, Mount Bayliss, Antarctica.

injected through a thick continental crust. These rocks show effects of alteration as evidenced from the presence of chlorite, serphophite and serpentine which are mostly alteration products of micas and olivines respectively (Halder and Ghosh 1981). Clement's contamination index (Clement 1982 quoted from

Mitchell 1995) for these rocks and also for typical orangeites of South Africa are always > 1 (cf. table 2) suggesting that the rocks are contaminated. Mitchell (1995) observed that the values of CI close to unity as found in the typical South African kimberlites can be interpreted as uncontaminated. However, many

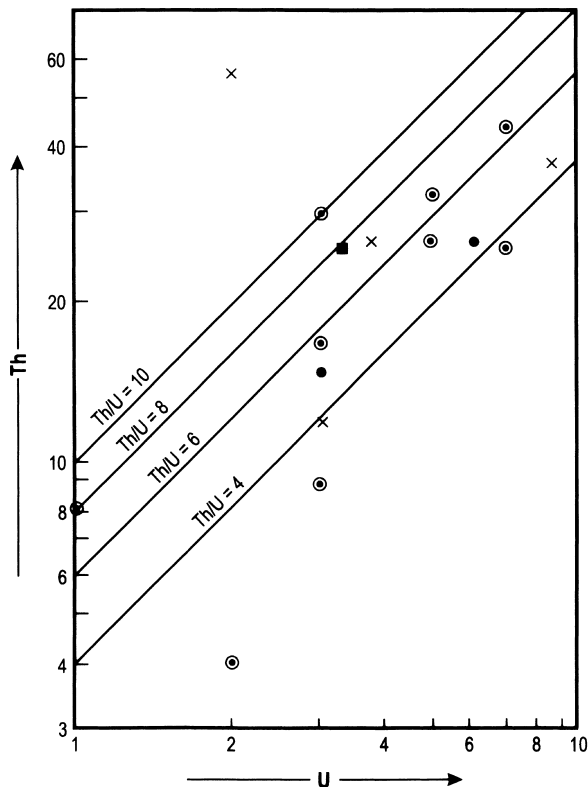


Figure 3. Logarithmic plots of Th versus U for the rocks of Majhgawan-Hinota along with the typical kimberlites, orangeites and lamproites. Symbols same as in figure 2.

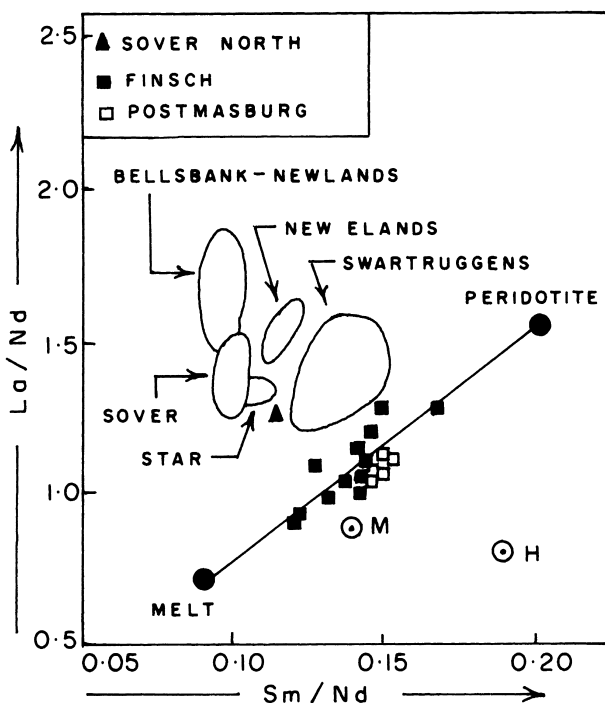


Figure 4. Sm/Nd versus La/Nd diagram showing the nature of plots of Majhgawan-Hinota rocks with that of Finsch orangeites. The different fields of unevolved and evolved orangeites are after Mitchell (1995). Centred circles: Plots for Majhgawan(M) and Hinota(H) rocks. Solid line (after Fraser 1987 in Mitchell 1995) represents mixtures between peridotite and melts formed from primary mantle.

apparently uncontaminated orangeites from Kaapvaal craton have CI's ranging from 1.5–2.6 (Dawson 1987). The Majhgawan orangeites have lower CI (always <1.5) than that of Hinota areas (always >2) and it can be surmised that the rocks are apparently uncontaminated or might have suffered negligible crustal contamination.

4. Conclusions

From the discussions made so far it can be concluded that:

- The mineralogical assemblages of Majhgawan-Hinota pipe rocks are akin to unevolved orangeites since they do not contain minerals such as sanidine, richterite and leucite. They are marked by the absence of monticellite and the presence of barite in contrast to kimberlite/lamproite.
- The Majhgawan-Hinota pipe rocks are unique in being the oldest orangeite reported so far. While Kaapvaal craton orangeite range in age from 200 Ma to 110 Ma with most of the samples having Rb-Sr ages of 112–114 Ma (Skinner 1989), the probable orangeite reported from Aries pipe, western Australia are ~820 Ma (Edwards *et al* 1992; Taylor *et al* 1994).
- Although Mitchell (1995) has suggested that a contamination index close to unity are considered as uncontaminated for kimberlites, many uncontaminated diatreme rocks have higher values (>1) mostly due to high modal phlogopite content. The contamination index $[CI = (SiO_2 + Al_2O_3 + Na_2O)/(MgO + K_2O) \text{ wt\%}]$, as deduced from the major element compositions of Majhgawan-Hinota rocks, ranges from 1.46–2.38 indicating that the rocks are apparently uncontaminated or may have suffered negligible alteration/contamination.
- The major element variations (except TiO_2) as a function of MgO clearly reveal that the rocks have appreciably low MgO as compared to archetypal kimberlites of S. Africa and are more akin to orangeites, having plotted with them in field II (see figure 2). The incompatible trace and rare earth abundances do not serve as discriminating criteria between kimberlites and orangeites, except the Sm/Nd and La/Nd ratios plots as discussed.
- The Majhgawan-Hinota pipe rocks should be taken up for intensive research work in identifying the minerals with greater precision and accuracy including mineral chemistry of different phases, major and trace element geochemistry of completely contamination-free samples coupled with Sr-Nd-Pb isotope systematics so as to confirm our suggestion that the pipe rocks are bonafide orangeites.
- Syngenetic inclusions in diamonds suggest that most diamonds crystallised at a depth between 150

and 200 km (Boyd *et al* 1985; Meyer 1987; Irifune *et al* 1989; Griffin *et al* 1994), but recent findings of ferropericlasite inclusions in diamonds (Harte and Harris 1994; Stachel *et al* 1998) and the experimental works of Liu and Lin (1995) and Liu (1999) suggest that diamonds are generated in the lower mantle at depths of ~900 and ~1100 kms at pressures of about 300kbar. Mitchell (1995) had argued that both orangeites and kimberlites, whether with or without diamonds, have distinctive source regions as lithospheric mantle and asthenospheric mantle respectively. So, intensive studies on syngenetic inclusions, if any, within diamonds (e.g. olivine, garnet, clinopyroxene, spinel, ferropericlasite, enstatite, etc.) from M–H pipe rocks are required to arrive at a conclusion whether these rocks have been generated in the lithospheric mantle or asthenospheric mantle.

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