

Chapter 2
Samples and Geochemical
Characterization

In this chapter I discuss the details of the rock samples collected for the present research work. The GPS locations of the samples are provided in Tables 2.1 – 2.8. The map of India in Figure 2.1 shows the general locations of the samples. Except for the carbonatites, some alkaline igneous rocks and kimberlites, all other samples were characterised geochemically using their trace element contents. The following section discusses the analytical methods used for geochemical characterization of the samples.

2.1 Geochemical Methods

Trace element concentrations including the Rare Earth Elements were determined using a Thermo X-Series 2 Q-ICPMS facility at the Geosciences Division of Physical Research Laboratory, India. The samples were dissolved using the standard protocol of HF-HNO₃ (2:1) for silicates. A complete dissolution was achieved through ~1 hour of ultra-sonication and heating at 60°C with closed cap for ~12 hours. After two rounds of 8N HNO₃ treatment and drying, stock solutions were prepared in 2 % HNO₃ with a 1000 times dilution. Further dilutions as required for the analyses were prepared from stock solutions using 2 % HNO₃. Concentrations were determined using the calibration curve obtained using different dilutions of the international rock standard BHVO-2. The same standard along with the rock standards BCR-2 and AGV-2 were used as an unknown for accuracy check. The precision of measurements for all elements were better than 3 % at 2SD. The data are presented in Table 2.9.

2.2 TTG from Singhbhum, Odisha

Tonalite, Trondhjemite and Granodiorites (TTG) are considered archetypical of the Archean Eon. The TTGs for the present study were collected from a previously well studied section of the Singhbhum Craton, Odisha. The Singhbhum Craton in Eastern India is oval in shape, bordered in the north by the North Singhbhum Mobile Belt (NSMB), to the southeast by the Eastern Ghats Belt and to the southwest by the Bastar Craton (Saha, 1994). It has extensive occurrences of greenschist to amphibolite facies TTGs and granites ranging in age from Paleoproterozoic (3.6 – 3.2 Ga) to Neoproterozoic (2.8 – 2.5 Ga) (Upadhyay et al., 2014 and references therein). As described by Saha (1994) the major Paleoproterozoic crustal units of the craton are the:

1. Older Metamorphic group (OMG) consisting of greenschist to amphibolite facies supracrustals

2. Older Metamorphic Tonalite Gneisses (OMTG) consisting primarily of the TTGs
3. Singhbhum Granite (SG) consisting of granitoids, tonalities; interlayered greenschist facies platformal sediments, banded iron formations (BIF), and mafic and felsic volcanic rocks of the Iron Ore Group (IOG).

Further details can be found in Upadhyay et al. (2014). Based on U-Pb ages of zircon these authors proposed a polycyclic evolution of the Archean crust in the Singhbhum Craton. They reported that tonalites and trondhjemites of OMTG were emplaced at 3.45 – 3.44 Ga together with Phase III of Singhbhum pluton.

I targeted the OMTG Group for collection of TTGs from the reported outcrops. The GPS co-ordinates of the rock samples collected by us and analysed for ^{142}Nd isotopic composition are given in Table 2.1. To make sure that the samples collected by us are in fact TTGs, they were geochemically characterized using the method described in section 2.1. The data are presented in Table 2.9 and are plotted Figures 2.2 - 2.4. The chondrite normalized patterns of these rocks show a strong enrichment in LREEs as compared to HREEs (Figure 2.2). On the Martin's plot (Martin and Moyen, 2002; Moyen and Martin, 2012) our samples (OD – series) fall in the Archean TTG field (Figure 2.5). Sample OD-12/2 shows a small positive Eu anomaly whereas OD-9(a) and OD-13/2 show a small negative Eu anomaly (Figure 2.2). The average composition of these three samples does not show any Eu anomaly. All three samples exhibit a positive Pb anomaly and negative anomalies in Nb and Ta (Figure 2.4), typical features of continental crustal rocks. Sample OD-12/2 exhibits a negative anomaly for Zr and Hf as well, whereas the other two samples do not show these. The lack of significant Eu, Sr anomalies and negative Nb-Ta anomalies of Singhbhum TTGs are typical of TTGs worldwide as observed by Moyen and Martin (2012).

2.3 Granitoids from Banded Gneissic Complex (BGC)-1, Rajasthan

Aravalli craton is divided into two parts, the eastern Mewar Craton and the western Marwar Craton. The eastern Mewar Craton consists of the Banded Gneissic Complex – 1, which has three major components - the Mewar Gneiss, Mangalwar Complex and Sandmata Complex. Of these, Mewar Gneiss consists of TTG gneiss (*sensu lato*) ranging in age from 3300 – 2900 Ma (Valdiya, 2010). The Mewar Gneiss contains multiple metamorphic components of varying ages (Wiedenbeck et al., 1996). Gopalan et al. (1990) studied biotite gneisses near the village of Jhamarkotra, SE of Udaipur (Rajasthan) and reported a six-point isochron Sm-Nd age of 3307 ± 65 (2SD) Ma, with an initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of $0.508402 \pm$

52 ($\epsilon^{143}\text{Nd} = 1.4 \pm 1$). The geochemical study of Ahmad and Tamep(1994) revealed that the REE and trace element compositions of these granitoids differ from those of typical Archean TTGs. The same is also observed by me for the samples analysed in the present study (Figures 2.3 and 2.6).

For the present study, granitoid samples were collected near the village of Jhamarkotra. Although many samples of biotite gneisses and amphibolite were collected and analysed for trace element study (Figure 2.7), only two of these were analysed for their ^{142}Nd isotopic composition. The details of GPS locations and trace element concentrations are given in Table 2.2 and Table 2.10. The trace element data reveals that these samples (JG – series) fall in the modern granitoids field of Martin (Martin, 1987; Moyen and Martin, 2012) as shown in the Figure 2.5. All except one sample, JG-01, show an enrichment in LREEs and negative Eu anomalies (Figure 2.6). The primitive mantle (PM) normalised trace element patterns show pronounced depletion in Nb and Ta and smaller depletions in Zr and Hf (Figure 2.7). They also show enrichments in Pb and Rb.

2.4 Nepheline syenites from Khariar alkaline complex, Odisha

The Khariar alkaline complex is one of the intrusives along the suture zone between Bhandhara/Eastern Dharwar cratons (EDC) and the Eastern Ghats Belt (EGB). The complex was emplaced at 1480 ± 17 (2σ) Ma (Upadhyay et al., 2006). It has been studied in detail by Upadhyay et al.(2006, 2009). The deformation of this complex during the Pan-African tectono-thermal event has been suggested along with the rift-related setting for the magmatic activity. These authors proposed a petrogenetic model for the complex, which suggests that the basanitic parental melt was derived from a metasomatised SCLM during the initiation of rifting. Based on Sr-Nd isotope data as shown in Figure 2.8, these rocks fall in a narrow field in the enriched quadrant (Upadhyay et al., 2006).

The 1.48 Ga nepheline syenites of the complex have attracted much attention, because of a report of negative $\mu^{142}\text{Nd}$ anomalies, as low as 13 ppm (Upadhyay et al., 2009). This was an important finding since these are the only younger than Archean rocks to possess signatures of the early silicate Earth differentiation process. The report supported the hypothesis of cratonic roots being sites of preservation of early differentiated reservoirs. Considering the importance of these results, independent verification of these was required. In one such effort (described in detail in Chapter 4), we studied the alkaline silicate rocks from the same localities as in Upadhyay et al. (2009) for their ^{142}Nd isotopic composition.

Sample details are presented in Table 2.3. In order to make sure that the samples collected by us are geochemically indistinguishable from those studied by Upadhyay et al. (2009), trace element analyses were carried out. Table 2.11 presents these data and in Figures 2.9 and 2.10 the chondrite normalized REE and primitive mantle normalized trace element patterns are plotted. The patterns observed in our samples are similar and fall well within the ranges of variations observed by Upadhyay et al. (2009).

2.5 Nepheline-syenites from Kishengarh, Rajasthan

With BGC (Banded Gneissic Complex) in the East and Delhi Supergroup to the West, the occurrence of nepheline-syenites in Kishengarh, Rajasthan, is considered unique because it is the only alkali pluton in this part of the Aravalli Craton (Roy and Dutt, 1995). There exist multiple hypotheses on the origin of these rocks. Some consider it to have formed due to alkalization of gabbro (Niyogi, 1966); others consider them of metamorphic origin (Mittal and Jain, 1955). The first study of these rocks by Heron (1924) suggested it to be of igneous origin and so did the latter studies by Srivastava (1988) and Roy and Dutt (1995). The nepheline syenite pluton occurs as a conformable body within a sequence of pre-Delhi metasedimentary and metavolcanic rocks, known as Kishengarh group (Roy and Dutt, 1995). A discontinuous thin zone, consisting of fenitized rocks, forms a capping over the nepheline syenite (Roy and Dutt, 1995). The only available information on the age of emplacement of this pluton comes from a three point Rb – Sr isochron by Crawford (1970) giving an age of 1490 ± 150 (2σ) Ma. Solanki (2011) attempted to date zircons and titanites of a nepheline syenite from this area. Zircons yielded an age (U-Pb) of ~ 990 Ma whereas the titanites yielded a minimum age of 1365 ± 65 Ma. The younger age from zircons indicates their resetting during a regional thermal event. Leelanandam (2006) classified this pluton as DARC (Deformed Alkaline Rock and Carbonatite) and extended an idea of these to be a part of the Great Indian Proterozoic Fold Belt.

Three samples of nepheline syenites were collected from the outcrop of ‘Nepheline Syenites Geological Monument’. The GPS locations of the samples are given in Table 2.4 and the whole rock trace element data are presented in the Table 2.12. The chondrite normalized REE and primitive mantle normalized trace element patterns are plotted in Figures 2.11 and 2.12, respectively. These rocks exhibit enrichment in LREEs with an almost flat pattern for HREEs. No Ce anomaly is observed, indicating absence of plagioclase fractionation. All the three texturally different varieties of these rocks show a positive

anomaly in Pb and one of the samples (KG-02) exhibit negative anomalies for HF and Zr, suggesting a possible crustal contamination of the parental melt of these rocks, which is also supported by the enrichments in LILEs (Figure 2.12).

2.6 Kimberlites from Eastern Dharwar Craton (EDC), Karnataka

Kimberlites in India are known from the EDC (Southern India) and Bastar Craton (Central India). The kimberlites of the EDC have been well studied for their petrogenesis and precise emplacement ages by Chalapathi Rao et al. (2013) and the samples for the present study were provided by them. The study of Chalapathi Rao et al. (2013) concluded that these kimberlites were emplaced episodically at ~ 1100 Ma. Our kimberlite samples come from Narayanpet Kimberlite field (NKF), Raichur Kimberlite Field (RKF) and Wajrakarur Kimberlite Field (WKF). WKF is the largest among these, consists of Wajrakarur (P-5) and Chigicherla (CC-5); NKF consists of Kotakonda and Narayanpet (KK-1 and NK-1, respectively) and RKF consists of Siddanpalle (SK-1). As reported by Chalapathi Rao et al. (2013), these rocks have high abundances of alkaline earth and high field strength trace elements (> 1000 ppm) and very low Rb contents (~7 ppm). They also show considerable enrichment of REE over chondrite and LREE over HREE, and lack any Eu anomaly. Perovskites from the kimberlites, however, show a distinct trace element chemistry of the perovskite from NKF, RKF and WKF. Their Sr-Nd isotope compositions plot in a depleted quadrant, similar to the kimberlites of South Africa and Greenland. Chalapathi Rao et al. (2013) proposed a model of emplacement which suggested derivation of parental magmas from variably enriched metasomatised SCLM sources. Some might have had asthenospheric overprints. Sample details are given in Table 2.5.

2.7 Alkali Basalts from Phenai Mata Igneous Complex, Gujarat

The Phenai Mata Igneous Complex is a part of the Chhota Udaipur alkaline sub province of the Deccan Flood Basalt Province (Basu et al., 1993). The under-saturated alkalic rocks of the Phenai Mata plug (22°7' N, 73°50' E) intrude into the earlier formed Deccan Trap flows of tholeiitic composition. This complex was reported to have an intrusion age of 64.96 ± 0.11 (2 σ) Ma, which probably marks the end phase of the Deccan volcanism on the Indian plate. Low $^3\text{He}/^4\text{He}$ ratios (3.4 to 3.1 R_A) of these basalts have been interpreted to represent crustal contamination of the parental magma of the complex (Figure 2.13), which is further substantiated by their low $\epsilon^{Nd}(t)$ values (-15 to -5) (Basu et al., 1993).

For the present study six samples of basalts from this plug (near village Jhajh) were collected and two of them (PMC-02 and 03) were analysed for their $^{142}\text{Nd}/^{144}\text{Nd}$. The details of the sample locations are given in Table 2.6 and their trace element contents are presented in Table 2.13. The data are plotted in Figure 2.14 and 2.15 in chondrite normalized and primitive mantle normalized plots, respectively. These rocks show enrichment in LREE with almost a flat pattern for the HREEs. All samples except one (PMC-06) do not show any anomalies in Eu. The trace elements show patterns consistent with the enrichment in incompatible elements. A small positive anomaly in Pb and negative anomalies in HFSE elements are consistent with the theory of crustal contamination of the parental magma.

2.8 Carbonatites and alkaline silicate rocks from Amba Dongar, Sung Valley and Newania Complexes, India

The samples analysed in the present study from Amba Dongar and Sung Valley carbonatite-alkaline complexes were originally collected by Ray (1997), who had done detailed investigations in these complexes using various geochemical and isotopic techniques and had determined their emplacement ages. The samples from Newania came from the study of Ray et al. (2013), which also have been well characterized geochemically by the authors. A total of twenty two samples of carbonatites and eleven samples of alkaline silicate rocks were analysed by me for their $^{142}\text{Nd}/^{144}\text{Nd}$.

2.8.1 Amba Dongar Carbonatite - Alkaline Complex, Gujarat

The Amba Dongar carbonatite-alkaline complex is part of the Chhota Udaipur alkaline sub-province of the Deccan Flood Basalt Province. Most of the alkaline and carbonatite activities of this sub province have been determined to be coeval (Ray and Pande, 1999; Ray et al., 2006). The entire sub province ($\sim 1200\text{km}^2$) belonged to a single magmatic episode that post-dated main tholeiitic pulse of Deccan flood basalts (Ray et al., 2003). The age of emplacement of this complex is 65.0 ± 0.3 (2σ) Ma which is based on $^{40}\text{Ar}-^{39}\text{Ar}$ dating of a phlogopite from carbonatite and three whole rock alkaline rocks (Ray and Pande, 1999). Works of Ray (1998, 2009) suggest that the carbonate magma and the silicate magma of this complex share a genetic relationship and were generated by liquid immiscibility and the parent magma was crustally contaminated (up to $\sim 4\%$). Since the carbonate rocks did not carry any evidence of crustal contamination, unlike the associated alkaline silicate rocks, the samples were analysed as separate carbonate and silicate fraction for their $^{142}\text{Nd}/^{144}\text{Nd}$.

isotopic composition. The details of the samples analysed in the present study are given in Table 2.7.

2.8.2 Sung Valley Carbonatite - Alkaline Complex, Meghalaya

Sung Valley is located 49 km south of Shillong, Meghalaya. It houses the largest alkaline complex of all the Eastern Indian carbonatite – alkaline complexes (Ray, 1997). The age of emplacement of this complex is reported to be 107.2 ± 0.8 (2 σ) Ma based on $^{40}\text{Ar} - ^{39}\text{Ar}$ dating of three phlogopite separates from carbonatite and one whole rock pyroxenite sample (Ray and Pande, 1999). Based on the Rb-Sr isochron, the age was found to be 106 ± 11 (2 σ) Ma (Ray et al., 2000). This complex consists of a variety of magmatic rocks including alkali pyroxenites and carbonatites. Unlike the Amba Dongar complex, carbonatites in this complex are a minor component. A DUPAL mantle source was suggested for these carbonatites based on the combined Pb, Sr and Nd isotopic study by Veena et al. (1998) which links the complex genetically to the Kerguelen plume. The carbonatites were studied as separate carbonate and silicate fractions for their ^{142}Nd compositions. The details of the samples are given in Table 2.7.

2.8.3 Newania Carbonatite Complex, Rajasthan

This carbonatite complex is unique because it is one of the few known dolomite carbonatites of the world. It is also one of the two carbonatites-only complexes of India, with no trace of alkaline silicate rocks. It occurs around 40 km north-east of Udaipur, Rajasthan. This complex is emplaced into the 2.95 Ga Untala Gneiss of the Aravalli Craton (Choudhary et al., 1984). The age of emplacement of this complex is reported to be 1473 Ma (Sm-Nd) by Ray et al. (2013). These authors also suggest that the primary melt for the complex was derived from a metasomatised subcontinental lithospheric mantle, which could have been a phlogopite bearing mantle located within garnet stability zone. The sample details are given in Table 2.8. It can be seen in Figure 2.16, that whereas the carbonatites from Amba Dongar and Sung Valley fall in the enriched mantle quadrants, the carbonatites from Newania carry signatures of metamorphism and possible derivation from SCLM.

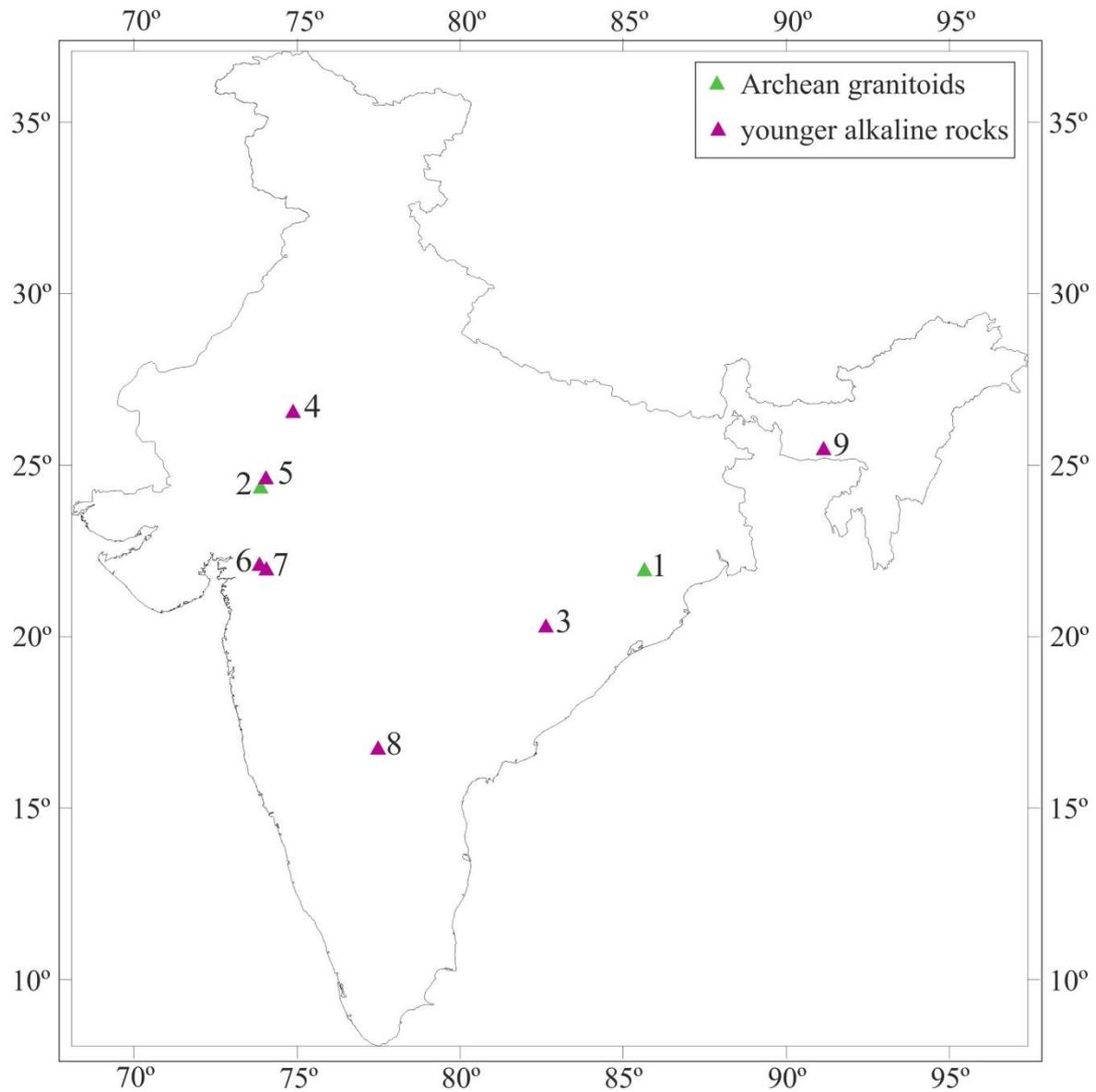


Figure 2.1 Map of India showing general locations of the samples collected for the present study. 1-Singhbhum (3.5 Ga), 2- Banded Gneissic Complex-1 (3.3 Ga), 3-Khariar (1.5 Ga), 4-Kishengarh (1.4 Ga), 5- Newania (1.5 Ga), 6- Phenai Mata (65Ma), 7- Amba Dongar (65 Ma), 8- Eastern Dharwar Craton (1.1 Ga) and 9- Sung Valley (107 Ma).

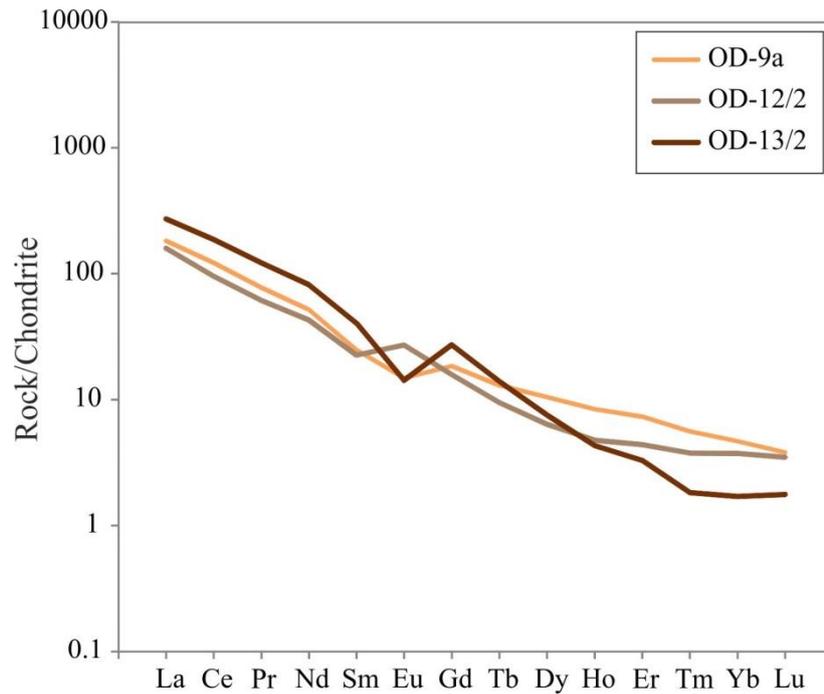


Figure 2.2 Chondrite normalised REE patterns for TTG samples of the Singhbhum Craton. The reference values for chondrite are taken from Mcdonough and Sun (1995).

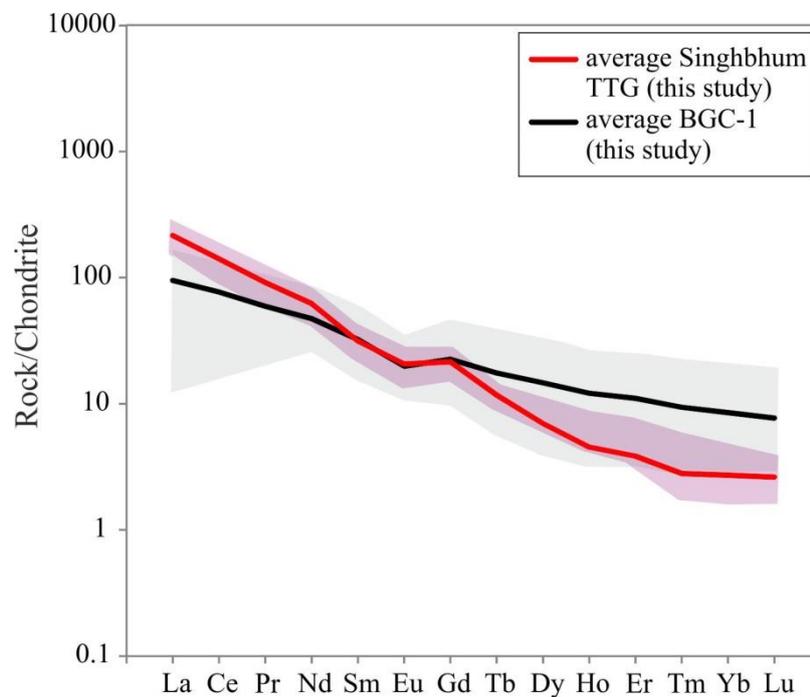


Figure 2.3 A comparison of chondrite normalised REE patterns for granitoids (shaded region) from the Singhbhum Craton and that from the Banded Gneissic Complex-1, Aravalli Craton, analysed in the present study.

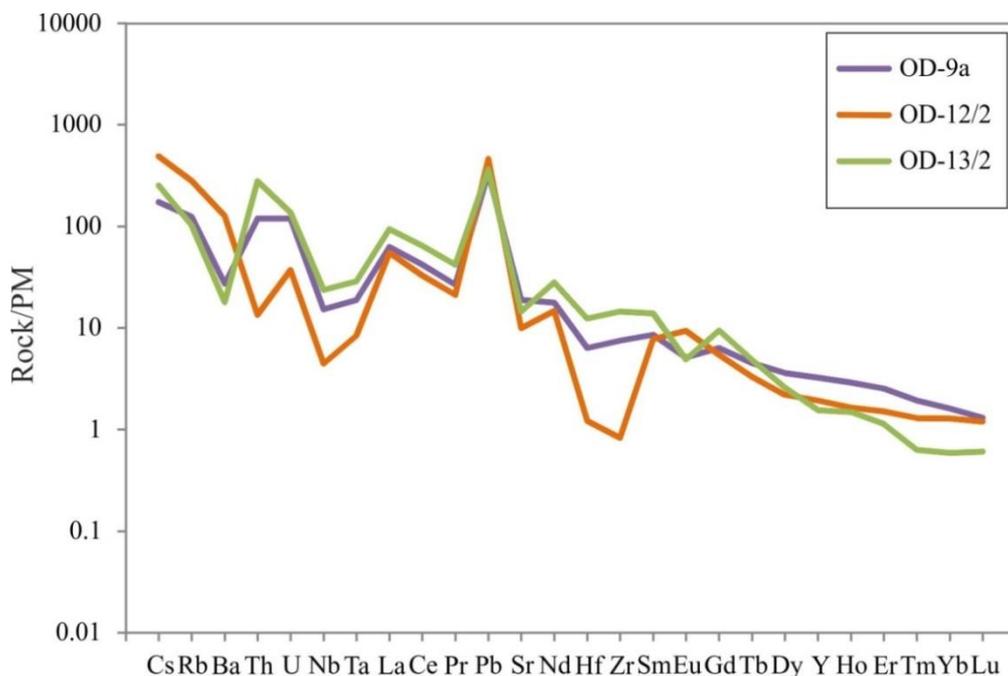


Figure 2.4 Primitive Mantle (PM) normalised multi elements plot for TTG samples from Singhbhum. PM values after Sun and McDonough, (1989).

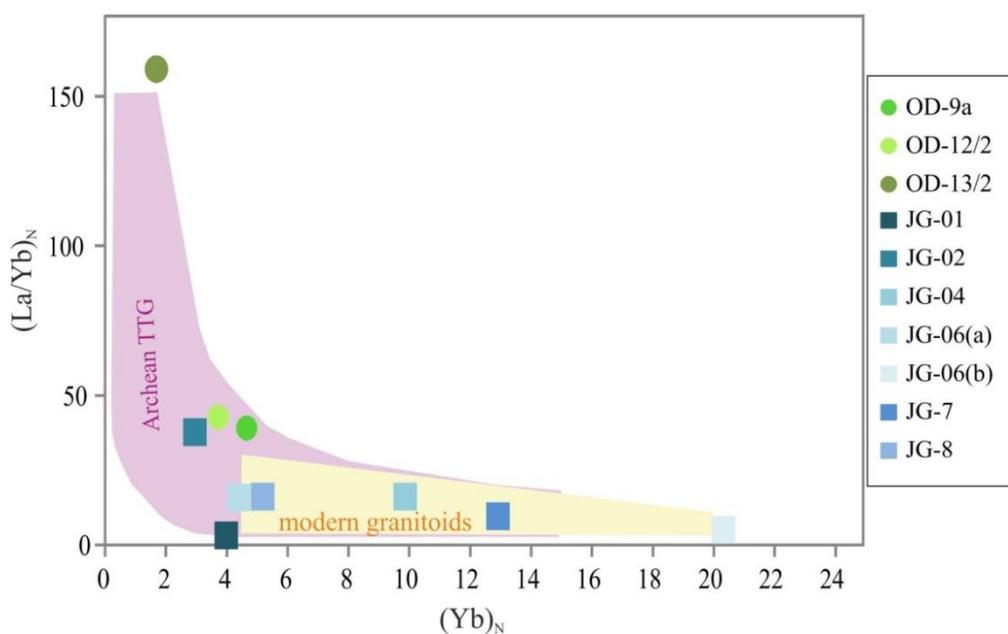


Figure 2.5 $(La/Yb)_N$ Versus $(Yb)_N$ plot of our samples in Hervé Martin diagram (Martin, 1987; Moyen and Martin, 2012). Pink field is for Archean TTGs whereas that in yellow is for the younger granitoids (Post 2.5 Ga granitoids). Primitive Mantle data used for normalization are from Sun and McDonough, (1989).

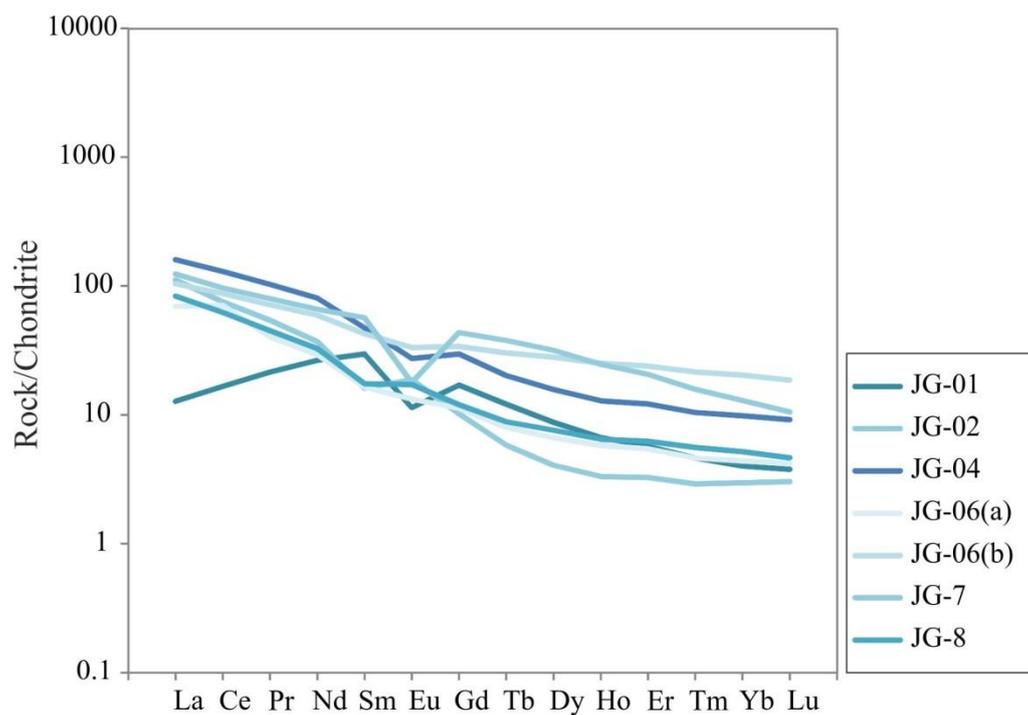


Figure 2.6 Chondrite normalised REE plot for BGC-1 rocks analysed in the present study. Sample details are in Table 2.2.

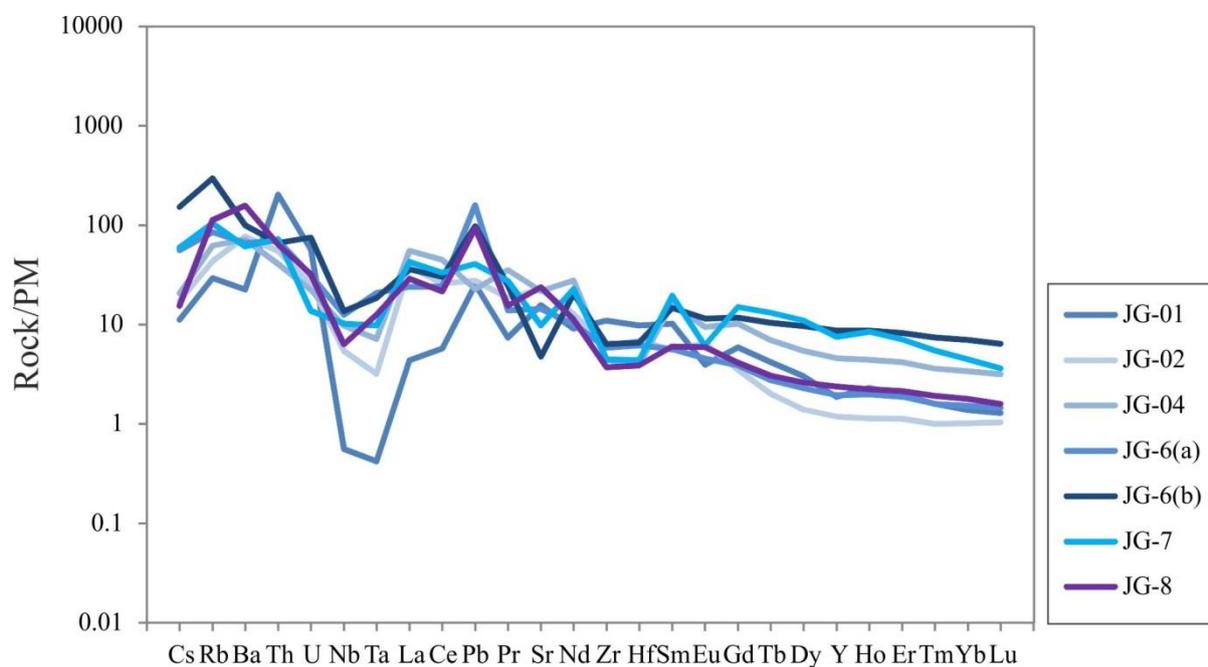


Figure 2.7 Primitive Mantle (PM) normalised multi element plot for samples from BGC-1. Sample details are given in Table 2.2.

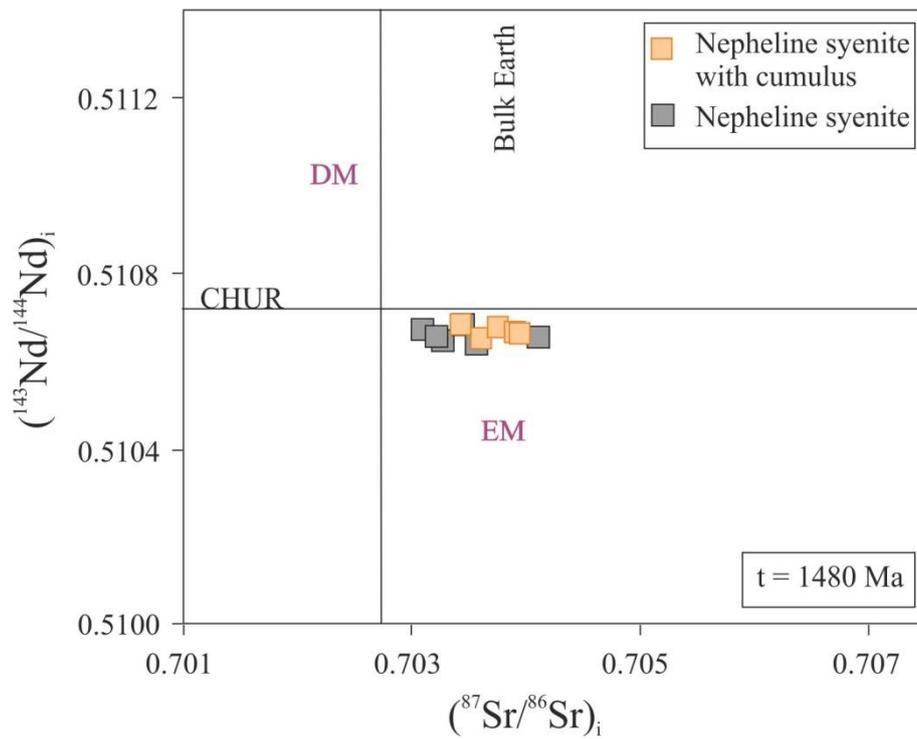


Figure 2.8 Plot of $(^{143}\text{Nd}/^{144}\text{Nd})_i$ versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ for nepheline syenites from Khariar (redrawn from Upadhyay et al. 2006). DM = Depleted Mantle; EM = Enriched Mantle.

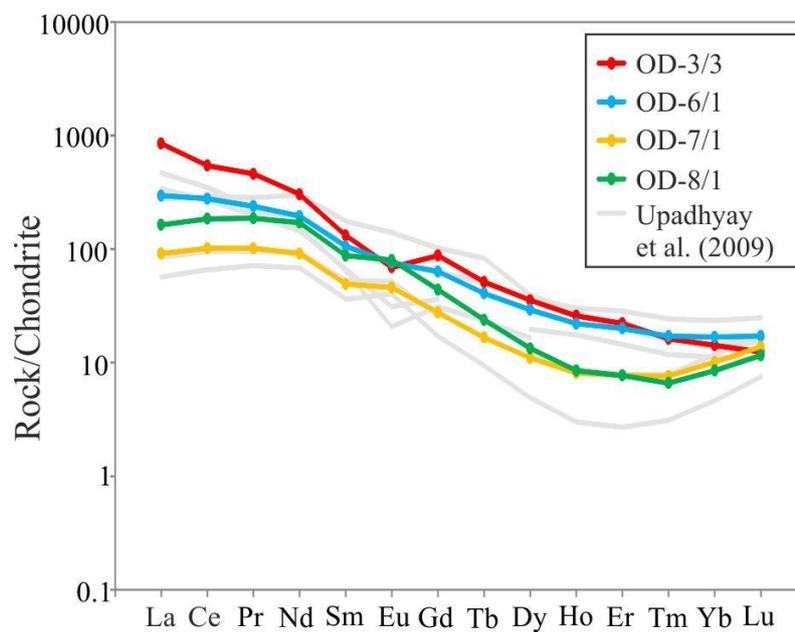


Figure 2.9 Plot of chondrite normalized REE patterns for our alkaline igneous rock samples from Khariar complex.

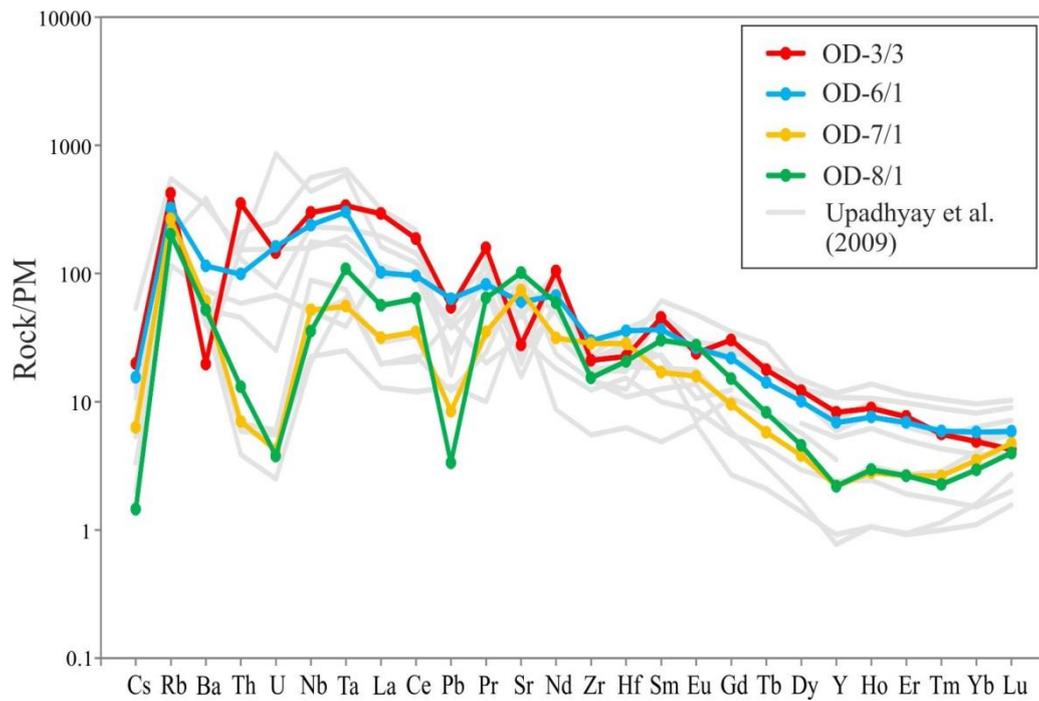


Figure 2.10 Plot of primitive mantle normalised multi-element plot for the alkaline igneous rock samples from Khariar complex.

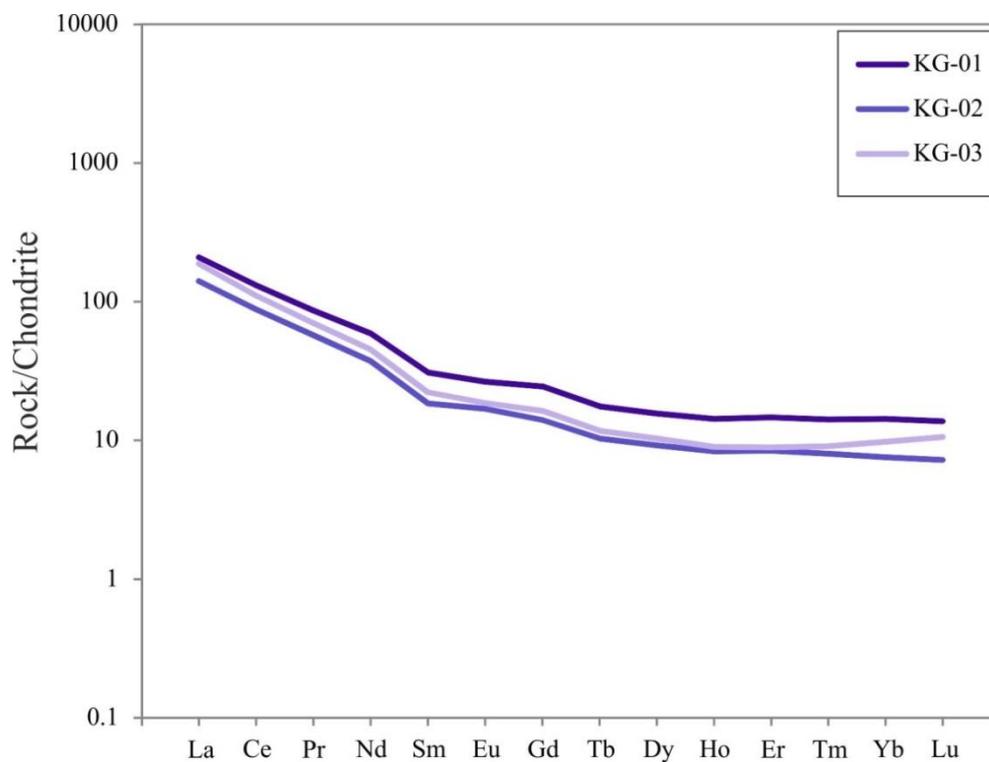


Figure 2.11 Chondrite normalised REE plot for nepheline syenites from Kishengarh.

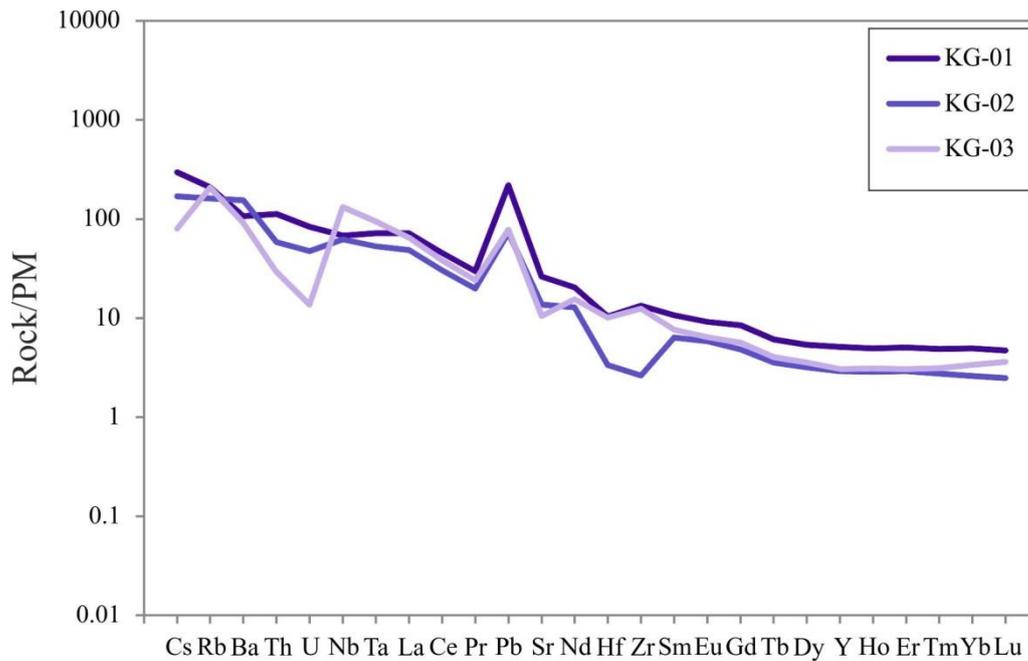


Figure 2.12 Primitive Mantle (PM) normalised trace elements plot for nepheline syenites from Kishengarh.

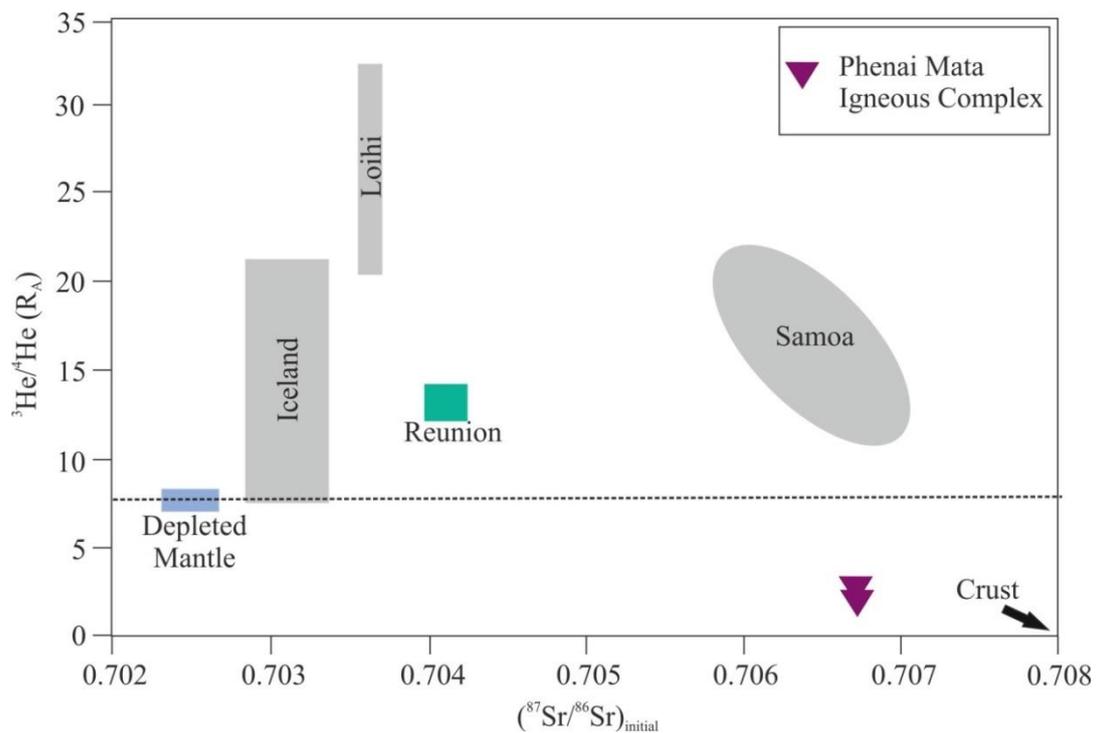


Figure 2.13 Plot re-drawn from Basu et al. (1993) showing He and Sr isotope composition for the pyroxene and olivine mineral separates from the rocks of Phenai Mata Igneous Complex. These rocks fall on a mixing trend between the Reunion hot spot (the plume source of these rocks) and the crust (values from Basu et al., 1993 and the references therein).

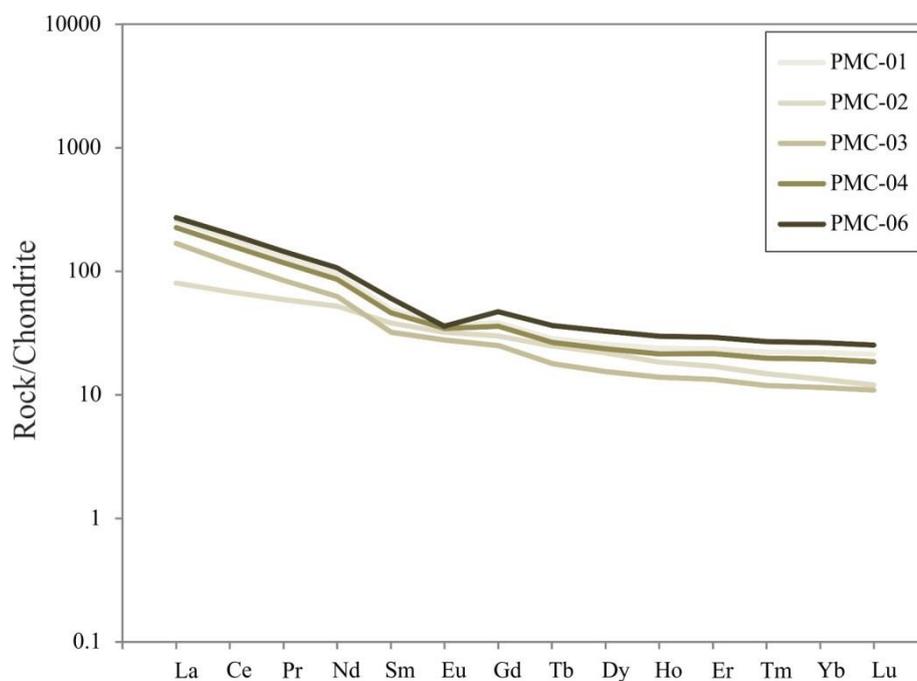


Figure 2.14 Chondrite normalised REE plot for basalts from the Phenai Mata Complex.

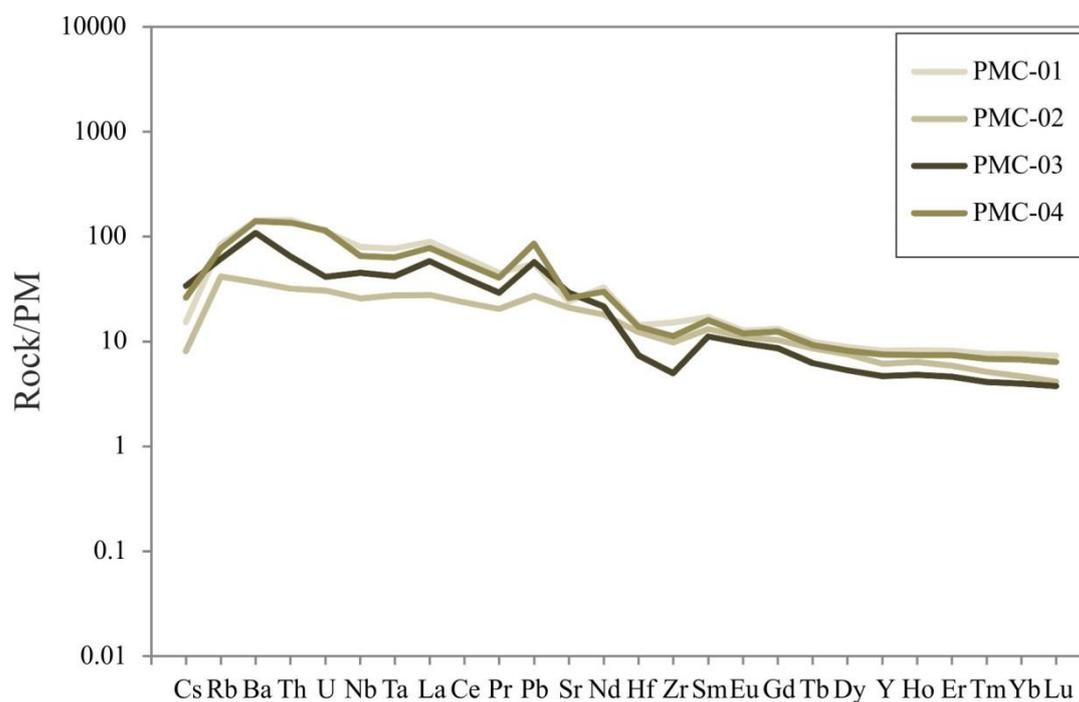


Figure 2.15 Primitive Mantle (PM) normalised trace elements plot for alkali basalts from the Phenai Mata Complex.

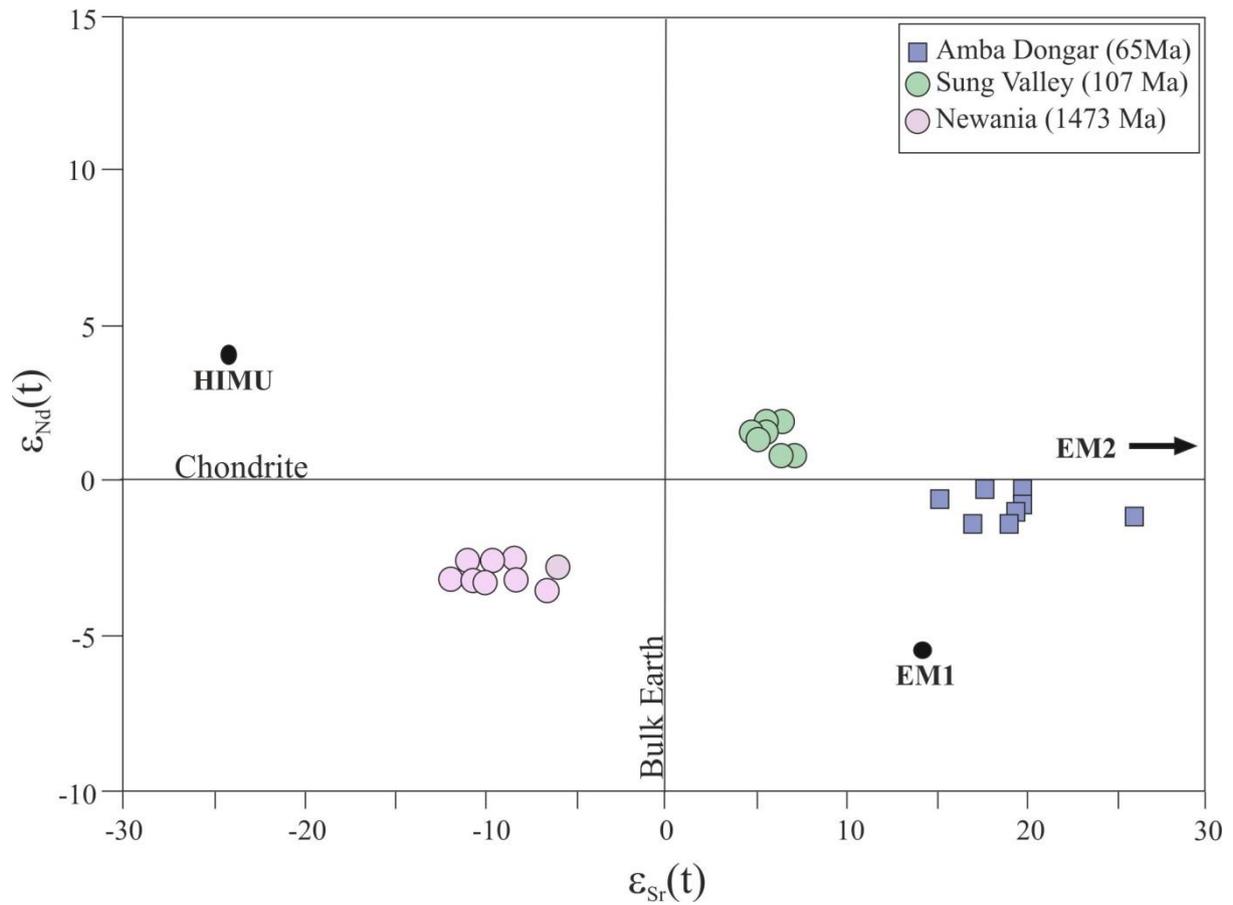


Figure 2.16 Plot of $\epsilon_{Nd}(t)$ versus $\epsilon_{Sr}(t)$ for samples from Amba Dongar, Sung Valley and Newania complexes, with t being the age of emplacement considered to be 65, 107 and 1473 Ma, respectively (re-drawn after Ray et al., 2013). Data as provided in (Ray et al., 2013).

Table 2.1 Details of samples collected from the Singhbhum Craton, Odisha.

Sample ID	GPS location	Rock description
OD-9(a)	N21°58'56.82" E85°38'24.24"	Plagioclase bearing granitoid
OD-12/2	N21°58'33.78" E85°39'07.98"	Trondhjemite
OD-13/2	N21°58'49.06" E85°38'25.02"	Amphibolite

Table 2.2 Details of the granitoids and amphibolites collected from the Aravalli Craton, Rajasthan.

Sample ID	GPS location	Rock description
JG -01	N24°23'11" E73°53'6"	Biotite gneiss
JG -02	N24°23'10" E73°53'7"	Biotite gneiss
JG -03	N24°23'11" E73°53'6"	Amphibolite
JG -04	N24°23'16" E73°53'1"	Biotite gneiss
JG -05	N24°23'54" E73°52'48"	Micaceous gneiss
JG -06(a)	N24°24'36" E73°52'35"	Leucosome from migmatite
JG -06(b)	N24°24'36" E73°52'35"	Melanosome from migmatite
JG -07	N24°26'29" E73°52'20"	Migmatite
JG -08	N24°27'04" E73°52'18"	Feldspar rich granite
JG -09	N24°28'17" E73°51'59"	Garnet bearing amphibolite

Table 2.3 Details of samples collected from Khariar Complex, Odisha.

Sample ID	GPS location	Rock description
OD-3/3	N20°19'44.6" E82°37'51.7"	Nepheline syenite
OD-6/1	N20°17'22.8" E82°38'24.7"	Nepheline syenite
OD-7/1	N20°13'25.9" E82°37'57.2"	Nepheline syenite
OD-8/1	N20°09'38.4" E82°36'55.3"	Nepheline syenite

Table 2.4 Details of samples collected from Kishengarh nepheline syenite plug, Rajasthan.

Sample ID	GPS location	Rock description
KG-01	N26°35'9" E74°53'4"	Nepheline syenite

Table 2.5 Details of the Kimberlite samples from the Eastern Dharwar Craton.

Sample ID	GPS location	Rock description
SK-1	N16°19'89" E77°55'43"	Kimberlite with macrocrysts of olivine, mica and crustal xenoliths
P-7	N14°56'00" E77°22'30"	Kimberlite emplaced as dyke in fault in the metabasalts

NK-1	N16°46'03" E77°29'08"	Kimberlite – north of Narayanpet cluster
KK-1	N16°46'05" E77°40'08"	Kimberlite – NE of Kotakonda
CC-5	N14°31'00" E77°38'00"	Kimberlite – crustal xenoliths are common

Table 2.6 Details of samples collected from the Phenai Mata Complex, Gujarat

Sample ID	GPS location	Rock description
PMC-2	N22°07'43" E73°50'52"	Olivine bearing basalt
PMC-3	N22°07'44.63" E73°50'57.68"	Olivine basalt

Table 2.7 Details of the samples from Amba Dongar and Sung Valley carbonatite-alkaline complexes.

Sample ID	Description
Amba Dongar	
AD 1	Medium grained calcite carbonatite (collected from a small dyke)
AD 8-1	Medium grained calcite carbonatite collected from fluorite mine
AD 10-1	Very coarse grained monomineralic calcite carbonatites
AD 13-1	Fine grained calcite carbonatites
AD 14	Nephelinite from the base of the main dome
AD 16	Nephelinite (groundmass does not contain calcite)
AD 17	Nephelinite from Khadla village
AD 21	Banded (gray and red) calcite carbonatites
AD 38	Monomineralic coarse grained calcite carbonatites
AD 45	Calcite bearing tinguaitite (from mine)
AD 47	Calcite bearing tinguaitite
AD 48	Carbonatite(?) (from mine)
AD 54	Coarse grained calcite carbonatites
AD 65	Phonolite
AD 66	Nephelinite
AD 67	Nephelinitic tuff
AD 69	Phonolite
AD 72	Alkaline silicate
Sung Valley	
SV 1	Medium grained dolomite bearing calcite carbonatites
SV 4	Very coarse grained pyroxenite
SV 5	Phlogopite bearing calcite carbonatites
SV 6	Apatite rich calcite carbonatites
SV 10	Apatite rich calcite carbonatites
SV 13	Dolomite bearing calcite carbonatites
SV 18	Dolomite bearing calcite carbonatites
SV 19	Olivine rich, dolomite bearing calcite carbonatites

Table 2.8 Details of the samples from the Newania, dolomite carbonatites, Rajasthan

Sample ID	GPS location	Description
NW-3	N24°39.050' E 74°03.461'	Ankeritic carbonatites
NW-5	N24°38.742' E 74°03.970'	Dolomitic carbonatites
NW-7	N24°38.417' E 74°04.585'	Fine dolomitic carbonatites
NW-8	N24°38.458' E 74°04.488'	Carbonatite
NW-17	N24°38.271' E 74°04.861'	Slightly altered carbonatites
NW-25(a)	N24°38.377' E 74°04.505'	Carbonatite vein (and underlying host rock)
NW-29	N24°38.379' E 74°04.465'	Dolomitic carbonatite

Table 2.9 Trace element concentrations of TTGs from Singhbhum, Odisha

Element	OD-9a (ppm)	OD-12/2 (ppm)	OD-13/2 (ppm)	BHVO-2 Measured (ppm)	BHVO-2 Reported* (2SD) (ppm)	AGV-2 Measured (ppm)	BCR-2 Measured (ppm)
Cs	1.39	3.90	2.02	0.11	0.1 (0.02)	1.20	1.23
Rb	78.75	177.60	64.62	9.42	9.11 (0.08)	67.55	50.10
Ba	190.00	884.10	124.70	135.40	131 (2)	1132.00	692.30
Th	10.16	1.14	23.63	1.21	1.22 (0.12)	5.77	5.69
U	2.51	0.78	2.87	0.40	0.403 (0.002)	1.70	1.57
Nb	10.86	3.16	16.80	18.37	18.1 (2)	14.82	13.81
Ta	0.77	0.34	1.18	1.15	1.14 (0.12)	0.79	0.72
La	43.08	37.70	64.31	15.72	15.2 (0.2)	37.16	25.03
Ce	74.57	58.29	114.30	38.59	37.5 (0.4)	67.10	52.37
Pr	7.36	5.81	11.57	5.51	5.35 (0.34)	7.97	6.89
Pb	23.67	32.92	25.62	1.63	1.6 (0.6)	12.51	10.91
Sr	399.20	209.90	306.10	401.60	396 (2)	641.80	437.20
Nd	24.11	19.93	38.13	25.27	24.5 (0.2)	29.78	28.89
Hf	1.95	0.38	3.81	4.41	4.36 (0.28)	4.81	4.71
Zr	83.89	9.26	162.30	177.50	172 (22)	230.60	194.10
Sm	3.79	3.44	6.17	6.11	6.07 (0.02)	5.35	6.66
Eu	0.86	1.57	0.82	2.11	2.07 (0.004)	1.65	2.10
Gd	3.78	3.25	5.60	6.28	6.24 (0.06)	4.97	7.01
Tb	0.49	0.35	0.52	0.94	0.92 (0.06)	0.62	1.04
Dy	2.65	1.62	1.92	5.44	5.31 (0.04)	3.37	6.44
Y	14.78	8.73	7.05	26.85	26 (4)	21.29	43.81
Ho	0.47	0.27	0.24	1.00	0.98 (0.08)	0.63	1.28
Er	1.21	0.73	0.54	2.62	2.54 (0.02)	1.76	3.66
Tm	0.14	0.10	0.05	0.34	0.33 (0.02)	0.24	0.52
Yb	0.79	0.63	0.29	2.07	2 (0.02)	1.57	3.37
Lu	0.10	0.09	0.04	0.28	0.274 (0.01)	0.23	0.48

* After Jocum et al. (2005). The associated 2SD is given in brackets.

Table 2.10 Trace element concentrations of granitoids from the Banded Gneissic Complex-1, Rajasthan

Element	JG-01 (ppm)	JG-02 (ppm)	JG-04 (ppm)	JG-6(a) (ppm)	JG-6(b) (ppm)	JG-7 (ppm)	JG-8 (ppm)
Cs	0.36	0.55	0.65	1.8	4.87	1.9	0.49
Rb	18.52	27.4	39.39	54.07	187.9	65.85	71.03
Ba	157.1	535	497.2	461.5	697.4	425.6	1098
Th	17.29	4.66	3.45	5.94	5.6	6.14	5.37
U	1.19	0.53	0.47	0.65	1.57	0.29	0.67
Nb	0.4	3.85	6.95	8.93	9.66	7.27	4.5
Ta	0.02	0.13	0.29	0.85	0.76	0.4	0.52
La	3.01	26.42	37.75	16.46	24.6	29.3	19.76
Ce	10.14	45.98	79.2	43.12	53.34	59	38.14
Pr	4.68	5.11	4.19	29.44	18.05	7.52	17.32
Pb	2.03	5.14	9.74	3.82	6.76	7.57	4.26
Sr	328.9	472.3	456.9	302.4	100.1	206.3	499.9
Nd	12.32	17.25	37.56	13.67	27.7	30.77	15.22
Hf	122.9	67.78	49.69	65.67	71.39	49.86	41.72
Zr	3.03	2.12	1.23	1.91	2.04	1.35	1.2
Sm	4.53	2.46	7.23	2.51	6.49	8.65	2.67
Eu	0.66	1.08	1.59	0.77	1.93	1.03	1
Gd	3.5	2.09	6.1	2.31	6.97	8.91	2.46
Tb	0.45	0.22	0.75	0.3	1.13	1.41	0.33
Dy	2.22	1.03	3.98	1.68	7.11	8.05	1.92
Y	8.5	5.4	20.79	8.84	39.63	34.27	10.84
Ho	0.38	0.19	0.73	0.33	1.42	1.39	0.37
Er	0.94	0.54	2.01	0.9	3.96	3.4	1.03
Tm	0.12	0.07	0.27	0.12	0.55	0.4	0.14
Yb	0.68	0.5	1.68	0.75	3.45	2.2	0.88
Lu	0.1	0.08	0.23	0.11	0.47	0.27	0.12

Table 2.11 Trace element concentrations of alkaline rocks (nepheline syenites) from Khariar alkaline complex.

Element	OD-01 (ppm)	OD-02 (ppm)	OD-3/1 (ppm)	OD-3/2 (ppm)	OD-3/3 (ppm)	OD-4/1 (ppm)	OD-4/2 (ppm)	OD-05 (ppm)
Cs	0.01	0.03	0.84	1.66	0.63	0.19	0.28	0.64
Rb	2.29	5.60	268.10	393.30	266.80	74.90	76.34	161.70
Ba	43.12	116.30	1271.00	1667.00	137.20	2496.00	2398.00	637.70
Th	0.20	0.51	20.96	6.20	29.79	5.99	12.62	25.83
U	0.04	0.10	5.61	1.60	3.05	0.74	0.94	2.96
Nb	4.86	6.49	274.30	47.08	212.70	7.36	14.43	62.69
Ta	0.29	0.40	13.55	3.15	13.82	0.23	0.45	2.84
La	4.14	6.24	144.50	57.18	200.70	27.61	49.14	182.50
Ce	10.26	14.61	293.30	110.70	331.80	48.20	97.34	294.40
Pr	1.57	2.13	33.07	12.41	43.58	5.36	11.97	32.21
Pb	3.03	4.24	8.16	8.22	10.06	14.75	13.03	22.56
Sr	160.70	210.20	1401.00	2064.00	584.50	1116.00	672.10	699.40
Nd	7.60	9.82	117.70	44.36	141.60	19.18	47.63	124.60
Hf	0.93	0.97	13.32	3.93	6.97	1.00	0.79	4.19
Zr	25.54	21.72	375.50	131.50	235.50	31.92	27.30	149.90
Sm	2.34	2.68	20.81	6.84	20.13	3.14	10.10	16.96
Eu	0.91	0.97	1.72	1.88	4.00	1.80	2.90	3.17
Gd	3.04	3.21	18.93	6.25	18.00	2.75	9.48	15.30

Tb	0.54	0.55	2.33	0.71	1.91	0.31	1.28	1.53
Dy	3.81	3.65	11.90	3.63	8.96	1.51	7.02	6.80
Y	22.95	21.03	50.18	18.49	37.52	7.88	36.35	26.63
Ho	0.82	0.77	2.01	0.65	1.46	0.27	1.26	1.09
Er	2.38	2.20	5.02	1.77	3.68	0.73	3.23	2.72
Tm	0.35	0.32	0.61	0.23	0.41	0.09	0.41	0.29
Yb	2.31	2.09	3.91	1.34	2.41	0.59	2.39	1.79
Lu	0.34	0.30	0.60	0.17	0.31	0.08	0.31	0.26

Table 2.11 (contd.) Trace element concentrations of alkaline rocks (nepheline syenites) from Khariar alkaline complex.

Element	OD-6/1 (ppm)	OD-6/2 (ppm)	OD-6/3 (ppm)	OD-6/4 (ppm)	OD-7/1 (ppm)	OD-7/2 (ppm)	OD-8/1 (ppm)	OD-8/4 (ppm)	OD-8/5 (ppm)
Cs	0.49	0.23	0.56	0.49	0.20	0.18	0.05	0.04	0.11
Rb	204.90	103.50	63.82	181.50	168.50	240.00	127.80	101.50	138.00
Ba	800.40	217.30	134.30	771.40	425.30	252.10	362.90	310.70	238.30
Th	8.41	10.04	3.24	3.69	0.59	0.05	1.11	0.62	0.70
U	3.40	1.16	1.12	0.49	0.09	0.02	0.08	0.04	0.08
Nb	169.50	361.20	10.98	49.05	37.01	52.48	25.22	31.90	12.44
Ta	12.34	29.93	0.73	2.99	2.28	2.25	4.44	6.48	0.89
La	69.95	122.30	10.67	37.31	21.62	8.39	38.66	34.76	13.78
Ce	169.90	325.10	22.26	104.40	62.08	24.79	112.90	103.70	32.02
Pr	22.62	42.99	2.80	16.05	9.64	3.91	17.70	16.31	4.47
Pb	11.73	5.50	8.03	6.16	1.56	1.14	0.62	0.31	1.61
Sr	1267.00	501.50	318.90	1424.00	1560.00	882.70	2138.00	2388.00	1475.00
Nd	91.02	171.50	11.27	72.15	42.51	17.12	79.88	73.11	18.96
Hf	11.02	35.89	1.49	9.32	8.80	6.83	6.37	6.86	1.80
Zr	334.20	914.90	57.09	305.70	317.60	220.50	171.50	185.90	50.79
Sm	16.21	30.78	2.46	13.29	7.52	3.22	13.35	12.02	3.27
Eu	4.40	6.09	0.97	4.15	2.65	1.44	4.63	4.11	1.94
Gd	13.01	26.46	2.58	10.20	5.68	2.40	9.01	8.01	2.41
Tb	1.52	3.36	0.39	1.13	0.62	0.27	0.89	0.79	0.26
Dy	7.41	17.91	2.40	4.98	2.80	1.25	3.37	3.00	1.14
Y	31.33	80.80	13.40	18.23	9.97	4.18	9.95	8.84	4.44
Ho	1.24	3.27	0.48	0.81	0.46	0.20	0.48	0.44	0.19
Er	3.30	8.94	1.35	2.11	1.27	0.52	1.27	1.18	0.51
Tm	0.44	1.22	0.19	0.30	0.19	0.07	0.17	0.17	0.07
Yb	2.86	8.34	1.26	2.38	1.72	0.61	1.45	1.55	0.61
Lu	0.43	1.32	0.18	0.44	0.35	0.13	0.29	0.31	0.12

Table 2.12 Trace element concentrations of Nepheline syenites from Kishengarh, Rajasthan.

Element	KG-X (ppm)	KG-01 (ppm)	KG-02 (ppm)	KG-03 (ppm)
Cs	1.23	2.37	1.35	0.64
Rb	110.90	132.60	102.30	131.60
Ba	291.60	745.30	1080.00	638.80
Th	3.57	9.54	4.96	2.48
U	0.82	1.75	0.99	0.29

Nb	45.84	48.51	44.11	93.78
Ta	2.19	2.94	2.16	3.88
La	24.99	49.42	33.39	44.44
Ce	45.62	80.23	53.92	67.61
Pr	4.98	8.21	5.45	6.66
Pb	9.45	15.60	5.12	5.53
Sr	68.34	551.70	288.70	220.90
Nd	16.91	27.59	17.39	21.07
Hf	0.37	3.19	1.04	3.12
Zr	10.10	148.70	29.35	138.80
Sm	2.77	4.73	2.83	3.39
Eu	0.61	1.53	0.98	1.08
Gd	2.75	5.04	2.87	3.36
Tb	0.38	0.66	0.39	0.44
Dy	2.20	3.97	2.34	2.63
Y	12.29	23.33	13.25	13.92
Ho	0.44	0.81	0.47	0.51
Er	1.30	2.43	1.40	1.47
Tm	0.19	0.36	0.20	0.23
Yb	1.31	2.43	1.28	1.66
Lu	0.19	0.35	0.18	0.27

Table 2.13 Trace element concentrations of alkali basalts from Phenai Mata Complex, Gujarat.

Element	PMC-01 (ppm)	PMC-02 (ppm)	PMC-03 (ppm)	PMC-04 (ppm)	PMC-06 (ppm)
Cs	0.12	0.06	0.27	0.21	1.61
Rb	53.71	26.38	39.00	49.08	113.70
Ba	992.00	256.10	756.50	979.80	839.70
Th	12.26	2.71	5.50	11.49	18.90
U	2.33	0.64	0.87	2.39	4.01
Nb	56.81	18.31	32.23	46.78	34.48
Ta	3.14	1.13	1.71	2.60	1.98
La	61.13	19.01	39.92	53.49	64.54
Ce	112.30	41.65	71.93	99.39	122.30
Pr	12.41	5.61	8.02	11.16	13.76
Pb	3.91	1.92	4.05	6.08	16.99
Sr	507.00	441.80	612.60	546.60	345.50
Nd	44.19	24.36	29.14	40.23	49.93
Hf	4.44	3.77	2.27	4.25	5.89
Zr	169.20	109.30	55.81	125.70	227.20
Sm	7.55	5.84	4.93	7.05	9.25
Eu	2.13	1.86	1.61	2.00	2.09
Gd	7.88	6.15	5.15	7.39	9.69
Tb	1.07	0.93	0.67	1.00	1.37
Dy	6.54	5.57	3.92	6.01	8.35
Y	37.23	27.93	21.32	34.12	47.71
Ho	1.35	1.04	0.79	1.22	1.69
Er	3.92	2.82	2.22	3.57	4.84
Tm	0.57	0.38	0.30	0.51	0.69
Yb	3.74	2.29	1.96	3.32	4.50
Lu	0.54	0.31	0.28	0.47	0.64