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Petrology and Geochemistry of Nakora Ring Complex with Emphasis on Tectonics and Magmatism, Neoproterozoic Malani Igneous Suite, Western Rajasthan, India

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Abstract

The present contribution reports on the field, petrographical and geochemical observations of the volcano-plutonic rocks of the Nakora Ring Complex (NRC) from the Neoproterozoic, Malani Igneous Suite (MIS) (Northwestern Peninsular India) and confers about their magmatic evolution and tectonic implications. Three magmatic phases are notable in the NRC which is Extrusive, Intrusive and Dyke phase where with small quantities of basaltic flows was initiated and accompanied by extensive/voluminous acidic flows. Petrographically, rhyolite shows flow bands, porphyritic, spherulitic, aphyritic and perlitic textures whereas basalt flows are distinguished by the presence of labradorite in lath-shaped crystals (plagioclase feldspar) and clinopyroxene (augite). The presence of high silica and total alkalis in NRC rocks, as well as high field strength elements (HFSE), enrichment of trace elements and negative anomalies of Sr, Eu, P, and Ti indicates that the emplacement of the lava flows was controlled by complex magmatic processes such as fractional crystallization, crustal contamination and partial melting. The association of basalt-trachyte-rhyolite means that the magma chamber was supplied a significant amount of heat to the crust before the eruption. Moreover, a volcanic vent was also reported at NRC where rhyolite was associated with agglomerate, volcanic breccia, perlite and tuff. The current research proposed that the Neoproterozoic magmatism at NRC was controlled by rift-related mechanism and produced from crustal source where the heat was supplied by mantle plume.

Keywords: Volcano-plutonic, Petrology, Nakora, Malani Igneous Suite

1. Introduction

Volcano mentions as the magma and associated ingredients erupt to the surface from the vent and also refer to the landform formed by solidified lava and volcanic debris near the vent. Abundant volcanic rocks in the Earth's upper continental crust are broadly studied because they are closely related to with magmatic processes,

Figure 1.
(A) Global map showing location of volcanoes and centers of volcanism on lithospheric plates and related to crustal evolution (modified after Encyclopedia Britannica, 2008). (B) Geological map of Nakora area, Western Rajasthan, India. (C) Aerial view of Nakora Ring Complex, Siwana Ring Complex and Luni lineament, Rajasthan, India.

crustal evolution, tectonics and geodynamics [1]. Volcanoes are almost located where tectonic plates diverge or converge on Earth surface/subsurface, and the majority of them are found underwater. Volcanic vent were documented from diverse settings of the world and they are sketched with crustal provinces, platforms, shield areas and orogenic belts (**Figure 1**). The volcanoes such as Mid-Atlantic Ridge and Pacific Ring of Fire are superlative example of divergent and convergent tectonic plates respectively. Volcanoes can also found in the East African Rift, Rio Grande Rift (North America), Hawaii, Arizona, Iceland, Mount Fuji (Japan), Stromboli (Italy), Valles Caldera and Yellowstone National Park in New Mexico and Narcondam Island (India). As isolated magma bodies ascend from large magma source regions, small volcanic vents are discovered within the Tharsis Volcanic Province [2]. The cooling efficiency inside the parent fountain determines the pyroclastic products are generated by basaltic Hawaiian fountaining [3, 4]. Big Ben lavas identified in Heard Island (Subantartic volcanic) are dominated by basalt, basanite and trachybasaltic rocks and discharge rate of average magma is very truncated [5].

On survey of India topographic sheet no. 45C/1; Scale 1: 50000; 25°45'–25°50' N; 72°05'–72°15' E Nakora Ring Complex is located in Western Rajasthan. NRC divided in many hills, i.e., Milara, Nakora, Dadawari, Variya, Sewadiya, Tikhi, Maini and Pabre which consists of granite, basalt, trachyte, rhyolite, tuff, gabbro and dolerite (**Figure 1B**). The NRC's rocks are related to the Malani Igneous Suite (MIS, Neoproterozoic) in the Trans Aravalli Block (TAB) of Indian Shield. The major period of anorogenic (A-type) is an exclusive event in the geological evolution of Indian Shield with the characteristics of bimodal in nature, high heat producing and Intraplate magmatism.

TAB consists of peralkaline, metaluminous to mildly peralkaline and peraluminous granites of Siwana, Jalor, Jhunjhunu and Tosham respectively with cogenetic association of acid volcanics [6–8]. MIS is India's largest anorogenic acid volcanism and the world's third largest with the characteristics of distinctive ring structures and radial dykes. It has a range of ~55,000 sq. Km with a broad initial phase of felsic and mafic volcanism, accompanied by granitic plutonism. MIS owes its origin to hot spot tectonics and is governed in the TAB by NE–SW trend lineaments [9, 10]. The objective of this research is to provide a relation between magmatism and tectonism by using petrological and geochemical data in Nakora area of MIS.

2. Geological setting

MIS (~780–750 Ma) spread in NW India which is a silicic large igneous province (Precambrian) and characterised by Pan-African thermo-tectonic event [11–13]. This event showed volcanic and plutonic igneous multiphase assemblages during the Neoproterozoic period that were operated by hot-spot tectonism. In NW India, TAB is leading with A-type magmatic felsic rocks having specific geochemical characteristics i.e., alkaline, peralkaline, metaluminous and peraluminous [7–9, 14]. In Tosham (Haryana), Siwana, Jalor, Jhunjhunu, Nakora, Mokalsar, Jodhpur, Sirohi (Rajasthan) and even in Nagar Parkar (Sind-Pakistan), Kirana Parkar (Kirana), they are well exposed (Lahore-Pakistan) [6, 9, 10, 15].

The tectonic, magmatic and geodynamic characteristics of NRC are enlightened on the basis of geological field mapping, petrography and major and trace elements chemical data. Different rocks are classified into different phases based on the field relationships of the region. They are categorizing as Extrusive phase (trachyte,

rhyolite, basalt, tuff, perlite, breccia, ash and agglomerate), Intrusive phase (granite and gabbro) and Dyke phase (basalt, dolerite, rhyolite and microgranite). In NRC, region first phase includes basic flows which is latter outpoured the acidic volcanic rocks and contains pyroclastic explosive rocks, acid lava flows and pyroclastic ash fall. Second phase having granite which is intruded the acid flows (plutons, ring dykes and bosses) and third phase consists of felsic and mafic dykes which cut the rocks of earlier phases [16, 17]. The NRC hill is located along the Luni River and the Luni River suddenly turns 'U' from West to South, reflecting the continental rift [18]. The Sukri lineaments are followed by NE–SW trend parallel lineaments of the Luni River and are called major Luni-Sukri lineaments (**Figure 1C**). These types of lineaments are caused by the release of stress after the orogenic cycles of Aravalli-Delhi and MIS magmatism, caused by mantle plume [19]. In TAB, the Luni rift is an important tectonic lineament [20]. This lineament is linked to significant continental rift model crustal dislocations for magma extrusions and intrusions [21]. Luni rift has therefore acted as the path for magma to rise through various major fractures, followed by anorogenic volcanism that may precede/follow the position of ring complexes. The NRC field, which is a small part of the NW continental block, a very significant element in explaining the petro-genetic, geodynamic evolution of MIS.

3. Field observations

In field photos, numerous lithological rock-suits with field relationships are drawn and the genuine petrological research is performed. The detailed physio-chemical features of various hills are defined as:

3.1 Extrusive phase

3.1.1 Basalt

The basalt flow occurs predominantly in the inner parts of the NRC hills of Sewadiya, Maini and Dadawari. Basalt has a fine grained and colour is black/dark brown, light greyish brown, and dark greyish brown. Basalt forms with a maximum thickness of 10 m and the rhyolite and trachyte flows are underlying. The flows of rhyolite and basalt display radial pattern (**Figure 2A**) and sharp contact with themselves (**Figure 2B**). The basalt contains large vesicles (4–6 mm) and often calcite fills the vesicles. Basalt xenoliths in the rhyolite (**Figure 2C**) and trachyte are found to suggest that basalt is older than rhyolite and trachyte.

3.1.2 Trachyte

At the outer margin of each hill, the trachyte flow is observed and it is the second dominant form of rock after the rhyolite. Trachyte flows of porphyritic as well as non-porphyritic nature are dark/light bluish color. It occurs on Milara hill at a maximum thickness of 50 m. Sharp contact is observed between trachytes and rhyolites. Basalt xenoliths in trachytes suggest that the flows of trachyte are younger than basalt.

3.1.3 Rhyolite

Rhyolite occurs in almost all the hills in NRC with the pyroclastic assemblages and is the most prevalent rock form in NRC. The color of rhyolite is primarily dark brown (**Figure 3A**) with different hues of light brown, red brick, grey, green, black, blue and purple. It is considered in nature to be porphyritic and non-porphyritic. In

Figure 2.
(A) Radial pattern present in Sewadiya hill, (B) basalt underlies the dark color rhyolite, (C) xenolith of basalt present in the rhyolite, (D) spherical weathering of the rhyolite rock.

the Nakora area, the maximum flow thickness is 200 m, represented by dark brown rhyolite at Sewadiya and Maini hill.

On the Northeastern flank of Sewadiya hill, spheroidal rhyolite is exposed. It is light yellow to pale brown in color. In a region of 200 sq. meters, the spheroidal rhyolite is exposed. The spheroidal structure is up to 5 m in size and shows a large number (up to 65) of few cm thick concentric shells surrounding a nuclei (**Figure 2D**). The shells consist of concentric layers of light and dark colors. They occur mostly in circular/semicircular and square shapes as well. A sharp contact is observed between the spheroidal rhyolite and the brown rhyolite.

3.2 Pyroclastic assemblages

There are exposures of ash, welded tuff, blast breccia, agglomerate and perlite. In the inner part of Sewadiya hill, there is a small bed of volcanic ash (light yellow color). Tuff demonstrates different colors, viz. Light yellow to light grey, but glassy material and tiny vesicles are also noted in it in a few areas. Sharp contact with basalt (**Figure 3B**) and rhyolite is indicated by Tuff. In the foothills of the Maini hill, angular fragments of explosive breccia and agglomerate (rounded to elongate in form with a diameter of 6–10 cm) are observed.

3.3 Intrusive phase

3.3.1 Granite

Granite is primarily exposed at three NRC sites, i.e. the inner parts of Sewadiya, Maini, and Dadawari hill. The granites display varying shades of pink, dark pink

Figure 3. (A) flow bands in non-porphyritic rhyolite, (B) contact between tuff and basalt, (C) contact between rhyolite and granite, (D) dolerite dyke.

and light pink, respectively. They are medium, large and compact grains. In the study zone, sharp contact of granite with rhyolite is observed. The intrusive aspect of granite in the rhyolite promotes volcanic plutonic association and sub-volcanic nature (**Figure 3C**).

3.3.2 Gabbro

Gabbro occurs in three locations i.e. Sewadiya hill, near Maini hill, and at Sewadiya hill and Pabre hill contact. Gabbro rocks types are connected to rhyolite as a small invasive body. Gabbro's color is dark black, coarse-grained and massive.

3.4 Dyke phase

3.4.1 Basalt

The basaltic existence of the dyke is found within the tuff and iron oxides encrusted porphyritic dark brown rhyolite in the Maini and Sewadiya hills. Basalt is observed in both the flow and the dyke shape. The color is black, fine grained with small (few cm) vesicles. The basalt dyke is 2 meters wide and 10–15 meters long.

3.4.2 Dolerite

In the inner circle of the research field, dolerite dykes are prevalent and have NE–SW patterns. In the study area, the radial pattern of dolerite dykes can easily be observed. They primarily cut through the rhyolites and trachytes. In color, the

dolerite dyke is black and medium grained. Dolerite dykes range in width from 1 m to a maximum of 50 m and can be tracked to a maximum of 300 m (**Figure 3D**).

3.4.3 Rhyolite and microgranite

The granite in Sewadiya hill has been cut by rhyolite (light brown) and microgranite (light pink). The granite is 100 m by 100 m in size. The rhyolite dyke has a width of between 1 m and 3 m and a length of up to 100 m. The rhyolite on the outcrop is marked by small bushes.

4. Petrography

This section contains the detailed petrographical characteristics of different rock types which are described as follows:

4.1 Extrusive phase

4.1.1 Basalt

Basalt reveals textures that are ophitic (**Figure 4A**) and sub-ophitic (**Figure 4B**). Plagioclase labradorite (feldspar) and augite (clinopyroxene) are the dominant in basalt flows (**Figure 4A**). As accessories minerals, fine grained quartz, hematite and magnetite are found in the groundmass. The lath-shaped crystal (plagioclase) takes place as a phenocryst and also occurs in ground mass (**Figure 4B**). In basalt, large vesicles (4–6 mm) are often packed with secondary minerals such as quartz and calcite. Labradorite is in shape from euhedral to subhedral and finely grained. It shows lamellar twinning and is changed to kaolin. Often it gives a cloudy appearance due to alteration. Augite has a medium grained and pale brown and grey color.

4.1.2 Trachyte

Trachyte illustrates the porphyritic texture (**Figure 4C**). Trachytic texture is often the directive flow and parallelism of elongated crystals (**Figure 4D**). Trachyte's petrographic properties are somewhat similar to rhyolite, with relatively less quartz and more ferromagnesian minerals viz. riebeckite, magnetite, arfvedsonite and hematite. It consists of quartz, orthoclase and riebeckite phenocrysts as important minerals in the groundmass of quartzofeldspathic. Orthoclase occurs in quartzofeldspathic groundmass as euhedral crystals. This illustrates the twinning and kaolin alteration of Carlsbad. The orthoclase phenocrysts are fractured and often filled with crystals of riebeckite. Quartz, with embayed margin and fractured shapes, happens as euhedral to subhedral crystals. The quartz veins cut the ground-mass quartzofeldspathic. The riebeckite is fine grained, blue in color, needle form and embedded in the ground mass.

4.1.3 Rhyolite

When viewed under a microscope, Rhyolite displays flow bands, porphyritic, aphyritic, spherulitic (radiating growth of feldspar and quartz from a common center) (**Figure 4F**) and perlitic textures. The rhyolite consists of orthoclase, quartz, and arfvedsonite phenocrysts as important minerals in the ground mass quartzofeldspathic. In some samples, high temperature alkali feldspar, i.e. euhedral

Figure 4.

(A). Labradorite and augite are present in basalt and shows ophitic texture; XPL. (B). Labradorite and augite are showing sub-ophitic texture in basalt; XPL. (C). Quartz, orthoclase which is showing Carlsbad twinning in trachyte; XPL. (D). Trachyte shows cryptocrystalline nature of flow direction; PPL. (E). Quartz, orthoclase occur in a matrix of fine grained quartz and feldspar of rhyolite, which shows a little flow structures; PPL. (F). Quartz, orthoclase, aniegmaitite shows equigranular texture by granite; XPL.

sanidine crystals, are also found. Microcrystalline aggregates of quartz, alkali feldspar, blue amphibole (riebeckite), pyroxene (light green aegirine), blood red aenigmatite, magnetite, and hematite are de-vitrified to the ground mass. The fine quartz-feldspar ground mass reflects the lava flow directions.

Phenocrysts of quartz occur in different ways, i.e. drop like, fractured and embayed. The orthoclase and ground mass are cut by the quartz veins and parallel to the lava flow path (**Figure 4E**). Alkali feldspar phenocrysts illustrate twinning in Carlsbad. Altered and fractured orthoclase is also found at a few stages. Arfvedsonite's fine crystals are correlated with alkali feldspar. Bluish green arfvedsonite occurs with pleochroic (X = dark bluish green, Z = yellowish green) as fine to medium grained prismatic crystals.

The spheroidal rhyolite displays layers of mafic (dark/light brown) and felsic (light grey), reflecting the texture of the flow. Hematite, magnetite and arfvedsonite are formed of the mafic layer and they are fine grained. The felsic layer is composed of quartz, perthite, and orthoclase and medium-grained. Medium

grained, lath/prismatic shaped, colorless and showing Carlsbad twinning are the orthoclase crystals. Orthoclase is scattered, sericitised spontaneously and combined with quartz intergrowth. Fine quartz veins are cut by the sericitised feldspars and display high order interference colour.

5. Analytical techniques

Major, trace and rare earth elements contents (min., max. and mean) for representatives samples of plutonic and volcanic rocks are reported in the **Tables 1–3**, respectively. Major elements are analyzed by using wet chemical method using a UVV is spectrophotometer108 and Atomic Absorption Spectrophotometer (Varian 240 FS AAS) at Department of Geology, Kurukshetra University, Kurukshetra. Trace and rare earth elements are analyzed by ICPMS (PerkinElmer Sciex ELAN DRC II) at National Geophysical Research Institute (NGRI), Hyderabad. Standard-ization for major and trace elements including 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 <5% for major and <105 for trace elements.

6. Bulk geochemistry

The whole-rock geochemical data of major and minor oxides, trace elements and rare earth elements for the acid volcano-plutonic rocks, are carried out to justify our mineralogical and petrographical results [22]. They are high in SiO₂, K₂O + Na₂O, Al₂O₃, Ba, Th, U, Y, Rb, Zr, Nb, REEs (except Eu) and low in TiO₂, CaO, MgO, V, Sr., Ni, Cr, Ti, P, Eu; typically A-type affinity. Based on the mineral chemical databank, it was investigated that K-feldspar, plagioclase and biotite are important silicate minerals in rock-formation.

6.1 Extrusive phase

Average values of SiO₂, Al₂O₃, Na₂O, K₂O, Fe₂O₃, TiO₂, CaO, MgO, MnO and P₂O₅ (in wt %) are in basalts samples as 51.30, 3.18, 1.40, 3.46, 12.24, 3.18, 5.53, 5.70, 2.01 and 0.60 respectively, in trachyte, values are 67.93, 7.93, 1.07, 5.96, 9.00,

Major elements	Basalt	Trachyte	Rhyolite	Granite	Gabbro	Dolerite
SiO ₂	45.59–54.00	66.7–69.4	64.80–71.90	66.20–69.60	45.49–53.20	54.5
TiO ₂	2.34–4.12	2.67–2.93	1.61–2.84	1.11–3.80	1.67–2.66	2.83
Al ₂ O ₃	11.20–17.40	6.1–10.5	7.20–13.10	7.10–11.90	14.90–15.60	13.5
Fe ₂ O ₃	9.67–14.50	8.1–10.2	5.40–9.70	2.60–10.00	8.90–17.20	9.7
MnO	1.62–2.70	1.25–3.13	0.19–1.06	0.56–1.69	1.38–1.58	1.1
MgO	4.42–6.56	0.49–1.47	0.49–3.28	0.98–4.75	6.25–6.50	7.2
CaO	1.68–7.60	0.8–1.52	0.80–3.64	1.41–3.56	2.80–3.50	4.96
Na ₂ O	1.00–2.71	1.06–1.09	0.94–1.18	0.99–1.19	5.11–7.10	2.18
K ₂ O	1.85–4.46	4.3–7.28	4.48–6.81	4.07–7.96	1.44–2.41	2.09
P ₂ O ₅	0.31–0.88	0.5–0.55	0.45–0.62	0.28–0.77	0.44–0.47	0.82

Table 1.
Major element concentrations of Nakora rocks.

Trace elements	Granite	Rhyolite	Trachyte	Basalt	Gabbro	Dolerite
Sc	5.77	1.64	2	30.23	20.99	28.4
V	6.5	3.35	4.15	201.58	149.31	206.89
Cr	3.31	5	23.68	37.55	57.11	55.1
Co	1.33	0.58	0.61	31.15	46.87	38.69
Ni	3.25	2.34	23.09	35.05	120.99	15.35
Cu	0.39	0.34	9.88	35.18	43.3	52.21
Zn	56.7	36.4	226.61	190.09	69.24	544.26
Ga	37	29.3	30.76	28.18	12.77	17.9
Rb	157	104	144.69	60.46	46.36	50.51
Sr	37.1	12.7	11.94	178.34	312.14	295.83
Y	216	154	227.51	74.86	18.84	42.86
Zr	1482	1459	2009.4	501.97	80.37	64.25
Nb	38.6	40.3	82.57	26.09	4.2	5.89
Cs	5.93	0.62	0.74	1.07	2.06	0.93
Ba	417	91.9	80.29	345.12	416.83	405.96
Hf	46.1	31.9	50.44	10.54	2.03	1.82
Ta	2.42	1.96	8.44	2.06	0.57	0.39
Pb	10.8	9.59	2.92	2.07	0.98	30.9
Th	16	11	17.39	2.92	0.3	1.11
U	4.93	2.8	1.78	0.41	0.07	0.11
Ba/Rb	3.15	0.9	0.55	6.45	8.99	8.04
Rb/Sr	4.88	8.46	12.12	0.35	0.15	0.17
Zr/Rb	7.02	14.7	13.89	6.79	1.73	1.27
Ba/Sr	10.9	7.59	6.72	1.98	1.34	1.37
Sr/Y	0.23	0.08	0.05	3.15	16.57	6.9
Nb/Y	0.2	0.26	0.36	0.31	0.22	0.14
Zr/Nb	27.7	33.6	24.34	17.23	19.14	10.91
Zr/Y	5.22	8.67	8.83	5.74	4.27	1.5
Y/Nb	5.17	4.18	2.76	4.8	4.49	7.28
K/Rb	0.03	0.05	0.02	0.04	0.02	0.03

Table 2.
Trace element concentrations of Nakora rocks.

2.84, 1.15, 1.09, 2.13 and 0.53 respectively whereas rhyolites show average values as 68.46, 9.73, 1.05, 5.65, 7.74, 2.40, 1.92, 1.62, 0.73 and 0.55 respectively.

6.2 Intrusive phase

The granites show (wt %) SiO₂ (66.20–69.60), Al₂O₃ (7.10–11.90), total alkalis (5.06–9.15), Na₂O (0.99–1.19), K₂O (4.07–7.96), total iron (2.60–10.00), TiO₂ (1.11–3.80), CaO (1.41–3.56) and MgO (0.98–4.75). Gabbros show a wide range of SiO₂ (45.49–53.20), Al₂O₃ (14.90–15.60), total alkalis (6.55–9.51), Na₂O

Rare earth elements	Granite	Rhyolite	Trachyte	Basalt	Gabbro	Dolerite
La	71.5	39.06	94.05	29.13	7.85	10.78
Ce	392.99	101.81	243.67	73.34	19.74	32.58
Pr	37.7	16.84	26.55	9.11	2.7	4.3
Nd	170.72	75.96	133.58	50.16	15.5	26.97
Sm	40.17	17.39	30.08	11.61	3.98	7
Eu	4.23	1.35	2.24	3.4	1.7	2.46
Gd	33.89	14.66	29.27	12.25	4.11	8.28
Tb	6.04	2.9	4.5	1.78	0.57	1.3
Dy	40.27	21.6	33.37	10.84	3.94	6.88
Ho	4.63	2.6	7.14	2.18	0.77	1.41
Er	16.11	9.17	20.64	6.06	1.93	4.3
Tm	2.14	1.24	2.63	0.82	0.22	0.7
Yb	22.22	12.86	17	4.84	1.33	3.73
Lu	3.67	2.1	3.69	0.93	0.3	0.55
Ce/Nd	1.89	1.08	1.82	1.09	1.27	1.21
Ce/Sm	7.96	4.73	8.1	4.68	4.96	4.65
Gd/Yb	1.4	0.94	1.72	2.22	3.09	2.22
Ce/Yb	13.36	6.55	14.33	12.46	14.84	8.73
Eu/Eu*	0.14	0.07	0.08	0.24	0.42	0.32

Table 3.
REE element concentrations of Nakora rocks.

Figure 5.
Total alkali-silica diagram showing classification of Nakora volcanics. Symbols: Rhyolite (▲), Dacite (☆), Trachydacite (★), Basalt (●).

(5.11–7.10), K_2O (1.44–2.41), wide variation of total iron (8.90–17.20), high TiO_2 (1.67–2.66), CaO (2.80–3.50) and less variation of MgO (6.25–6.50) (wt%).

6.3 Dyke phase

6.3.1 Dolerite

As compare to basalts, the dolerite shows (wt %) high SiO_2 (54.50), low Al_2O_3 (13.50), low total alkalis (4.27), (Na_2O : 2.18, K_2O : 2.09), low total iron (9.70), low TiO_2 (2.83), low CaO (4.96) and high MgO (7.20).

On the basis of geochemical data, Nakora acidic volcanic and basic rocks are plotted in the TAS diagram (Figure 5) [23] in which rhyolites lie in the field of rhyolite and dacite however dacite is very close to rhyolite where basic rocks lie in the field of basalt, trachybasalt, basaltic trachy-andesite and basaltic andesite. In tectonic discrimination $R_1 - R_2$ diagram [24], the Nakora granites fall in the field of anorogenic (Figure 6). Usually, the intrusion of anorogenic felsic magma into upper crust follows a cycle of compressive tectonic activity and orogenic magmatism [25]. The clustering of the granites in the anorogenic field indicates the limited melting of a crustal source [24].

In the Harker diagram, 1909 [26], the SiO_2 (wt %) is plotted along the X axis and other oxide concentrations are plotted along Y axis. These diagrams reveal that Nakora rocks show four different distribution trends (Figure 7). The Nakora rocks show a regular decrease in Al_2O_3 , MgO , Fe_2O_3 and CaO with increasing silica and continuous increase in K_2O with increasing value of silica. In the case of TiO_2 and P_2O_5 , the rocks show constant distribution trend. In case of Na_2O , the rocks show totally constant Na_2O concentration with increasing silica content. The Nakora basalts contain more Al_2O_3 , K_2O , Fe_2O_3 , TiO_2 , CaO and P_2O_5 as compared to other basic rocks. MgO and Na_2O are more in dolerite and gabbro respectively. Granites show high MgO , TiO_2 , K_2O and P_2O_5 as compared to other acid volcanic rocks. Al_2O_3 and Fe_2O_3 are more in tuff and trachydacite respectively.

Figure 6. R_1 - R_2 diagram [24] of major granitoid association. Symbols: Grey granite ($\oplus$), Pink granite ($\otimes$).

Figure 7. Harker variation diagram of SiO vs. oxide showing the variation of Nakora rocks. Symbols: Peralkaline Granite (+), Metaluminous Granite (x), Peraluminous granite (+), Rhyolite (▲), Dacite (☆), Trachydacite (★), Tuff (*), Basalt (●), Gabbro (○), Dolerite (◆).

On the basis of different tectonic discrimination diagrams [27], which are based on mineral assemblages, the tectonic environment of the Nakora rocks is clarified. In the various tectonic discriminating diagrams (Y+Nb vs. Rb), when Nakora granites are plotted, they fall within plate granites (**Figure 8**). The above diagrams therefore demonstrate that this phase of magmatism was anorogenic. The primitive mantle normalized multi-element pattern (normalization values from Sun and McDonough [28]) for three Nakora basic rocks (2 basalts and 1 dolerite) displays similar pattern (**Figure 9**). However, the dolerite dyke is showing highly Pb enrichment as compared to basalts. The Nakora basic rocks show LREE enriched nature and they have consistent negative Nb, Ta, Sr. and Zr anomalies. The HREE pattern of dolerite dyke is showing parallel arrangement with HREE pattern of

Figure 8.
Y + Nb vs. Rb diagram of Nakora acidic rocks.

Figure 9.
Primitive mantle normalized trace element patterns for Nakora basic rocks [28].

other basic rocks. Hence close resemblance is observed between the dolerite dyke and Nakora basalts in terms of their LREE enrichment and negative Nb, Ta and Zr anomalies. Thus based on the above observations we conclude that these rocks may be related to same source. The chondrite normalized REE patterns for all types of Nakora rocks are shown in **Figure 10**. REE patterns in the Nakora acid volcanics and basic rocks are characterized by sub-parallel patterns with strong negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.06$ to 0.12 , avg. 0.08). But in basic, positive Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.24$ 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 and granites are showing almost similar abundances of REE which is probably due to

Figure 10.
Chondrite normalized REE patterns for Nakora rocks [28].

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.

The Siwana magma is derived from the mantle and has A-type geochemical parameters [29]. With the assimilated Achaean crust, the Jalor complex suggests primary mantle derivation with a variable degree of crustal contamination [30]. The Jhunjhunu granites seem to have come from a granodioritic composition source [31].

In the **Figure 11**, 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. The Bhilwara mafic metavolcanic which is taken from outside the study area and mixed Nakora gabbros

Figure 11.
Chondrite-normalized diagram showing the calculated REE patterns for melts produced by 33% batch partial melting of mafic metavolcanic from Bhilwara leaving a residue consisting of 48% plagioclase, 33% orthopyroxene and 19% clinopyroxene.

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.

7. Magmatism and tectonism

MIS shows the within plate environment that is related to the activity of the hot spot and represents the tensional environment in its spot that is flanked by different elliptical/ring structures [17, 21]. About 700–900 m.y., the magma of the Trans Aravalli MIS erupted. Alkaline magmatism, like subalkaline subvolcanic complexes in lithospheric continents, represents the igneous activity, while the plume gives rise to basaltic oceanic chains/aseismic ridges in oceanic crustal regions. Intraplate, anorogenic existence and extensional tectonic environment are well known by MIS granites and Mahe (750 Ma) and Ste. Anne (764 Ma) Seychelles granites [32] show the similar environment. They are aligned with Siwana (732 Ma old) hypersolvus granites and subsolvus granites from Jalor (MIS).

The higher amount of Zr is reported by Kochhar et al., [33] in the Siwana rhyolites which formed during the Zr crystallization and Nakora area also exhibits the appreciable amount of Zr concentrations. Partial melting and enrichment of alkali elements initiate due to releasing of pressure at a depth which influx the volatiles in to the crust [20]. The peralkaline association of trachyte–rhyolite and basalt within–plate character denotes the zones of crustal extension [34]. The Arabian–Nubian shield shows the tensional tectonic environment which is formed by the bimodal magmatic activity during the uppermost Precambrian crustal evolution [35]. The Nakora area is characterized by the close association of trachyte, rhyolite, granite (peralkaline, peraluminous and metaluminous) with gabbro, basalt and dolerite. Close association of granite is observed with trachyte flows in Mokalsar [36] and Goliya Bhaylan area [37] of Siwana. Granites are associated with gabbro and basalt in Guru Nal area and Jalor area respectively [38]. In view of association of trachyte, rhyolite, basalt and gabbro, with the subsolvus and hypersolvus granite of the Malani area, it is suggested that the model of deep crustal hot zone which is suggested by Annen et al. [39] as outlined above can be applied to the area under study.

A deep crustal hot zone is created in the model by mantle-derived hydrous basalts accumulated as a series of sills into the lower crust. Melts are generated in Nakora area from two distinct sources; partial crystallization of basalt to produce residual H₂O-rich melts; and partial melting of pre-existing crustal rocks. Partially melting of the underlying crust, which may involve meta-sedimentary and meta-igneous basement rocks, as well as earlier basalt intrusions, is aided by heat and H₂O transfer from the crystallising basalt [39]. According to the evidence in the literature and the geochemical and petrological findings presented, MIS is the result of a complex series of geological processes that include partial melting, fractional crystallisation, magma mixing and assimilation, crustal contamination, and fluid-melt interactions. However, while Nakora is made up of common hydrous minerals such as biotite, amphiboles, apatite, and muscovite, it also contains volatile components in the form of halogens, indicating that the comagmatic rocks went through many phases during their evolution.

Kochhar [40] explained the similarities between Trans–Aravalli Block (TAB) and Arabian Nubian shield (ANS) in terms of granite emplacement, ring structures and cauldron subsidence. In both the terrines, the alkali granites mark the cratonisation of the shield and show evidences of Strutian glaciation. Western Central Madagascar granites near Ambistra were emplaced during extensional collapse of Pan–African orogen and indicate emplacement age of 804–775 Ma. They are

very similar to Jalor granites in terms of gabbroic sleeves [41]. 750 Ma alkaline magmatism which is widespread and well developed in the continents viz., TAB, Central Iran, Arabian–Nubian shield, Madagascar and South China, Somalia, Seychelles [40] were characterized by common crustal stress pattern, rifting and thermal regime, shrutian glaciation and dessiciation and similar paleolatitudinal positions which could be attributed to the existence of a Supercontinent–the Malani Supercontinent. Rogers [42] has also suggested the similarities of their development including production of alkali granites, subsidence of thick partly deformed basin on recently formed crust and ultimate development of platform cover sediments. Hence in future, the significance of mantle plume and crust–mantle interaction should be studied for the emplacement of MIS.

A volcanic vent is observed in NRC with steep slope. It is characterized by elongated or semicircular depression with various volcanic flow products. Volcano–plutonic associations of NRC are located along the Luni River which flows 2 km Northeast of NRC. The Luni River takes sudden ‘U’ turn from West to South direction which represents the continental rift. Luni rift is an important tectonic lineament in TABLE [19]. This lineament is related to major crustal dislocations of continental rift type for the exrusions and intrusions of the magma [20]. Hence Luni rift served the way for magma rising through various major fractures, it is accompanied by anorogenic volcanism which may precede/follow the emplacement of ring complexes. The Nakora peralkaline granites support the view of association of rifting of crust in the area [43]. The semi–circular ring structure of Nakora area indicates the emplacement of magma into tensional environment. Hence, NRC indicates the presence of rift mechanism operated in the area in their emplacement vis–a–vis the tectonism and volcanism (**Figure 12**).

Figure 12.
Schematic presentation of Nakora area (after Annen et al. [39]), showing magma chamber and intrusion basaltic magma producing a zone of melting in the continental crust.

8. Conclusion

The rock types exposed in Nakora Ring Complex were classified into three major lithological divisions: basalt and rhyolite as first phase, second phase of granites of different colors and third and last phase magmatism of dykes of fine-grained granites and rhyolites. Based on petrographical observations, it is suggested that rhyolites show ophitic, sub-ophitic, porphyritic, granophyric, glomeroporphyritic, aphyritic, spherulitic, perlitic, hypidiomorphic, granophyric and microgranophyric textures. These textures have close similarities with A-type, anorogenic and within-plate granitoids as early reported by MIS rock-types behave. The volcano-plutonic rock associations and physio-chemical characteristics showed that during complex geological processes, the rock types of the Nakora Ring Complex were formed. Volcanic vent (approx. 40 m wide and semicircular to elongated shape) and sudden change pathways of Luni River advocates the relationship between tectonism and volcanism. Magmatic growth, phase petrology and geodynamic indicated that the studied areas in the NW Indian shield belonging to the MIS extension could be developed under the plume-related hot spot extension model.

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