

Geochemistry of volcanic flows of Nakora area of Malani igneous suite, Northwestern India: Constraints on magmatic evolution and petrogenesis

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Abstract

The geochemical characteristics of volcanic flows of Nakora area of Malani Igneous Suite have been determined to understand their magmatic evolution and petro-genetic aspects. Geochemically, they are high in silica, total alkalis, high field strength elements (HFSE), low ion lithophile elements (LILE), rare metals and rare earth elements; represent A-type affinity with potential mineralization associations. Here, we carried out average geochemical data bank of representative samples of 44 individual lava flows of isolated hill-locks. The relative enrichment of trace elements and negative anomalies of Sr, Eu, P and Ti in the multi-element spider diagrams suggests that the emplacement of the lava flows was controlled by complex magmatic processes i.e. fractional crystallization, partial melting, magma mixing, crustal contamination and assimilation. Moreover, NRC magma provides new geochemical approaches to understand geodynamic evolution of MIS and emplaced in plume related extensional geodynamic settings in NW Indian shield.

Keywords: Geochemistry; Volcanic flows; Nakora; Malani Igneous Suite; Rajasthan; Rodina

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1. Introduction

The widely distributed Malani Igneous Suite (bimodal, anorogenic, plume related, area; 55000 km² and thickness; 3-7 km) in Trans-Aravalli Block (TAB) has a geodynamic interest as they represent complex magmatic process occurred during Neoproterozoic time. This event indicated multiphase volcanic and plutonic igneous activities in the form of voluminous silicic lava which was erupted between ~780-750 Ma. The geological conditions required to erupt such voluminous felsic magma suggest high rate of magma generation, migration and accumulation in Northwestern peninsular India (Wang et al., 2017; Kumar et al., 2019). The Malani Igneous Suite (MIS) displays cyclic sequence of volcanic flows (felsic and mafic) in association with South China, Seychelles, Madagascar, Australia, Africa, Arabia, Siberia, Somalia, Kazakhstan, Egypt, Namibia and Tarim, which establish co-tectonic linkage in their emplacement (positive test for Rodina reconstruction) (Kochhar, 2015). In previous literature, many geoscientists carried out field observations, petrography, whole rock geochemical data, isotopic and EPMA interpretations to construct various tectonic models of MIS, but no perfect consensus on chemical stratigraphical study are recorded which could evaluate phase petrology of different volcanic flows. NRC consisting residual hill tops, inselbergs and scattered hummocks belongs to Neoproterozoic MIS. NRC has been deeply incised, revealing stacks of lava flows. Rock types in the studied area include, in order of decreasing abundance; (a) acid lava flows (rhyolites, trachytes and tuff), (b) basaltic lava flows and (c) dikes (dolerite, basalt and microgranitic). The distribution of elemental abundances and rock-suites marked chemical stratigraphy in the order of their evolution in complex tectonic setting. A-type rock-suites are dominant in TAB of northwestern peninsular India which exposed in the form of scattered and ring structured during Neoproterozoic time. The magma generation of MIS was considered co-magmatic with other segments of anorogenic nature worldwide, during same period of time (Kochhar, 2015). The controversial assumptions are going on to propose a close linkage among the continental blocks of Greater India, South China, Seychelles,

Madagascar, Australia, Africa, Arabia, Siberia, Somalia, Kazakhstan, Egypt, Namibia and Tarim which we argue, that is, MIS was emplaced due to plume related rift environment. There are mainly two privileges and accepted models for Malani geodynamic system: (a) Plume related extensional model (Pareek, 1981; Bhushan, 1985; Eby and Kochhar, 1990; Baskar, 1992; Dhar et al., 1996; Singh and Vallinayagam, 2003, Singh et al., 2006; Vallinayagam and Kumar, 2008; Kumar and Vallinayagam, 2014; Kochhar, 2015; Sharma and Kumar, 2017; Kumar et al., 2019; Sharma et al., 2019) and (b) Subduction model (Gregory et al., 2009; Ashwal et al., 2013; Wang et al., 2017). There is a direct relationship between mantle plume anorogenic magmatism and assembly of Supercontinent in late proterozoic time. The seismic, gravity, thermal and chemical anomalies in the TAB of Indian shield are symptomatic of plume activity in the region (Kochhar, 2000b). The isotopic data interpreted by some previous workers recorded that MIS magmatism was contemporaneous with breakup of Rodina during Neoproterozoic and formation of new supercontinent in starting of Cambrian period; Gondwanaland (Kochhar, 2015). The petrographical, geochemical and radioactive characteristics of NRC in MIS fulfill the requirements of A-type, anorogenic and promising high mineralized magmatic suites.

More than 200 lava flows were recognized during field investigation and were compiled in the geochemical studies. Several different flows with mineralogical variations are associated with different hills viz., Tikhi, Pabre, Sewadiya, Maini, Milara, Mewanagar, Variya and Dadawari in NRC. The acidic magmatic rocks are more dominant than basic rocks in NW peninsular India. They are characterized by high silica, TiO_2 , Al_2O_3 , Fe_2O_3 , high HFSE, LREE, HREE and high (H_2O , F) in late-stage, indicating A-type, anorogenic and extensional tectonic environment (Kumar and Vallinayagam, 2014). Most of the volcanoes and volcanic successions are complex. They are characterized by rapid lateral and vertical changes in facies and composition. Petrogenetic studies of these volcanoes are strongly dependent on three dimensional stratigraphic controls which are influenced by a large number of variables. The geochemical study shows changes in lava compositions reflecting different parental magmas and the secular dominance of different petrogenetic processes. Most of the previous studies on ancient volcanic belts have relied on chemical discrimination diagrams to deduce the tectonic setting of the volcanic successions, with little emphasis on petrogenetic processes or stratigraphic relationships. Geochemistry can also be the basis for defining a member, bed or subdivision of a geologic unit. Any geochemical criteria could be used to define chemo-stratigraphic units (silica, aluminium, carbonate content, or a ratio of one or more elements to another etc.). Geochemistry is useful in areas of sparse outcrop for making correlations between separate, distant sections of stratigraphy, especially in layered intrusions and granite terrains which have poor outcrops (Leybourne et al., 1997). Here, chemical trends of the different flows can be used to correlate individual hills of Nakora Ring Complex (NRC).

2. Geological Setting

The lithologies studied during this investigation are part of the Malani Igneous Suite, Western Rajasthan, India, covering an area of 55,000 sq km with light - dark colored lava flows and pyroclastic materials. MIS consists of felsic volcano-plutonic with less amount of mafic lithounits represent the largest felsic magmatism. They are well exposed in Tusham (Haryana), Jhunjhunu, Siwana, Jalor (Rajasthan) and also in Nagar Parkar (Sind-Pakistan), Kirana (Lahore-Pakistan) areas. They are characterized as A-type, peralkaline, metaluminous to peraluminous, anorogenic and owe its origin to hotspot tectonics (Kochhar, 1984; 2000; 2004; Pareek, 1981; Bhushan and Chandrasekaran, 2002; Vallinayagam, 2004a, 2004b; Sharma and Kumar, 2017; Kumar et al., 2019; Sharma et al., 2019). The occurrence of NRC rocks demarcated by different phases viz., extrusive (Basalt, trachyte, rhyolite and pyroclastic assemblages), intrusive (Gabbro and granite) and dyke phases (Basalt, dolerite, rhyolite and microgranite). The volcanic rocks are predominantly of acidic in nature with less volume of pyroclastic materials and subordinate basic flows with or without vesicles. The location and geological sketch map of Nakora with reference to MIS is shown in Figure 1. To study geochemistry in terms of geochemical data, Stratigraphic resolution of the volcanic rocks was identified in terms of several flows of different 8 hills (Tikhi, Pabre, Sewadiya, Maini, Milara, Mewanagar, Variya and Dadawari hill) of the studied area. Dadawari hill consists of massive columnar joints which represent a shield building stage. The Sewadiya hill lavas are overlain by the crudely stratified proximal and vent-facies breccias reflect the systematic growth and maturation of this vent-complex. In NRC, 44 volcanic flows have been exposed comprising of 4 basalts, 26 rhyolites, 7 trachytes and 7 tuffs on 8 different hills (Tikhi hill – 4, Pabre hill – 7, Sewadiya hill – 7, Maini hill – 8, Milara hill – 4, Mewanagar hill – 5, Variya hill – 3, Dadawari hill – 6 flows) (Figure 2) (Table 1).

Field criteria adopted to mark individual flows are identification of the volcanic assemblages, pyroclasts, colour, form, structure, minerals – type, occurrence, association, alteration, ratio of phenocrysts/groundmass and order of superposition of volcanic flows in different hill. The total thickness of 44 flows is 1776 m out of which 40 flows (1743 m total thickness) are of felsic composition (> 60% SiO_2). The approximate thicknesses of individual flows and phenocrysts (Q-quartz, F-feldspar): groundmass ratio (P:G) are given in the Table 1. This paper deals with the comparison of chemical characters of the volcanic flows and their relationship with physical characters from different hills to illustrate the geochemical aspects of the study area.

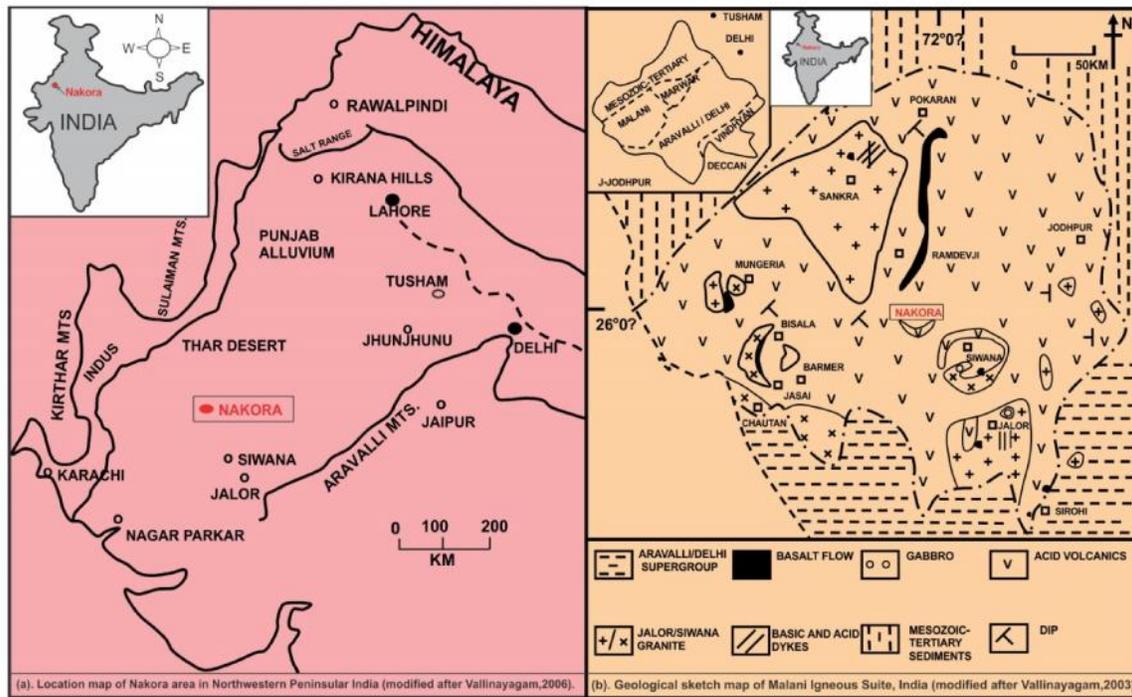


Fig.1. (a) Location map of Nakora area in Northwestern peninsular India (modified after, Vallinayagam, 2006). (b) Geological sketch map of Malani Igneous Suite, India (modified after, Vallinayagam, 2003).

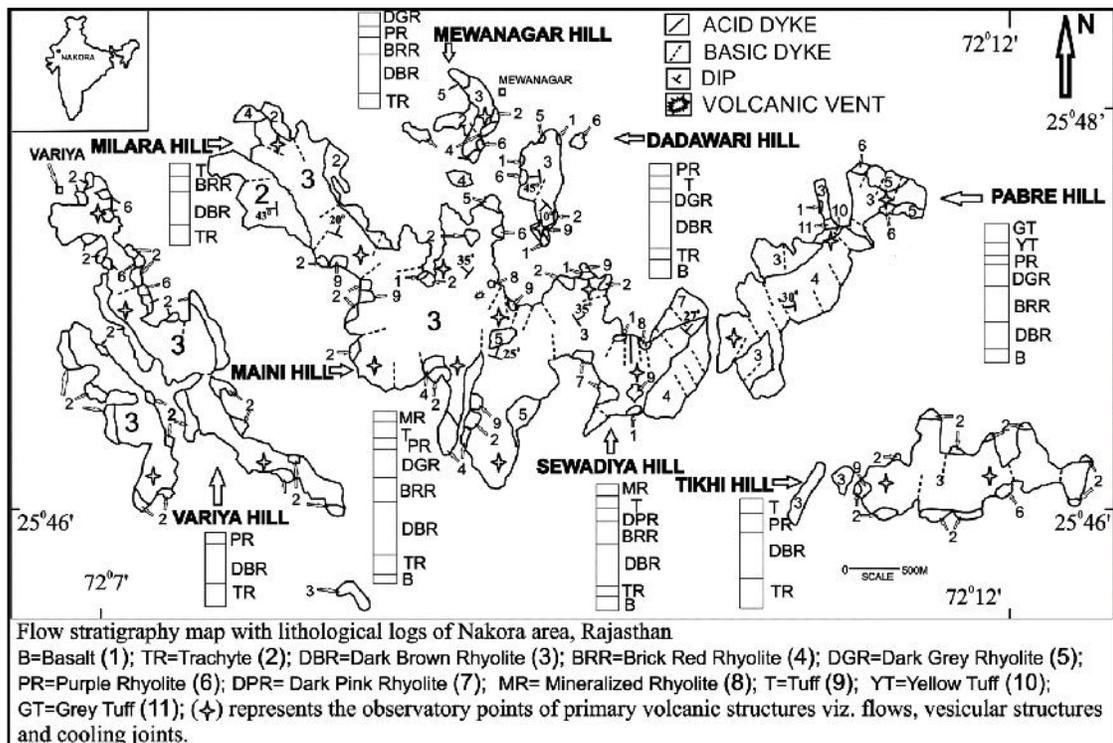


Fig. 2. Flow Stratigraphy Map with lithologs of Nakora Area, Western Rajasthan, India (modified after, Vallinayagam and Kumar, 2008).

Table 1. Flow stratigraphy of Nakora area, Rajasthan, India (modified after Vallinayagam and Kumar, 2008).**TIKHI HILL**

Rock	Thickness in meters	Pheno-crysts	Diagnostic properties
Tuff	8	Q	Tuff shows shades viz. light yellow to light grey, at few places shows glassy material in it, small vesicles observed, quartz as phenocrysts is distributed in the entire rock, P:G ratio is 4:96.
Purple rhyolite	10	Q+F	Purple rhyolite is observed in small area having P:G ratio 7:93 with very small amount of vesicles. This portion lies in Southern side of the hill and difficult to identify joint pattern here.
Dark brown rhyolite	110	Q+F	Dark brown rhyolite occupy large areas, shows phenocrysts of quartz and feldspar, P:G ratio is 10:90; contains coffee brown rhyolite also, mostly rhyolite is enveloped by trachyte. This zone contains 2-4 facies joints with 1-2 m height.
Trachyte	15	F+Q	Light grey and blue colour, non porphyritic to porphyritic nature with very small no of vesicles, P:G ratio is 3:97, middle zone exposed mainly in outer portion of Tikhi hill consists mainly vertical joints having 0.5 to 1 m height.

PABRE HILL

Rock	Thickness in meters	Pheno-crysts	Diagnostic properties
Grey tuff	10	Q	After tracing some distance from previous observed yellow tuff becomes into grey tuff, P:G ratio is 4:96.
Yellow tuff	8	Q	Tuff shows yellow colour but rarely green colour having P:G ratio is 4:96.
Purple rhyolite	4	Q+F	Purple rhyolite occupy very small area, quartz and feldspar are present as phenocrysts having P:G ratio 9:91, few places very small vesicles noted .
Dark grey rhyolite	50	F+Q	Eastern end of Pabre hill is exposed with dark grey rhyolite, feldspar and quartz are phenocrysts but quartz in less amount, P:G ratio is 5:95.
Brick red rhyolite	90	F+Q	Brick red rhyolite with small amount of quartz having P:G ratio 8:92, 4-5 facies joints developed , Western part of the hill showing radiating and inclined joints with caves (2*5 m dimensions) and spheroidal weathering also exposed.
Dark brown rhyolite	60	F+Q	Mostly outer part of Pabre hill is covered by DBR rhyolite with phenocrysts of feldspar (pink) and quartz, P:G ratio is 15:85, small tubes / caves (upto 5*10 m dimensions) are exposed.
Basalt	10	Q	Grey colour, occur as a small flow (at Northern side of the hill) with phenocryst of quartz, P:G ratio is 2:98.

SEWADIYA HILL

Rock	Thickness in meters	Pheno-Crysts	Diagnostic properties
Mineralised rhyolite	5	F+Q	Mineralised rhyolite is enriched with iron oxides, quartz veins and vugs (few cm to 5cm size) P:G ratio is 10:90, at few places phenocrysts covers more than 30% of rock.
Tuff	10	Q	Light green tuff consists quartz as a phenocrysts, P:G ratio is 5:95 and this occurs as smaller area as patch like structure in Sewadiya hill, spheroidal weathering also exposed.

SEWADIYA HILL (cont'd)

Rock	Thickness in meters	Pheno-crysts	Diagnostic properties
Dark pink rhyolite	50	F+Q	Orthoclase feldspar as phenocrysts shows 1–5 mm size, P:G ratio is 15:85, at places no. of phenocrysts occupy 40% of rock body. Small tubes / caves are also exposed.
Brick red rhyolite	80	F+Q	Phenocrysts of orthoclase feldspar gives rise brickred colour to rock; P:G ratio is 20:80, phenocrysts (1–3 mm) size varies with distance, at few places flow bands are present in the rock , small tubes/caves (2*5 m dimensions) also exposed.
Dark brown rhyolite	200	F+Q	Rhyolite flows are mostly porphyritic in nature having feldspar and quartz as a phenocrysts, P:G ratio is 12:88, DBR occupy 70% area of Sewadiya hill, middle portion of this flow contains horizontal flow, upper part shows well developed joints with more height (upto 10 m),caves (5*10 m) and tubes exposed.
Trachyte	8	F	Trachyte shows blue colour and look like rhyolite in hand but less vitreous with orthoclase as a phenocrysts, P:G ratio 12:88.
Basalt	10	Q	Basalt underlies tuff and shows light grey to dark grey colour, having quartz phenocrysts , vesicles filled by calcite, P:G ratio is 5:95, spheroidal weathering also exposed.

MAINI HILL

Rock	Thickness in meters	Pheno-crysts	Diagnostic properties
Mineralized rhyolite	10	F+Q	Pink mineralized – iron oxides rich rhyolite is very close to vent having quartz veins and vugs and also shows calcite veins, P:G ratio is 25:75, it contained geod rhyolite which shows spheroidal weathering.
Tuff	5	Q	Flow bands are easily recognizable in yellow to green tuff, quartz occurs as phenocryst, P:G ratio 7:93, this is highly fractured tuff with multiple nucleus and exposed spheroidal weathering also.
Purple rhyolite	5	Q+F	At few places purple rhyolite shows very less vesicles, quartz is dominated than feldspar, P:G ratio is 8:92.
Dark grey rhyolite	20	F+Q	Feldspar and quartz are phenocrysts, P:G ratio is 6:94.
Brick red rhyolite	30	F+Q	Brick red non porphyritic rhyolite also exposed and also shows flow bands, feldspar and quartz as phenocrysts and shows P:G ratio 7:93.
Dark brown rhyolite	200	F+Q	Dark brown rhyolite having feldspar and quartz as a phenocrysts and exposed 70% area of Maini hill, P:G ratio is 12:88, back of temple a small outcrop (50*100 m dimensions) contained inclined joints (20°–30° dipping towards West), Northern flank of this hill shows spheroidal weathering also.
Trachyte	20	F+Q	Light blue colour trachyte exposed at lower end of the hill, feldspar and quartz as a phenocrysts, P:G ratio 30:70, Maini is covered by small–2 outcrops of this hill.
Basalt	5	Q	Basalt underlies dark brown rhyolite, shows dark grey to black colour having quartz as a phenocrysts and P:G ratio is 5:95.

MILARA HILL

Rock	Thickness in meters	Pheno-crysts	Diagnostic properties
Tuff	15	Q	Occur as small patches and has quartz as a phenocryst, P:G ratio is 7:93.
Brick red rhyolite	30	F+Q	Brick red rhyolite is exposed at lower end of Milara hill, feldspar and quartz as a phenocrysts shows P:G ratio 6:94.
Dark brown rhyolite	150	F+Q	Dark brown rhyolite is maximum dominant almost 60% of Milara hill, P:G ratio 9:91.
Trachyte	50	F+Q	Dark blue porphyritic trachyte covers almost 30% of Milara hill, feldspar and quartz as phenocrysts and shows P:G ratio 25:75, alternating layers of trachyte are common here.

MEWANAGAR HILL

Rock	Thickness in meters	Pheno-crysts	Diagnostic properties
Dark grey rhyolite	25	F+Q	Dark grey rhyolite is mostly concentrated in Northern end of Mewanagar hill, feldspar and quartz occurs as phenocrysts, P:G ratio is 15:85.
Purple rhyolite	15	Q+F	In purple rhyolite quartz is more dominant than feldspar, feldspar size varies from 1mm to 5 mm, P:G ratio is 12:88.
Brick red rhyolite	30	F+Q	Brick red rhyolite is mostly concentrated in two patches near Mewanagar hill, P:G ratio is 12:88.
Dark brown rhyolite	70	F+Q	Dark brown rhyolite lies in central portion of Mewanagar hill and shows 70 m thickness, feldspar and quartz are phenocrysts, P:G ratio is 20:80.
Trachyte	15	F+Q	Dark blue trachyte of Mewanagar hill shows flow bands, feldspar and quartz are phenocrysts, P:G ratio is 25:75, vesicles are small, feldspar % varies with place to place.

VARIYA HILL

Rock	Thickness in meters	Pheno-crysts	Diagnostic properties
Purple rhyolite	20	F+Q	Purple rhyolite is observed near Variya village and as a small outcrops in the scattered pattern, feldspar and quartz occur as phenocrysts, P: G ratio 5:95, vesicles are observed at few places.
Drak brown rhyolite	100	F+Q	Porphyritic nature of rhyolite is decreases in Variya hill as compared to another hills, P:G ratio 10:90, non porphyritic nature also observed.
Trachyte	30	F+Q	Trachyte is exposed along the fringes of Variya hill, feldspar and quartz are scattered homogeneously, P:G ratio is 10:90.

DADAWARI HILL

Rock	Thickness in meters	Pheno-Crysts	Diagnostic properties
Purple rhyolite	10	Q+F	Quartz content is slightly more than feldspar, both are scattered uniformly, P:G ratio is 13:87.
Tuff	20	F	Tuff overlies the basalt, presence of orthoclase feldspar as a phenocryst, P:G ratio is 7:93.

DADAWARI HILL (cont'd)

Rock	Thickness in meters	Pheno-crysts	Diagnostic properties
Dark grey rhyolite	25	Q+F	Dark grey rhyolite contains quartz and feldspar as a phenocrysts, DGR is located in small area towards Northern end of Mewanagar, P:G ratio is 7:93.
Dark brown rhyolite	125	F+Q	Almost in the all area it is exposed, feldspar and quartz are phenocrysts, P:G ratio is 18:82, feldspar and quartz are almost in equal amount and uniformly distributed, perfecticity can be easily observed with sharp facies having upto 8 m height.
Trachyte	5	F+Q	Trachyte is observed at few places, P:G ratio is 10:90.
Basalt	8	Q	Outcrop of basalt is exposed upto main road of Nakora temple, basalt has sharp contact with dark brown rhyolite, it consists mainly quartz as phenocryst, P:G ratio is 5:95, few and large size vesicles present, spheroidal weathering also exposed.

4. Petrography

Most of the acid lavas within the studied area show porphyritic, aphyritic, spherulitic (radiating growth of feldspar and quartz from a common centre) and perlitic textures. They consist of phenocrysts of orthoclase, quartz and arfvedsonite as essential minerals in the quartzofeldspathic groundmass. The groundmass is devitrified to a microcrystalline aggregates of quartz, alkali feldspar, blue colour amphibole (riebeckite), pyroxene (light green aegirine), blood red aenigmatite, magnetite and hematite. The fine quartz-feldspathic groundmass represents the flow directions of the lava flow. According to model mineral compositions, they fall in the field of alkali rhyolite and quartz alkali trachyte (quartz 25-45 and orthoclase 30-51 vol. wt %) in the quartz-alkali feldspar-plagioclase (QAP diagram of Streckeisen, 1978) diagram. Basic flows show ophitic – subophitic textures with up to 45 % plagioclase content with pyroxene and Fe-Ti oxides being the primary interstitial phases. It contains a fine grained groundmass with phenocrysts of plagioclase and pyroxene along with microlites of plagioclase. Opaque minerals are also within the groundmass.

5. Geochemistry

There are 39 samples from different hills are used to explain the chemical parameters in terms of major elements and 25 samples in terms of trace and rare earth elements of the different flows. The trace and rare earth elements for Nakora granites were determined by ICP-MS (PerkinElmer Sciex ELAN DRC II) at National Geophysical Research Institute, Hyderabad. Standardization for trace and rare earth elements was based on USGS rock standards RGM-1, JG-2 and MRG-1. The analytical precision is found to be in the error level of <10% for trace and rare earths elements.

5.1. Major elements geochemistry: Out of 44 volcanic flows, 39 samples have been taken from different hills for major geochemical data analyses. 2 samples of rhyolites, 1 of tuff and 4 of basalts are taken from Sewadiya hill. Maini hill contains 5 rhyolites and 1 basalt. Milara hill consists of 1 rhyolite and 1 tuff. Pabre hill consists of 3 rhyolites and 1 tuff. Dadawari hill consists of 1 rhyolite. Variya hill consists of 1 rhyolite and 3 trachytes. Tikhi hill contains 3 rhyolites. The different volcanic flows are distinguished from each other on the basis of major elements and their ratio / index viz SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , Total alkalies ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) content, A/CNK ratio, AI (Aqpaitic Index) and DI (Differentiation Index). The Nakora acid volcanics and basic rocks (basalts) are plotted in the TAS diagram (Figure 3). 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 trachy-andesite and basaltic andesite. The trachytes of Nakora area lie in the field of trachydacite.

(a) *SiO₂ content:* Most of the basaltic flows are exposed on Sewadiya hill in which basalts show the SiO_2 content from 45.59 – 53.8 wt %. Trachyte flows are mainly exposed on Variya hill and their SiO_2 concentration varies from 66.7–69.4 (wt %). The rhyolite flows of Maini hill show a wide variation in silica content (65.0–71.9) (wt %) which shows the maximum SiO_2 concentration also. The rhyolites of Sewadiya and Pabre hill show the ranges of SiO_2 which are 64.8–68.2 and 67.4–70.2 respectively. The maximum amount of silica in tuff is 66.6 which is located on Pabre hill.

(b) *TiO₂ content:* The maximum TiO_2 content (2.34–4.12) (wt %) is observed in the Sewadiya basalts but in case of acid rocks, it varies 2.67–2.93 for Variya trachytes. Tikhi rhyolites show 2.28–2.84 which is comparable with the Variya trachytes.

(c) *Al₂O₃ content:* In case of basalts, Al_2O_3 varies 11.2–17.4 for Sewadiya basalts. Al_2O_3 varies 7.6–11.7 for Sewadiya rhyolites, 7.3–13.1 for Maini rhyolite, 8.4–11.5 for Pabre rhyolites and 7.2–10.5 for Tikhi rhyolites. The Maini rhyolites show high amount of Al_2O_3 as compared to rhyolites of other areas.

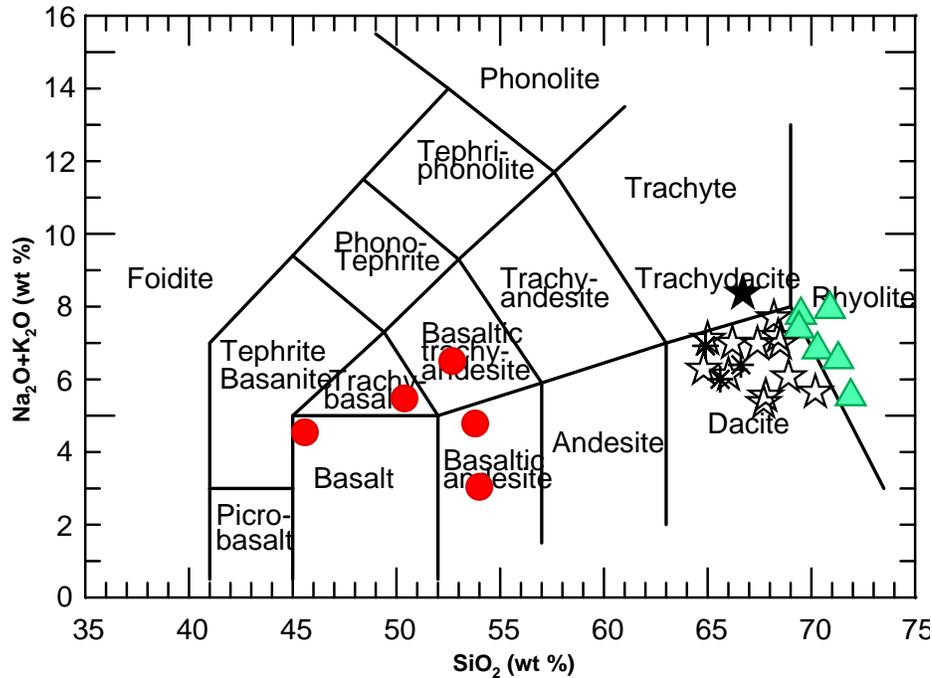


Fig. 3. Total alkali-silica diagram shows classification of the volcanic rocks (Le Bas et al.,1986)

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

(d) *Fe₂O₃ content:* Fe₂O₃ varies 9.67–14.5 and 7.4–9.2 for Sewadiya basalts and rhyolites respectively. Variya trachytes show 8.1–10.2 (wt %) of Fe₂O₃. It ranges 6.9–9.7 for Maini rhyolites, 6.05–7.5 for Pabre rhyolites, 8.1–9.1 for Tikhi rhyolites. Maini rhyolites show high value of Fe₂O₃ as compared to other rhyolites of different hills.

(e) *Total alkalis content:* Total alkalis (Na₂O + K₂O) varies 2.85–7.17 for Sewadiya basalts, 5.36–8.37 for Variya trachytes, 6.28–7.69 for Sewadiya rhyolites, 5.43–7.33 for Maini rhyolites, 7.77–7.80 for Pabre rhyolites and 5.53–6.58 for Tikhi rhyolites. In case of tuffs, the maximum concentration of total alkalis (6.83) is observed on Milara hill.

(f) *A/CNK content:* A/CNK varies 0.12–1.67 for Sewadiya basalts, 0.55–1.43 for Variya trachytes, 0.54–1.10 for Sewadiya rhyolites, 0.44–1.08 for Maini rhyolites, 0.53–1.29 (high than others rhyolites) for Pabre rhyolites and 0.7–1.11 for Tikhi rhyolites.

(g) *DI content:* DI varies between 33.37–54.07 (Sewadiya basalts), 70.71–78.26 (Variya trachytes), 74.44–74.54 (in wt %) (Sewadiya rhyolites), 72.76–81.64 (Maini rhyolites), 77.5–78.19 (Pabre rhyolites) and 73.66 – 81.78 (Tikhi rhyolites).

(h) *AI content:* AI for Sewadiya basalts varies within a range of 0.31–0.73 whereas Variya trachytes lie within 0.62–1.59. Sewadiya rhyolites show the range (0.62–1.19) (high than other rhyolites), for Maini rhyolites (0.63–1.13), for Pabre rhyolites (0.70–1.06) and for Tikhi rhyolites (0.66–1.06).

Malani rhyolites are characterized by high SiO₂, Al₂O₃, Fe₂O₃ and DI than the rocks of others Nakora hills. The average major element data for different volcanic flows is summarized in the Table 2 which is used to explain the comparison of chemical characteristics for volcanic flows from any particular hill.

Table 2. Average major element data (wt %) of volcanic flows from Nakora hills.

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O +K ₂ O	DI	AI	A/CNK
Sewadiya Hill									
Tuff	65.6	2.9	13.8	7.2	0.6	3	75.4	0.5	1.8
Rhyolite	66.5	2.4	9.7	8.3	2.3	6.9	74.5	0.9	0.8
Basalt	49.7	3.2	14.3	12	5	5	43.7	0.5	0.9
Maini Hill									
Rhyolite	68.4	2.5	10.2	8.3	2.3	6.3	77.2	0.8	0.8
Basalt	54	3.5	12.6	12.1	7.6	1.5	42.3	0.3	0.7

Note: The above mentioned values are the mean of the range. Bold letters represent the highest values.

Table 2 (cont'd). Average major element data (wt %) of volcanic flows from Nakora hills.

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	DI	AI	A/CNK
Milara Hill									
Tuff	64.9	2.6	12.3	8.5	2	3.4	74.4	0.7	1
Rhyolite	70.9	1.85	8.9	6.7	1.8	4	84.7	1	0.8
Pabre Hill									
Tuff	66.6	3.2	10.2	8.9	0.6	3.2	77	0.7	1.3
Rhyolite	68.8	2.5	10	6.8	2.2	7.7	77.5	0.9	0.9
Dadawari Hill									
Rhyolite	68.5	1.6	11.9	8.7	1.4	3.5	81	0.7	1.2
Variya Hill									
Rhyolite	70.3	2.7	7.8	5.4	1.4	3.4	81.3	1	0.9
Trachyte	68	2.8	8.5	9.1	1.2	6.9	74.4	1.1	0.9
Tikhi Hill									
Rhyolite	69.5	2.6	8.8	8.5	1.6	2.9	77.7	0.9	0.9

Note: The above mentioned values are the mean of the range. Bold letters represent the highest values.

The NRC rocks are formed about 732±41 Ma ago with basic rocks as a first episode which is followed by acid volcanics and culminated with acid/basic dykes. Sewadiya basalts show high content of TiO₂, Al₂O₃, Fe₂O₃, CaO and A/CNK than the rhyolites whereas silica, total alkalis (Na₂O+K₂O), DI and AI concentrations are low as compared to acid volcanics from the same hill. The Sewadiya basalt flows have oriented vesicles filled with calcite and show spheroidal weathering which is very less exposed in Maini basalts. Same chemical compositional behavior is reported by Maini hill except A/CNK ratio. Maini basalts have high content of A/CNK ratio than the rhyolites. The Maini basalts are more enriched in silica, TiO₂, Fe₂O₃, CaO and A/CNK ratio than Sewadiya basalt flows. The Sewadiya basalts underlie the tuff whereas Maini basalt flows underlies the dark brown rhyolite. Variya trachytes are more enriched in TiO₂, Al₂O₃, Fe₂O₃, total alkalis and AI than the rhyolites whereas rhyolites are showing more concentration of silica, CaO, DI and A/CNK ratio than the trachytes. Variya trachytes are scattered at outer parts of the hill with homogeneous distribution of quartz and feldspar in rock samples. Sewadiya tuffaceous rocks are showing enrichment of TiO₂, Al₂O₃, DI and A/CNK ratio than the rhyolites.

The rhyolites from Sewadiya hill show high content of silica, Fe₂O₃, CaO, total alkalis and AI than the tuffaceous rocks. Sewadiya rhyolites are characterized by small tubes/caves (2*5 m) and well developed joints. But Milara hill is showing less sharp contacts between rhyolite and tuff than the contacts shown by Sewadiya hill. Milara tuff contains high TiO₂, Al₂O₃, Fe₂O₃, CaO and A/CNK ratio than the Milara rhyolites. The Milara rhyolites show the maximum silica content than the other rhyolites from the different Nakora hills. Generally, the Nakora rhyolites are more enriched in silica, total alkalis, DI and AI than the tuffaceous rocks. Almost similar chemical behaviour is shown by Pabre hill as shown by Milara and Sewadiya rhyolites. Pabre tuff shows more TiO₂, Al₂O₃, Fe₂O₃, CaO and A/CNK ratio than rhyolites. Pabre rhyolites with average thickness of 51 m show the radiating and inclined joints. Tikhi and Dadawari hills are showing enrichment of silica. Therefore, the major rock geochemistry attests that they belong to A-type, anorogenic, bimodal, plume-related and formed in complex geodynamic setting.

5.2. Trace and rare earth elements geochemistry: There are 25 samples are taken from different Nakora hills for trace and rare earth data (in ppm) analysis. Sewadiya hill consists of 4 basalts. Maini hill contains 3 rhyolites and 1 basalt. Milara hill consists of 1 tuff whereas Pabre hill consists of 2 rhyolites. Variya hill consists of 1 trachyte but Tikhi hill contains 1 rhyolite. The rocks from different hills are compared with each other on the basis of Ni, Cu, Zn, Rb, Zr, Th and U (in ppm) concentrations.

Sewadiya basalts show 11.62–69.28 of Ni, 27.02–50.14 of Cu, 127.63–251.07 of Zn, 45.62–87.13 of Rb, 97.81–1604.39 of Zr, 1.28–6.88 of Th and 0.17–1.04 of U (in ppm). Sewadiya basalts are showing enrichment of Ni, Cu, Rb, Zr, Th and U as compared to Maini basalts except Zn (Table 3).

Table 3. Average trace elements data (in ppm) of volcanic flows from Nakora hills.

	Ni	Cu	Zn	Rb	Zr	Th	U
Sewadiya Hill							
Basalt	41.1	38.2	164.2	65.2	600.5	3.2	0.5
Maini Hill							
Rhyolite	2.3	0.4	30.6	102	2004.3	12.8	3.2
Basalt	10.7	23.1	293.5	41.4	107.8	1.7	0.2

Note: Bold letters represent the highest values

Table 3 (cont'd). Average trace elements data (in ppm) of volcanic flows from Nakora hills.

	Ni	Cu	Zn	Rb	Zr	Th	U
Milara Hill Tuff	1.7	0.2	30.1	184	2500	22.6	5.9
Pabre Hill Rhyolite	2.6	0.3	47.5	116.5	976.5	9.5	2.5
Variya Hill Trachyte	23.1	9.9	226.6	144.7	2009.4	17.4	1.8
Tikhi Hill Rhyolite	1.8	0.2	31.1	86.3	786.4	8.4	2.4

Note: Bold letters represent the highest values

For classification of Nakora volcanic rocks, Nb/Y vs Zr/TiO₂ diagram (Winchester and Floyd, 1977) 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 are lying in the field of andesite / basalt (Figure 4). In the Th–Hf/3–Nb/17 plot, the Nakora basic rocks are showing the less concentrations of Nb as well as away from the mantle trend and dispersed along the Th-Hf/3 join (Figure 5).

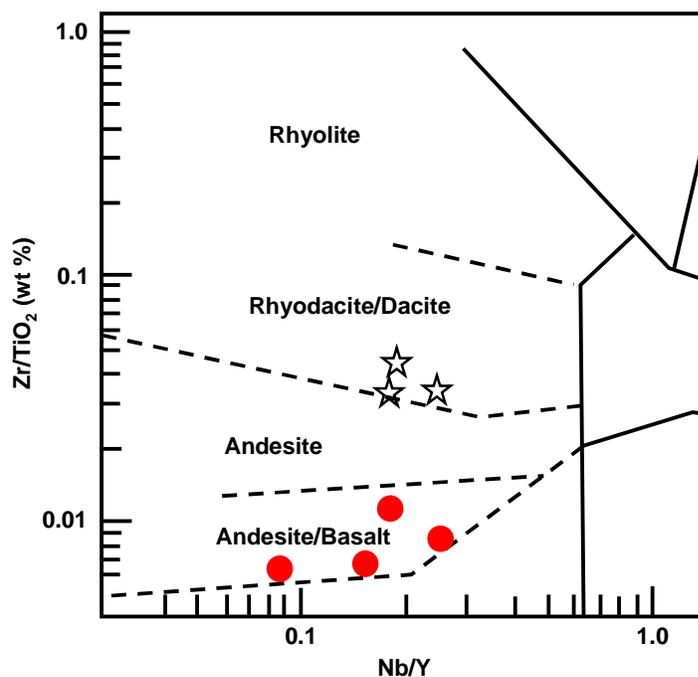


Fig. 4. Nb/Y vs Zr/TiO₂ plot for Nakora volcanics (Winches and Floyd, 1977). Symbols are same as in Fig. 3.

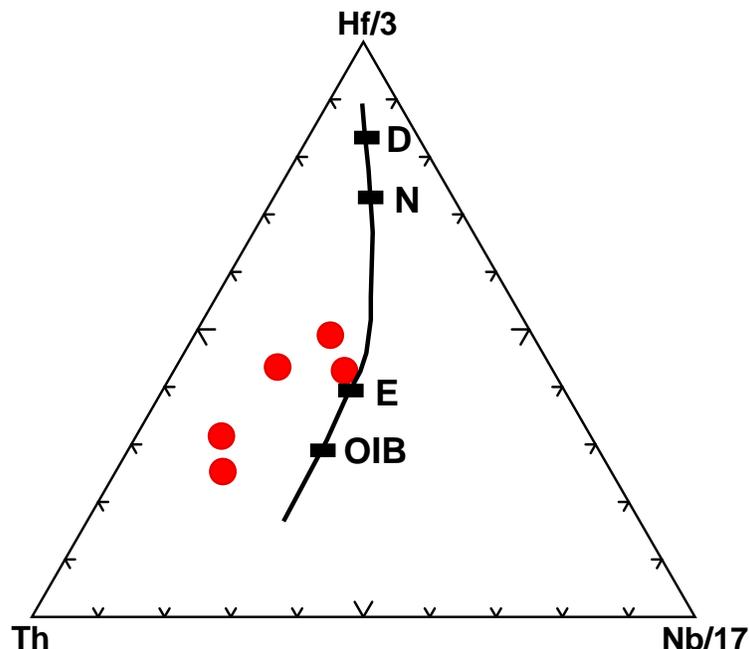


Fig. 5. Th–Hf/3–Nb/17 plot showing increasing subduction component toward the Th apex and away from the mantle trend (After Wood 1980). N- and E-type MORB and OIB data from Sun & McDonough (1989). D-type MORB from Leybourne & Van Wagoner (1991).

Variya trachytes show 1.79 Ni, 0.23 Cu, 31.13 Zn, 86.27 Rb, 786.43 Zr, 8.35 Th and 2.35 U (in ppm). Maini rhyolites show 1.64–3.27 of Ni, 0.22–0.54 of Cu, 20.79–50.77 of Zn, 94.28–133.34 of Rb, 906.44–4053.14 of Zr, 7.18–19.71 of Th and 2.27–3.7 of U (in ppm). The average values of Ni, Cu, Zn, Rb, Zr, Th and U are given in the Table 3. As compared to Maini rhyolites, Pabre rhyolites show low (2.4–2.9) value of Ni, high (0.22–0.29) Cu, high (30.09–57.58) Zn, high (94.49–138.43) Rb, low (818.49–1134.88) Zr, low (7.78–11.3) Th and low (1.36–3.58) U (in ppm). Pabre rhyolites contain high Ni, Zn and Rb whereas Maini rhyolites are enriched in Zr, Cu, Th and U (Table 3). As compared to Variya trachytes, Milara tuff shows low 1.68 Ni, low 0.18 Cu, low 30.06 Zn, high 184.02 Rb, high 2500.05 Zr, high 22.57 Th and high 5.92 U (in ppm). Furthermore, the concentrations of important rare earth elements of different hill-locks are shown in Table 4.

Table 4. Average rare earth elements data (in ppm) of volcanic flows from Nakora hills

	La	Ce	Nd	Eu	Gd	Tb	Dy	Yb
Sewadiya Hill								
Basalt	18.53	52.69	38.66	3.19	10.57	1.57	7.89	4.03
Maini Hill								
Rhyolite	63.65	138.08	97.7	2.36	17.75	3.5	25.92	14.69
Basalt	15.55	48.55	43.08	3.73	14.47	2.31	12.29	6.65
Milara Hill								
Tuff	35.38	212.07	102.38	1.67	26.89	6.68	52.36	31.08
Pabre Hill								
Rhyolite	25.59	96.88	74.86	0.87	13.17	2.5	18.13	11.48
Variya Hill								
Trachyte	94.05	243.67	133.58	2.24	29.27	4.5	33.37	17
Tikhi Hill								
Rhyolite	46.1	180.89	113.88	1.68	21.03	3.94	27.84	15.9

These values (in ppm) suggest that lava flows related to different hill have close resemblance with A-type magmatic affinity through different sources. The spider diagrams (Figures 6, 7) of different average rocks from different hills show the variable abundances of trace and rare earth elements. The trace element patterns of Maini and Sewadiya basalts is almost parallel to each other except Nb, Pb and K. Maini basalts are showing positive Nb and Pb anomalies whereas Sewadiya basalts are showing negative anomaly with high concentration of K as compare to Maini basalts (Figure 6). The Milara tuff is showing more enrichment of trace elements (e.g. HFSE) than the rhyolites from Maini and Pabre rhyolites except Pb which is more enriched by Maini rhyolites. Milara tuff occurs as small patches in field but most of the area is covered by rhyolites in Maini hill. Pabre rhyolites are more depleted but Maini rhyolites are showing intermediate composition between Milara tuff and Pabre rhyolites (Figure 6).

They are enriched in Rb, Th, K and Zr. The low Sr in Nakora acid volcanics may be due to plagioclase fractionation and Zr enrichment indicates the original alkaline nature of the magma (Figure 6). The chondrite normalized REE patterns (Figure 7) of Nakora rocks show a gradual depletion with negative Eu anomaly except in Nakora basalts. Sewadiya basalts are less enriched than the Maini basalts. The volcanic vent area is the part of Maini hill. The Maini hill consists of more thickness (10 m) of basalt flow than the thickness of the Sewadiya basalt flow (5 m).

In REE patterns, both are showing parallel arrangement with no Eu anomaly which indicates the least role of plagioclase fractionation. Pabre rhyolites are less enriched than the Tikhi rhyolites and Variya trachytes whereas Variya trachytes are highly enriched. The rhyolites of Pabre and Tikhi and Variya trachytes have more concentration of LREE than the HREE with strong negative Eu anomaly (Figure 7). The LREE enrichment of Milara tuff and Maini rhyolite is almost similar with negative Eu anomaly but HREE pattern is quite different. In hand specimen, the Maini rhyolites are characterized by flow bands with vein and vugs whereas 60% area is covered by dark brown rhyolite in Milara hill. Milara tuff is showing highly enrichment of HREE than Maini rhyolites. Therefore, the geochemical characteristics of different hills of NRC are good indicators of A-type, anorogenic and plume related magmatism occurred in TAB of NW Indian shield in pre-historic time during Rodina's fragmentation and amalgamation.

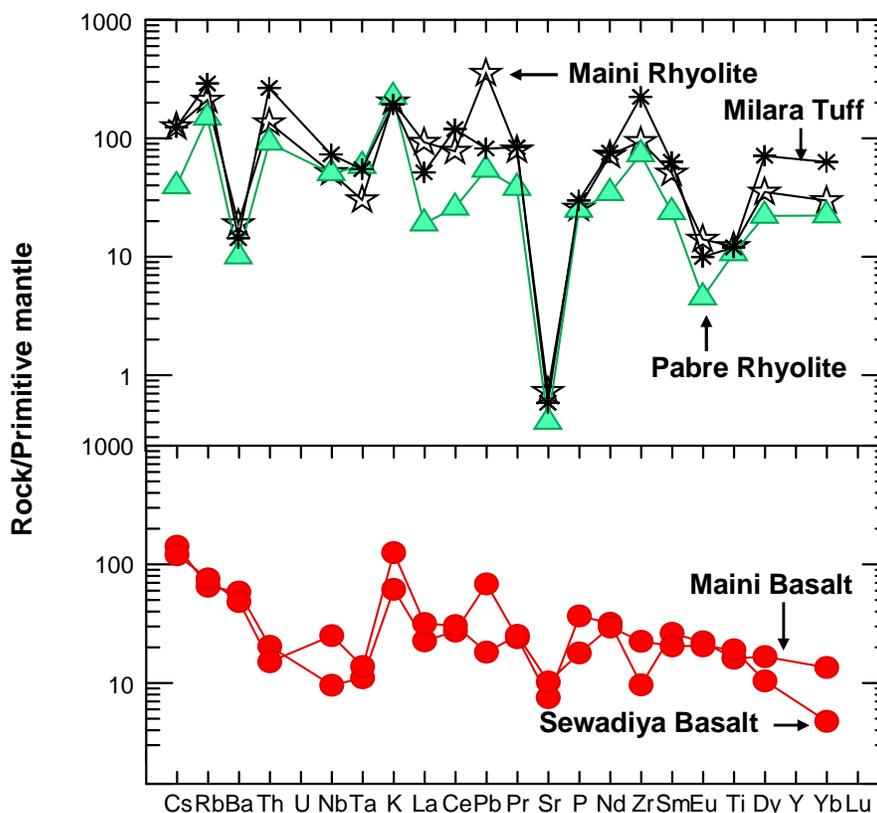


Fig. 6. Primitive mantle-normalized average trace element patterns of rocks from different hills. Normalizing values after Sun and McDonough (1989). Symbols are same as in fig. 3.

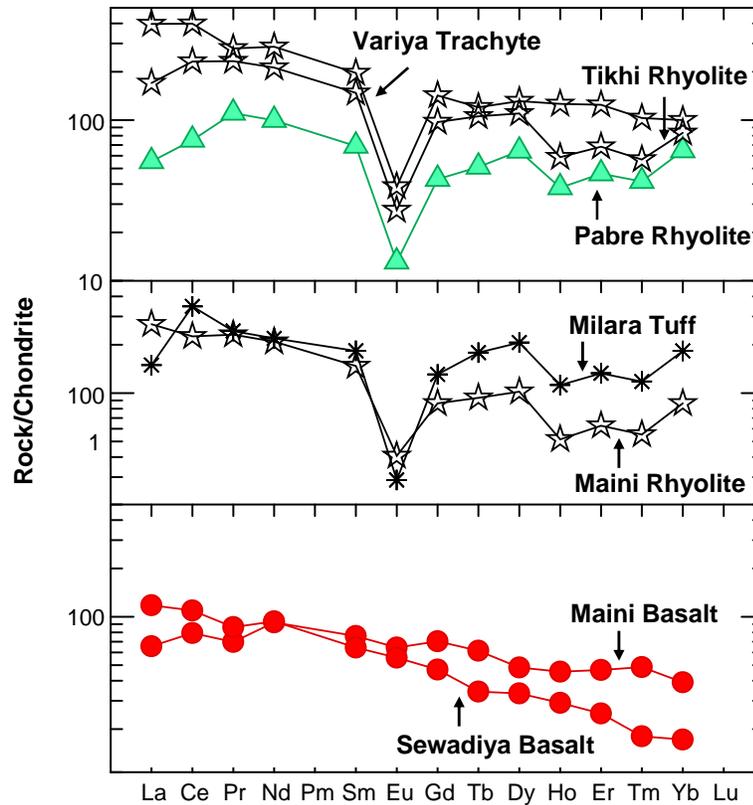


Fig. 7. Chondrite-normalized diagram showing the average REE patterns of rocks from different hills. Normalizing values after Sun and McDonough (1989). Symbols are same as in fig. 3.

6. Discussion

The tectono-magmatic features, mineralogical properties, geochemical and post-magmatic activity (role of H_2O , F, Cl) with physiochemical factors in different lava flows of NRC in MIS suggest some discussion remarks which are key points of the present contribution:

6.1. Magmatic evolution: Nakora acid lavas are characterized as alkali rhyolite and quartz alkali trachytes in the QAP diagram. In Nakora rocks, SiO_2 ranges from 49.7 to 70.9 wt % with high contents of TiO_2 , Al_2O_3 and Fe_2O_3 . Mineralization potentiality and alkalinity of the magma of the studied area is indicated by high concentrations of incompatible element abundances, particularly Zr in rhyolitic flows (786.43 - 4053.14 ppm). Nakora acid lavas show the enrichment of LREE and HREE elements with strong negative Eu anomaly and shows almost parallel trends. In REE patterns, both are showing parallel arrangement with no Eu anomaly which indicates the least role of plagioclase fractionation. The rhyolites of Pabre and Tikhi and Variya trachytes have more concentration of LREE than the HREE with strong negative Eu anomaly. The LREE enrichment of Milara tuff and Maini rhyolite is almost similar with negative Eu anomaly but HREE pattern is quite different. Results of the trace and rare – earth element analyses reveal that the volcanic rocks at Nakora are formed from co-magmatic source by cogenetic process in rift tectonic setting and could have been derived by different degree of partial melting of the source rock (Kumar and Vallinayagam, 2014).

6.2. Tectonic constraints: More importantly, our geochemical results, particularly those of the trace and REE concentrations in spider and discrimination diagrams, were used in deciphering the tectonic setting of the volcanic rocks within the NRC. The Th-Ta-Hf/311 tectonic discrimination diagram proposed by Wood (1980) shows that the volcanic rocks are showing increasing subduction component toward the Th apex and away from the mantle trend (Figure 4). Total alkali silica diagram of Le Bas et al., (1986) shows the types of basalts (basalt, trachybasalt, basaltic trachy-andesite and basaltic andesite), rhyolites and trachytes (Figure 2). In Nb/Y vs Zr/TiO₂ diagram (Winchester and Floyd, 1977), Nakora volcanics are lying in the field of rhyodacite /

dacite and the Nakora basic rocks are lying in the field of andesite / basalt (Figure 3). When comparing the results of the studied volcanic samples with that of the REE in spider diagram (Sun and McDonough, 1989) (Figure 7), it is found that they are quite comparable in pattern. These volcanic rocks are the part of Malani Igneous Suite and are formed from co-magmatic source by cogenetic process in rift tectonic setting.

6.3. Petrogenesis: The significance and importance of anorogenic volcanism and plutonism exposed in MIS has not received much attention in the past, but with the discovery of commercial mineralization and complex petrogenetic geodynamic setting, the scenario has been changed in recent time. Bimodal, anorogenic magmatism, protolith, paleopoles and Strutian glaciation and subsequent desiccation factors play an important role in the identification of separate phase of magma emplaced in MIS and other micro-continents of Rodina during ~780-750 Ma (Kochhar, 2015; Wang et al., 2017). Now it is evident that the plutonic rocks and associated volcanic show considerable variations of their color and texture in conjunction with chemical stratigraphy of primitive magma, spatially and temporally (Kumar et al., 2019; Sharma et al., 2019). The areas to the west of Proterozoic Aravalli and Delhi Supergroup in western Rajasthan are dominated by widespread isolated occurrences of volcanic and plutonics grouped under the MIS of Neoproterozoic age (Sharma and Kumar, 2017). The MIS constitutes mainly acidic rocks, i.e. plutonic rocks (granites) with cogenetic carapaces of acid volcanic (rhyolites, trachytes, welded tuff, breccias and perlite) and minor amount of basic rocks (gabbro, dolerite and basalt) (Kochhar, 1984; Bhushan and Chandrasekaran, 2002; Kumar et al., 2019). This magmatism is controlled by NE-SW trending lineaments (zone of extension of high heat flow) of fundamental nature and owes its origin to hot-spot tectonics (Kochhar, 1984; Sharma and Kumar, 2017; Sharma et al., 2019). The geochemistry explains that the magmatic activity in MIS commenced with a volcanic phase marked by felsic lava outpouring give rise to volcanic rocks of acidic nature. This was followed by co-magmatic plutonic intrusions phases giving rise to different kind of granites which are highly mineralized and stored high heat production capacity (Kochhar, 2000; Vallinayagam, 2004a; Sharma et al., 2019). This geochemical feature i.e. high mineralization potentiality with high radioactive elemental distribution is very common in MIS (Kochhar, 2000; Singh and Vallinayagam, 2003; Vallinayagam, 2004a; Sharma and Kumar, 2017; Sharma et al., 2019). Dykes phases with post magmatic fluids marked the end of large igneous activity and metasomatic reactions phase and also established a strong relationship between metallogeny and petrogenesis.

6.4. Positive test for Rodina reconstruction and reconfiguration with respect to MIS and TAB: The period Ca. 732±41 Ma B.P. marked a major Pan-African thermo-tectonic event of widespread magmatism of alkali granites and co-magmatic acid volcanic (anorogenic, A-type) in the TAB of the Indian Shield, Central Iran, Somalia, Nubian-Arabian Shield, Madagascar and South China (Kochhar, 2015; Kumar et al., 2019). Keeping in view, all geological observations, it is proposed that all those micro-continents were characterized by common crustal stress pattern, rifting, thermal regime, strutian, glaciations and subsequent desiccation and similar palaeo-latitude positions which could be attributed to the existence of a Supercontinent-The Greater Malani Supercontinent (Kochhar, 2015). They were united in specific continental framework during Neoproterozoic time as Rodina supercontinent and then drifted due to some tectonic movements (Figure 8) (Figure 9) (Li et al., 2008; Kochhar, 2015; Wang et al., 2017; Kumar et al., 2019). On the basis of geochemical and petro-genetic studies, it is also possible that MIS as well as other micro-continents i.e. TAB of the Indian Shield, Central Iran, Somalia, Nubian-Arabian Shield, Madagascar and South China are represented by similar geochemistry and petro-genetic framework.

7. Conclusions remarks

The geochemistry and petrogenesis in conjunctions with geochemical data presented here, from Nakora Ring Complex of MIS allow us to reach the following conclusions:

- (1) Volcanic flows of NRC are formed in A-type, anorogenic, bimodal, hot-spot tectonic setting indicating more complex magmatic processes are involved in their emplacement.
- (2) Phase petrology of NRC magmatic suites revealed that felsic lava had been erupted firstly, then followed by basic and intermediate compositional lava. The felsic and basic dykes and post-magmatic fluid crossing host rocks marked the end of the event.
- (3) On the basis of high concentration of radioactive elements and HFSE as well as LILE contents, NRC is best represented by high heat production capacity and subsequent mineralization of rare metals and rare earth metals.
- (4) The different elevations of investigated hills provided that different lava flows were separated from magma reservoir, at different stages and emplaced at higher levels along pre-existed fractures.
- (5) MIS and NRC being a part of Rodina supercontinent, is remarkably indicate palaeo-tectonic environment of continental part during Neoproterozoic time.

(a)-(C) Rodinia configuration

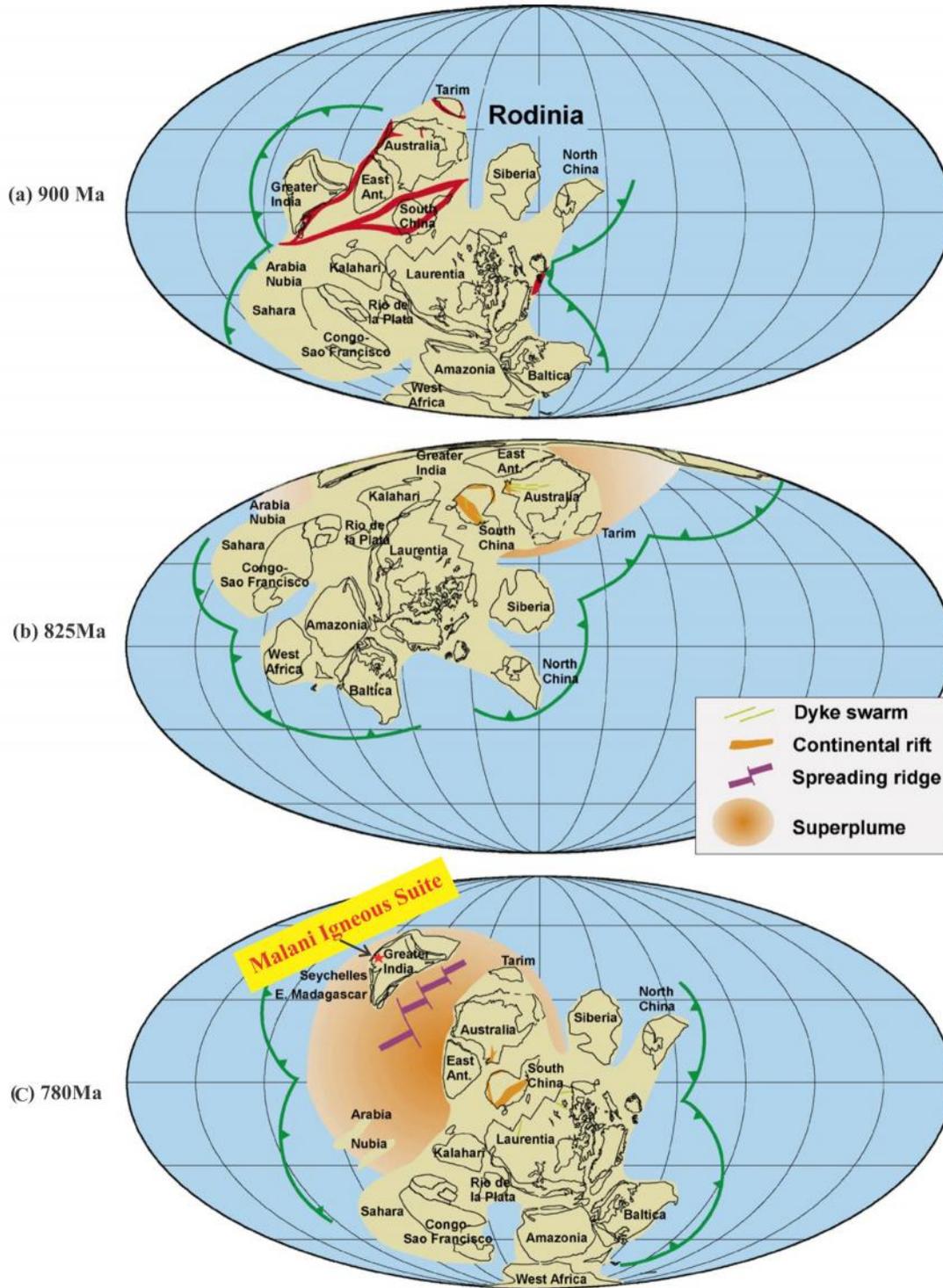


Fig. 8. (A-C) Rodinia configuration map in successive intervals of Neoproterozoic time (modified after Li., et al., 2008)

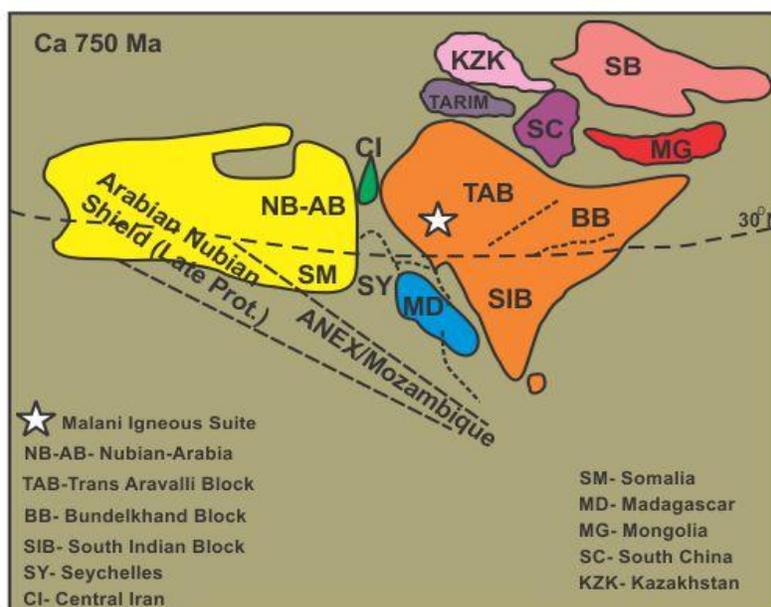


Fig. 9. Micro-continents positions near ~780-750 Ma age, with reference to Malani Igneous Suite (modified after Kochhar, 2015).

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