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Geochemistry of the Neoproterozoic Volcanic Rocks of the Nakora Area of Malani Igneous Suite, Barmer District, Western Rajasthan, India

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Abstract

The Neoproterozoic rocks of the Nakora Ring Complex (NRC) consist of three phases (Extrusive, Intrusive and Dyke) that are based on the detailed geological mapping (contact relationship, mode of occurrence, position of xenolith, flows, dykes and veins) and their stratigraphic position. NRC consists mainly of acid volcanic rocks besides minor amount of basic rocks with intermediate calc-alkaline to tholeiitic affinities and occurs in the form of ring structures. The Nakora basaltic rocks show LREE enriched nature and they have consistent negative Nb, Ta, Sr and Zr anomalies. The HREE pattern is showing parallel arrangement with HREE pattern of other basic rocks. The Nakora acid volcanic rocks exhibit high LREE enrichment than the HREE with negative Ba, Sr, Eu and Ti anomalies in primitive mantle normalized multi-element diagrams. All the samples show negative Ba, Sr, Eu and Ti anomalies. The diminution in amounts of Sr and Eu is apparently related to the fractionation of feldspars or their retention in the refractory minerals resistant to melting in the lower crust. As compared to trachytes, the rhyolites show high SiO_2, high Al_2O_3, low total alkalis, low total iron, low TiO_2, high CaO and high MgO. The petro-mineralogical and geo-chemical data specifies that the NRC rocks are generated from a co-magmatic source through a co-genetic process in a rift tectonic context. Petrogenetic modeling indicates that both the basic rocks and acid volcanic rocks of Nakora may have been derived from rocks akin to Bhilwara mafic metavolcanic/mixed Nakora gabbros and Siwana rhyolite/banded gneiss from Kolar Schist Belt by different degrees of partial melting respectively.

Keywords

Neoproterozoic, Volcanic Rocks, Geochemistry, Nakora, Malani Igneous Suite

1. Introduction

The rock exposure revealed in the Nakora Ring Complex (NRC) is from the Trans-Aravalli Block's (TAB) Neoproterozoic Malani Igneous Suite (MIS). TAB is unique in the geological evolution of Indian Shield and Nakora area is located Northwestern part of the Indian Peninsular Shield. MIS is the Peninsular India's greatest A-type, anorogenic, high heat producing (HHP) acid magmatism (55, 000 km^2, 732 Ma) owing its origin to hot spot tectonics (**Figure 1**) (Kochhar 1973 [1]; Pareek 1981 [2]; Kochhar 1984 [3]; Bhushan 1985 [4]; Bhushan and Mohanty 1988 [5]; Vallinayagam 1988 [6]; Bhushan 1989 [7]; Eby and Kochhar 1990 [8]; Baskar 1992 [9]; Kochhar and Dhar 1993 [10]; Baskar and Sharma 1994 [11]; Sharma 1994 [12]; Kochhar *et al.* 1995 [13]; Dhar *et al.* 1996 [14]; Vallinayagam 1997 [15]; Bhushan and Chittora 1999 [16]; Vallinayagam 1999 [17]; Bhushan 2000 [18]; Pandit *et al.* 2001 [19]; Torsvic *et al.* 2001 [20]; Vallinayagam 2001 [21]; Bhushan and Chandrasekaran 2002 [22]; Kochhar 2004 [23]; Singh and Vallinayagam 2004 [24]; Vallinayagam 2004a [25]; Bhushan and Chittora 2005 [26]; Singh and Vallinayagam 2006 [27]; Vallinayagam and Kumar 2007 [28], Vallinayagam and Kumar 2008 [29]; Kochhar 2009 [30]; Singh and Vallinayagam 2009 [31]; Vallinayagam 2009 [32]; Kumar, N. and Kumar, N. 2020 [33]).

MIS is one of the most important alkaline anorogenic magmatisms in the Indian subcontinent which represents the Pan-African thermos-tectonic episode. The rocks of MIS are granite (hypersolvus and subsolvus), rhyolite, dacite, trachyte, andesite, pyroclasts, basalt, gabbro and dolerite. They have been encountered in the form of ring structures, ring dykes, residual hills, inselbergs and scattered hummocks where the exposures are covered by sand dunes. MIS representatives are well exposed in the Bhiwani district (at Tusham area) of Haryana, Jhunjhunu, Jodhpur, Pali, Barmer (at Siwana, Kundal and Nakora areas), Jalor, Jaisalmer districts of Rajasthan. The representatives of MIS rocks are also reported from Nagar Parkar, Kirana hills in Pakistan (Qasem Jan *et al.* 1997) [34] (**Figure 1**).

The term "Malani beds" for a series of volcanics rocks was introduced by Blanford (1877) [35]. La Touche (1902) [36] provided initial accounts on the geology of the suites of rocks belonging to MIS. He first sighted Malani Igneous Suite in which the rocks are well exposed in the erstwhile region of Malani in Western Rajasthan. Many geoscientists have worked to know the petrological, geochemical and petrogenetic aspects of the MIS (La Touche 1902 [36]; Pascoe 1959 [37]; Mukherjee 1962 [38]; Pareek 1981 [2]; Bhushan 1985 [4]; Kochhar *et al.* 1991 [39]; Dhar *et al.* 1996 [14]; Vallinayagam and Kochhar 1998 [40]; Bhushan and Chittora 1999 [16]; Kochhar 2000 [41]; Vallinayagam 2001 [21]; Bhushan and Chandrasekaran 2002 [22]; Singh and Vallinayagam 2006 [27]; Sharma, R., and Kumar, N. 2017 [42]; Kumar, N., Kumar, N. and Singh, A. K. 2019 [43]), but the details are still insufficient. So, in the light of the above the present research paper discusses the geochemical observations of the Neoproterozoic volcanic rocks of the Nakora area which is further used to understand the petrogenetic

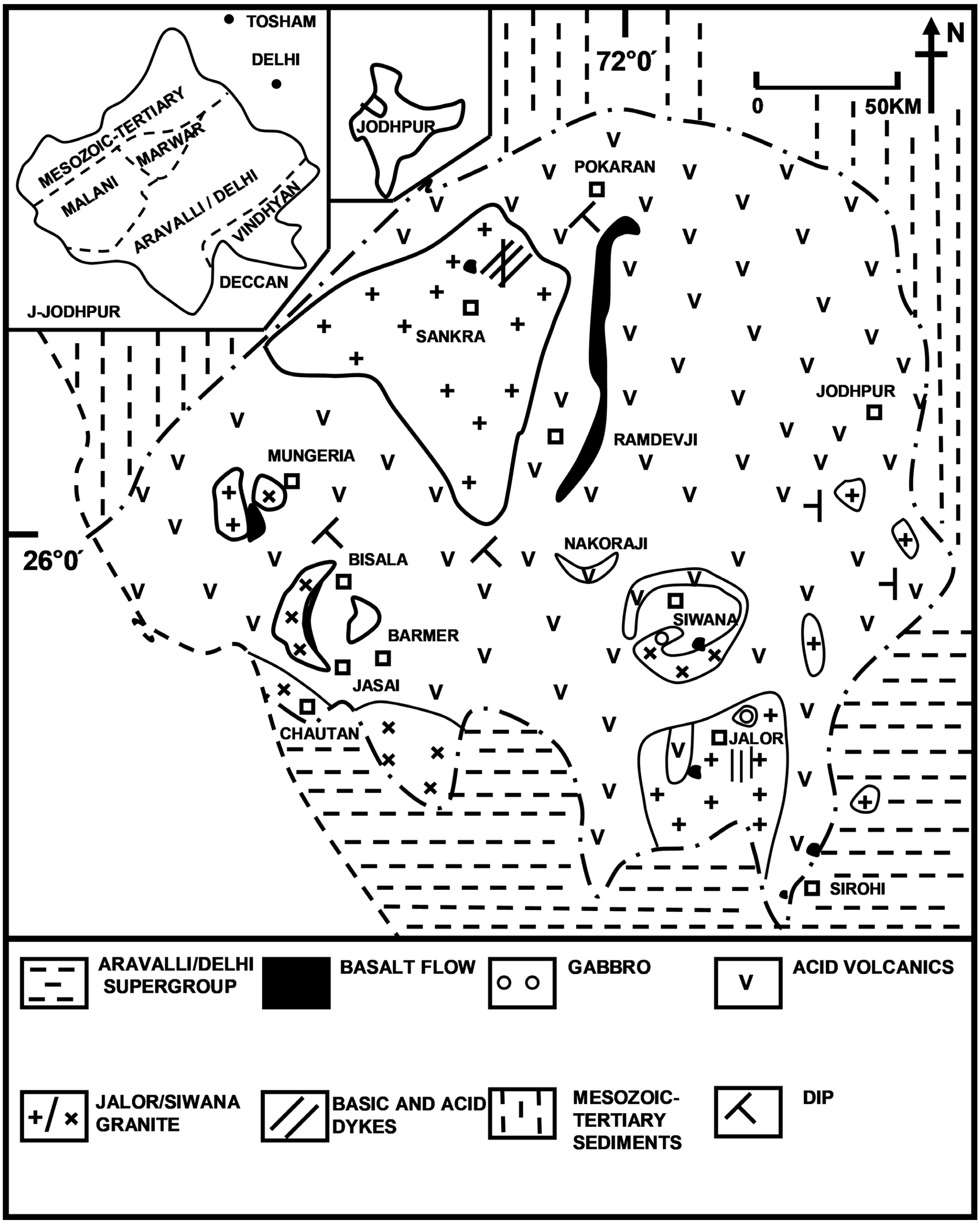


Figure 1. Geological map of Malani Igneous Suite, Rajasthan, India (modified after Vallinayagam 2003) [44].

modelling of the Malani Igneous Suite (MIS).

2. Geological Setting

A-type MIS magmatism (55,000 sq. km) is the result of tectono-magmatic event in Western Rajasthan which was related to hot spot activity (Kochhar 1984 [45]; Eby and Kochhar 1990 [8]; Kochhar 2000 [41]). In comparison to intermediate and basic rocks, the NRC has a prevalence of acid volcanic rocks and their occurrence is given below in terms of the extrusive, intrusive and dyke phases.

1) Extrusive phase: Basalt, trachyte, rhyolite, pyroclastic assemblages (ash, tuff, breccia, agglomerate and perlite)

2) Intrusive phase: Gabbro, granite

3) Dyke phase: Basalt, dolerite, rhyolite, microgranite

The above explained rock types occur on the various hills such as Sewadiya hill, Maini hill, Milara hill, Pabre hill, Mewanagar hill, Dadawari hill, Variya and Tikhi hill in the study area (**Figure 2**). Basalt is fine-grained, with colors ranging from black to dark brown to light greyish brown to dark greyish brown. Basalt shows large size vesicles (approx. 4 - 6 mm) and sometimes these vesicles are permeated by calcite. Basalt xenoliths are observed in the rhyolite (**Figure 3(a)**). Rhyolite with pyroclastic assemblages may be found in nearly every hill in the NRC, and it is mostly dark brown in colour with various hues of light brown, brick red, grey, green, yellow, blue and purple. It shows both porphyritic and

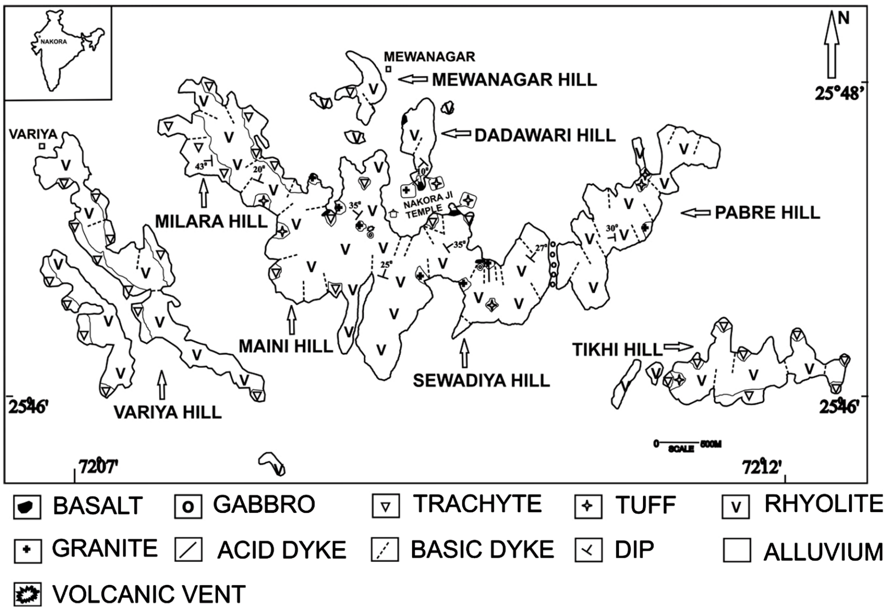


Figure 2. Geological map of Nakora area, Western Rajasthan, India.

Figure 3. (a) Basalt xenoliths observed in the rhyolite; (b) The sharp contact between rhyolite and tuff.

non-porphyritic nature. Maximum flow thickness in Nakora area *i.e.* 200 m represented by dark brown rhyolite at Sewadiya and Maini hill. The sharp contact between rhyolite and tuff (**Figure 3(b)**) is observed.

3. Sampling and Analytical Methodology

Geological field work was carried out in Nakora and adjoining areas for geological mapping (in 1:25,000 scale) using Survey of India topographical sheet no.45C/1 and Brunton Compass. Various rock types exposed in the area were identified and their interrelationships have been delineated based on a thorough field investigation (including the nature of contact between distinct lithological units, the mode of occurrence of rock types, the structure and mineralogy of outcrop rocks, and hand specimens, study of flows, intrusions, xenoliths, dykes, veins, alterations etc.). Flow stratigraphy of the area is established and various volcanic features were studied. Important rock samples were collected (in chips 3 × 5 × 7 cm and in blocks 6 × 10 × 10 cm) using geological hammer and chisels for petrographical and geochemical investigations. Field photography has been carried out depicting the important characters and interrelationships among various lithological units exposed in the study area. Petromineralogical investigations (including modal analysis and photomicrography) were carried out by using Leitz 12 pol S microscope with Swift Counter and Photoautomat.

Based on the field and petromineralogical studies, 39 samples were selected and analyzed for major elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO and P_2O_5) by using wet chemical method after Shapiro and Brannock (1962) [46] using a Systronics UV-VIS spectrophotometer-108 and Atomic Absorption Spectrophotometer (Varian 240 FS-AAS) at Department of Geology, Kurukshetra University, Kurukshetra; alkalies (Na_2O and K_2O) were determined using Systronics Mediflame Photometer-128 at Department of Chemistry, Kurukshetra University, Kurukshetra. 25 samples (9 granites, 6 rhyolites, 1 trachyte, 1 tuff, 5 basalts, 2 gabbros, 1 dolerite) were analyzed for trace (Rb, Ba, Sr, Zr, Y, V, Cr, Co, Ni, Zn, Ga, Sc, U, Th, Pb and Nb) and rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) by ICP-MS (PerkinElmer Sciex ELAN DRC II) at National Geophysical Research Institute (NGRI), Hyderabad. Standardization for major and trace elements including rare earth elements was based on USGS rock standards RGM-1, JG-2, MRG-1. The analytical precision is found to be in the error level of <5% for major and <10% for trace elements.

4. Geochemistry: Major Elements

Geochemical data is used to determine the rock nomenclature/classifications, to depict chemical variations, the nature of the igneous suite and the tectonic environment and post magmatic process, pressure and temperature conditions in the development of the suite of rocks. The norms suggest the over and undersaturation of silica as the presence of quartz in the norm shows that the rocks are oversaturated with silica; the presence of olivine, perovskite, nepheline, leucite, calcium, and orthosilicate in the norm indicates that the rocks are undersaturated with silica. The presence of corundum, on the other hand, suggests that the rocks contain an excessive amount of alumina. The excessive amount of iron is indicated by the presence of hematite and magnetite. After the formation of anorthite, diopside is formed when there is an excess of CaO. After the development of feldspars, the presence of an excessive amount of CaO allows wollastonite and calcite to form. The presence of acmite, soda, and potash metasilicates in the rocks supports their alkaline character.

Basalt: In basalts samples, SiO_2, Al_2O_3 and total alkalies (Na_2O, K_2O) (in wt%) ranges from 45.59 - 54.00, 11.20 - 17.40 and 2.85 - 7.17 (1.00 - 2.71, 1.85 - 4.46) respectively. Total iron (Fe_2O_3), TiO_2, CaO, MgO, MnO and P_2O_5 (in wt%) ranges from 9.67 - 14.50, 2.34 - 4.12, 1.68 - 7.60, 4.42 - 6.56, 1.62 - 2.70 and 0.31 - 0.88 respectively (**Table 1**).

Trachyte: In trachyte, SiO_2 varies from 66.7 wt% to 69.4 wt% (**Table 1**). Al_2O_3 ranges from 6.1 wt% to 10.5 wt%. Total alkalies (Na_2O, K_2O) and total iron (Fe_2O_3) show 4.36 - 8.37 (1.06 - 1.09, 4.3 - 7.28) and 8.1 wt% - 10.2 wt% respectively. TiO_2, CaO, MgO, MnO and P_2O_5 (in wt%) ranges from 2.67 - 2.93, 0.8 - 1.52, 0.49 - 1.47, 1.25 - 3.13 and 0.5 - 0.55 respectively.

Rhyolite: As compared to trachytes, the rhyolites show (wt%) high SiO_2 (64.80 - 71.90), high Al_2O_3 (7.20 - 13.10), low total alkalies (5.42 - 7.99) (Na_2O: 0.94 - 1.18, K_2O: 4.48 - 6.81), low total iron (5.40 - 9.70), low TiO_2 (1.61 - 2.84), high CaO (0.80 - 3.64) and high MgO (0.49 - 3.28).

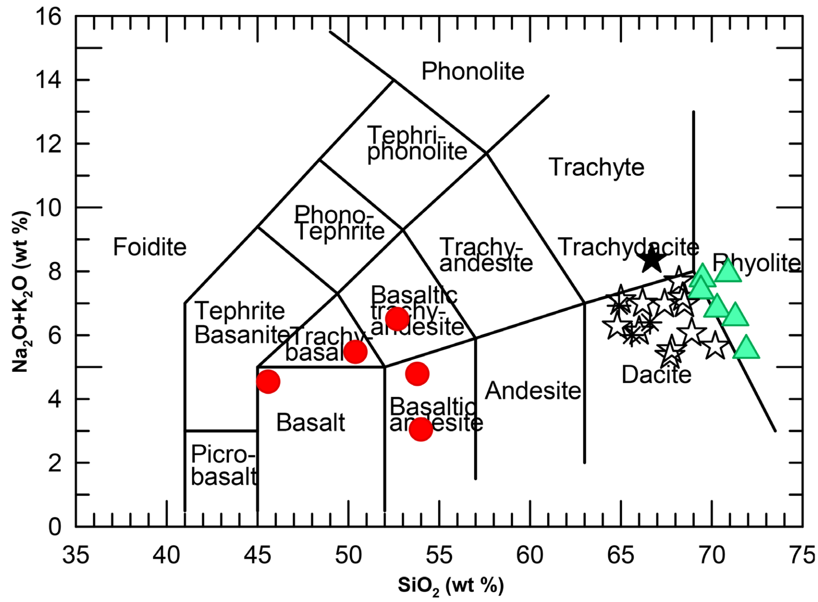
In normative composition, quartz ranges from 29.20 wt%to 46.37 wt%. Orthoclase varies from 26.47 to 40.24 whereas DI ranges from 72.76 to 84.67. AI content varies from 0.55 to 1.19 and average value is 0.84. AI value is less than 1 for ten samples (sample no. 27, 28, 118, 124, 126, 135, 152, 35, 113 and 82) which indicate peraluminous nature of rhyolites except six samples (no. 104, 164, 170, 15, 48 and 116) indicating the peralkaline nature (Giret *et al.* 1980) [47]. Alkali nature of rhyolites is also indicated by presence of acmite in above samples (no. 104, 164, 170, 15, 48 and 116). The samples (no. 28, 118, 124, 126, 135, 152, 35, 113 and 82) which show corundum (ranges from 0.29 to 5.38) indicate the aluminous nature of the rocks.

Tuff: As compare to rhyolites, the tuff shows low SiO_2 which varies from 64.90 wt% to 66.60 wt% (**Table 1**). Al_2O_3 ranges from 10.2 to 13.8 wt%. Low total alkalies (Na_2O, K_2O) and low total iron (Fe_2O_3) varies from 5.87 - 6.92 (0.94 - 1.10, 4.93 - 5.82) and 7.2 wt% - 8.9 wt% respectively. High TiO_2, low CaO, low MgO, MnO and P_2O_5 (in wt%) ranges from 2.6 - 3.16, 0.56 - 1.96, 2.13 - 2.56, 0.75 - 1.25 and 0.58 - 0.65 respectively.

Total Alkali-Silica (TAS) diagram: The Nakora acid volcanics and basic rocks (basalts) are plotted in the TAS diagram (**Figure 4**) (Le Bas *et al.* 1986) [48]. The Nakora rhyolites lie in the field of rhyolite and dacite however dacite is very close to rhyolite. The basaltic rocks lie in the field of basalt, trachybasalt, basaltic trachyandesite and basaltic andesite. The trachytes of Nakora area lie in the field of trachydacite.

Table 1. Major element data (in wt%) of Nakora rocks, Barmer District, Rajasthan.

	RHYOLITE		TRACHYTE		TUFF		BASALT	
ROCK TYPE OXIDES	Maximum value (with sample number)	Minimum value (with sample number)	Maximum value (with sample number)	Minimum value (with sample number)	Maximum value (with sample number)	Minimum value (with sample number)	Maximum value (with sample number)	Minimum value (with sample number)
SiO_2	71.9 (35)	64.8 (113)	69.4 (51)	66.7 (63)	66.6 (13)	64.9 (89)	54 (154)	45.59 (159 {2})
TiO_2	2.84 (116)	1.61 (152)	2.93 (51)	2.67 (63)	3.16 (13)	2.6 (89)	4.12 (6)	2.34 (5)
Al_2O_3	13.1 (28)	7.2 (116)	10.5 (56)	6.1 (63)	13.8 (2)	10.2 (13)	17.4 (159 {2})	11.2 (160a)
Fe_2O_3	9.7 (35)	5.4 (48)	10.2 (63)	8.1 (56)	8.9 (13)	7.2 (2)	14.5 (159 {2})	9.67 (160a)
MnO	1.9 (170)	0.13 (152)	3.13 (56)	1.25 (51)	1.25 (13)	0.75 (89)	2.7 (160a)	1.62 (159 {2})
MgO	3.28 (135)	0.49 (104)	1.47 (56)	0.49 (51)	2.56 (13)	2.13 (89)	6.56 (160a)	4.42 (154)
CaO	3.64 (164)	0.8 (135)	1.52 (51)	0.8 (56)	1.96 (89)	0.56 (13)	7.6 (154)	1.68 (6)
Na_2O	1.18 (164, 170)	0.94 (116)	1.09 (63)	1.06 (56)	1.1 (89)	0.94 (13)	2.71 (160a)	1 (6)
K_2O	6.71 (15)	4.48 (35)	7.28 (63)	4.3 (56)	5.82 (89)	4.93 (2)	4.46 (5)	1.85 (154)
P_2O_5	0.66 (113)	0.32 (104)	0.55 (56)	0.5 (63)	0.65 (89)	0.58 (13)	0.88 (160a)	0.31 (159 {2})
H_2O	0.5 (15)	0.1 (116, 126)	0.2 (63)	0.1 (51, 56)	0.4 (13)	0.2 (2, 89)	0.8 (159 {2})	0.3 (154, 6)
CIPW Norms								
Quartz	46.4 (35)	29.2 (28)	42.72 (56)	37.4 (63)	37.25 (2)	30.69 (89)	23.27 (6)	3.71 (159 {2})
Orthoclase	39.7 (15)	26.5 (35)	37.29 (51)	25.41 (56)	34.39 (89)	29.13 (2)	26.36 (5)	10.93 (154)
Albite	9.22 (135, 152)	2.85 (170)	8.97 (56)	1.9 (51)	9.31 (89)	7.95 (13)	22.93 (160a)	8.46 (6)
Anorthite	8.25 (28)	0.44 (135)	0.38 (56)	---	5.48 (89)	0.75 (2)	30.22 (159 {2})	5.79 (6)
Corundm	5.38 (82)	0.29 (35)	3.96 (56)	---	3.11 (13)	---	---	---
Diopside	8.08 (170)	2.63 (104)	0.65 (63)	---	7.05 (2)	2.18 (89)	7.64 (6)	0.79 (159 {2})
Hypersthene	8.17 (135)	0.34 (170)	3.66 (56)	1.22 (51)	6.38 (13)	---	9.7 (160a)	2.72 (154)
Wollastonite	0.72 (164)	0.21 (104)	2.69 (63)	---	6.13 (2)	5.3 (89)	15.44 (159 {2})	9.75 (154)
Olivine	---	---	8.13 (63)	---	---	---	---	---
Acmite	6.29 (170)	0.84 (48)	6.3 (51)	1.78 (56)	---	---	---	---
Illmenite	6.28 (152)	0.41 (15, 82)	5.53 (56)	2.67 (51)	2.67 (13)	1.6 (89)	5.78 (160a)	3.47 (159 {2})
Hematite	9.7 (35)	5.11 (48)	7.39 (63)	6.52 (51)	8.9 (13)	7.2 (2)	14.5 (159 {2})	9.67 (160a)
Apatite	1.53 (113)	0.74 (104)	1.27 (56)	1.16 (63)	1.51 (89)	1.34 (13)	2.04 (160a)	0.72 (159 {2})
Sphene	5.14 (15)	0.49 (170)	2.83 (51)	1.02 (63)	2.59 (2)	2.24 (89)	1.92 (6)	0.79 (159 {2})
Rutile	2.48 (82)	0.81 (48)	0.47 (51)	---	2.24 (13)	---	3.81 (154)	1.04 (5)
DI	84.7 (104)	72.76 (164)	78.26 (51)	70.71 (63)	77.08 (13)	74.39 (89)	54.07 (6)	33.37 (159 {2})
AI	1.19 (170)	0.55 (82)	1.59 (63)	0.62 (56)	0.73 (13)	0.51 (2)	0.73 (160a)	0.31 (159 {2})
Na + K	7.92 (104)	5.52 (35)	8.37 (63)	5.36 (56)	6.92 (89)	6 (2)	6.5 (160a)	3.04 (154)
Na/K	0.24 (135)	0.15 (28)	0.25 (56)	0.15 (63)	0.22 (2)	0.17 (13, 89)	0.72 (160a)	0.23 (5)
KN/C	7.06 (135)	2.19 (15)	7.47 (63)	4.85 (51)	8 (13)	1.66 (2)	2.85 (6)	0.4 (154)
A/CNK	1.44 (82)	0.47 (164)	1.43 (56)	0.55 (63)	1.75 (2)	1 (89)	1.67 (6)	0.12 (160a)
An/An + b	0.51 (28)	0.05 (135)	0.04 (56)	---	0.37 (89)	0.08 (2)	0.76 (159 {2})	0.24 (160a)
Mg#	---	---	---	---	---	---	54.1 (154)	45.9 (159 {2})



Symbols: Rhyolite (▲), Dacite (☆), Trachydacite (★), Tuff (✳), Basalt (●).

Figure 4. Total Alkali Silica (TAS) diagram showing the classification of Nakora Volcanics.

5. Geochemistry: Trace and Rare Earth Elements

Basalt: In basalts, Ni, Cu and Zn ranges from 10.69 - 69.28, 23.08 - 50.14 and 127.63 - 293.47 (in ppm) respectively (Table 2). Average values of Ni, Cu and Zn are 35.05, 35.18 and 190.09 respectively. Rb, Sr, Y and Zr show a range (average) from 41.42 - 87.13 (60.47), 140.88 - 214.83 (178.34), 42.9 - 156.22 (74.87) and 97.81 - 1604.39 (501.98) respectively. The radioactive elements (Th and U) ranges from 1.28 - 6.88 (average 2.92) and 0.17 - 1.04 (average 0.41) respectively. In the rare earth elements (Table 3), La, Ce, Eu and Yb ranges from 15.55 - 90.77, 48.55 - 211.55, 3.19 - 6.64 and 2.34 - 11.19 and average values are 34.91, 86.74, 4.05 and 5.43 respectively. Eu/Eu* varies from 0.24 - 0.38 with average of 0.31.

Trachyte: It has Ni (23.09), Cu (9.88), Zn (226.61), Rb (144.69), Sr (11.94), Y (227.51), Zr (2009.4), Th (17.39) and U (1.78) concentrations in ppm. In REE, La, Ce, Nd, Sm, Eu and Yb show 94.05, 243.67, 133.58, 30.08, 2.24 and 17 ppm concentration with Eu/Eu* ratio of 0.08 ppm.

Rhyolite: As compared to trachyte, it shows low ranges of Ni, Cu, Zn and Rb and vary from 1.64 - 3.27, 0.22 - 0.54, 20.79 - 57.58 and 79.03 - 138.43 respectively. Sr, Y, Zr, Th and U show high values and ranges from 8.5 - 16.8, 99.44 - 240.18, 786.43 - 4053.14, 7.18 - 19.71 and 1.36 - 3.07 respectively. In REE, La, Ce, Nd, Sm, Eu and Yb ranges from 13.09 - 91.68 (low), 45.98 - 188.27 (low), 46.56 - 137.53 (high), 10.55 - 31.84 (high), 0.76 - 2.51 (high) and 10.98 - 25.89 (high).

Tuff: As compared to average concentrations in rhyolite, it shows low Ni (1.68), low Cu (0.18), low Zn (30.06), high Rb (184.02), low Sr (12.31), high Y (306.05), high Zr (2500.05), high Th (22.57) and high U (5.92) concentrations in ppm. In REE, La, Ce, Nd, Sm, Eu and Yb show low 35.38, low 212.07, high

Table 2. Trace element data (in ppm) of Nakora rocks, Barmer District, Rajasthan.

ROCK TYPE	RHYOLITE		TRACHYTE	TUFF	BASALT	
	Maximum value (with sample number)	Minimum value (with sample number)	Value from single sample (59)	Value from single sample (89)	Maximum value (with sample number)	Minimum value (with sample number)
Sc	2.29 (126)	1.13 (15)	2	1.82	35.52 (154)	26.25 (6)
V	4.99 (28)	1.61 (15)	4.15	3.68	247.32 (154)	106.42 (5)
Cr	16.89 (126)	1.53 (28)	23.68	4.62	67.48 {159 (2)}	23.52 (154)
Co	0.87 (126)	0.38 (27)	0.61	0.62	36.47 (6)	18.85 (5)
Ni	3.27 (164)	1.64 (28)	23.09	1.68	69.28 {159 (2)}	10.69 (154)
Cu	0.54 (27)	0.22 (164, 15)	9.88	0.18	50.14 (160a)	23.08 (154)
Zn	57.58 (126)	20.79 (28)	226.61	30.06	293.47 (154)	127.63 (160a)
Ga	33.54 (126)	23.71 (28)	30.76	27.44	42.09 (5)	18.61 (6)
Rb	138.43 (126)	79.03 (164)	144.69	184.02	87.13 (5)	41.42 (154)
Sr	16.8 (28)	8.5 (15)	11.94	12.31	214.83 (6)	140.88 (5)
Y	240.18 (28)	99.44 (15)	227.51	306.05	156.22 (5)	42.9 (6)
Zr	4053.14 (28)	786.43 (124)	2009.4	2500.05	1604.39 (5)	97.81 (160a)
Nb	81.24 (28)	20.97 (164)	82.57	52	78.96 (5)	6.82 (154)
Cs	1 (27)	0.31 (15)	0.74	0.98	1.34 (5)	0.82 (160a)
Ba	132.48 (27)	52.15 (154)	80.29	100	407.11 (154)	286.58 {159 (a)}
Hf	54.38 (28)	24.01 (124)	50.44	75.54	33.17 (5)	2.43 (160a)
Ta	2.42 (126)	1.23 (27)	8.44	2.23	7.03 (5)	0.36 (160a)
Pb	25.13 (27)	3.84 (15)	2.92	5.82	4.85 (154)	1.29 (6)
Th	19.71 (28)	7.18 (164)	17.39	22.57	6.88 (5)	1.28 (6)
U	3.58 (126)	1.36 (15)	1.78	5.92	1.04 (5)	0.17 (160a, 154)
Ba/Rb	1.56 (164)	0.6 (124)	0.55	0.54	9.83 (154)	3.56 {159 (2)}
Rb/Sr	11.12 (15)	5.61 (28)	12.12	14.95	0.62 (5)	0.22 (6)
Zr/Rb	42.99 (28)	7.9 (27)	13.89	13.59	18.41 (5)	2.14 (160a)
Ba/Sr	12.94 (164)	4.56 (28)	6.72	8.12	2.56 (154)	1.53 {159 (2)}
Sr/Y	0.1 (27)	0.07 (28, 124)	0.05	0.04	5.01 (6)	0.9 (5)
Nb/Y	0.36 (15)	0.18 (164, 124)	0.36	0.17	0.51 (5)	0.09 (154)
Zr/Nb	49.89 (28)	22.67 (15)	24.34	48.08	24.89{159 (2)}	11.11 (160a)
Zr/Y	16.88 (28)	4.8 (124)	8.83	8.17	10.27 (5)	1.37 (154)
Y/Nb	5.65 (124)	2.75 (15)	2.76	5.89	11.55 (154)	1.98 (5)
K/Rb	0.06 (15, 164)	0.03 (126)	0.02	0.03	0.07 (160a)	0.03{159 (2)}

Table 3. Rare earth element data (in ppm) of Nakora rocks, Barmer District, Rajasthan.

ROCK TYPE	RHYOLITE		TRACHYTE	TUFF	BASALT	
	Maximum value (with sample number)	Minimum value (with sample number)	Value from single sample (56)	Value from single sample (89)	Maximum value (with sample number)	Minimum value (with sample number)
La	91.68 (28)	13.09 (15)	94.05	35.38	90.77 (5)	15.55 (154)
Ce	188.27 (28)	45.98 (15)	243.67	212.07	211.51 (5)	48.55 (154)
Pr	29.9 (28)	10.5 (15)	26.55	23.12	25.47 (5)	6.52 (160a)
Nd	137.53 (28)	46.56 (15)	133.58	102.38	129.09 (5)	38.66 (160a)
Sm	31.84 (28)	10.55 (15)	30.08	28.03	28.22 (5)	9.1 (160a)
Eu	2.51 (28)	0.76 (15)	2.24	1.67	6.64 (5)	3.19 (160a)
Gd	28.24 (28)	8.81 (15)	29.27	26.89	27.1 (5)	9.15 (6)
Tb	5.54 (28)	1.91 (15)	4.5	6.68	3.85 (5)	1.2 (6)
Dy	41.3 (28)	16.3 (15)	33.37	52.36	26.37 (5)	7.66 (6)
Ho	4.9 (28)	2.15 (15)	7.14	6.35	5.32 (5)	1.42 (6)
Er	17.48 (28)	7.68 (15)	20.64	22	14.31 (5)	3.57 (6)
Tm	2.43 (28)	1.06 (15)	2.63	3.01	1.72 (5)	0.37 (6)
Yb	25.89 (28)	10.98 (15)	17	31.08	11.19 (5)	2.34 (6)
Lu	4.31 (28)	1.73 (15)	3.69	5.01	2.6 (5)	0.52 (6)
Ce/Nd	1.59 (126)	0.99 (15)	1.82	2.07	1.64 (5)	1.13 (154)
Ce/Sm	7.07 (126)	4.36 (15)	8.1	7.57	7.5 (5)	4.18 (154)
Gd/Yb	1.41 (124)	0.8 (15)	1.72	0.87	3.91 (6)	2.18 (154)
Ce/Yb	11.38 (126)	4.19 (15)	14.33	6.82	23.07 (6)	7.3 (154)
Eu/Eu*	0.12 (27)	0.06 (164)	0.08	0.06	0.38 (6)	0.24 (5)

102.38, high 28.03, high 1.67 and high 31.08 ppm concentrations respectively. Eu/Eu* ratio shows 0.06 ppm concentration.

Nb/Y vs Zr/TiO_2 diagram (Winchester and Floyd 1977) [49] is used in which the selected samples of Nakora volcanics are plotted. The selected acid volcanic rocks are lying in the field of rhyodacite/dacite and the Nakora basic rocks lie in the field of andesite/basalt (**Figure 5**).

6. Primitive Mantle Normalized Patterns of Trace Elements

The Nakora acid volcanic rocks have high LREE enrichment than the HREE which is observed in primitive mantle normalized multi-element diagram using normalization values from Sun and McDonough (1989) [50] and show quite parallel pattern (**Figure 6**). All the samples show negative Ba, Sr, Eu and Ti anomalies. Sr and Eu depletion is thought to be linked to feldspar fractionation or their retention in refractory minerals resistant to melting in the lower

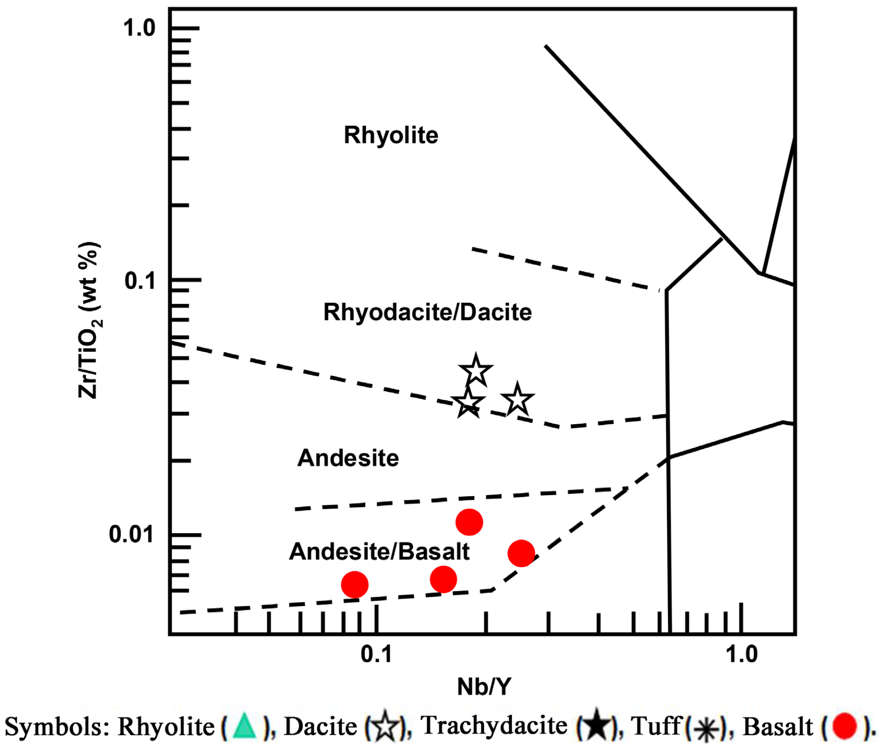


Figure 5. Nb/Y vs Zr/TiO_2 plot for Nakora volcanics (Winchester and Floyd, 1977) [49].

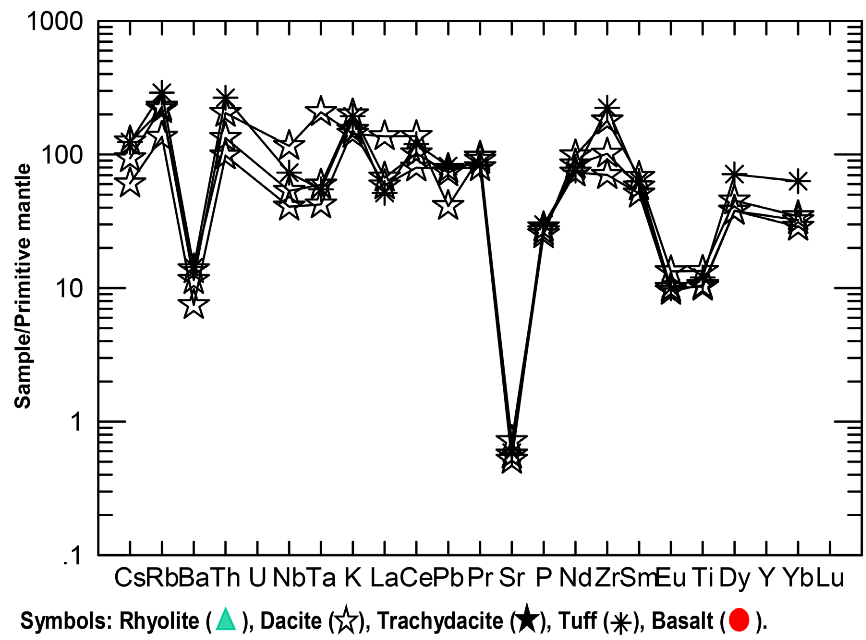


Figure 6. Primitive mantle normalized trace element patterns for selected Nakora acid volcanic rocks (124, 56, 152 & 89) (Sun and McDonough, 1989) [50].

crust (Green 1980) [51].

7. Chondrite Normalized Patterns of Rare Earth Elements

The chondrite normalized patterns for acid volcanics are shown in **Figure 7**

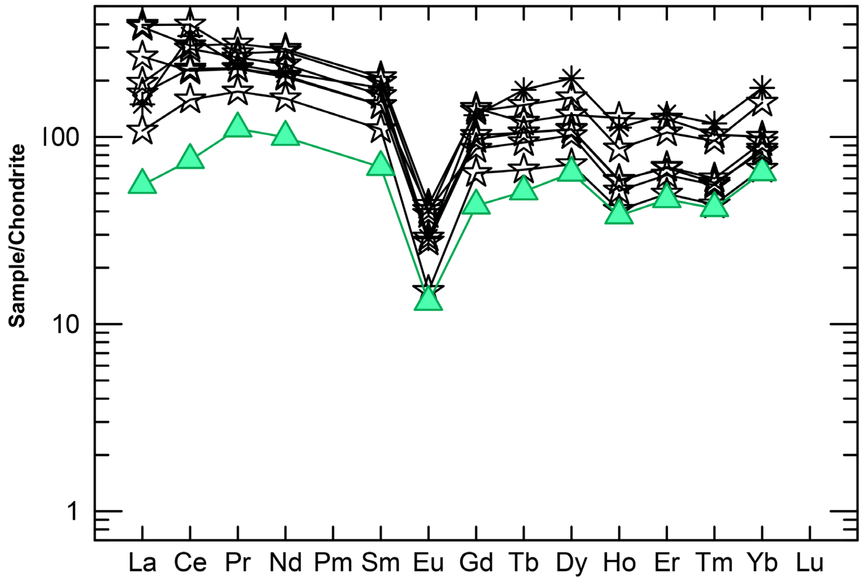


Figure 7. Chondrite normalized REE patterns for Nakora acid rocks (27, 28, 164, 15, 56, 124, 126 & 89) (Sun and McDonough, 1989) [50].

(normalization values after Sun and McDonough (1989) [50]. The Nakora acid volcanics show higher concentrations of flat LREE with increasing negative anomaly and lower concentration of HREE. The REE concentration of rhyolite is less as compared to dacite and tuff. The very pronounced negative Eu anomaly indicates strong fractionation and partioning by feldspar. A significant distinguishing feature in REE values is related to the magnitude of Eu anomalies.

REE patterns in the Nakora acid volcanics and basic rocks are characterized by sub-parallel patterns with strong negative Eu anomaly (Eu/Eu* = 0.06 to 0.12, avg. 0.08). But in basic, positive Eu anomaly (Eu/Eu* = 0.24 to 0.44, avg. 0.34) is observed. The Nakora basic rocks are less enriched in LREE and HREE as compared to acid volcanics. On the other hand, rhyolites are showing almost similar abundances of REE which is probably due to their comagmatic nature. In general, the fractionation is more in HREE as compared to LREE in Nakora acid volcanic rocks, whereas in basics, almost flat normalized patterns are observed. Thus the sub-parallel REE patterns of all Nakora rocks suggest a common magmatic source.

8. Petrogenesis

The basic rocks of MIS are derived by different degree of partial melting of lithosphere source rocks (alkaline and subalkaline) in Aravalli block (Vallinayagam 2003) [44]. Kundal basic rocks are derived from Fe enriched source with higher Fe/Mg ratio than primitive mantle source (Singh and Vallinayagam 2004) [24]. Siwana basic rocks are formed as a result of low degree partial melting of crustal rocks which are enriched in incompatible elements and Fe under the influence of fluid/melt in the lithosphere (Vallinayagam 2001) [21].

Bhilwara area are considered as sources for Nakora basalts. In Figure 8, the chondrite normalized pattern is derived for partial melt by 33% partial melting leaving a residue 48% plagioclase, 33% opx and 19% cpx which closely approaches the REE patterns of Nakora basalts.

In Figure 9 Nakora gabbros are considered as source. It represents the melt generated by 37% batch partial melting of the Nakora gabbro leaving a residue consisting of 48% plagioclase, 33% opx and 19% cpx which approaches the REE patterns of Nakora basalts.

Hence the Nakora basalts can be derived from the source similar of Nakora gabbro. Here, Bhilwara mafic metavolcanic which is taken from outside the study area and Nakora gabbros taken from the study area are showing maximum similarities with the REE patterns of the Nakora basalts. Hence, the Nakora basalts could have been derived by different degrees of partial melting of source rock similar to Bhilwara mafic metavolcanic/Nakora gabbros composition.

Malani volcanics (Siwana, Barmer and Korna) are generally associated with the central type of eruptions. Alkalinity is associated with central type of eruptions and increase by the breakdown of alkali pyroxene to alkali amphibole by

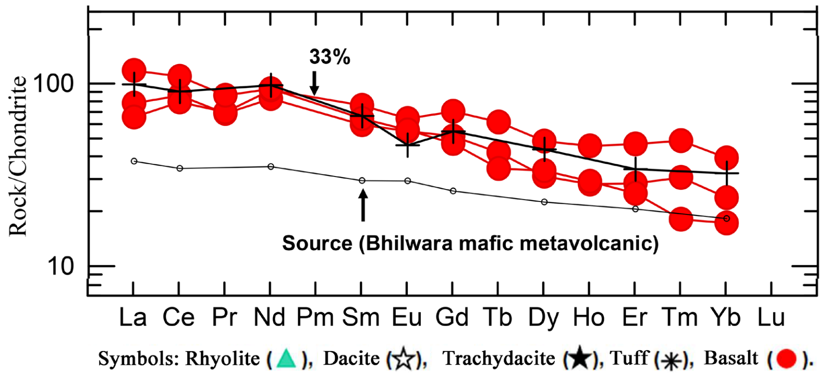


Figure 8. Chondrite normalized diagram showing the calculated REE patterns for melts produced by 33% batch melting of mafic metavolcanic from Bhilwara leaving a residue consisting of 48% plagioclase, 33% opx and 19% cpx.

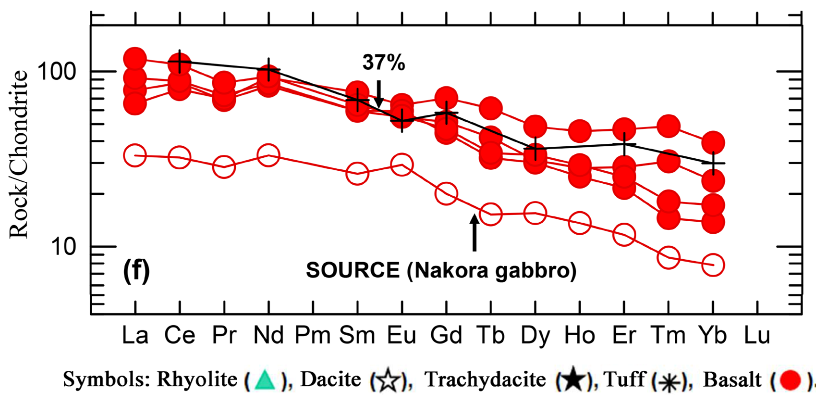


Figure 9. Chondrite normalized diagram showing the calculated REE patterns for melts produced by 37% batch melting of Nakora gabbro leaving a residue consisting of 48% plagioclase, 33% opx and 19% cpx.

lowering of fO_2 (Bailey 1969) [52]. Silicic magma can be related to partial melting of pre-existing crust, enriched in silica, alumina and alkalies (Mc Burney 1984) [53]. The stability of peralkaline silicates is buffered by arfvedsonite-aegirine equilibrium under NNO buffer conditions (Grapes *et al.* 1979) [54]. Generally, peralkaline magma exists with non-peralkaline volcanics within a centre and peralkaline rhyolites are produced by late stage fractionation of metaluminous rhyolites (Ewart 1982) [55]. In REE modeling of Nakora acid volcanic rocks, normalization values are taken from Sun and McDonough (1989) [50] and the calculations were made using the mineral/melt partition coefficients of Arth (1976) [56]; Arth and Barker (1976) [57]; Fujimaki (1984) [58] and Green and Pearson (1985) [59].

Siwana rhyolite is considered as a similar source rock for REE modeling of Nakora acid volcanics. The calculated melt is derived by 30% batch partial melting of Siwana rhyolite leaving a residue consisting of 45% alkali feldspar, 40% quartz, 10% plagioclase and 5% cpx (**Figure 10**). The calculated REE pattern of source rock is similar to REE pattern of Nakora acid volcanics. Hence, Nakora acid volcanic rocks could have been generated from a source similar to Siwana rhyolite.

In **Figure 11**, the calculated REE patterns for 25% partial melting of banded

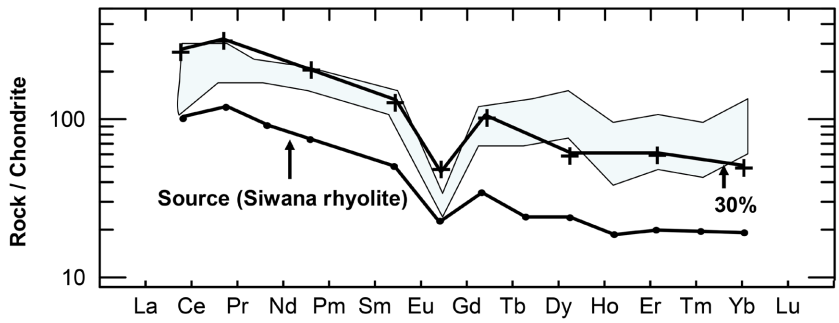


Figure 10. Chondrite normalized diagram showing the calculated REE patterns for melts produced by 30% batch partial melting of Siwana rhyolite leaving a residue consisting of 45% alkali feldspar, 40% quartz and 10% plagioclase and 5% cpx. The REE abundances of the Nakora acid volcanics (shaded zone of rhyolites and trachytes) are comparable to that of magma derived from the source.

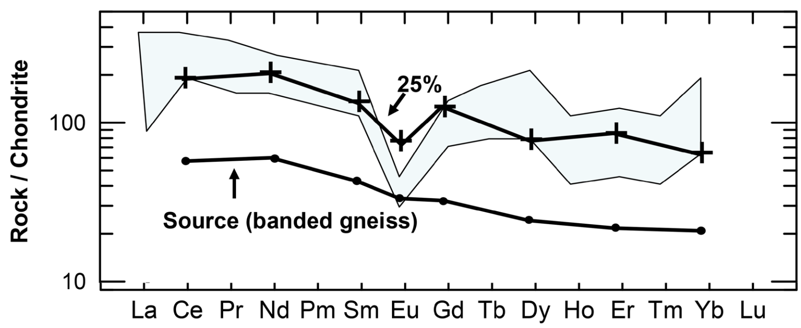


Figure 11. Chondrite normalized diagram showing the calculated REE patterns of Nakora acid rocks (shaded zone) for melts produced by 25% batch partial melting of banded gneiss leaving a residue consisting of 45% alkali feldspar, 40% quartz and 10% plagioclase and 5% cpx.

gneiss from Kolar Schist Belt and 35% partial melting of Delhi granite is considered. The source sample is leaving a residue consisting of 45% alkali feldspar, 40% quartz, 10% plagioclase and 5% cpx. REE pattern of banded gneiss is showing more similarities with REE patterns of Nakora acid volcanic rocks. After the Siwana rhyolite, banded gneiss may be the source rock for Nakora acid volcanics.

9. Conclusions

Nakora basalts have transitioned from basalt to basaltic andesite. The Nakora basalts show the close affinity to continental field in the MgO-Fe_2O_3-Al_2O_3 diagram (Pearce *et al.* 1977) [60]. As compared to trachytes, the rhyolites show high SiO_2, high Al_2O_3, low total alkalies, low total iron, low TiO_2, high CaO and high MgO. The presence of acmite indicates the alkali nature of rhyolites. As compared to rhyolites, the tuff shows low SiO_2, high Al_2O_3, low total alkalies, low total iron, high TiO_2, low CaO and low MgO.

In the trace and REE geochemical studies, Nakora basalts show high Cu, Zn, Rb, Y, Zr, Th, U, La, Ce, Eu and Yb and low content of Ni and Sr. In the primitive mantle normalized diagram of trace elements, Nakora basic rocks show LREE enriched nature with negative Nb, Ta, Sr and Zr anomalies. As compared to trachyte, rhyolites show low ranges of Ni, Cu, Zn, Rb, La and Ce and high contents of Sr, Y, Zr, Th, U, Nd, Sm, Eu and Yb. Tuff shows low concentrations of Ni, Cu, Zn, Sr, La and Ce and high value of Rb, Y, Zr, Th, U, Nd, Sm, Eu and Yb than rhyolites. Higher concentrations of LREE and lower concentration of HREE are observed in Nakora acid volcanics. Nakora acid volcanics are enriched in Rb, Th, K and Zr. The low Sr in Nakora acid volcanics may be due to plagioclase fractionation and Zr enrichment in the source indicates the original alkaline nature of the magma.

Petrominerolgical and geochemical data suggest that the rocks of NRC are formed from comagmatic source by cogenetic process in rift tectonic setting. Petrogenetic modeling studies indicate that the Nakora basic rocks may be derived from a rock similar to Bhilwara mafic metavolcanic/mixed Nakora gabbros by different degrees of partial melting. Nakora acid volcanic rocks could have been derived by different degree of partial melting of source rock similar to Siwana rhyolite/banded gneiss from Kolar Schist Belt.

The acid volcanic (rhyolites and trachytes) flows are dispersed after the eruption of magma through a volcanic vent in NRC. Basalt-trachyte-rhyolite association suggests that the large amount of heat is supplied to the crust from the magma chamber before the eruption. MIS is characterized by within plate environment which is related to hot spot activity and represents the tensional environment in their emplacement as indicated by various elliptical/ring structures. Trans-Aravalli block of the Indian shield shows the similarities with Central Iran, Nubian-Arabian shield, Medagascar, South China, Somalia and Seychelles in terms of intraplate, mantle plume, crust-mantle interaction, anorogenic nature and extensional tectonic setting. Hence, mantle plume and crust-mantle interaction can play an important role in understanding the genesis of MIS which should be studied in the future.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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