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Mineralogy and geochemistry of nephelinite–phonolite occurrences from Barmer region, Rajasthan, India

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ABSTRACT

In Barmer alkaline complex, Rajasthan, melanephelinites are closely associated with two types of phonolites. Details of petrography, mineralogy and geochemistry are presented. Based on the trends defined by the major and trace element data, it seems highly unlikely that the origin of the phonolites from the Sarnu–Dandali region may be attributed to differentiation of a closed magma system. The contamination by crustal components is evident from the number of xenoliths in all alkaline rocks of this area. Without the data on radiogenic isotope, it is very difficult to test models involving phonolite magma derivation exclusively either by low-pressure crystal fractionation of a parental, mantle-derived melanephelinitic magma, or crustal contamination of a melanephelinitic melt undergoing crystal fractionation.

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1. Introduction and General Geology

Rocks of nephelinite-phonolite association occur in Barmer at Sarnu, Dandali and Kamthai (Rajasthan). In addition, similar nephelinite-phonolite rocks are exposed in Chhota Udaipur carbonatite-alkaline rocks sub province. A minor occurrence is exposed along the coastal areas of Maharashtra in Murud–Janjira. The occurrence of alkaline rocks at Sarnu–Dandali was first reported by Udas et al. (1978) and later described by Narayan Das et al. (1978). This was followed by Chawade and Chandrasekaran (1984). Later, geochemistry for various alkaline silicate rocks was described by Chandrasekaran et al. (1990) and Shastri and Kumar (1996). Recently, Viladkar and Zaitsev (2011), Viladkar (2012) studied the pyroxenes from alkaline rocks and petrological problems in Barmer respectively. These rocks have been dated as 68.5 Ma by Basu et al. (1993).

The rocks studied in detail here comprise mainly three types: Melanephelinites, melaphonolites and felsic phonolites. Melanephelinite occurs as small plugs proximal to Barmer and Sarnu Village (Fig. 1A and 1B). Melaphonolite occurs as an isolated small plug (up to 20 m across) near Dandali. In addition, dikes (Fig. 1C and D) of melaphonolite are dispersed in the same area near Dandali. These dikes strike practically East–West. The melaphonolite exposure in the plug is zoned with melanocratic part on the periphery and more felsic towards its center. Both melanephelinite and melaphonolite contain mafic xenoliths composed essentially of pyroxene and small amount of olivine. Felsic phonolites form small and large dikes that contain xenoliths of both melanephelinite and melaphonolite (Fig. 1E, F, G, and H) and also of metamorphic basement. Thin veins consisting mainly of K-feldspar invade the felsic phonolites. The contact between melaphonolite and felsic phonolite is usually sharp; the latter intrude the former in the form of thin dikes.

Rhyolitic lava and tuff of the Malani series (ca 745 Ma old) cover a significant portion of the area, and these are overlain by sediments of lower Cretaceous age (ca 120 Ma). At various locations, field relations show that melanephelinite and associated phonolite intrude both the Precambrian Malani series and the Cretaceous sediments. Carbonatite, alvikite and ankeritic carbonatite occur as small, thin dikes

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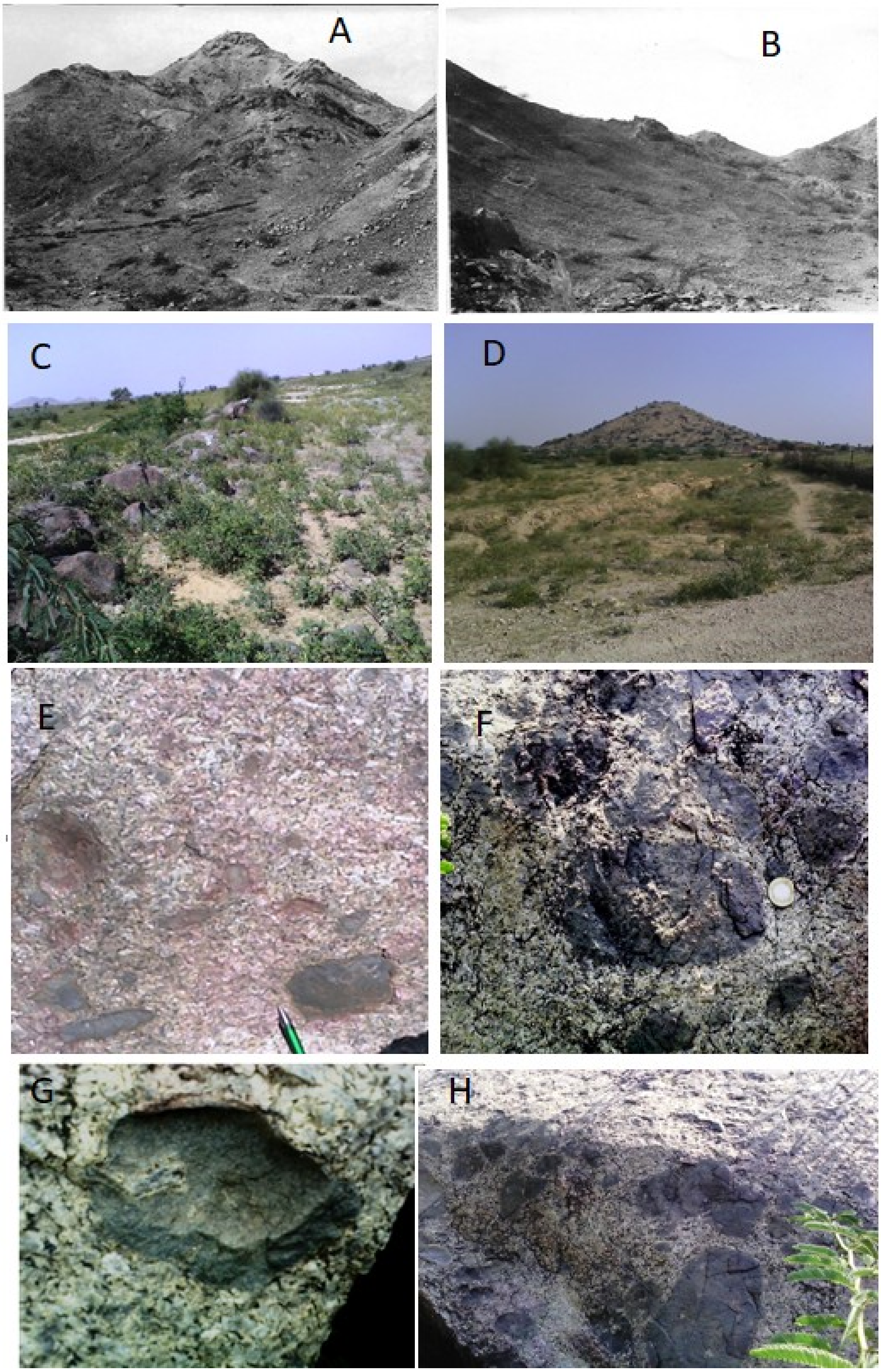

Fig. 1. A and B Melanephelinite plugs close to Barmer on way to Sarnu. C and D- Melaphonolite dike and plug near Dandali. E, F and H are xenoliths of melanephelinite in felsic phonolites, G. Xenolith of melaphonolite in felsic phonolite.

(usually from 10 to 30 cm) within nephelinite or phonolite, and vary in length from 5cm to >1 meter at Kamthai. However, carbonatite is not the subject of this paper.

This communication intends to provide a detailed account of the mineralogy and geochemistry of melanephelinite, melaphonolite and felsic phonolite occurrences found within the Sarnu–Dandali area and discuss the possible origin of this suit of alkaline rocks.

2. Petrography

2.1. Melanephelinite

In general, melanephelinite is fine-grained, microporphyritic rock that contains strongly zoned phenocrysts of clinopyroxene and rounded olivine grains. Clinopyroxene may also form glomeroporphyritic clusters. Olivine phenocrysts (Fo_{80}) commonly exhibit resorption or are mantled by clinopyroxene. Titaniferous magnetite is abundant in all thin sections examined, either as skeletal grains or surrounding clinopyroxene phenocrysts. The groundmass consists predominantly of second generation clinopyroxene as tiny elongated laths. Nepheline occurs as interstitial mineral. A small amount of brown glass (around 5 modals %) is present in some samples. On the basis of its pyroxene-rich nature, the rock may be termed a pyroxene-melanephelinite according to the classification from Le Bas (1989).

2.2. Melaphonolite

On the basis of texture, mineralogy and geochemistry phonolites have been divided into two types. **Type I- Melaphonolite** is strongly porphyritic and contain a high content of mafic minerals as compared to the **felsic phonolite.** Phenocrysts present in order of decreasing abundance are clinopyroxene, nepheline and sanidine. Titaniferous magnetite occurs sparingly in some samples. Clinopyroxene phenocrysts are zoned, having diopsidic cores and aegirine augite-rich rims. The groundmass consists mainly of feldspar with a minor amount of analcime and tiny aegirine needles.

In contrast, **type II- Felsic phonolite** is leucocratic, at times aphyric (glassy), but in some thin sections it exhibits a trachytic texture (alignment of feldspar laths enclosed by euhedral nepheline). Along with sanidine laths it contains tiny nepheline grains and strongly pleochroic aegirine laths that vary in proportion. Nepheline occasionally forms pools of tiny granules surrounded by feldspar. In some samples, strongly pleochroic biotite (deep brown to pale-brown) occurs as small flakes. Sodalite and apatite are common accessory minerals.

3. Mineral chemistry

3.1. Analytical procedure

Minerals were analysed on the Joel Superprobe JXA-8200 microprobe with accelerating voltage of 15 kV and beam current 10 nA, at the Max Planck Institute for Chemistry, section geochemistry, Mainz, Germany. Major and trace elements were analyzed on XRF and AAS at the Mineralogisch-Petrographisches Institute der Universität Freiburg im Breisgau, Germany when the author was a AvH fellow in 1980. Analytical data (Major, trace and REE) on four samples (2BAR, 9BAR, 12BAR and 13BAR) was obtained from Professor Mukul Sharma, Department of Earth Sciences, Dartmouth University, U.S.A.

3.2. Olivine

Olivine is present only in melanephelinite and all analyzed grains show uniform composition of $\sim Fo_{80}$ (Table 1). Such composition of olivine seems to be common from nephelinite rocks of some other complexes for example, Napak volcano, Uganda (Simonetti and Bell, 1994).

Table 1. Analyses of olivine from nephelinite.

Analysis wt%	1	2	3	4
SiO_2	38.92	38.88	39.2	39.15
TiO_2	0	0	0.08	0.02
FeO	18.03	18.5	16.4	16.52
MnO	0.24	0.15	0.36	0.15
MgO	41.95	41.6	43.3	43.3
CaO	0.28	0.33	0.49	0.24
Cr_2O_3	0.03	0.09	0.06	0
Total	99.45	99.55	99.89	98.38
Formula Proportions Based On 3 Cations and 4 Oxygen Atoms				
Si	0.996	0.996	0.993	0.005
Ti	0	0	0.002	0.001
Fe	0.384	0.395	0.346	0.349
Mn	0.003	0.003	0.007	0.003
Mg	1.611	1.599	1.645	1.651
Ca	0.007	0.009	0.013	0.006
Mg#*	80	80.2	82	82.37

3.3. Clinopyroxene

Representative analyses of clinopyroxene from melanephelinite and phonolite are given in Table 3,

Table 2. Composition of nepheline from melanephelinite and phonolites*.

Analysis (wt%)	1	2	3	4	5	6
SiO_2	44.46	43.41	45.65	44.36	48	47.3
Al_2O_3	32.9	33.27	32.55	33.01	31.17	30
FeO	0.28	0.81	0	0	0	0
CaO	2.82	0.53	0.14	0.14	0.64	0.18
Na_2O	14.08	13.86	16.09	15.85	16.64	18.54
K_2O	5.13	8.65	4.9	6.14	3.96	3.7
Total	99.67	100.53	99.33	99.5	100.41	99.72
Formula Proportions Based on 32 Oxygen Atoms						
Si	8.508	8.443	8.713	8.54	9.018	9.008
Al	7.417	7.5	7.305	7.465	6.898	6.722
Fe^{3+}	0.046	0.057				
Fe^{2+}	0	0.07	0	0	0	0
Ca	0.574	0.104	0.034	0.023	1.24	0.034
Na	5.213	5.153	5.954	5.893	6.042	6.836
K	1.263	2.117	1.191	1.502	0.947	0.891

Analyses No. 1 and 2 are from melanephelinite, 3-melaphonolite, 4,5 and 6 from felsic phonolite.

Table 3. Clinopyroxenes from melanephelinites of Barmer.

Analysis (wt%)	1	2	3	3	4
SiO_2	46.8	45.81	47.34	45.65	48.56
TiO_2	3.45	3.56	2.77	3.75	1.9
Al_2O_3	6.4	7.08	5.52	7.05	5.81
Cr_2O_3	0	0.06	0.06	0.1	0.42
FeO	6.85	6.64	6.76	6.85	6.78
MnO	0.11	0.03	0.02	0.05	0.16
MgO	12.95	12.67	13.77	12.62	13.8
CaO	23.32	23.28	23.4	23.34	22.17
Na_2O	0.54	0.69	0.31	0.55	0.65
Total	99.88	99.82	99.95	99.96	100.25
Formula Proportions Based On 4 Cations and 6 Oxygen Atoms					
Si	1.732	1.703	1.757	1.7	1.795
Aliv	0.268	0.297	0.241	0.3	0.205
Alvi	0.011	0.013		0.009	0.048
Ti	0.096	0.1	0.077	0.105	0.053
Fe^{3+}	0.039	0.05	0.02	0.04	0.047
Fe^{2+}	0.173	0.157	0.187	0.174	0.163
Mn	0.003	0.001	0.001	0.002	0.005
Mg	0.714	0.702	0.762	0.7	0.76
Ca	0.925	0.927	0.93	0.931	0.878
Na	0.039	0.05	0.022	0.04	0.047
Mg#*	76.8	77.1	78.3	76.4	77.9

Mg# = 100*(molar Mg/(molar Mg + molar Fe)). An equivalent proportion combined with Na as aegirine Fe^{3+} was calculated from total iron with the remaining iron calculated as Fe^{2+}.

4, 5. Clinopyroxene from melanephelinite is titaniferous diopside (TiO_2 up to 4.25 wt %) with a considerable amount of ^{iv}Al. The absence of ^{vi}Al suggests crystallization at low pressure, a common feature of clinopyroxene from basic, alkaline silicate rocks (e.g., Wass, 1979; Meyer and Mitchell, 1988; Simonetti et al., 1996). In a back scattered image of pyroxene phenocrysts in melanephelinite shows uniform Mg-rich, Ca-poor core (Fig. 2a). It is surrounded by nepheline along the crystal margin. Ti-rich magnetite occurs abundantly in the groundmass. In zoned clinopyroxenes from melanephelinite, both Al and Ti contents show an increase from core-to-rim (Fig. 2d). In the same BSE abundant Ti-magnetite is seen in the groundmass. Compared to the composition of clinopyroxene from melanephelinite, those from melaphonolite show an increase in Fe and Na contents over Mg and Ca abundances, and a decrease in Al and Ti contents. This is reflected in the back scattered image (BSE image Fig. 2b and 2c) of these pyroxenes. Core is rich in Mg and Ca while there is distinct increase of Fe and Mn towards rim. Na shows marginal increase towards rim of the pyroxene. Ti shows patchy distribution in the core and is relatively more concentrated in the outer rim of the pyroxene but then it slowly decreases in the outer-

Table 4. Representative analyses of clinopyroxene from melaphonolite.

Analysis (wt%)	1	2	2	3	4	5	6
		core	rim				
SiO_2	45.38	45.56	48.3	47.71	51	51.82	48.06
TiO_2	1.64	1.78	0.46	0.92	0.82	1.03	0.50
Al_2O_3	7.7	7.2	2.15	4.36	2.95	1.52	1.05
Cr_2O_3	0.03	0	0.08	0.22	0	0.00	0.00
FeO	15.25	14.19	22.43	16.13	15.9	5.41	21.92
MnO	0.85	0.53	1.97	1	1.2	0.08	1.73
MgO	6.86	7.68	3.27	7.3	7.62	14.74	3.50
CaO	19.5	20.8	18.17	19.5	17.84	23.60	17.90
Na_2O	2.52	1.78	3.07	2.6	3.39	0.75	3.24
Total	99.73	99.52	99.9	99.74	100.72	0.00	0.00
Formula Proportions Based On 4 Cations and 6 Oxygen Atoms							
Si	1.726	1.737	1.896	1.823	1.916	1.938	1.974
Al^{IV}	0.274	0.263	0.099	0.177	0.084	0.062	0.026
Al^{VI}	0.071	0.061	0.019	0.047		0.005	0.025
Ti	0.047	0.051	0.014	0.026	0.023	0.029	0.015
Fe^{3+}	0.186	0.132	0.234	0.193	0.247	0.082	0.334
Fe^{2+}	0.299	0.321	0.503	0.323	0.253	0.086	0.398
Mn	0.027	0.017	0.065	0.032	0.038	0.003	0.06
Mg	0.389	0.437	0.191	0.416	0.427	0.822	0.214
Ca	0.795	0.85	0.764	0.798	0.718	0.949	0.788
Na	0.186	0.132	0.234	0.193	0.247	0.054	0.258
Mg#*	43.17	48.18	19.23	43.15	44.25	0.000	

Table 5. Representative analyses of clinopyroxenes fron felsic. phonolites.

Analysis (wt%)	1	2	3	4
SiO_2	54.08	55.73	53.41	53
TiO_2	1.43	0.74	0.94	1.34
Al_2O_3	1.91	1.94	2.05	1.9
FeO	22.67	20.6	25.42	26.24
MnO	0.57	0.67	0.32	0.52
MgO	2.9	14.97	0.61	0
CaO	1.76	1.01	1.76	2.79
Na_2O	14.14	12.99	15.4	13.98
Total	99.47	98.74	99.99	99.77
Formula Proportions Based on 4 Cations and 6 Oxygen Atoms				
Si	2.129	2.137	2.119	2.116
Ti	0.042	0.022	0.028	0.04
Al	0.099	0.089	0.098	0.09
Fe^{3+}	0.747	0.676	0.844	0.876
Mn	0.019	0.022	0.011	0.018
Mg	0.134	0.289	0.036	0
Ca	0.074	0.042	0.075	0.199
Na	1.08	0.983	1.182	1.082
mg #*	14.9	29.3	4	

most part of the crystal. Ti was depositing from the melt but the distribution is irregular. Nature of Ti-rich is evident from presence of titano-magnetite in groundmass of both melanephelinite and melaphonolite (Fig. 2d). The most aegirine-rich compositions are found in the felsic phonolite. The chemical compositions for clinopyroxene are shown in a Mg–Fs + Mn–Na ternary plot (Fig. 3). The most diopsidic pyroxene is from melanephelinite and though there is an enrichment in Fe^2 resulting in a trend of increasing hedenbergite content from melanephelinite to melaphonolite, and finally in Na enrichment in felsic phonolite, there is no continuity in the observed trend. On the other hand, there is an abrupt change, to highly sodic compositions for clinopyroxene from felsic phonolite with virtually no hedenbergite component. This abrupt change in composition suggests a sharp increase in the peralkalinity and oxygen fugacity of the magma system at the time of crystallization (Nash and Wilkinson, 1970; Larsen, 1976).

3.4. Nepheline

Nepheline occurs in the groundmass of melanephelinite, whereas in both melaphonolite and felsic phonolite it is present as unaltered, euhedral phenocrysts. Nephelines from melanephelinite have maximum 8.65wt% K_2O ($Ne_{66}Ks_{30}Qtz_4$), while those from melaphonolite and felsic phonolites have lesser K_2O ($Ne_{81}Ks_{11}Qtz_8$) (Table 2). All nepheline grains are homogeneous in composition. The compositions of nephelines from melanephelinite, mela phonolites are comparable to those from phonolites Sadiman Volcano, Tanzania (Zaitsev et al., 2012). On the basis of nepheline geothermometry (Hamilton, 1961), the inferred temperature of crystallization ranged from 750^{o} to 890^{o}C.

3.5. Feldspar

K-Feldspar occurs both in melaphonolite and felsic phonolites however, compositionally there are

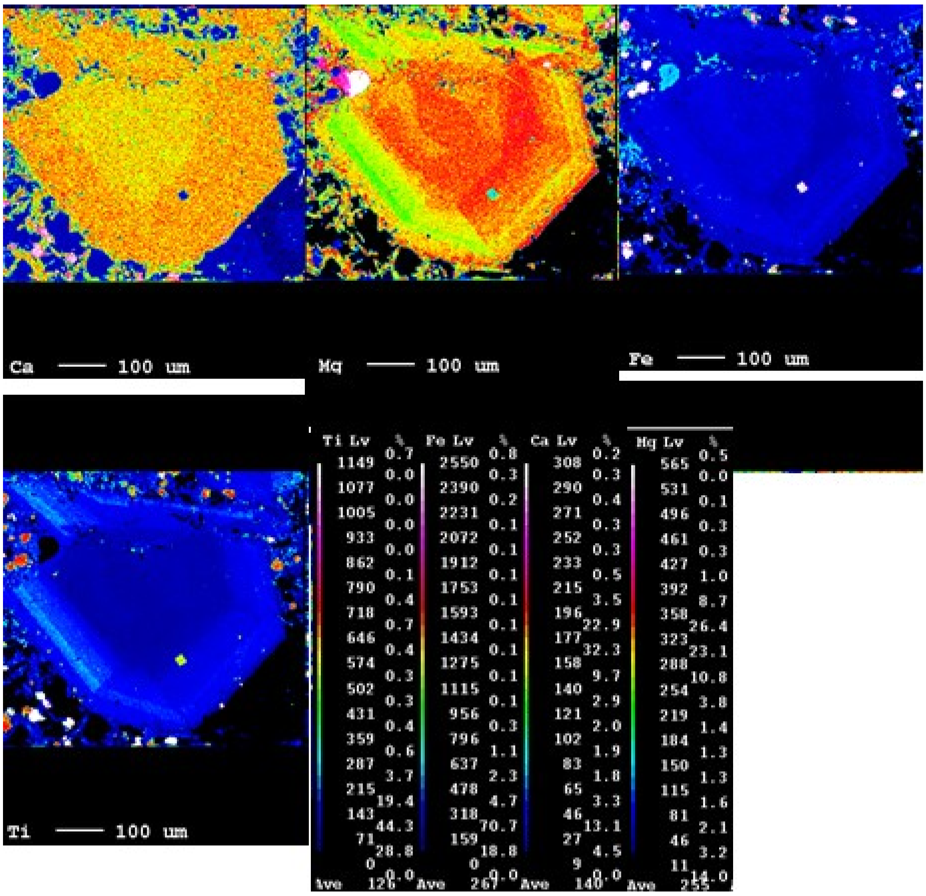

Fig. 2a. BSE of clinopyroxene in melanephelinite showing zoning patterns of Ti, Mg, Ca and Fe.

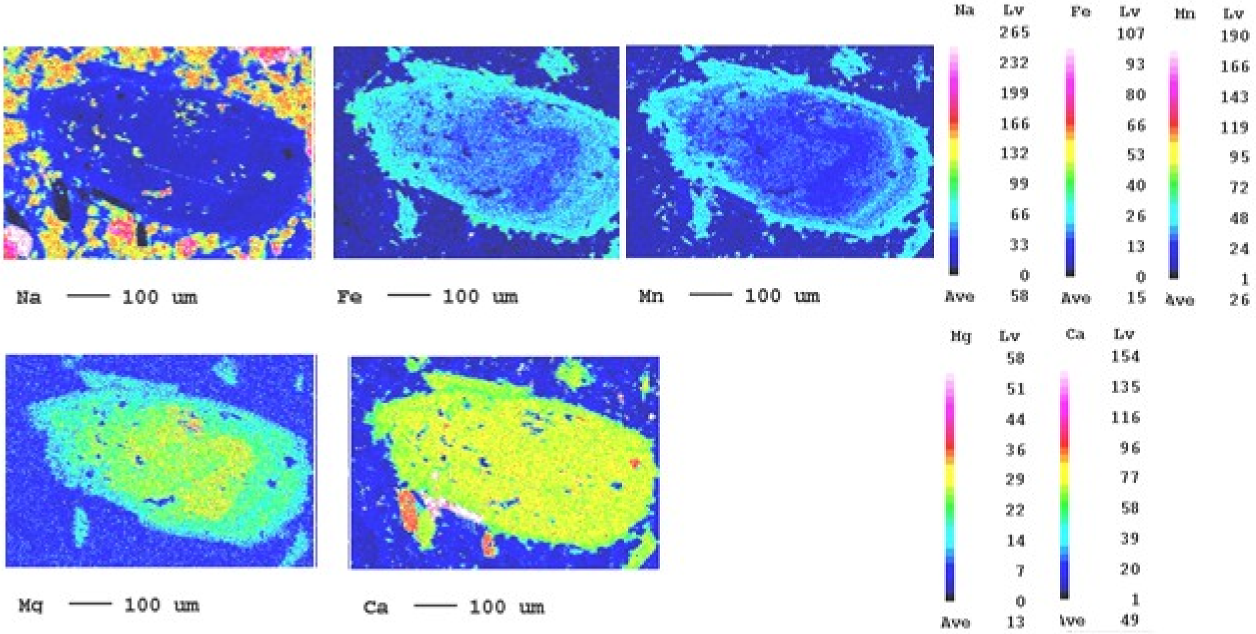

Fig. 2b. Distribution and zoning characteristics of elements Na, Fe, Mn, Mg and Ca in pyroxene of melaphonolite of Barmer.

marked differences. It is mainly sanidine (most around Or_{50}, Table 7). However, the main characteristic feature that distinguishes sanidine of melaphonolite from the K-feldspar of felsic phonolites is their high Ba content of the former. Ba contain varies from 2wt% to 10wr% and it's distributed is highly

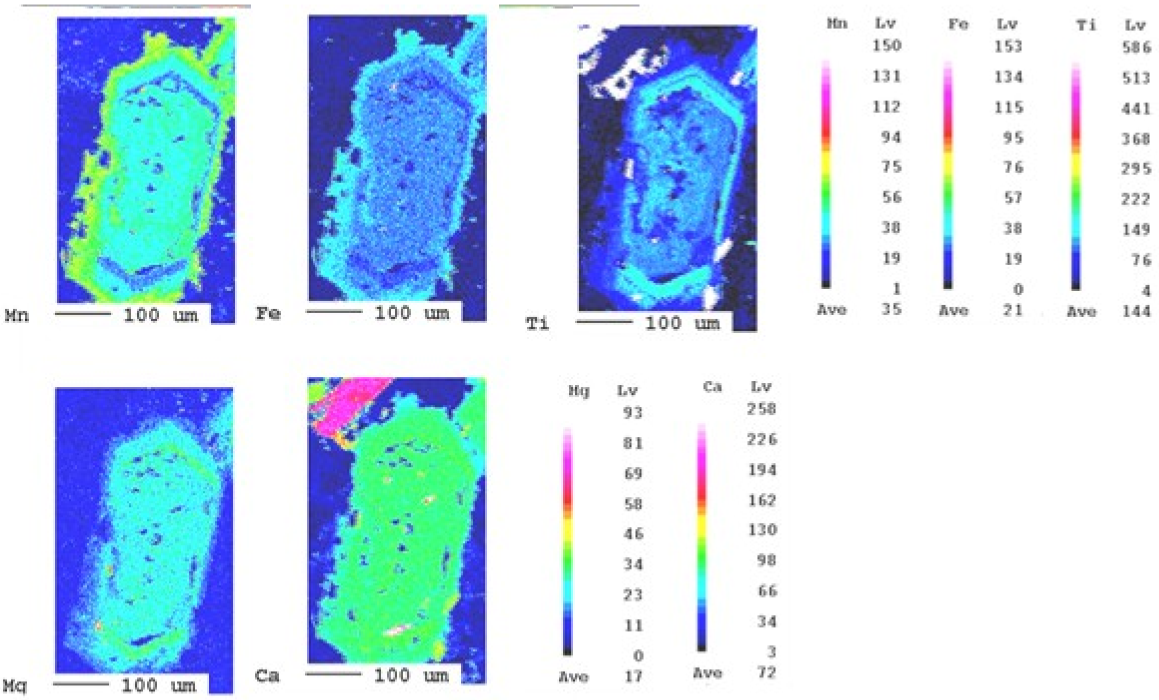

Fig. 2c. Zoned pyroxene in melaphonolite.

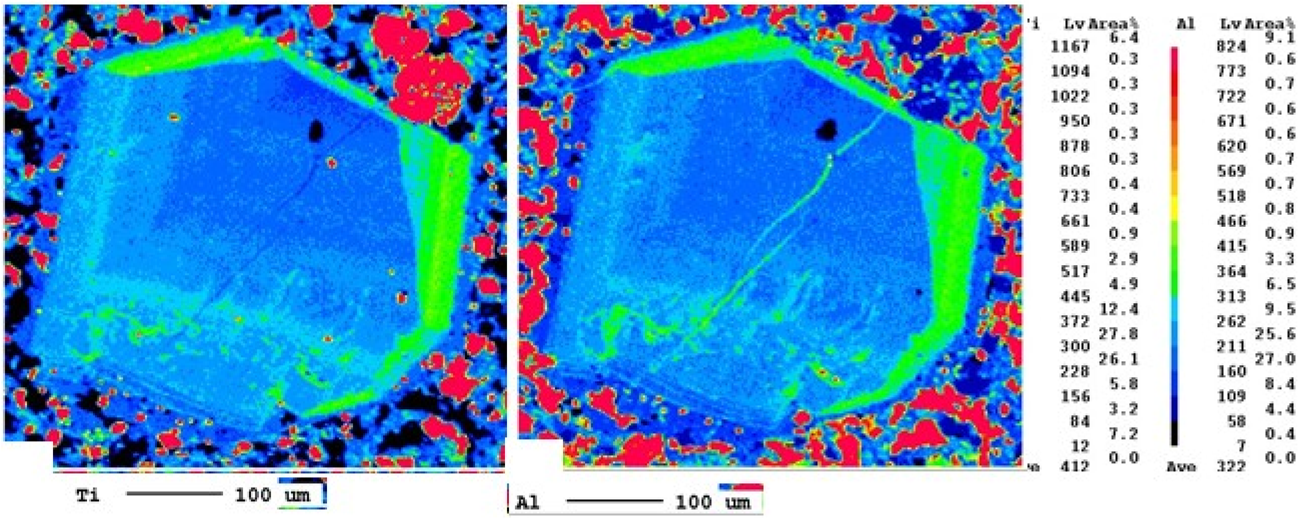

Fig. 2d. BSE of Zoned pyroxene with characteristic zoning pattern of Ti and Al.

irregular and patchily in the centre while it forms a strong continuous rim around the crystal (Fig. 4a). In majority of phenocrysts there is an oscillatory zoned overgrowth of Ba-rich layers. The variation and distribution of Ba in a single crystal of sanidine from core to rim reflected in (Fig. 4b). In addition to high content of Ba these feldspars also show high content of Sr (up to 4wt %). The details of Ba-rich feldspar can be found in Viladkar (2015). In felsic phonolites, the dominant feldspar is more K-rich (Or54Ab44An2 to Or70Ab30) and occurs along with discrete grains of albite. In addition, feldspar occurring in veins has an almost pure K-feldspar end-member composition.

3.6. Titaniferous magnetite

The ulvospinel component of the titaniferous magnetite varies from 49% to 55% (Table 8). The concentration of Cr_2O_3 varies from 0.18 to 1.64 wt% and is much higher than in the coexisting olivine. In addition, the MgO content varies from approximately 2.00 to 6.94 wt%. No exsolution lamellae of ilmenite are evident. The range in composition shown in Table 8 is similar to that reported for titaniferous

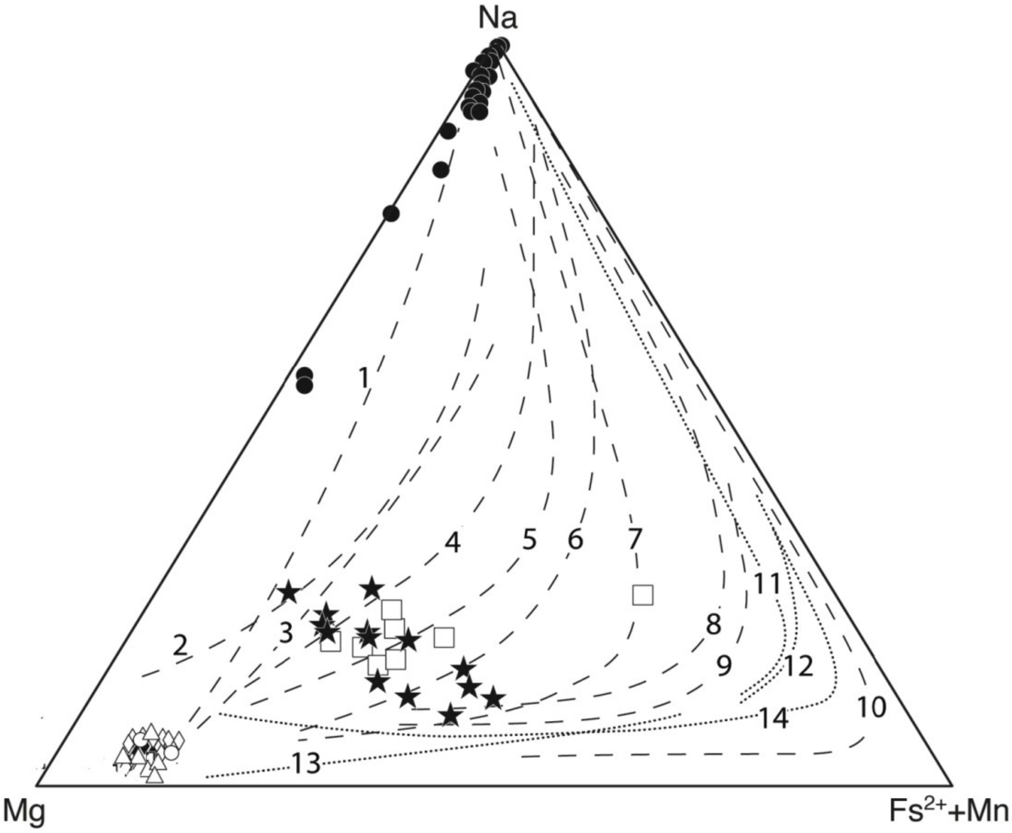

Fig. 3. Composition of pyroxenes from melanephelinite, melaphonolite and felsic phonolite in terms of Mg–Fe^{2+}Mn–Na. Open circle, open triangle, open diamond and filled diamond- pyroxenes from three melanephelinite plugs, open square and star-pyroxenes from melaphonolite dikes, filled circle-pyroxenes from felsic phonolites dikes. Pyroxene trends from undersaturated (1–10) and oversaturated (11–13) alkaline rocks of other complexes: (Ref: Viladkar and Zaitsev, 2011) 1. Bardiner, East Greenland (Nielsen, 1979), 2. Auvergne, France (Varet, 1969), 3. Oslo (Neumann, 1976), 4. Itapirapua, Brazil (Gomes et al., 1970), 5. Uganda (Tyler and King, 1967), 6. Norutu, Sakhaline (Yagi, 1966), 7. South Greenland, 8. Mortzfeldt, South Greenland (Jones and Peckett, 1981), 9. Igdlerfigssalik, Greenland and 10. Illimaussaq, South Greenland (Larsen, 1976), 11. Gough Island (Ferguson, 1978), 12. Pantellerrite (Nicholls and Carmichael, 1969), 13. Japannese alkali basalts (Aoki, 1964).

magnetite from nephelinite lavas from Napak volcano, Uganda (Simonetti et al., 1996).

3.7. Accessory minerals

Minerals present in trace amounts include titanite (Table 9), analcime, Sodalite and biotite are shown in Table 9. Both analcime and sodalite occur in the groundmass.

3.8. Rock Chemistry

Total number of 24 samples from the Barmer complex were analyzed (5-melanephelinites, 12-melaphonolites and 7-felsic phonolites) while major, trace and Rare Earth elements data of the representative samples covering all alkaline rocks (melanephelinite, melaphonolite and felsic phonolite) is tabulated in Table 10. Their major elements compositions in terms of total alkalis vs silica (TAS) are shown in Fig. 5. Compared to our rock nomenclature (TAS plotting, used in Fig. 5. Chandrasekaran et al. (1990) adopted a nomenclature based primarily on plutonic rocks for samples of similar chemical composition. Shastri and Kumar (1996) also used the terms “melteigite” and Alkali pyroxenite. We believe, however, that based on the fine-grained, glassy and porphyritic nature of the melanephelinites and two types of phonolites from Sarnu–Dandali, the rocks are volcanic or sub-volcanic in origin. A nomenclature using plutonic rock names, therefore, is inappropriate.

Melanephelinites of Barmer shows high MgO content and high Mg #. (63 to 70) over both phonolites.However, low Cr (146 to 484 ppm) and Ni (54

Table 6. Representative analyses of Ba-rich sanidine from melaphonolite.

Analysis (wt%)	1	2	3	4	5	6	7
SiO_2	58.26	56.54	56.92	63.64	57.59	59.26	58.85
Al_2O_3	20.02	20.99	20.62	18.47	21.37	19.86	20.58
FeO	0.21	0.38	0.32	0.18	0.38	0.26	0.31
BaO	5.18	7.12	7.44	0.31	7.26	4.34	7.23
CaO	0.10	0.13	0.07	0.06	0.15	0.04	0.10
Na_2O	3.32	3.49	3.43	4.19	3.58	3.39	3.35
K_2O	9.24	7.68	8.11	10.64	7.62	9.48	8.05
SrO	1.44	2.29	1.83	0.50	2.43	1.38	2.02
Total	96.33	96.33	96.91	97.49	97.95	96.63	98.47
Si	11.36	11.10	11.17	11.88	11.10	11.44	11.29
Al	4.60	4.85	4.76	4.06	4.85	4.52	4.65
Fe2	0.03	0.06	0.05	0.03	0.06	0.04	0.05
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.40	0.55	0.57	0.02	0.55	0.33	0.54
Ca	0.02	0.03	0.02	0.01	0.03	0.01	0.02
Na	1.26	1.33	1.31	1.52	1.34	1.27	1.25
K	2.30	1.92	2.03	2.53	1.87	2.34	1.97
Ab	35.10	40.50	39.00	37.30	41.30	35.10	38.50
An	0.60	0.80	0.40	0.30	1.00	0.20	0.60
Or	64.30	58.70	60.60	62.40	57.80	64.60	60.90

Table 7. Analyses of titaniferous magnetite from melanephelinite.

Analysis (wt%)	1	2	3	4	5
SiO_2	0.26	0.16	0.22	0.41	0.3
TiO_2	19.57	18.52	17.01	16.72	17.51
Al_2O_3	1.4	3.31	4.37	4.96	3.84
Cr_2O_3	0.18	0.38	0.88	1.64	0.8
FeO	74.55	72.18	69.34	68.08	69.23
MnO	0.96	0.9	0.9	0.8	0.78
MgO	2.88	3.95	6.74	6.97	6.94
CaO	0	0.12	0.1	0	0
Total	99.8	99.52	99.56	99.58	99.4
Fe_2O_3	32.43	32.66	35.4	34.08	34.9
FeO	45.37	42.79	37.43	37.42	37.83
Mol % Usp.	55.11	53.41	49.41	50.31	50.63

Table 8. Sphene from melaphonolite.

Analysis (wt%)	1	2	3	4	5	6	7	8	9	10	11
SiO_2	29.76	30.19	29.18	29.79	29.70	29.71	29.93	29.66	30.24	29.96	30.23
TiO_2	33.55	36.06	34.13	33.88	33.76	33.33	34.64	32.58	36.45	34.22	36.94
Al_2O_3	1.71	1.39	1.66	1.56	1.79	1.47	1.57	1.57	1.30	1.77	1.25
FeO	1.55	1.51	1.94	2.02	1.82	2.36	1.48	2.59	1.18	1.75	1.05
MnO	0.09	0.08	0.20	0.06	0.09	0.09	0.13	0.06	0.05	0.12	0.09
MgO	0.00	0.02	0.03	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.02
CaO	26.33	27.78	25.63	26.79	26.74	26.64	26.78	26.70	27.88	27.19	28.06
Na_2O	0.12	0.00	25.63	26.79	26.74	26.64	0.06	0.05	0.15	0.11	0.11
K_2O	0.00	0.00	0.00	0.01	0.03	0.00	0.00	0.02	0.00	0.00	0.00
Total	93.12	97.03	92.93	94.17	93.98	93.63	94.60	93.23	97.27	95.11	97.74

Table 9. Analyses of analcime (1–3), sodalite (4) in the ground mass of melaphonolite stray biotite (5–7) in felsic phonolite.

Analysis (wt%)	1	2	3	4	5	6	7
SiO_2	54.08	48.07	47.61	38.48	35.03	35.25	35.57
TiO_2	0.01	0.02	0.03	0.00	4.06	4.04	3.98
Al_2O_3	22.69	28.33	27.69	31.37	14.66	14.24	14.40
FeO	0.07	0.37	0.67	0.00	14.26	12.94	14.52
MnO	0.17	0.02	0.04	0.00	0.90	0.90	0.96
MgO	0.00	0.00	0.00	0.00	14.68	15.19	14.58
CaO	1.44	1.01	1.37	0.00	0.00	0.00	0.03
Na_2O	11.60	12.00	11.69	22.00	0.68	0.65	0.64
K_2O	0.03	0.06	0.10	0.00	8.86	8.64	8.67
Total	90.09	89.89	89.21	91.85	93.13	91.85	93.34

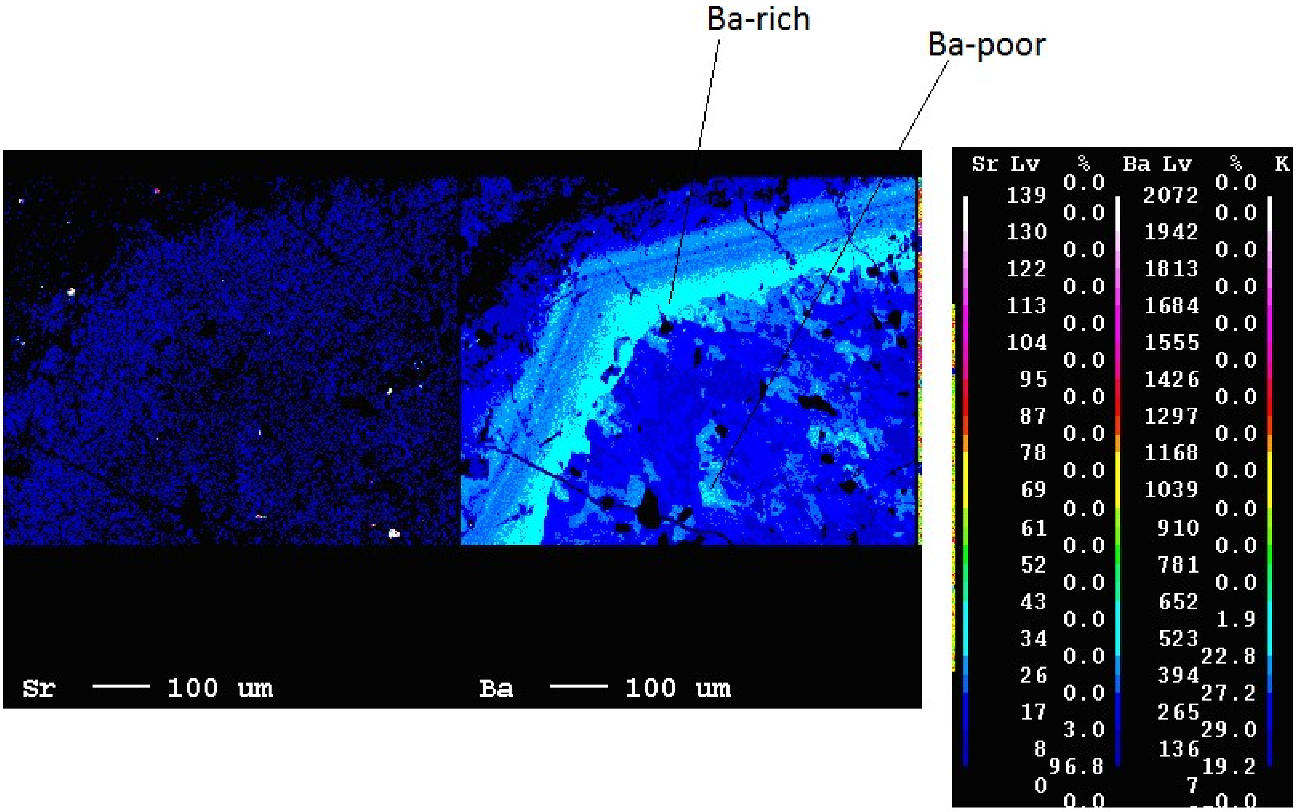

Fig. 4a. BSE of Ba-rich sanidine in melaphonolite.

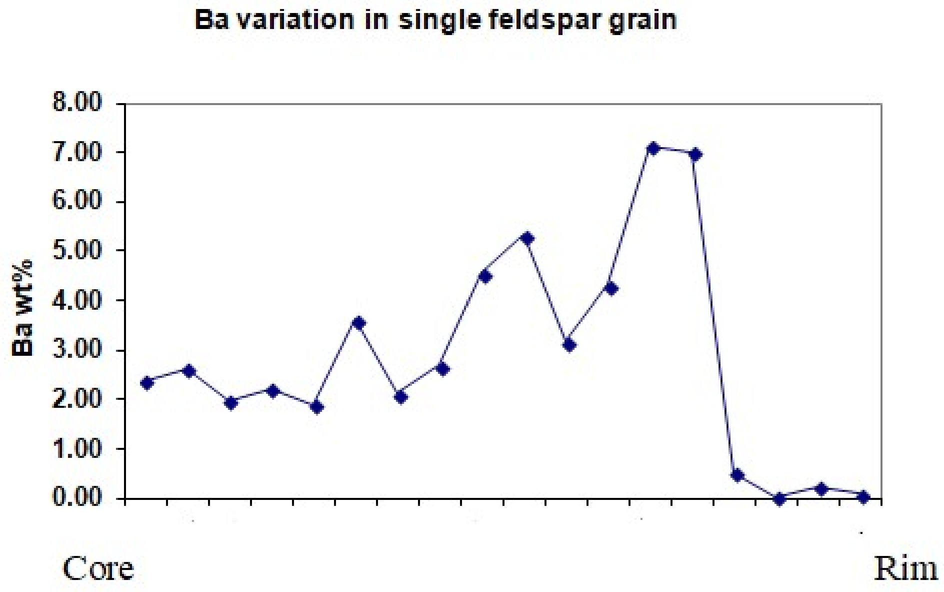

Fig. 4b. Variation Ba content of zoned Ba-rich sanidine in melaphonolite.

to 123 ppm, Table 10) content. These values from melanephelinites of Barmer are similar to those from olivine-bearing nephelinites from Napak (Simonetti and Bell, 1994). Such low abundances of Ni and Cr may be attributed to olivine fractionation and are not indicative of primitive magmas (Roeder and Emslie, 1970). These elements are mostly absent in both types of phonolites. The composition of melanephelinite is also similar to the average composition of olivine-poor nephelinite as determined by Le Bas (1987). Compared to the major element composition from melanephelinite, analyses for felsic phonolites

Table 10. Representative analyses of melanephelinite, melaphonolite and felsic phonolite and CIPW norms.

	MN	FP	FP	MP					
	2 BAR	**9 BAR**	**12 BAR**	**13 BAR**		**2BAR**	**9 BAR**	**12 BAR**	**13 BAR**
SiO_2	37.27	54.74	55.79	49.60	**Plagioclase**	12.81	14.47	23.64	33.27
TiO_2	5.04	0.33	0.30	1.04	**Orthoclase**	16.66	40.02	36.57	23.22
Al_2O_3	10.64	19.27	19.69	16.76	**Nepheline**	15.9	29.45	27.27	22.09
Fe_2O_3	15.20	4.60	3.83	6.41	**Leucite**	0	0	0	0
FeO					**Kalsilite**	0	0	0	0
MnO	0.17	0.24	0.31	0.37	**Corundum**	0	0	0	0
MgO	10.00	0.16	0.12	1.27	**Diopside**	27.62	0.74	0.66	6.23
CaO	13.31	1.77	0.80	7.58	**Hypersthene**	0	0	0	0
Na_2O	2.80	10.10	10.44	7.45	**Wollastonite**	0	2.95	1.22	9.32
K_2O	2.200	6.280	5.750	3.420	**Olivine**	8.8	0	0	0
P_2O_5	0.690	0.050	0.020	0.450	**Larnite**	0	0	0	0
Volatiles	1.74	2.19	3.00	5.26	**Acmite**	0	10.2	8.48	0
Total	99.064	99.735	100.048	99.610	**K_2SiO_3**	0	0	0	0
ICP-MS analyses (ppm)					**Na_2SiO_3**	0	1.66	1.74	0
V	488.92	86.81	69.93	82.75	**Rutile**	0	0	0	0
Cr	389.29				**Ilmenite**	0.24	0.29	0.33	0.48
Co	69.94	53.25	19.86	17.67	**Magnetite**	0	0	0	0
Ni	136.98				**Hematite**	9.5	0	0	3.59
Cu	98.09	26.61	-10.00	17.18	**Apatite**	1.64	0.1	0.04	0.96
Zn	127.24	219.29	227.36	220.87	**Zircon**	0.02	0.02	0.02	0.02
Rb	77.37	235.95	220.61	88.30	**Perovskite**	6.77	0.08	0	0.79
Sr	819.20	1900.00	886.22	4440.00	**Chromite**	0.03	0.02	0.02	0.03
Y	23.90	19.76	27.98	55.22	**Sphene**	0	0	0	0
Zr	280.46	615.84	776.94	791.25	**Pyrite**	0	0	0	0
Nb	85.98	162.02	226.58	296.49	**Halite**	0	0	0	0
Cs	0.65	2.88	3.38	1.40	**Fluorite**	0	0	0	0
Ba	793.71	1990.00	421.80	2890.00	**Anhydrite**	0	0	0	0
Hf	8.16	9.00	12.55	13.76	**Na_2SO_4**	0	0	0	0
Ta	6.74	1.66	3.30	13.91	**Calcite**	0	0	0	0
Pb		59.08	56.73	23.16	**Na_2CO_3**	0	0	0	0
Th	8.91	75.22	34.13	28.53	**Total**	99.99	100	99.99	100
U	1.98	18.00	13.22	7.31					
Ga	28.34	49.07	46.20	31.08					
Ge	1.66	0.93	1.14	1.44					
La	72.40	170.05	124.87	328.68					
Ce	155.91	219.70	201.87	588.99					
Pr	17.24	14.49	15.55	56.39					
Nd	65.41	34.88	42.44	179.49					
Sm	12.42	3.93	5.78	24.41					
Eu	3.71	1.20	1.70	7.02					
Gd	9.94	2.22	3.92	16.73					
Tb	1.39	0.46	0.74	2.22					
Dy	6.18	2.93	4.58	11.37					
Ho	1.00	0.64	0.99	2.09					
Er	2.45	2.32	3.40	5.88					
Tm	0.28	0.37	0.56	0.78					
Yb	1.56	2.50	3.63	4.86					
Lu	0.20	0.37	0.55	0.68					
$^{87}Sr/^{86}Sr$ age corr. 65 Ma	0.704338	0.704301	0.704360	0.704375					

MN-Melanephelinite, MP-Melaphonolite FP-Felsic phpnolite.

show higher Si, Al, Na and K contents, and lower Ca, Fe, Mg, P and Ti abundances (Table 10). The trend shown in figure CaO vs MgO (Fig. 6a and 6b) overlaps with the differentiation trend defined by olivine-rich and olivine-poor nephelinites via fractional crystallization of varying proportions of clinopyroxene and olivine (Le Bas, 1987). Compared to the data from melaphonolite, the higher Al_2O_3 contents for the felsic phonolites (Fig. 6b) cannot be easily explained by crystal fractionation involving mineral phases found in the phonolites, such as clinopyroxene (with ~7.0 wt Al_2O_3 in core, Table 4) and feldspar (~20 wt% Al_2O_3, Table 7). Combined clinopyroxene and feldspar crystal fractionation in a melaphonolite melt would result in lower abundances of elements such as Al, K, and Na in the residual liquid (e.g., felsic phonolite). In addition, decrease in TiO_2 contents from melanephelinite to felsic phonolite indicate crystal fractionation involving Ti-bearing phases, such as titaniferous magnetite and clinopyroxene.

Abundances for various trace elements from the melanephelinites, mela- and felsic phonolites have

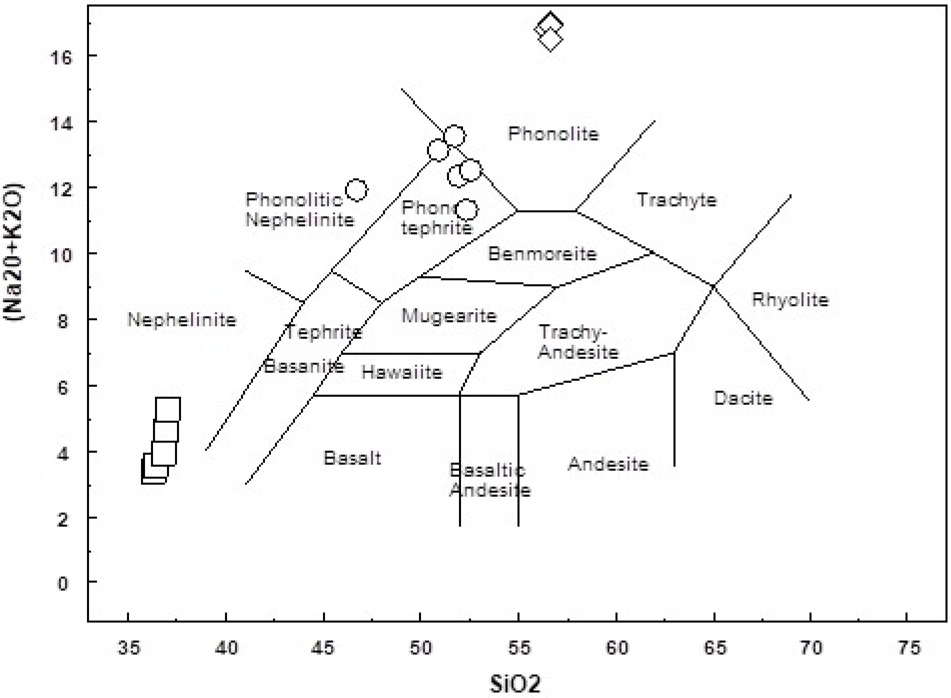

Fig. 5. Classification of Barmer alkaline rocks on SiO_2 vs $Na_2O^+K_2O$ (Cox et al., 1979). Open Square-melanephelinite, Diamond -Felsicphonolite, Open circle – Melaphonolites.

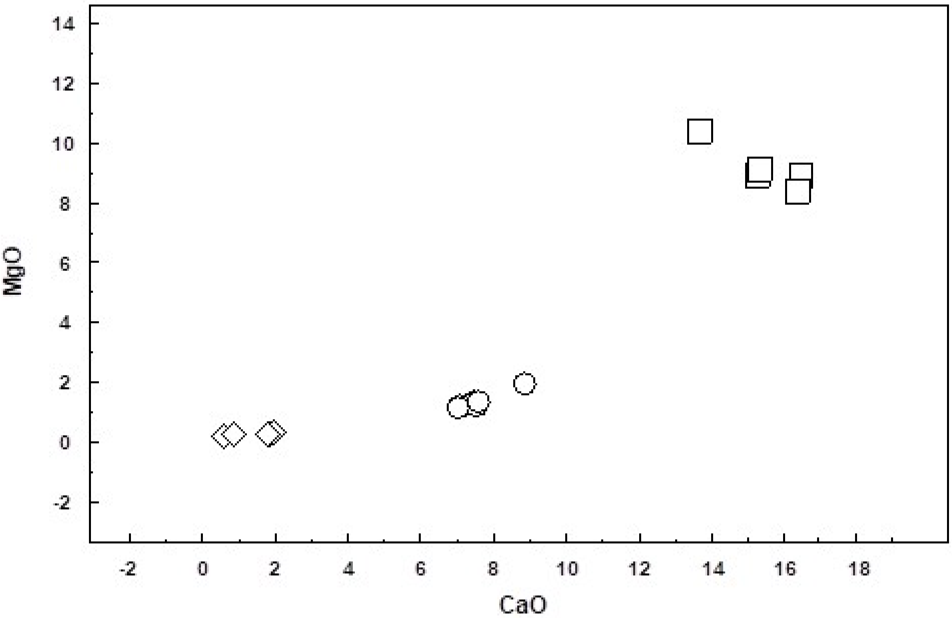

Fig. 6a. Plot of MgO vs CaO in melanepelinite and two types of phonolites. Open box-melanephelinite diamond-Melaphonolite, Open circle - felsic phonolite.

been plotted against MgO and Al_2O_3 contents (Fig. 7a, 7b, 7c). In general, there is an increasing trend of incompatible elements from melanephelinite to the felsic phonolite (e.g., Rb from 77 ppm in nephelinite to 88 ppm in the melaphonolite and 235 ppm in felsic phonolites). However, this is not true in case of Sr and to some extent Ba contents of these rocks. Compared to the felsic phonolites, melaphonolite has very high both Ba (2890 ppm) and Sr (4440 ppm). This may be attributed to the Ba and Sr-rich nature of sanidine in the melaphonolites. Fig. 7a, 7b, 7c plot an incompatible element (e.g. Sr, Rb

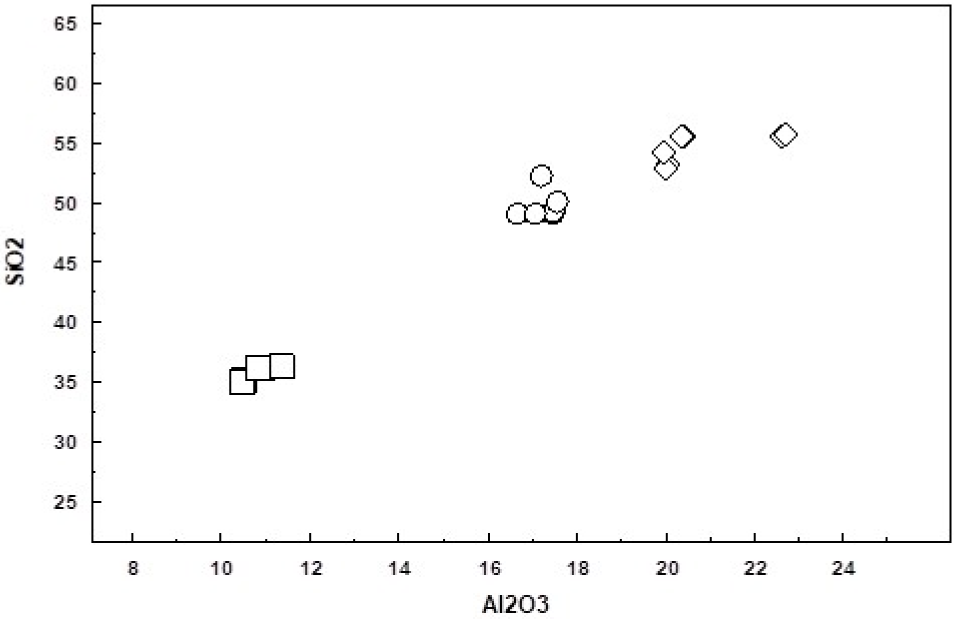

Fig. 6b. Plot of Al_2O_3 vs SiO_2 in melanephelinite and two types of phonolites. Open box-melanephelinite, diamond - Felsic phonolite, Open circle – Melaphonolite.

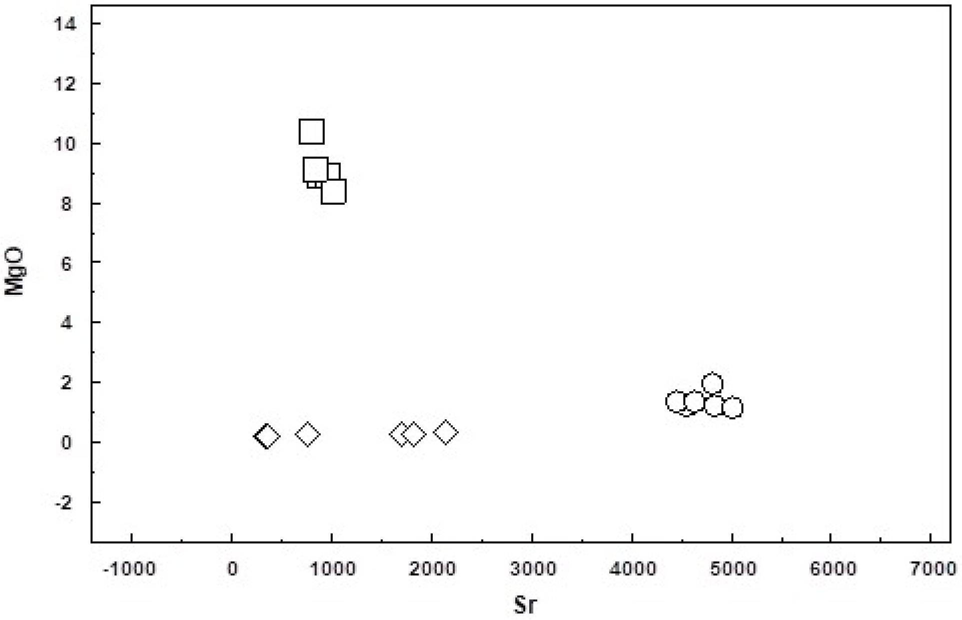

Fig. 7a. MgO vs Sr from melanephelinite and two types of phonolites. Open square-melanephelinite, diamond-Melaphonolite, Open circle - felsic phonolite.

and Zr) versus and compatible element (e.g. Al_2O_3 and MgO), and trends shown by the data are as follows: 1- Assuming fractional crystallization was the dominant process of melt differentiation, Fig. 7a indicates that in relation to the Sr abundances for the melanephelinites, Sr behaved as an incompatible element for the melaphonolites but as a compatible element for the felsic phonolites; 2- Compared to the behaviour of Sr with relation to the different rock types, Rb shows the inverse behaviour (more incompatible in the felsic phonolites); 3- The felsic phonolites show a large range in Rb (~180 to 300 ppm) and Sr (~350 to 2000 ppm) contents which are difficult to explain by melt differentiation involving fractional crystallization. The variations in trace element ratios shown in Fig. 7a, 7b, 7c may be interpreted to suggest that each sample of phonolite represents a distinct partial melt. Alternatively, the enrichment

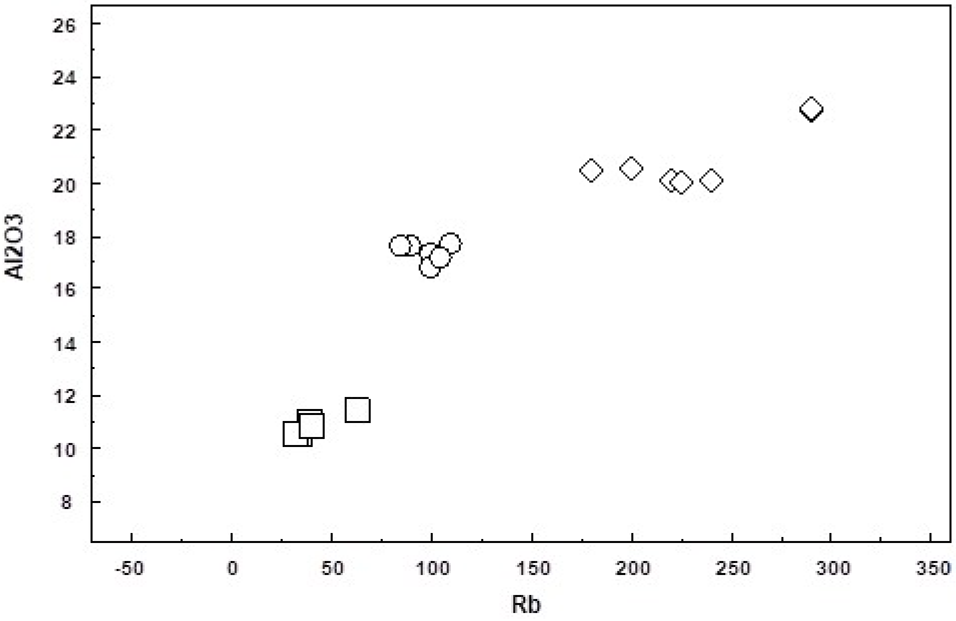

Fig. 7b. Al_2O_3 vs Rb in melanephelinite and two types of phonolites. Open box-melanephelinite, diamond-Melaphonolite, Open circle -felsic phonolite.

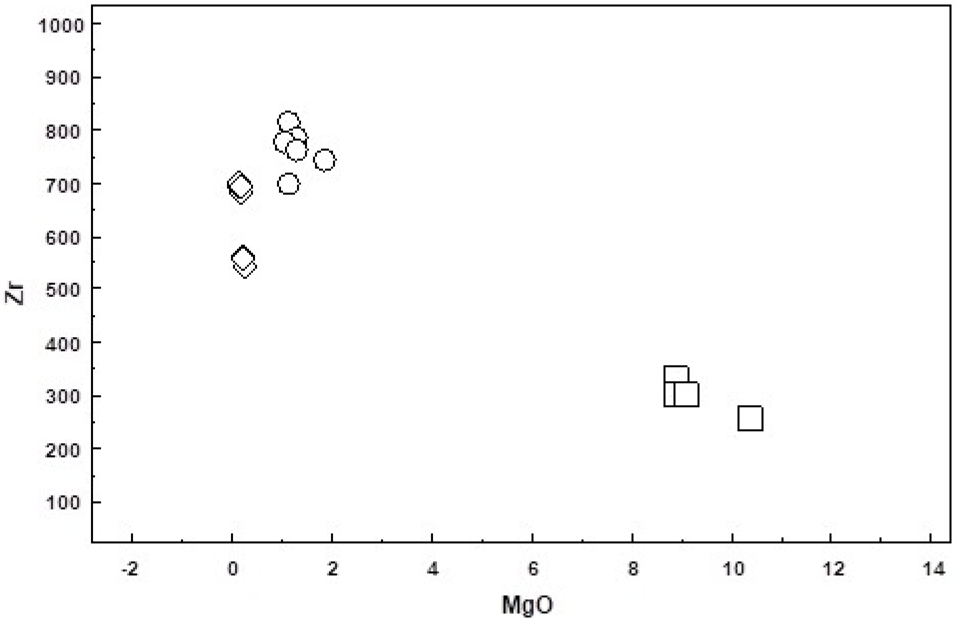

Fig. 7c. MgO vs Zr in melanephelinite and two types of phonolite. Open square-melanephelinite, diamond-Melaphonolite, and Open circle - felsic phonolite.

in incompatible elements for the phonolites (Fig. 7a, 7b, 7c) may be attributed to combined crystal fractionation and crustal contamination. In general, the melaphonolites contain higher contents of Ba, Sr, Ti and Y, and lower amounts of Pb, Rb and Th compared to the felsic phonolites.

A Ne–Ks–Qtz ternary diagram (Fig. 8) reveals that both the mela- and felsic phonolites plot along the phonolite minima. Among all of the silicate rocks analyzed from Barmer, melanephelinite contains the lowest abundance of REEs, and their Chondrite-normalized patterns are steeply-sloping. Highest HREE is found in melaphonolite and the Chondrite normalized pattern is also almost flat (Table 10). Two melaphonolites contain high content of total REEs. Fig. 9 Chondrite normalized REE patterns of melanephelinite and two types of phonolites clearly show that the different alkaline silicate rocks from

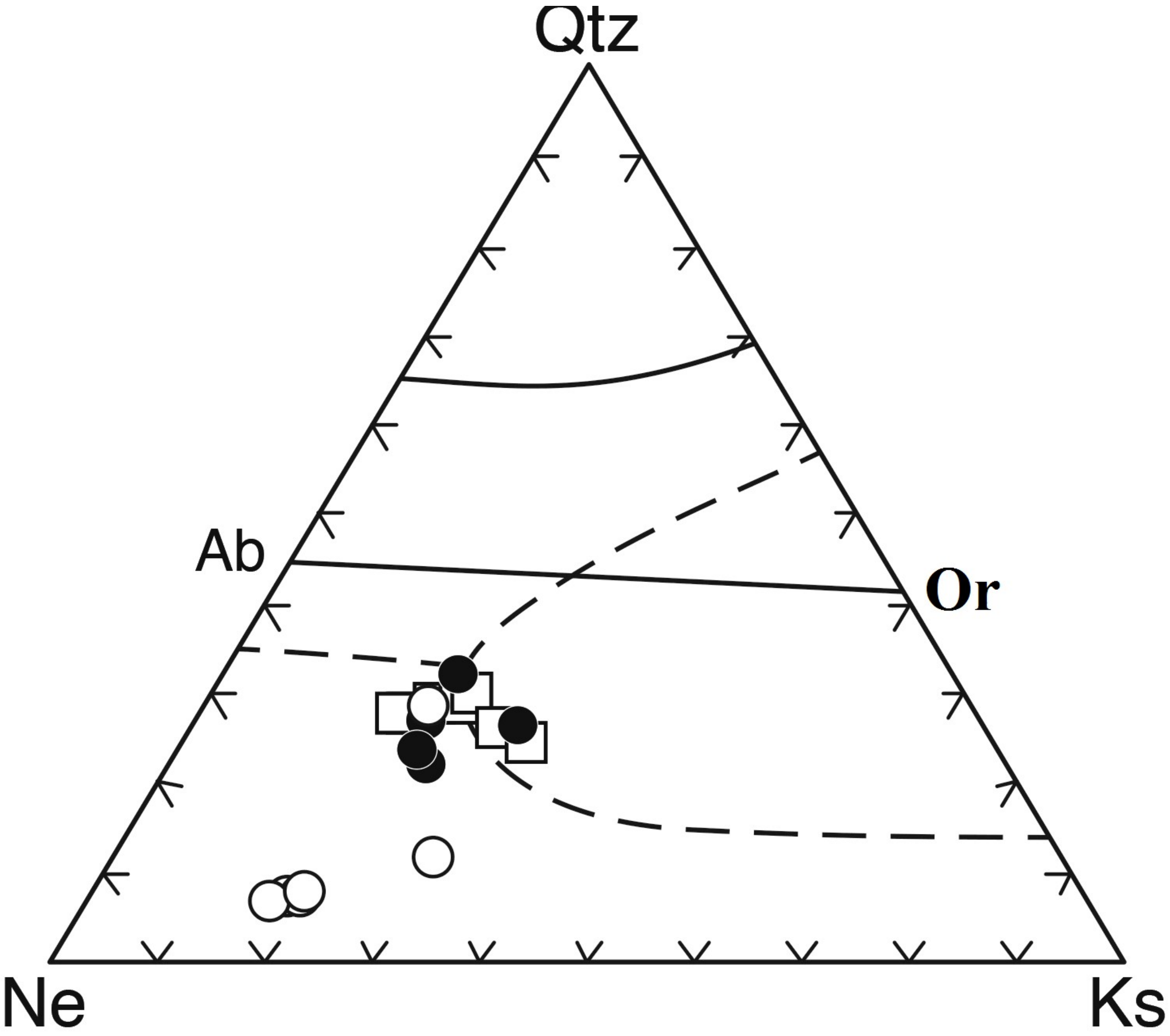

Fig. 8. Composition of melanephelinites, melaphonolites and felsic phonolites plotted in the system Ne–Ks–Qtz at 1 kbar (Hamilton, 1961). Open circle-nephelinite, filled circle-melaphonolite and open square-felsic phonolites.

Sarnu–Dandali are not characterized by similar, parallel patterns indicating that they are not simply related by crystal fractionation. Among all alkaline rocks melaphonolite has the highest concentrations of all REEs.

4. Discussion and conclusion

Similar to Barmer nephelinite-phonolite association there are other alkaline complexes wherein the phonolite is derived by differentiation from a parental, nephelinitic magma (King, 1965; Williams, 1970; Le Bas, 1987). Peterson (1989) suggested that the process of fractionation of nephelinitic magma is initiated by separation of olivine, clinopyroxene, Fe–Ti oxide and nepheline from the melt. Wilkinson and Stolz (1983) stated, however, that derivation of alkali feldspar-rich differentiates is dependent on the level of sialic saturation in the parent nephelinitic melt through crustal contamination. The large number of crustal xenoliths present in many outcrops of melaphonolite would support such an interpretation. On the basis of Nd and Sr isotopic compositions of phonolites from Shombole volcano (Kenya), Bell and Peterson (1991) attributed the range in values to interaction between the magmas and lower crustal granulites. Similar interpretations were also made by Simonetti and Bell (1994) for nepheline syenites from the Chilwa Island carbonatite complex, Malawi. In the present case, without available radiogenic isotope data, it is extremely difficult to favour a model for phonolite magma derivation involving either low-pressure crystal fractionation of a parental, mantle-derived melaphonolitic magma, or crustal contami-

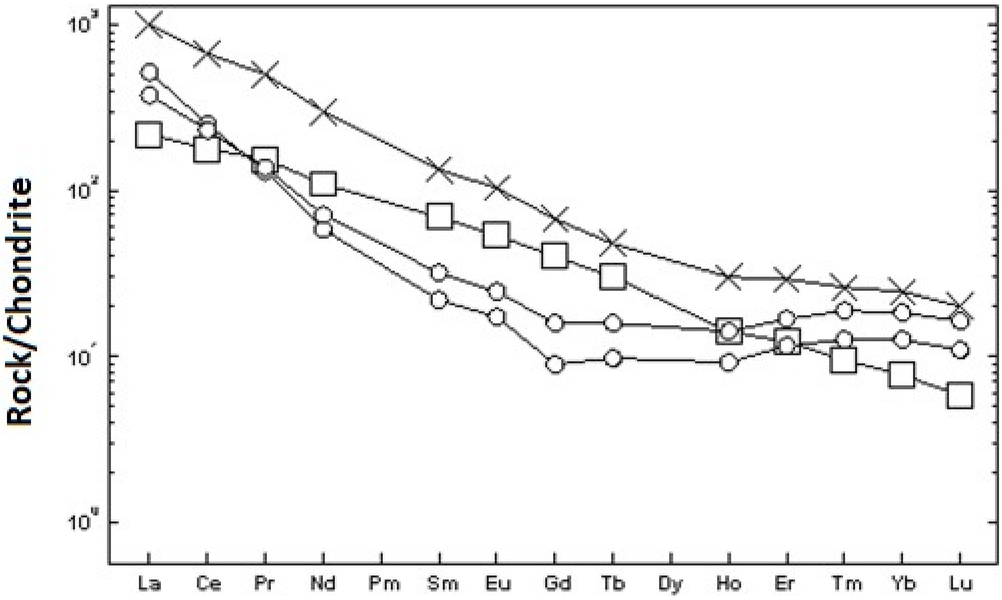

Fig. 9. Chondrite normalized REE patterns in Barmer rocks.Open box: Melanephelinite Cross : melaphonolite, Open circle : two phases of felsic phonolite.

nation of a melanephelinite melt undergoing crystal fractionation. Based on the trends defined by the major and trace element data, however, it seems highly unlikely that the origin of the phonolites from the Sarnu–Dandali region may be attributed to differentiation of a closed magma system (regardless of the exact nature of the parental magma). Nevertheless, the fractionation of REE from nephelinite to phonolite is pertinent here and in favour of the fractionation story. As shown earlier by Viladkar and Zaitsev (2011) melanephelinite contains the lowest abundance of REEs, and their chondrite-normalized patterns are steeply-sloping, LREE-enriched. One melaphonolite contains highest total REE and high LREE. The felsic phonolites, show both the high abundance (but less than melaphonolite) of total REEs and LREEs indicating that it is likely to be the differentiated from the melanephelinite and it also shows negative Eu anomaly in the felsic phonolite can be attributed to the fractionation of the alkali feldspar.

Recently (Chattopadhaya et al., 2025) studied the Deccan nephelinites and they observe that the Sarnu–Dandali and the Kutch alkaline complexes show the most primitive signature. According to these authors Kutch and Sarnu–Dandali are more primitive, with higher MgO, Ni, and Cr content, suggesting limited fractional crystallization and a less-depleted, deeper mantle source.

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Conflict of interest

I declare that there is no conflict of interest involved in this work

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