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Early Neoproterozoic evolution of Southeast Pakistan: evidence from geochemistry, geochronology, and isotopic composition of the Nagarparkar Igneous Complex

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\textbf{ABSTRACT}

Rocks of the early Neoproterozoic age of the world have remained in discussion for their unique identity and evolutionary history. The rocks are also present in Sindh province of Pakistan and have been in debate for a couple of years. Yet, these igneous rocks have been studied very poorly regarding U-Pb and Lu-Hf age dating. The early Neoproterozoic rocks located in Nagarparkar town of Sindh have been considered as shoulder of Malani Igneous Suite (MIS) discovered in Southwest of India. The Nagarparkar Igneous Complex (NPIC) rocks are low-grade metamorphosed, mafic and silicic rocks. These rocks are accompanied by felsic and mafic dikes. Two types of granite from NPIC have been identified as peraluminous I-type biotite granites (Bt-granites), of medium-K calc-alkaline rocks series and A-type potash granites (Kfs-granites) of high-K calc-alkaline rocks series. Geochemical study shows that these Kfs-granites are relatively high in K and Na contents and low MgO and CaO. The Bt-granites have positive Rb, Ba, and Sr with negative Eu anomalies rich with HFSEs Zr, Hf, and slightly depleted HREEs, whereas Kfs-granites have positive Rb with negative Ba, Sr, and Eu anomalies and have positive anomalies of Zr and Hf with HREEs. In addition, these rocks possess crustal material, which leads to the enrichment of some incompatible trace elements and depletion of Sr and Ba in Kfs-granites and relatively high Sr and Ba in Bt-granites, indicating a juvenile lower continental crust affinity. Zircon LA-ICP-MS U-Pb dating of these granites yielded weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 812.3 ± 14.1 Ma ($N = 18$; MSWD = 3.7); and 810 ± 7.4 Ma ($N = 16$; MSWD = 0.36) for the Bt-granites, and 755.3 ± 7.1 Ma ($N = 21$; MSWD = 2.0); NP-GG-01 and 736.3 ± 4.3 Ma ($N = 24$; MSWD = 1.05) for Kfs-granites, respectively. The Bt-granites and Kfs-granites have positive zircon $\varepsilon_{\text{Hf}}(t)$ values, which specify that they are derived from a juvenile upper and lower continental crust. Based on the geochemical and geochronological data, we suggest that the Bt-granites were formed through lower continental crust earlier to the rifting time, whereas the Kfs-granites were formed via upper continental crust, during crustal thinning caused by Rodinia rifting. These zircon U-Pb ages 812 to 736 Ma, petrographic, and geochemical characteristics match with those of the adjacent Siwana, Jalore, Mount Abu, and Sirohi granites of MIS. Thus, we can suggest that NPIC granites and adjacent MIS can possibly be assumed as a missing link of the supercontinent Rodinia remnants.
1. Introduction

The Nagarparkar Igneous Complex (NPIC) in southeast Pakistan (Figure 1) is recognized as the Precambrian basement rocks of igneous and metamorphic origins in Northwest India (Wynne 1867; Fermor 1932; Eby and Kochhar 1990; Baskar and Kochhar 1995; Vallinayagam 1997; Malone et al. 2008; Meert et al. 2010; Khan et al. 2012; de Wall et al. 2018). Neoproterozoic NPIC granites show temporal, spatial, petrologic, and tectonic links with those of the Malani Igneous Suite (MIS) in the western part of India (Eby and Kochhar 1990; Torsvik et al. 2001a; b; Khan et al. 2012; de Wall et al. 2018). The NE-SW Aravalli Mountain Belt in the western India and the N-S Kirthar fold belt in Pakistan are two large physiographic features located in the eastern and western landscapes of the Nagarparkar town. Direct linkage of the NPIC granites and Siwana, Jalore, Mt-Abu is hampered, because the intervening area is covered by sand and alluvium.

The NPIC granites are classically subdivided into grey and pink granites on account of their macroscopic appearance (Jan et al. 1997; Kazmi and Jan 1997; Khan et al. 2012). In this study, these granites have been classified as biotite granite and Kfs-granites on petrographic basis. Geochemical and petrographic studies reveal that Bt-granites are I-type and Kfs-granites are...
2. Regional geological background and sample description

2.1. Geological background

The landscape of Nagarparkar rocks comprises island-like rocky highlands, spanning the desert of Thar. The southeastern extremity is occupied by a pile of basaltic flows of the Deccan Traps of Cretaceous age (Chandrasekhar and Mishra 2002). The representatives of MIS are present in southeastern Pakistan; these rocks are the NPIC granites (Kochhar 2004). This study compares these rocks, which are of the same geochronological age and petrographic and geochemical signatures with the NPIC granites.

Geodynamic history of Nagarparkar and the surrounding areas is quite complex. The complexity is the result of several major events that include development of Kutch, Narmada, and Cambay rifts/grabens (Campbell and Griffiths 1990; Sharma 2007b) (Figure 1(b)). The structure of the areas is characterized by block faulting and consequent folding.

A-type. Geochemical analysis, zircon U-Pb geochronology, and petrographic work further suggest that the NPIC and MIS rocks are similar in nature and characteristics, exposed at the western margins of Indian shield in Rajasthan. Previous study of Khan et al. (2012) presented U-Th-Pb EMPA zircon and monazite radiometric ages 1100–700 Ma for NPIC granites, indicating mid–late Proterozoic formation (Table 1). The latest study of Markhand et al. (2017) shows an older zircon U-Pb ages of 803 ± 7.8 Ma for the NPIC pink granite (Kfs-granite) than the adamellite (767 ± 12 Ma) (Table 1), which is not consistent with field observation in the adjacent MIS area that Kfs-granite formed after formation of the grey granite or Bt-granite. To further clarify this, detailed zircon geochronology study of the NPIC granites is required, for detailed zircon Lu-Hf analysis has not been reported for NPIC rocks in Nagarparkar area as yet. This study comprises field investigation, petrographic, geochemical, zircon U-Pb age dating, and new analytical data in the light of Lu-Hf isotope analysis of the NPIC granites. The geodynamic model for the tectonic setting has been used to reveal more precise petrogenetic history and evolution of the NPIC granites.

<table>
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<tr>
<th>Location</th>
<th>Area Name</th>
<th>Age (Ma)</th>
<th>Method</th>
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<td>Zircon LA-ICP-MS U-Pb</td>
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<td>771 ± 6</td>
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<td>Zhou et al. (2018)</td>
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2.2. Lithological units

The NPIC area was mapped by Kazmi and Khan (1973); Butt et al. (1994); Jan et al. (1997). The oldest rocks are metamorphosed basic igneous ones. The metamorphic condition reaches up to epidote-amphibolite facies. Geological and geophysical surveys carried out by Farah and Jaffrey (1966) in the area indicate that they cover large subsurface area and obviously form the basement for the later rocks. Massive granite plutons of unknown age developed and contain the xenoliths of the former rock type. There is an evidence from the field relationship that the Kfs-granite intrudes into the Bt-granite and also carries xenoliths of mafic rocks. Lastly, all the major rocks, including both the granites, are intruded by mafic dikes. Six major magmatic events have been proposed by Jan et al. (1997) in a comprehensive and decisive petrographic study. Biotite granite: The Bt-granite is fundamentally composed of perthitic feldspar and quartz, with a small amount of plagioclase and traces of sodic minerals. The best exposed Bt-granite is visible at Karunjhar Hills. The granite shows magmatic fabric without any indication for a later deformation. These granites also contain iron oxide, zircon, and several other accessory minerals (Figure 2(a, b, and c)). Kfs-granite: The Kfs-granite is commonly medium to coarse-grained in size. It is generally made up of 'light minerals' such as perthitic feldspar. This Kfs-granite intruded into Bt-granite. Felsic dikes: This unit includes porphyritic microgranite dikes, rhyolitic dikes, and rhyolite porphyry and equigranitic aplite dikes. In brief, this unit ranges from aplite to micro-granite to quartz trachyte, containing phenocrysts of perthite, plagioclase, and quartz. These rocks generally

Figure 2. Microphotographs and field photographs of the Bt-granite and Kfs-granites. (a) Contact of the Bt and Kfs-granites near Nagarparkar town; (b) Microphotograph of NPIC granites. The images were taken under plane polarized light and crossed polars. Bt-granite with Qtz-quartz; Pl-plagioclase; Agr-aegirine Bt-biotite; Kfs-K-feldspar; with ore minerals; (c) Bt-granite; (d) plagioclase and biotite; quartz with biotite and K-feldspar present; altered biotite and visible cloudy plagioclase; (E) Kfs-granite.
occur as small bodies, but in Dinsi village, these rocks occur as up to 6-m-thick dikes extending to more than 0.5 km (Figure 3(a)). Rhyolite Plugs: The rhyolites occur in small dome-shaped outcrops surrounded by alluvium. These rhyolites are dark-grey to black, glassy-looking rocks, and consist of phenocrysts of feldspar and quartz in a very fine-grained matrix. The rocks are fine-grained and porphyritic to sub-porphyritic, containing phenocrysts of K-feldspar, perthite, and quartz with a small amount of plagioclase and accessory minerals such as zircon and apatite (Figure 3(b, c)). Mafic dikes: All the major rock units of the NPIC complex are intruded by basic dikes. They show significant petrographic distinction and range from hornblende microdiorite to gabbro and dolerite, some of them contain titanium augite, which is suggestive of alkaline affinity (Jan et al. 1997).

On the basis of petrography, these basic dikes can be divided into two types, which contain amphibole and other clinopyroxene as the principal mafic mineral (Jan et al. 2017). The amphibole-bearing dikes are locally cut by the pyroxene-bearing type rocks and appear to be older. Both are fine-grained and commonly porphyritic, with local clustering of phenocrysts (Jan et al. 2017). Some dikes have distinct chilled margins, generally 5 cm thick (Figure 3).

2.3. Sample description

Eleven samples of granite were collected from different outcrops (Karunjhar, Dhedvero, Chanida, Dinsi, Karai, and Seerhiyoon) for geochemical analysis and petrography. Two samples were collected from Bt-granite and other two from Kfs-granite for U-Pb zircon dating (Figure 1(c)).

2.4. Petrography and field observations of Bt-granite and Kfs-granites

The Bt-granite is a principal variety in the NPIC. Previously termed as Karunjhar grey granite (Kazmi and Khan 1973), it constitutes about 50–60% of the total plutonic rocks in the Complex. The Bt-granite is well exposed at Karunjhar hills, and hillocks of Berano village near Nagarparkar town (Figure 2(a)). It is fractured and exfoliated in some places due to weathering effect. The Bt-granite is grey in colour. At some places, weathered colour of the Bt-granite appears greyish-white or greyish pink. Texturally, the granite is medium to coarse-grained, equigranular, porphyritic, and at some places granophyric. This granite is composed of perthitic feldspar, quartz, plagioclase, aegirine, and biotite (Figure 2(b, c)); accessory minerals biotite, rutile, zircon, monazite, epidote, magnetite, and ferro minerals are

Figure 3. Field photographs of Felsic and Mafic rocks from Nagarparkar area. (a) Mafic rock, Gabbro in black colour and felsic rocks intrusion, (b) Rhyolite body, (c) Mafic and felsic intrusion and aplite vein, (d) Gabbro body.
commonly present in this granite, while opaque minerals can be observed in thin sections (Figure 2(b)).

The outcrops of Kfs-granites are best preserved along the northeastern margin of the Karunjhar hills with Bt-granite (Figure 2(a)). The Kfs-granites constitute of nearly 40% of the total granitic rocks in the NPIC area. The largest outcrops of this granite intrusion are exposed in the west of the Nagarparkar town, which cover about 8 km². They are characterized by a typical pink colour (Kazmi and Jan 1997). The Kfs-granites are also exposed in different localities of Tharparkar (Figure 1(c)). Texturally, the Kfs-granites are medium to coarse-grained and pink to reddish-pink in colour. These granites include feldspar up to 1.2 cm in size, medium-grained quartz, and minor quantity of biotite; they also have xenoliths of mafic rocks and quartz veins. Major minerals include potassium feldspar and quartz, plagioclase, biotite, ferro-ede-nite ± riebeckite, titanite, epidote, and rutile (Figure 2(d, e)). The accessory minerals are apatite, monazite, and zircon. Sericite and kaolinite can be observed in some places among the outcrops, which may have been caused by the alteration of feldspar.

3. Analytical methods

3.1. Major and trace elements of whole rocks

Major and trace elements of whole rocks were analysed at the ALS Mineral Laboratory in Guangzhou, China. Fresh samples were powdered, using an agate mill to grain sieves <200 mesh. Major elements were determined, using XRF spectrometry with standard deviations within 5%. The detailed methodology is as follows: Loss of ignition (LOI) was determined after igniting sample powders at 1000°C for 1 h. A calcined or ignited sample (0.9 g) was added to 9.0 g of Lithium Borate Flux (Li2B4O7-LiBO2), mixed well and fused in an auto fluxer between 1050°C and 1100°C. A flat molten glass disc was prepared from the resulting melt. This disc was then analysed by wavelength-dispersive X-ray fluorescence spectrometry (XRF), using an AXIOS Minerals spectrometer. Trace elements, including REE, were determined by inductively coupled plasma mass spectrometry (ICP-MS) of sample solutions on an Elan DRC-II instrument (Element, Finnigan MAT) after 2-day closed beaker digestion using a mixture of HF and HNO3 (Element, Finnigan MAT) after 2-day closed beaker digestion using a mixture of HF and HNO3 (Element, Finnigan MAT). The GeoLas 200M laser ablation system equipped with a 193-nm excimer ArF laser used in connection with ELAN100 DRC ICP-MS. Helium was used as the carrier gas to enhance the transport efficiency of the ablated material. All these measurements were performed, using zircon 91,500 as the external standard with a recommended 206Pbb/238U age of 1065.4 ± 0.6 Ma (Wiedenbeck et al. 1995). Common Pb correction was conducted by using the excel program of ComPbCorr#3_181 (Andersen et al. 2002). Ages were calculated using ISO-PLT program (Ludwig, 2003). Results have been shown in Supplementary Table 2.

3.2. Zircon U-Pb isotopes

Zircons were separated from samples NP-RAPG-01, NP-RAGG-01 of Bt-granites and NP-PINK-01, NP-GG-01 of Kfs-granites, and mounted on adhesive enclosed in epoxy resin, polished and then photographed under both transmitted and reflected light. The internal structures were examined, using the Cathodoluminescence Image (CL) technique at the Analytical Center of the University of Science and Technology of China, Hefei, Anhui, China. The laser ablation (LA-ICP-MS) zircon U-Pb analyses were carried out at the Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, USTC. In situ zircon U-Pb isotopic analysis was carried out on a Neptune Plus multi-collector ICP-MS equipped with a RESOLution M-50 laser ablation system, at the State Key Laboratory of Isotopic Geochemistry, GIG-CAS. The Lu-Hf isotopic measurements were made on the same spots that were previously analysed for U-Pb ages. The laser parameters were as follows: spot size, 45 mm; repetition rate, 8 Hz; energy, 80 mJ. Helium was used as a carrier gas and a small flow of nitrogen was added in the gas line to enhance the sample signal. A normal single spot analysis consists of 30 s gas blank collection and 30 s laser ablation. The integration time was 0.131 s and about 200 cycles of data were collected. 173Yb and 175Lu were used to correct the isobaric interference of 176Yb and 176Lu on 176Hf. The 176Hf/177Hf was normalized to 176Hf/177Hf 0.7325, using an exponential law for mass bias correction. Penglai sample was used as the reference standard (Li et al. 2010). Analyses of every eight samples were followed by the standard sample (Penglai) twice. The analytical procedures were the same as those described by Wu et al. (2006) and Yuan et al. (2008). The initial Hf isotope ratios are denoted as εHf(t) values that were calculated with the Chondritic Uniform Reservoir (CHUR) at the time of zircon...
crystallization, and the present-day $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of chondrite and depleted mantle of 0.28277 and 0.0332, 0.28325 and 0.0384, respectively (Blichert-Toft and Albarède 1997). Initial $^{176}\text{Hf}/^{177}\text{Hf}$ values were calculated based on $^{176}\text{Lu}$ decay constant of $1.865 \times 10^{-11}$ year$^{-1}$ (Scherer et al. 2001). The single-stage model Hf ages (TDM$_1$) were computed with reference to the depleted mantle with a present-day $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.28325 and a $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0384 (Griffin et al. 2000). Two-stage model Hf ages (TDM$_2$) was computed, using a $^{176}\text{Lu}/^{177}\text{Hf}$ value of 0.015 for the average continental crust (Griffin et al. 2002). During the analyses, the $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of standard zircon (Penglai) were 0.282907 ± 0.000010 (2σ, n = 26). These values agree with the recommended $^{176}\text{Hf}/^{177}\text{Hf}$ values for Penglai (0.282906 ± 0.000016, 2σ, n = 117) (Li et al. 2010).

4. Results

4.1. Geochemistry

4.1.1. Major elements

The Bt-granites contain range (69.99–72.25 wt.%) SiO$_2$, (4.62–4.86 wt.%) Na$_2$O, (1.98–2.64 wt.%) K$_2$O, (0.24–0.27 wt.%) TiO$_2$, (14.60–14.90 wt.%) Al$_2$O$_3$, (0.67–0.69 wt.%) MgO, (1.84–2.60 wt.%) CaO, (0.07–0.09 wt.%) P$_2$O$_5$ (Table 2). They classify as granite in Figure 4(a). The granites are plotted in the medium-K calc-alkaline field, except two samples, which are on distribution line of peraluminous and metaluminous field, A/NK = Al/(Na+ K) (molar ratio), K = Al/(Ca+ Na+ K) (molar ratio). (b) SiO$_2$ vs P$_2$O$_5$ diagram, Bt-granites showing I-type nature along with Siwana, Jalore, Mt-Abu, granites of MIS (Eby and Kochhar 1990; de Wall et al. 2012, 2014).

![Figure 4](image.png)

Figure 4. Classification of the NPIC granites on alkali-silica diagrams. (a) TAS (total alkali silica) diagrams (cf Wilson 1989), (b) SiO$_2$ versus K$_2$O diagram, (after Peccei and Taylor 1976). Siwana, Jalore, Mt-Abu, granites of MIS (Eby and Kochhar 1990; de Wall et al. 2012, 2014) are plotted for comparison.

![Figure 5](image.png)

Figure 5. A/NK versus A/CNK diagram of NPIC granites. (a) Kfs-granites in the field of peralkaline rocks, Bt-granites in the peraluminous, except two samples, which are on distribution line between the peraluminous and metaluminous fields, A/NK = Al/(Na+ K) (molar ratio), K = Al/(Ca+ Na+ K) (molar ratio). (b) SiO$_2$ vs P$_2$O$_5$ diagram, Bt-granites showing I-type nature along with Siwana, Jalore, Mt-Abu, granites of MIS (Eby and Kochhar 1990; de Wall et al. 2012, 2014).
$P_2O_5$ (0.007–0.022 wt.%) and total alkali contents range from 6.80 to 9.11 wt.% (Supplementary Table S1). The Kfs-granites plot in the high-K calc-alkaline field (Figure 4B). Their $Al_2O_3$ and $Na_2O/K_2O$ contents range from 10.81 to 11.92 wt.% and 0.71 to 1.93 wt.%, respectively. They have $A/NK$ ratios (of 0.91–0.99, with two samples plotting in the metaluminous field, two on the boundary line of metaluminous and Peralkaline fields, and one in the Peralkaline field in A/NK-A/CNK diagram (Figure 5(a)).

### 4.1. Trace elements

High field strength elements (HFSE) of Bt-granites (Supplementary Table S1), Figure 6(a), show positive anomalies of Zr and Hf and negative anomalies of Nb and Ta in the N-MORB diagram (Figure 6(b)). From the REE distribution diagram of Bt-granites, LREE enrichment and HREE depletion can be observed with slightly negative Eu/Eu* (0.79–0.89) anomalies. Their REE distribution patterns are similar to that of the lower crust. Their LILs (Supplementary Table S1) show positive Rb, Ba, Ce, and slightly positive Sr anomalies in the trace element distribution diagram.

HFSE, of Kfs-granites (Supplementary Table S1), indicate positive anomalies of Zr and Hf with negative anomalies of Nb and Ta in the N-MORB diagram of Sun and McDonough (1989) (Figure 6(b)). LREE enrichment and flat HREE can be observed from the REE distribution diagram of the Kfs-granites, with pronounced negative Eu/Eu*(0.14–0.22) anomalies (Figure 6(a)). Negative Eu anomalies of these Kfs-granites indicate removal of plagioclase by crystal fractionation. Consistently, decrease in Ba, Sr and increase in Rb with increasing $SiO_2$ may also indicate plagioclase fractionation. Their LILs, such as Rb, Ba, and Sr, range from 151.5 to 7.9 ppm, 392.0 to 28.3 ppm, and 33.0 to 8.3 ppm, respectively (Supplementary Table S1).

### 4.2. Zircon U-Pb dating

The CL images of representative zircon are shown in Figure 7(a). The results of LA-ICP-MS U-Pb isotopic data are provided in Supplementary Table S2. Although Zircons were separated from NPIC Bt-granites and Kfs-granites, all of the zircons are generally prismatic, colourless, transparent, and euhedral with obvious oscillatory zoning. These features, along with their high Th/U ratios (>0.1), indicate the igneous origin. The Bt-granite samples NP-RAGG-01, NP-RAG-01, have high Th and U contents of 191–633 ppm and 233–812 ppm, 30–144 ppm and 47–217 ppm, and Kfs-granite samples NP-PINK-01, NP-GG-01 have Th 36–85 ppm and U 78–110 ppm, Th 40–243 ppm and U 73–193 ppm, respectively (Supplementary Table S2). The Bt-granites analysis of >20 spots yielded concordant U-Pb ages with weighted mean $^{206}Pb/^{238}U$ ages of 812.3 ± 14.1 Ma and 810 ± 7.4 Ma, respectively (Figure 7(a, b, c, d)), for Kfs-granites analysis of >25 spots yielded concordant U-Pb ages with weighted mean $^{206}Pb/^{238}U$ ages 736.3 ± 4.3 Ma and 755.3 ± 7.1 Ma, respectively (Figure 8(a, b, c, d)).

### 4.3. Zircon Lu-Hf isotopes

Lu-Hf isotopic analysis of zircon grains from NPIC Bt-granites yield $\varepsilon_{Hf}(t)$ ($t$ = 812 Ma and 810 Ma, U-Pb data are listed in Supplementary Table S2) values from +8.6
to + 13.2 and + 10.3 to + 12.2, Supplementary Table S3. The zircon grains have mainly tDMc ages (943–1093 Ma) and (932–1052 Ma) of NP-RAPG-01, NP-RAGG-01, respectively. The NPIC Kfs-granites have $\varepsilon_{\text{Hf}}(t)$ ($t = 736$ and 755 Ma) values from + 8.2 to + 14.0 and + 11.0 to + 14.1 with model ages (tDMc) from 761 to 1151 Ma and 771 to 1151 Ma, respectively (Figure 9), (Supplementary Table S3).

5. Discussion

5.1. Significance of zircon U-Pb geochronology

Khan et al. (2012) dated the granitic rocks (EPMA U-Th-Pb of zircon or monazite) from NPIC (Table 1). But the results were different with large margins of errors, i.e. 900 ± 50 Ma for the Bt-granite and 750 ± 30 Ma to 730 ± 60 Ma for the Kfs granite. The much precise zircon U-Pb ages of 812.3 ± 14.1 Ma to 810 ± 7.4 Ma for the Bt-granites and 736.3 ± 4.3 Ma to 755.3 ± 7.1 Ma for Kfs-granites are newly reported in this study, suggesting two periods of granitic magmatism in the NPIC area: ca. 812–810 Ma for the older Bt-granite and ca. 755–736 Ma for the younger Kfs-granite. These two age groups are also recorded in the adjacent Northwest Indian terrane. The 812.3 ± 14.1 Ma age of the Bt-granite is also strikingly similar to the 815 ± 30 Ma age (Table 1) reported from the Erinpura granite by Choudhary (1984). Murao et al. (2000) reported Ar-Ar ages of 818 Ma for granite at Tosham, and the age cluster at around 820 Ma for this suite is thought to mark the maximum age for the culmination of the Delhi orogeny (Deb et al. 2001). Other granites with similar ages include the Khnanak granite (803 Ma, Murao et al. 2000) and Jhunjhunu granite porphyry (805 Ma, Choudhary et al. 1981a; 1981b, 1984). The age is also
consistent with zircon U-Pb ages of 807 ± 5.3 Ma (Table 1) reported from magmatic monazite in Erinpura granites of the Sirohi region (Just et al. 2011).

The second age group comprises the A-type granites and shows coeval intrusion ages of the Nagarparkar Kfs granites and granites from Sirohi and MIS. Consequently, the NPIC granites together with those of the MIS, Seychelles, and Madagascar regions (Table 1) give evidence for a vast Neoproterozoic magmatic terrain.

5.2. A-type granite affinity of the NPIC Kfs-granite

The NPIC Kfs-granites are characterized by the enrichment of K\sub{2}O + Na\sub{2}O and incompatible elements, such as LREEs (except Eu), Zr, Y, and Ce, and have high FeOT/ (FeOT+ MgO), which are the typical features of A-type granites (Eby 1990). A number of A-type granites plutons have been reported from the western part of Indian Shield and Seychelles island, formed between 760 and 736 Ma, e.g. Mt-Abu pink granite (767 ± 4 Ma, Ashwal 2013), Mirpur Pink granite (753 ± 9 Ma, de Wall et al. 2018), NPIC pink granite (750 ± 30 Ma and 730 ± 60 Ma, Khan et al. 2012), Praslin pink granite (750 ~ 752 Ma, Tucker et al. 2001; Ashwal...
et al. 2013), and Marianne pink granite (758 ± 2 Ma, Tucker et al. 2001). All NPIC Kfs-granite samples present high Ga/Al ratios, which are comparable with MIS granites. In the 10,000*Ga/Al versus Zr, and FeO/T/MgO dia-
grams, all analyses of the NPIC Kfs-granites and MIS granites classify as A-type granites (Figure 10(a, b)). In N-MORB normalized trace element diagram (Figure 6 (b)), the Kfs-granites show strong Sr, Ba, Eu depletion and enrichment in Rb, La, Ce, Zr, and Hf, which are features of A-type granites (Collins et al. 1982; Whalen et al. 1987; Wu et al. 2002).

The A-type granites are further classified into A₁ and A₂ types; the A₂ subgroup has high concentrations of Y and Ce relative to Nb and high ratios of Ce/ Nb and Y/Nb (Eby 1990). A₂-type granites can form in a wide range of tectonic settings (e.g. post-orogenic extensional environment different from the within plate A₁ granites) (Eby 1992). The rocks of NPIC, Siwana, Jalore, Mt-Abu of MIS are characterized by a major period of anorogenic A-type within-plate granite magmatism (Kochhar 1973; Khan et al. 2012). The NPIC Kfs-granites, together with the MIS granites, all plot in the A₂ granite field in Y/Nb-Yb/Ta and Y/Nb-Ce/Nb diagrams (Figure 11(a, b)). They can be derived from continental crust or underplated crust that has experienced a cycle of continent–continent collision or island-arc magmatism (Eby 1992).

5.3. Petrogenesis of NPIC biotite granites and Kfs-granites

The origin of I-type granites also remains in debate. It is generally accepted that they are formed by any of these two processes: fractional crystallization of mantle-derived
I-type granites could be drawn at an A/CNK ratio of 1.1. Chappell and White (1974) proposed that the boundary between S-type and I-type (often referred to as anorogenic) was a distinct group that had characteristics of magma derived from an OIB source and was inferred to be the fractionation product of an OIB-like basalt magma. A2-type granites, the A2-type (often referred to as post-collisional or post-orogenic) represented all A-type granitoids not derived by fractionation of an OIB-like magma. These granitoids were generally emplaced shortly after an orogenic period and may have originated by melting of mantle material with crustal interaction or solely by the melting of crustal material (Eby, 1990). (b) the NPIC Kfs-granites are depleted in Sr and Ba normally suggesting the residue of plagioclase in their sources, in favour of partial melting of a dehydrated source in a shallow level with plagioclase in residue (Peate et al. 1984). The enrichment of some incompatible trace mafic magmas, or partial melting of a magmatic precursor (e.g. Chappell and White 1974). I-type granites have relatively high sodium contents with Na2O normally >3.2% in felsic varieties, decreasing to >2.2% in more mafic types. I-type granites show molar Al2O3/ (CaO + Na2O + K2O) <1.1 (A/CNK). Chappell and White (1974) proposed that the boundary between S-type and I-type granites could be drawn at an A/CNK ratio of 1.1. The NPIC Bt-granites have low A/CNK ratios with two samples plotting in peraluminous field, whereas other two straddle the boundary line of metaluminous and peraluminous fields (Figure 5(a)). They exhibit a negative correlation between P2O5 and SiO2 contents (Figure 5(b)), probably indicating fractional crystallization of plagioclase during magma evolution. Additionally, S-type granites generally contain Al-rich minerals such as cordierite or muscovite, which are not found in the samples of the present study. I-type affinity of the Bt-granites indicates that they were produced by partial melting of an igneous source (Chappell and White 1992; Chappell 1999). The Bt-granites show a progressive decrease in middle HREE (Figure 6(b)), suggesting breakdown of amphibole in the source. This may have supplied enough water to induce partial melting of middle-to-lower crust to generate granitic melt (Rapp and Watson 1995; Huang et al. 2013a). The breakdown of amphibole can progress through a variety of reactions under varying P-T conditions (Wyllie and Wolf 1993; Wolf and Wyllie 1994). In an anhydrous source in the middle-to-lower crust (<8 kbar), an extremely high temperature (high thermal gradients >35°C/km) is required for the breakdown of amphibole (Huang et al. 2013b). However, the Kfs-granites do not show an obvious depletion of mid-to-heavy REEs. Finally, they are characterized by relative enrichments of LREE and depletion of Nb and Ta, relatively curved-HREE patterns, and negative Eu anomalies. This behaviour of elements shows the inclination towards a lower crust affinity (Xiong 2006; Yu et al. 2016) (Figure 7(a, b)).

A-type magma with alkaline and anhydrous characteristics (Loiselle and Wones 1979) can be formed through a number of magmatic processes involving fractional crystallization of mantle-derived basaltic magma (Turner et al. 1992; Smith et al. 1999; Andersen et al. 2003), assimilation partial melting of mantle or crust and magma mixing between basaltic and crustal melts (Collins et al. 1982; Frost and Frost 1997; King et al. 1997; Frost et al. 1999; Wu et al. 2002; Yang et al. 2006; Bonin 2007; Dall’ Agnol and De Oliveira 2007). A-type granites are typified by their specific geochemical features and their tectonic affinity (Zhao et al. 2008). The high HSFE contents of A-type granites have been attributed to a dry source (e.g. the granulitic source) (Collins et al. 1982). The dehydration melting of tonalite or granodiorite with a plagioclase-rich residual at high temperature and low pressure (900°C, 4 kbr) is capable of generating A-type magma (Patino Douce 1997) with strong negative anomalies of Eu, Ba, and Sr. The NPIC Kfs-granites are depleted in Sr and Ba suggesting the residue of plagioclase in their sources, in favour of partial melting of a dehydrated source in a shallow level with plagioclase in residue (Peate et al. 1984).
elements, i.e. Zr, Ce, and depletion of Sr and Ba in these rocks indicate their possible genesis in a shallow environment during a continental extension period with a crustal source (Currie 1989; Sun and McDonough 1989). The continental rift zones are generally associated with peralkaline rocks with a low abundance of associated mafic rocks (Wilson 1989). The most probable genesis for these peralkaline rocks from NPIC area is the low-pressure partial melting of continental crust. Thus, the biotite-granites and the Kfs-granites were likely generated by partial melting of crustal sources under different P-T conditions.

The highly positive zircon $\varepsilon_{Hf}(t)$ values (+8.6 to +13.2, av. +10.8) of the Bt-granites are close to those of the Kfs-granites counterparts (+7.8 to +14.1, av. +10.2), indicating a similar source of the juvenile continental crust, although they differ in some of other geochemical features, such as the I-type affinity for the Bt-granites and A-type affinity for the Kfs-granites as discussed above. Positive initial $\varepsilon_{Hf}(t)$ values are consistent with long-term depleted mantle source, whereas negative initial $\varepsilon_{Hf}(t)$ values could imply the involvement of crustal components into the mantle source. Their $\varepsilon_{Hf}(t)$ values are also close to +13.8 on the evolution curve of the depleted mantle (Griffin et al. 2000) (Figure 9), with average Hf model ages (1151 and 761 Ma, respectively) close to their formation ages, suggesting a dominant juvenile crust in the source. In addition, gabbro intrusion found in the NPIC area (Figure 3(a, c, d)), which shows similar formation age and Hf isotope compositions to the NPIC granites (our unpublished data). Therefore, it is inferred that the NPIC Bt-granites were formed by partial melting of a juvenile lower continental crust which has similar isotopic composition with the gabbro. Gabbro has been emplaced before the crustal extension and refers to field observation (Figure 12(a)). In contrast, Kfs-granites were likely generated through partial melting of a juvenile continental crust at a shallower depth within an extensional environment, most likely caused by Rodinia rifting (Figure 12(b)).

5.4. Tectonic evolution and regional implication

The NPIC Bt-granite and Kfs-granites show similarities in geochemistry and geochronological ages with

![Figure 12. A simplified tectonic model for a generation of NPIC granites. (a) Proposed model of the NPIC Bt-granites at 812 Ma before rifting of Rodinia. The Bt-granites were formed in lower continental crust environment. (b) Model of the NPIC Kfs-granites at 736 Ma after the rifting of Rodinia, A-type granites were formed in upper continental crust.](image-url)
those of Neoproterozoic MIS rocks, Seychelles, and Madagascar rocks. The MIS rocks are a mixture of peralkaline to peraluminous, riebeckite-aegirine bearing peralkaline granite (Siwana granite), peraluminous biotite-hornblende granite (Jalore granite), Mt-Abu pink granites, and Sirohi grey granites. The Siwana granites are peralkaline rocks at Siwana and Barmer areas and associated with other per-alkaline mafic and felsic rocks. These rocks are also enriched in HFSE, such as, Zr, Zn, Be, La, Y, and Ce (Bhushan and Mohanty 1988). The chondrite-normalized and N-MORB-normalized diagrams show good agreement of NPIC and MIS rocks (Figure 7(a, b)). Similarly, the NPIC Kfs-granites also show affinity with within-plate Seychelles pink granites and Siwana granites in tectonic discrimination diagram (Figure 11(c, d)). They have the similar characteristics of A-type granites in Figure 12(a, b). The NPIC Bt-granites can be linked with Sirohi Bt-granites, which are VAG granites in MIS (Figure 11(c, d)).

The NPIC along with MIS of the western Rajasthan marks an important late Proterozoic thermal event in the continental evolution of this part of the subcontinent. It is generally believed that the extensional tectonic environment triggers the peralkaline rocks. The rocks of anorogenic occurrences have been reported worldwide (Currie 1989). The continental rift zones are, in general, coupled with the peralkaline rocks, and sometimes associated with mafic rocks (Wilson 1989). The most probable source for these peralkaline rocks appears to be partial melting of metasomatized crust (Currie 1989). According to Leat and Thorpe (1986), the basalts of within-plate character associated with peralkaline rocks characterize the zones of crustal extension. Peralkaline magma can be generated by the extension and thinning of the continental lithosphere. The contribution of continental crust in the evolution of granite from the NPIC is supported by high concentration of incompatible elements and low Sr contents. Extensive tectonic regime may be accountable to produce heat by rising basaltic magma from the mantle to promote melting of the lower crust rich in LILE, HFSE, and halogens (Bailey 1978). Neoproterozoic magmatism in Northwest India can be compared with equivalent Neoproterozoic igneous in Madagascar, Seychelles provinces, and South China (Handke et al. 1999; Kroner et al. 1999; Tucker et al. 2001; Torsvik et al. 2001a, 2001b; Ashwal et al. 2002; Collins 2006; Zhou et al. 2018). Regionally, we can assume that NPIC, MIS, Seychelles, and Madagascar and South China granitic rocks were positioned at same place before rifting of the Rodinia supercontinent.

6. Conclusion

(1) LA-ICPMS zircon U-Pb dating of the NIC granites in Southeast Pakistan yielded weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 812.3 ± 14.1 Ma to 810 ± 7.4 Ma for the Bt-granite and 755.3 ± 7.1 Ma to 736.3 ± 4.3 Ma for the Kfs-granite, indicating at least two major Neoproterozoic magmatic events.

(2) The A-type Kfs-granites were constituted during the crustal thinning triggered by the Rodinia rifting. Sources of both Bt-granite and Kfs-granite are supposed to be the juvenile lower crust and upper continental crust, respectively.

(3) This work supports the earlier suggestions that the NIC and the MIS in Rajasthan can be correlated on the basis of geochronology, geochemistry, and petrography, suggesting that their granitic bodies represent the same magmatic events.

Highlights

- Neoproterozoic Bt-granites and Kfs-granites are distinguished in Nagarparkar area.
- Both the two types of NPIC granites were derived from juvenile crustal sources.
- The NPIC Bt-granites were formed before rifting of Rodinia and Kfs-granites were formed during rifting period.
- NPIC, MIS, Seychelles, and Madagascar granites were formed together before breakup of Rodinia.

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Disclosure statement

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