abandoned small to large mine-dumps of the NMB, as documented by the present and earlier studies of AMD, indicates that there is a potential to recover these minerals as by-products by physical beneficiation techniques from the waste dumps. It may therefore be worthwhile to take up further studies to quantify resources of these minerals for their recovery.

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# Mafic and ultramafic dykes of Singhbhum craton from Chaibasa district, Jharkhand, Eastern India: geochemical constraints for their magma sources

The Singhbhum Granitoid Complex (SGC) of 3.2–2.8 Ga forms a major part of the Singhbhum craton (Figure 1 *a*)[1]. It is intruded by ultramafic, mafic and felsic dykes (having NE–SW and NW–SE as major trend directions) which are jointly called newer dolerite dykes (NDD)[2–10]. Available K/Ar age data[3] indicate that mafic members of NDD swarm had intruded the SGC intermittently during 2200 to 950 Ma. On the basis of K–Ar ages, Mallik and Sarkar[4] suggested three pulses of mafic intrusive activity, viz. 2100 ± 100, 1500 ± 100 and 1100 ± 200 Ma. Recently, mafic dykes of Singhbhum craton are reported as having 1765 Ma age by using Pb–Pb baddeleyite thermal extraction–thermal ionization mass spectrometer method[10]. The, ultramafic members of NDD swarms are dated 2613 ± 177 Ma on the basis of Rb–Sr isochron method[5]. Some workers have suggested that the ultramafic, mafic and felsic members of NDD swarms are genetically related representing cumulates, direct crystallization and partial melting products respectively[3]. However, Bose[6] opined that more studies are required to know possible genetic link between the mafic and ultramafic members of NDD swarms. Thus, it is not yet clear whether the mafic and ultramafic members of NDD swarms are genetically related or

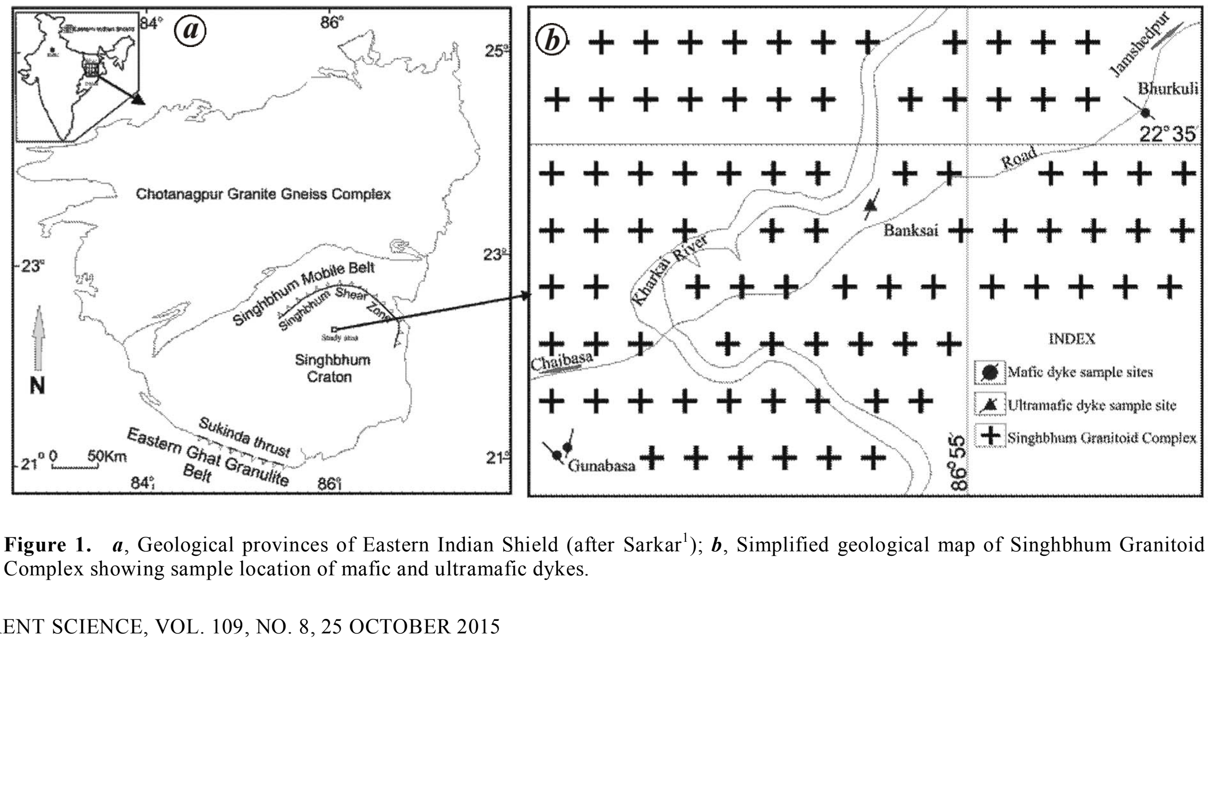


**Figure 1.** ***a***, Geological provinces of Eastern Indian Shield (after Sarkar[1]); ***b***, Simplified geological map of Singhbhum Granitoid Complex showing sample location of mafic and ultramafic dykes.

**Table 1.** Major and trace element data with CIPW norms of mafic and ultramafic dykes of Singhbhum craton, Chaibasa district, Jharkhand, Eastern India

| Group | Mafic dykes | | | Ultramafic dykes | | |
|---|---|---|---|---|---|---|
| sample no. | MD-1 | MD-2 | MD-4 | UD-1 | UD-2 | UD-3 |
| $SiO_2$ | 52.78 | 56.69 | 53.62 | 37.3 | 42.21 | 36.21 |
| $TiO_2$ | 1.43 | 0.86 | 0.9 | 0.19 | 0.21 | 0.16 |
| $Al_2O_3$ | 10.45 | 11.38 | 10.5 | 3.54 | 4.76 | 3.46 |
| $Fe_2O_3$ | 16.67 | 12.19 | 12.52 | 14.56 | 8.89 | 15.19 |
| MgO | 8.19 | 8.13 | 12.34 | 40.39 | 34.72 | 42.15 |
| CaO | 7.13 | 7.06 | 7.87 | 3.38 | 8.59 | 2.43 |
| $Na_2O$ | 2.27 | 2.90 | 1.39 | 0.21 | 0.25 | 0.15 |
| $K_2O$ | 0.78 | 0.59 | 0.57 | 0.21 | 0.16 | 0.06 |
| MnO | 0.19 | 0.15 | 0.17 | 0.21 | 0.19 | 0.19 |
| $P_2O_5$ | 0.1 | 0.05 | 0.11 | 0.01 | 0.01 | 0.01 |
| Total | 99.99 | 100 | 99.99 | 100 | 99.99 | 100.01 |
| Mg # | 49 | 57 | 66 | 85 | 89 | 85 |
| CIPW norms | | | | | | |
| Quartz | 13.42 | 14.43 | 12.20 | | | |
| Orthoclase | 4.61 | 3.49 | 3.37 | | 0.95 | |
| Albite | 19.21 | 24.54 | 11.76 | | 0.48 | |
| Anorthite | 16.02 | 16.29 | 20.73 | 8.10 | 11.39 | 8.59 |
| Diopside | 11.26 | 12.45 | 11.78 | 6.58 | 24.25 | 0.98 |
| Hypersthene | 15.18 | 14.48 | 25.28 | | | |
| Olivine | | | | 68.36 | 52.72 | 73.25 |
| Nepheline | | | | 0.96 | 0.89 | 0.69 |
| Leucite | | | | 0.97 | | 0.28 |
| Larnite | | | | 0.05 | | 0.66 |
| Ilmenite | 0.41 | 0.32 | 0.36 | 0.36 | 0.40 | 0.30 |
| Sphene | 2.98 | 1.70 | 1.74 | | | |
| Apatite | 0.23 | 0.12 | 0.25 | 0.02 | 0.02 | 0.02 |
| Magnetite | | | | 0.13 | 0.01 | 0.16 |
| Hematite | 16.67 | 12.19 | 12.52 | 14.47 | 8.88 | 15.08 |
| Total | 99.99 | 100.00 | 99.99 | 100.00 | 99.99 | 100.01 |
| Trace elements | | | | | | |
| Ni | 19 | 36 | 33 | 208 | 150 | 304 |
| Cr | 93 | 86 | 226 | 1772 | 2458 | 559 |
| Co | 48 | 50 | 48 | 97 | 75 | 102 |
| V | 266 | 172 | 205 | 56 | 86 | 30 |
| Sc | 29 | 19 | 29 | 14 | 22 | 9 |
| Pb | 7.00 | 7.00 | 7.69 | 7.98 | 8.94 | 5.22 |
| Zn | 98 | 77 | 82 | 180 | 81 | 39 |
| Cu | 135 | 65 | 84 | 30 | 35 | 15 |
| Ga | 15 | 15 | 13 | 3 | 5 | 2 |
| Rb | 36 | 17 | 25 | 11 | 12 | 4 |
| Sr | 160 | 330 | 216 | 58 | 65 | 13 |
| Ba | 190 | 195 | 164 | 114 | 91 | 38 |
| Zr | 89 | 57 | 68 | 19 | 29 | 10 |
| Nb | 6.82 | 3.44 | 5.11 | 0.96 | 2.42 | 0.97 |
| Ta | 0.43 | 0.22 | 0.32 | 0.06 | 0.15 | 0.06 |
| Y | 37 | 18 | 23 | 5 | 10 | 4 |
| U | 0.18 | 0.12 | 0.10 | 0.06 | 0.12 | 0.07 |
| Th | 1.60 | 1.04 | 1.25 | 0.58 | 1.53 | 0.42 |
| Hf | 2.28 | 1.46 | 1.74 | 0.49 | 0.74 | 0.26 |
| Cs | 4.04 | 0.86 | 0.81 | 1.69 | 1.42 | 0.40 |
| La | 11.07 | 9.81 | 9.16 | 2.73 | 6.75 | 2.04 |
| Ce | 28.01 | 23.20 | 22.39 | 5.87 | 14.80 | 4.36 |
| Pr | 3.23 | 2.57 | 2.53 | 0.59 | 1.45 | 0.44 |
| Nd | 18.68 | 14.13 | 13.90 | 2.86 | 6.95 | 2.19 |
| Ce | 28.01 | 23.20 | 22.39 | 5.87 | 14.80 | 4.36 |
| Sm | 4.71 | 3.32 | 3.29 | 0.60 | 1.43 | 0.49 |
| Eu | 1.56 | 1.19 | 1.11 | 0.18 | 0.40 | 0.14 |
| Gd | 6.02 | 3.81 | 4.18 | 0.72 | 1.78 | 0.61 |

(*Contd*)

**Table 1.** *Contd*

| Group sample no. | Mafic dykes MD-1 | MD-2 | MD-4 | Ultramafic dykes UD-1 | UD-2 | UD-3 |
|---|---|---|---|---|---|---|
| Tb | 1.03 | 0.58 | 0.67 | 0.13 | 0.29 | 0.10 |
| Dy | 5.76 | 2.91 | 3.70 | 0.71 | 1.56 | 0.58 |
| Ho | 1.23 | 0.60 | 0.78 | 0.15 | 0.33 | 0.13 |
| Er | 3.84 | 1.72 | 2.38 | 0.53 | 1.07 | 0.42 |
| Tm | 0.63 | 0.29 | 0.41 | 0.09 | 0.18 | 0.07 |
| Yb | 3.43 | 1.44 | 2.03 | 0.52 | 0.97 | 0.41 |
| Lu | 0.50 | 0.21 | 0.29 | 0.08 | 0.14 | 0.06 |
| Ratio | | | | | | |
| La/Yb | 3.23 | 6.81 | 4.51 | 5.25 | 6.96 | 4.98 |
| Nb/U | 37.89 | 28.67 | 51.10 | 16.00 | 20.17 | 13.86 |
| Zr/Y | 2.41 | 3.17 | 2.96 | 3.80 | 2.90 | 2.50 |
| Ti/Y | 232 | 286 | 235 | 228 | 126 | 240 |
| Nb/Th | 4.26 | 3.31 | 4.09 | 1.66 | 1.58 | 2.31 |
| (La/Lu)n | 2.30 | 4.85 | 3.28 | 3.54 | 5.01 | 3.53 |
| (La/Sm)n | 1.48 | 1.86 | 1.75 | 2.86 | 2.97 | 2.62 |
| (Gd/Lu)n | 1.50 | 2.26 | 1.79 | 1.12 | 1.58 | 1.27 |
| Eu/Eu* | 0.90 | 1.02 | 0.91 | 0.84 | 0.77 | 0.78 |

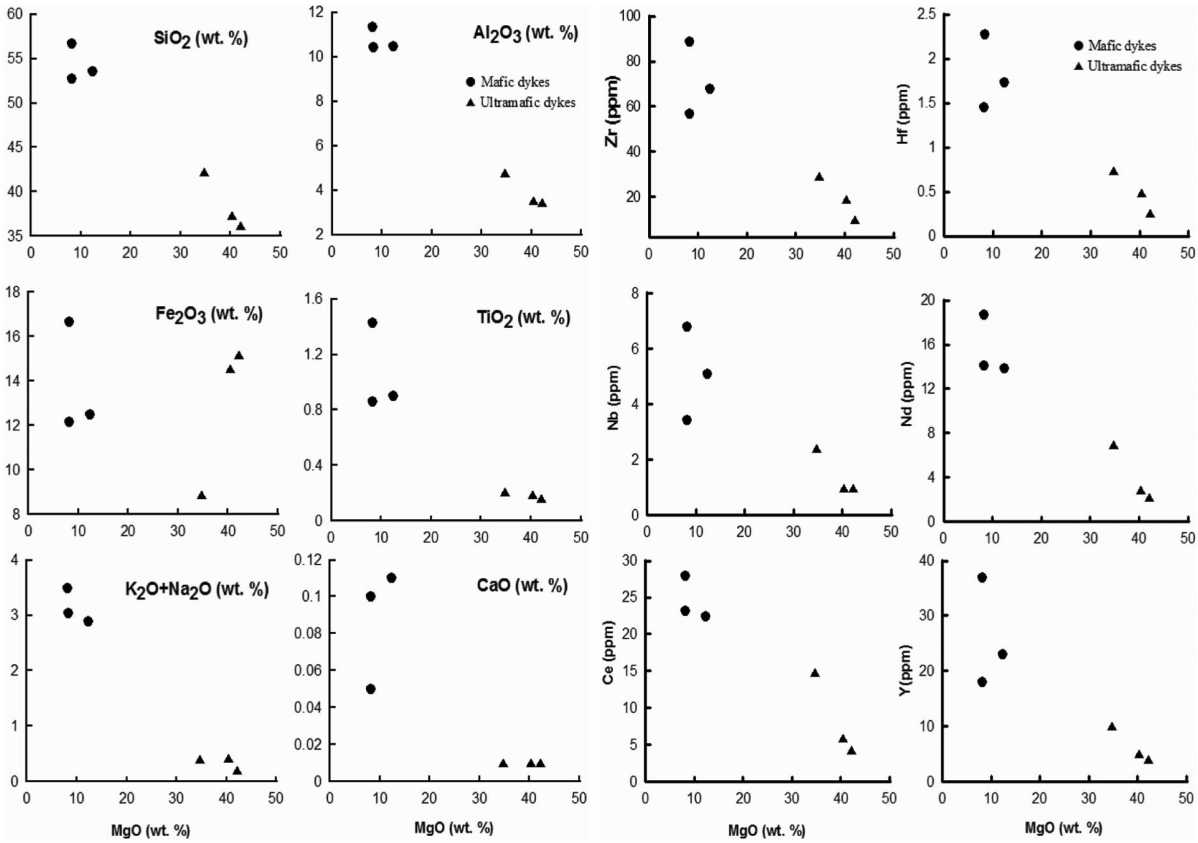


**Figure 2.** MgO versus oxides and high field strength elements variation diagrams for mafic and ultramafic dykes of Singhbhum craton.

whether these two compositionally different sets of dykes represent two independent, temporally distinct magma sources. Hence, the present preliminary geochemical study has been carried out on mafic and ultramafic dykes that are placed on either side of Chaibasa to Jamshedpur road (near Gunabasa, Banksai and Bhurkuli) (Figure 1 *b*) to test the genetic linkage between these two members of NDD swarms.

On the basis of petrography and major element geochemical characteristics, the studied dykes are grouped as mafic and ultramafic dykes. Mafic dykes, trending NW–SE and NE–SW, are medium to fine-grained and possess clinopyroxene of augite composition and plagioclase of labrodorite variety as essential minerals. Ultramafic dykes, showing NE–SW trend, are mainly composed of olivine and orthopyroxene. Major and trace element geochemical analysis of selected samples was done at the National Geophysical Research Institute, Hyderabad. Whole-rock major elemental analyses were carried out by X-ray fluorescence (Philips Magi X PRO model PW 2540 sequential X-ray spectrometer) technique. Trace elements including rare earth elements (REEs) were determined by inductively coupled plasma–mass spectrometry technique using Perkin Elmer Sciex ELAN DRC-II system. The precision of ICP-MS data is <5% RSD for all REE[11]. Table 1 provides the geochemical data and Cross, Iddings, Pirsson and Washington (CIPW) normative mineralogy of studied dykes. Ultramafic dykes have high MgO (>30.0%) and low $SiO_2$ (<45.0%), $Al_2O_3$ (<5.0%) and alkalies (<1.0%). Mafic dykes have lower contents of MgO (<12.00%) and higher $SiO_2$ (>51.00%), $Al_2O_3$ (>10.00%) and total alkalies (>1.0%) relative to ultramafic dykes. Low $Al_2O_3$ concentrations in mafic dykes may indicate presence of garnet as residual aluminous phase. $TiO_2$ is low in ultramafic dykes and varies from 0.16% to 0.21%, whereas in mafic dykes it varies from 0.86% to 1.43%. CaO shows large variation in ultramafic dykes from 2.43% to 8.59%, which indicates fractionation of plagioclase. In mafic group it shows least variation ranging from 7.06% to 7.88%. Mafic dykes with Mg# ranging from 49 to 66 have high-Fe tholeiitic nature whereas ultramafic dykes with Mg# ranging from 85 to 89 show Mg-rich tholeiitic nature. In variation diagrams (Figure 2), normal crystallization trend shown by the studied samples does not favour the possibility of mobilization/crustal contamination of these elements. No crustal contamination is also supported by their Nb/U ratio (Table 1), which is higher than that of the upper continental crust (Nb/U = 9)[12]. On variation diagrams (Figure 2), the studied samples show two distinct crystallization trends. Mafic samples show higher concentration of high field strength elements (HFSEs) than the ultramafic samples. Both groups have neither overlapping MgO content nor the same HFSE contents; this feature strongly suggests that these two groups are not derived from a single magma source but they might have been derived from different magma sources. Trace element plots such as (La versus La/Yb)[13] and (Ni versus La/Yb)[14] also support their derivation from different sources (Figure 3). Primitive mantle normalized multi-element (ME) diagram[15] (Figure 4 *a*) and chondrite normalized REE diagram[12] (Figure 4 *b*) show distinct patterns for both groups. Mafic dykes have higher concentration of all incompatible elements than ultramafic dykes. The most distinguishable feature noted in these two groups on ME patterns (Figure 4 *a*) is that ultramafic dykes show slight depletion of Rb, Ba and Sr whereas these elements do not show depletion in the case of mafic dykes. However, both groups show prominent negative anomalies of Nb, P, Ti and shallow Zr negative anomalies and well-defined positive Pb anomaly. On chondrite-normalized REE diagram (Figure 4 *b*), mafic dykes are characterized by parallel, moderately fractionated patterns $\{(La/Lu)_n = 2.30–4.85\}$ and a relatively weak fractionated heavy REE (HREE)

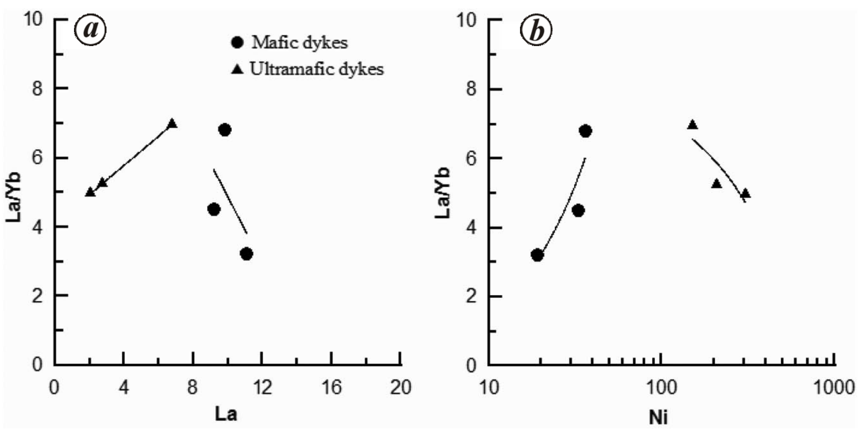


**Figure 3.** La versus La/Yb[13] (***a***) and Ni versus La/Yb[14] (***b***) diagrams for mafic and ultramafic dykes of Singhbhum craton.

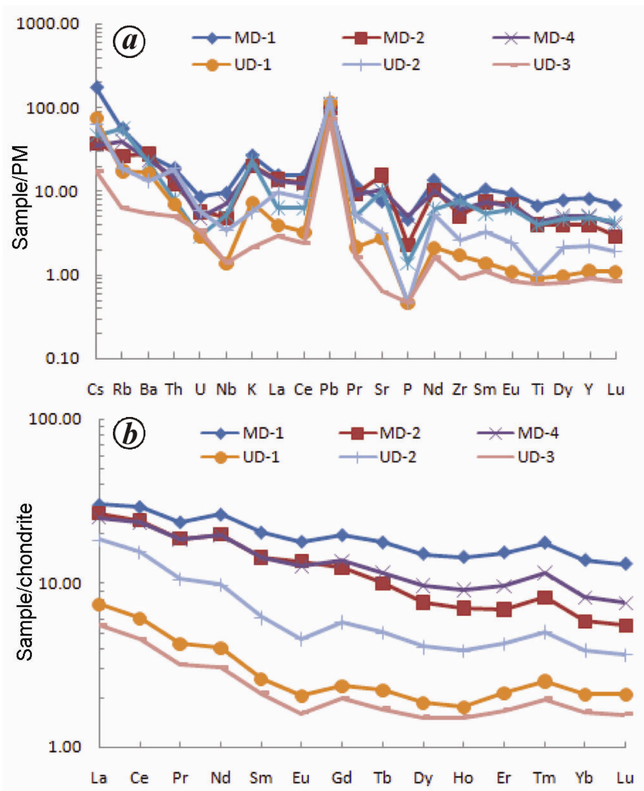


**Figure 4.** Primitive mantle normalized[15] multi-element diagram (***a***) and chondrite-normalized REE diagram[12] (***b***) for mafic and ultramafic dykes of Singhbhum craton.

segment $\{(Gd/Lu)_n = 1.50–2.26\}$, with absence of significant Eu anomalies (Eu/Eu* = 0.90–1.02). This pattern suggests the presence of residual garnet in the source and may indicate a minimum depth of generation of 80 km (ref. 16). The ultramafic dyke samples, on the other hand, are characterized by lower REE content than the mafic dykes (Figure 4 *b*). They display least to moderate lower REE (LREE) fractionated patterns $\{(La/Sm)_n = 2.62–2.97\}$ and almost flat HREE $\{(Gd/Lu)_n = 1.12–1.58\}$ with negative Eu anomalies {Eu/Eu* = 0.77–0.84}. Such REE plots may indicate that both groups do not have any genetic relationship but have different petrogenetic history. The Ni versus Zr petrogenetic model[17] (figure not shown) suggests that the ultramafic dykes are derived from a higher percentage of melting (30–50%) of a mantle source than the mafic dyke samples, which are probably derived from (20–25%) melting of a mantle source. Hence it is concluded that the geochemical characteristics of mafic and ultramafic dykes do not clearly indicate any genetic relationship between them. It is more likely that these two members of NDD swarms may have originated from different magmatic sources. Therefore, isotopic data is recommended to support the conclusion.

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