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GEOCHEMICAL COMPARISON OF QUARTZITES OF THE ARCHAEAN BASEMENT COMPLEXES OF THE ARAVALLI AND BUNDELKHAND BLOCKS OF THE NORTH INDIAN SHIELD: IMPLICATION FOR PROVENANCE COMPOSITION AND CRUSTAL EVOLUTION

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ABSTRACT: The petrography as well as major, trace element including rare earth element (REE) compositions of Archaean quartzites of the Aravalli and Bundelkhand blocks of the North Indian Craton (NIC) of the Indian shield are compared and investigated to assess the influence of sorting and recycling, source area weathering and provenance composition. Petrological evidence suggests derivation of detritus of both of the sedimentary sequences from stable part of the craton. Geochemically, both quartzites are distinguished as litharenite-arkose. The quartzites are not mature as their SiO_2/Al_2O_3 ratio remains < 10. CIA (chemical index of alteration) and CIW (chemical index of weathering) values and Th/U ratios indicate low to moderate degree of chemical weathering in the source area of studied rocks, which reflect high erosion rate coupled with short distance and rapid sedimentation in a tectonically active basin. Provenance modelling indicates that the quartzites of the Aravalli block can be best modelled with a mixture having 50% TTG (tonalite-trondhjemite-granodiorite), 40% granite and 10% mafic rocks. On the other hand the quartzites of the Bundelkhand block were derived from a source terrain comprising 80% TTG, 10% granite and 10% mafic rocks. TTG and granite-derived material, with smaller amount of mafic-derived debris, explains the geochemical characteristics of these quartzites. It is inferred that these sedimentary sequences were probably deposited on the margin of young cratons, consisting newly accreted TTG and granite bodies. Comparatively higher amount of TTG and lesser amount of granites in the source terrain of Bundelkhand quartzites indicate more primitive nature of continental crust in the Bundelkhand block in comparison to the Aravalli block that had comparatively more evolved crust at the time of sedimentation during the Archaean.

Keywords: Geochemistry, quartzites, Aravalli Craton, Bundelkhand Craton, crustal evolution.

INTRODUCTION

Geochemical studies of clastic sedimentary rocks had long been used to constrain the composition and geological evolution of sedimentary source areas and to discriminate the tectonic setting prevailing at the time of deposition (Bhatia and Crook, 1986; McLennan et al., 1993; Wronkiewicz and Condie 1987; Lahtinen, 2000; Condie et al.,2001; Tran et al., 2003; Armstrong et al., 2004; Hofmann et al., 2005; Absar et al., 2009; Raza et al.,2010a, b; 2011; PurevjavandRoser 2013). In recent years, there has been a great interest in the Archaean siliciclastic successions (Hessler and Low 2006; Sugitani et al., 2006; Raza et al., 2010a). These successions have been viewed as critical in understanding the crustal development during the early part of the earth history. The geochemical studies of these rocks have been successfully used to model provenance, Archaean intracrustal processes, tectonic setting and overall crustal evolution (Taylor and McLennan, 1985; Naqvi et al., 1983, 2002; Condie and Wronkiewicz, 1990; Fedo et al., 1995). In this regard, the most important are certain immobile trace elements, which are quantitatively transferred into sedimentary basins and thus preserve the record of the average upper crustal element concentrations (Taylor and McLennan, 1985).

The north-western part of the Indian shield, popularly known as North Indian Craton (NIC) is made up of two crustal blocks namely the Aravalli cratonic block (ARB) in the west and the Bundelkhand cratonic block (BKB) in the east separated by a NE-SW trending major lineament referred to as Great Boundary Fault Zone (GBFZ). However, it is not clear if the Aravalli and the Bundelkhand blocks of the north Indian shield share a common history. Unlike many Archaean shield of the world, this part of Indian shield lacks the occurrence of coherent greenstone belts. However, the mafic-sedimentary sequences, occurring as enclaves of variable sizes, within the Archaean basement complex, have been considered as dismembered greenstone belts of Archaean age (Ramakrishnan and Vaidyanadhan 2010; Sinha-Roy, 1985; Mohanty and Guha, 1995; Guha, 2007). In Aravalli block, the mafic-sedimentary enclaves are best developed in Mavli and Jagat areas occurring to the northeast and south-west of Udaipur city

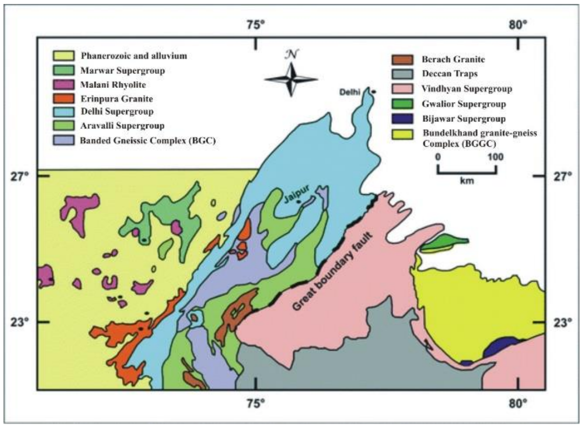

Figure 1: Generalized geological map of the Aravalli-Bundelkhand protocontinent, NW India, showing major lithounits (after Naqvi and Rogers 1987; Ramakrishnan and Vaidyanathan 2008).

respectively (Fig.1). In Mavli area the sedimentary rocks are predominantly quartzite and have been referred to as Naharmagra quartzite (Roy and Jakhar, 2002). These quartzites have been recently studied for their geochemistry (Raza et al., 2010a). No geochemical and petrographic data are available on sedimentary rocks occurring as mafic-sedimentary rock bodies within the BGC of Jagat area. In Bundelkhand block the volcanic-sedimentary sequences occur along linear zones within the gneissic complex (Basu 1986, 2007; Prasad et al. 1999; Ramakrishnan and Vaidyanadhan 2010; Singha and Slabunov, 2014). Two east-west trending linear zones have been recognized (Fig. 1). These are (i) Mauranipur-Babina greenstone belt in the north and (ii) Madaura-Girar greenstone belt in the south. The sedimentary rocks of Mauranipur-Babina greenstone belt have been studied for their geochemistry by Raza and Mondal (2018). These authors have suggested that the basin experienced contemporaneous sedimentation of immature detritus derived from a young craton comprising TTG and granitic batholiths and syn-depositional volcanic centres in an active tectonic environment. In the present paper the new geochemical data of Archaean quartzite of Aravalli block (ARB) are reported and compared with available geochemical data of Archaean quartzite of Bundelkhand block (BKB) (Raza and Mondal, 2018).The aim is to constrain influence of sorting and recycling, sediment maturity and depositional environment, source rocks weathering, and composition of provenance of this sedimentary sequence. The drawn interpretations are thus used to infer the composition and evolution of continental crust of NIC during the early part of the earth history, and also to ascertain whether the Aravalli and the Bundelkhand blocks share a common evolutionary history or not.

GEOLOGICAL SETTING

In ARB an important feature of the BGC is the presence of isolated bodies of sedimentary-mafic rocks of variable sizes which are considered to be the vestiges of dismembered greenstone sequences (Mohanty and Guha, 1995; Guha, 2007). The metasediments present in the BGC basement include quartzite, metagreywacke, marble, calc-silicate and mica schists. Out of all these types, only quartzites/ greywacke and marble occur as mappable units. Other types are rare, highly weathered and/or migmatized. There are numerous bodies comprising quartzite/ greywacke-amphibolite association of Archaean age occurring within the BGC.

These units are well exposed in two areas (1) Rakhiawal-Naharmagra and (2) Jagat areas east of Udaipur city (Upadhyaya et al., 1992; Roy et al., 2000). Here the quartzite and/ or metagreywacke bodies are interlayered/intruded by 2800 Ma old (Sm-Nd isochrones; Gopalan et al., 1990) amphibolite (metabasalt), indicating a Mesoarchaean age. In Jagat area the sedimentary rocks are interbedded with metabasaltic rocks. The presence of minor conglomerate and primary sedimentary structures such as cross-bedding attest their sedimentary origin.

The BKB consists predominantly of Proterozoic granites containing linear slivers of gneisses of tonalite-trondhjemite-granodiorite composition (TTG) and volcanic-sedimentary sequences of Archaean age. The major lithological units of BKB are: i) Archaean gneisses of tonalite, trondhjemite and granodiorite (TTG) composition (Basu, 1986; Mondal and Zainuddin, 1996; Mondal et al., 2002), ii) metamorphosed supracrustal basement rocks (BIF, interbedded quartzite, schist, amphibolite and/or clac-silicate rocks) exposed along the E-W trending lineament namely Bundelkhand Tectonic Zone (BTZ) that is a major brittle ductile shear zone extending along Mauranipur-Babina section and iii) undeformed younger granites (Mondal and Zainuddin, 1996). In this block the clastic metasedimentary rocks occur as minor but distinct components of volcanic-sedimentary greenstone succession of Mauranipur-Babina belt. The clastic metasedimentary rocks are best exposed in and around Naugao, Jugalpur and Baruasagar, where they are found interlayered with volcanic flows of basaltic to basaltic andesitic composition (Malviya et al., 2004; Raza and Mondal, 2018). Two distinct metasedimentary rocks were identified based on their mineralogical and textural characteristics. These are: (I) fine grained metapelitic rocks consisting predominantly of mafic minerals in association with quartz grains and (II) medium to coarse grained, quartzites consisting predominantly of quartz and feldspars. In the present study the samples of quartzites occurring within the Archaean basement complexes of BKB and ARB are studied for petrography and geochemical characteristics.

PETROGRAPHY

The ARB siliciclastic are generally fine- to coarse-grained, poorly to moderately sorted rocks having angular to sub angular grains. The detrital content is mainly composed of quartz, followed by feldspars as major constituents and biotite as minor minerals, and accessory phases are grains of heavy minerals such as zircon, monazite and opaques. The quartz varieties include common quartz with a few grains of recrystallized and stretched metamorphic quartz. Feldspar varieties include plagioclase and microcline. Plagioclase grains are more abundant in comparison to microcline. Both fresh and weathered varieties of feldspar are present. They are compositionally mature.

The BKB samples are light-coloured, texturally, immature medium to coarse grained, sedimentary rocks appearing as quartzite. The framework grains of these meta-sedimentary rocks are dominantly feldspars (plagioclase + microcline) and quartz among which monocrystalline quartz (Q_m) is in abundance than polycrystalline quartz (Q_p). The relative abundance of monocrystalline quartz to that of polycrystalline quartz appears to reflect the maturity of the sediments, because polycrystalline quartz is eliminated by recycling and disintegrates in the zone of weathering as does strained quartz (Basu, 1986). The occurrence of small percentage of feldspar may be attributed to the fact that it was lost in the soil profile in warm, humid climate with low relief or by abrasion during transport or lost in solution during digenesis. It is inferred that studied sediments were derived from continental block provenance of low relief, witnessing a warm tropical climate.

ANALYTICAL PROCEDURES

Samples for this study were powdered to -200 mesh size by using agate pulverizer. Major element oxides were determined by X-Ray fluorescence Spectrophotometry (XRF) technique in geochemical laboratory of Wadia Institute of Himalayan Geology, Dehradun with precision of ± 1%. Trace elements were analysed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS, Perkin-Elmer, SCIEXELAN DRC II) at National Geophysical Research Institute (NGRI), Hyderabad with <10% precision.

GEOCHEMISTRY

Major Elements

The ARB samples are characterized by SiO_2 content ranging from 74.35 to 75.89% (avg.74.86%), Al_2O_3 contents from 12.82 to 14.84%, (avg.13.63 %) and Fe_2O_3contents from 2.25 to 5.06 % (avg. 4.45 %). The BKB samples display higher contents of SiO_2 (73.53-87.18%, avg. 79.85%), lower contents of Fe_2O_3 (0.5-1.6%, avg.1.05%) but comparable Al_2O_3 (BKB= 8.15-14.78, %, avg.11.79 %; ARB= 12.82-

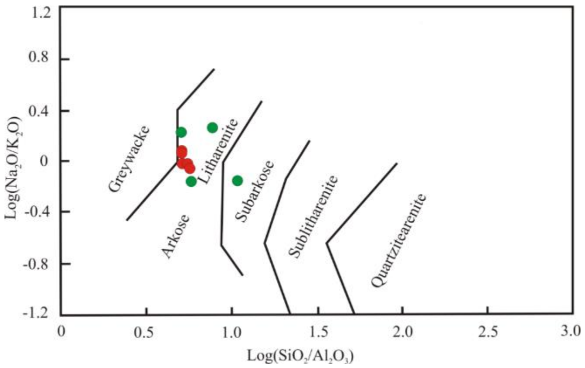

Figure 2: Geohemical classification diagram of Pettijhon (1972). The samples of the Bundelkhand quartzite (green circles) and Aravalli quartzite (red circles) occupies litharenite field.

14.84, avg. 13.63). The BKB rocks contain MgO contents (0.6-0.29%; avg.0.13%) and CaO (0.27-1.61%; avg.0.73%) comparable to ARB quartzite (MgO= 0.76-0.93%; avg.0.82%; CaO= 0.76-0.93%; avg.0.82%). On Log (SiO_2/Al_2O_3) versus Log (Na_2O/K_2O) classification diagram of Herron (1988), all the studied samples plot in the field of litharenite-arkose (Fig. 2). The samples of BKB appear to be more heterogeneous in comparison to those of ARB (Table-1).

Trace elements

The trace element abundances of clastic sedimentary rocks have long been used to investigate composition of the source terrain, weathering history, transportation, digenesis and metamorphism. Many authors have suggested the use of immobile or relatively immobile elements as discriminant tool (Cann 1970; McLennan 1989; Rollinson 1993; Taylor and McLennan, 1985). These elements include Al_2O_3, TiO_2, HFSE such as Zr, Y, Nb, Hf, Ta and Ga and transitional elements such as Sc, Ni, and V. The REEs are also considered to be relatively immobile during chemical weathering and digenesis (Nesbitt 1979; Humphris 1984) such that provenance information may not be lost even after considerable alteration of framework grains (Johnsson 1993). For these reasons, selected major, minor and trace elements are increasingly being employed as tool in igneous discrimination and sedimentary provenance characterization studies.

High Field Strength Elements (HFSE)

The HFSE are strongly incompatible during magmatic differentiation and anatexis, as a result these elements are concentrated more in felsic rather in mafic rocks. They are immobile or less mobile during sedimentary processes and have low residence time in the sea water (Holland, 1978; Sugitani et al., 2006). Therefore abundances of these elements along with REE represent the composition of source materials of sedimentary rock formations. HFSE concentration of analyzed samples of ARB

	BUNDELKHAND QUARTZITE					**ARAVALLI QUARTZITE**					
(Wt.%)	**MR142**	**MR144**	**N209**	**N210**	**Average**	**JG1**	**JG2**	**JG3**	**JG4**	**JG5**	**Average**
SiO_2	87.18	82.04	76.65	73.53	79.85	74.35	74.35	74.95	74.74	75.89	74.86
TiO_2	0.1	0.03	0.09	0.14	0.09	0.13	0.15	0.15	0.16	0.13	0.14
Al_2O_3	8.15	10.83	13.38	14.78	11.79	13.78	13.85	12.82	12.88	14.84	13.63
Fe_2O_3	1.6	0.5	0.79	1.31	1.05	4.85	5.03	5.06	5.06	2.25	4.45
CaO	0.66	0.27	0.38	1.61	0.73	0.77	0.84	0.79	0.76	0.93	0.82
MgO	0.06	0.08	0.09	0.29	0.13	0.12	0.13	1.11	1.11	1.09	0.71
Na_2O	0.5	4.6	3.86	5.4	3.59	1.96	1.95	1.79	1.93	1.93	1.91
K_2O	0.71	2.51	5.62	3.28	3.03	2.19	2.07	1.95	2.07	1.65	1.99
MnO	0.03	0.01	0.02	0.03	0.02	0.04	0.05	0.05	0.05	0.04	0.05
P_2O_5	0.02	0.01	0.02	0.04	0.02	0.13	0.13	0.13	0.13	0.13	0.13
Sum	99.01	100.88	100.90	100.41	100.30	99.21	99.42	99.56	99.65	99.53	99.47
(ppm)											
Sc	2.57	1.04	1.20	1.93	1.69	2.02	2.81	3.75	3.09	2.43	2.82
V	4.88	3.07	3.45	4.70	4.03	13.44	5.56	6.88	7.27	9.78	8.59
Cr	6.37	4.05	4.28	4.07	4.70	16.16	15.19	17.67	19.1	16.25	16.87
Co	21.9	18.24	25.43	27.37	23.24	1.37	1.52	1.67	1.81	1.9	1.65
Ni	7.52	5.62	3.21	3.11	4.87	4.64	10.1	3.45	7.32	5.58	6.22
Cu	1.327	1.33	0.71	0.91	1.07	1	0.32	0.32	0.38	0.36	0.48
Zn	11.13	17.14	13.84	9.11	12.81	0.77	0.96	1.29	1.17	0.74	0.99
Ga	3.73	5.44	11.22	13.62	8.51	21.5	23.35	29.29	25.37	26.05	25.11
Rb	21.82	52.66	222.9	85.41	95.70	210.46	251.4	387.3	336.02	208.94	278.82
Sr	33.61	58.18	43.48	153.11	72.10	5.08	4.6	4.68	4.98	9.96	5.86
Y	5.64	8.06	8.55	6.34	7.15	17.44	22.07	62.78	49.69	17.97	33.99
Zr	69.97	67.02	69.73	87.04	73.44	113	198.21	247.25	219.1	139.7	183.45
Hf	2.013	2.63	3.08	3.00	2.69	2.90	5.08	6.34	5.62	3.58	4.70
La	10.47	7.39	12.75	14.06	11.17	21.01	12.65	44.59	48.6	28.5	31.07
Ce	18.22	15.80	25.54	23.89	20.87	47.53	21.79	102.5	116.89	58.87	69.52
Pr	1.94	1.47	1.99	2.21	1.91	4.72	2.45	9.54	11.17	5.99	6.77
Nd	7.03	5.25	6.33	7.61	6.56	17.73	9.32	35.49	41.12	23.31	25.39
Sm	1.30	0.99	1.02	1.19	1.13	3.95	2.3	7.93	9.04	5.39	5.72
Eu	0.38	0.28	0.19	0.36	0.31	0.47	0.4	0.46	0.53	0.6	0.49
Gd	1.04	0.85	0.89	1.00	0.95	3.32	2.48	6.9	7.3	4.08	4.82
Tb	0.16	0.15	0.14	0.14	0.15	0.54	0.48	1.28	1.2	0.63	0.83
Dy	1.01	1.14	1.06	0.86	1.02	3.57	3.04	8.58	7.45	3.25	5.18
Ho	0.11	0.13	0.12	0.10	0.12	0.36	0.41	1.51	1.22	0.33	0.77
Er	0.38	0.55	0.50	0.38	0.46	1.11	1.32	3.88	3.24	0.93	2.10
Tm	0.05	0.08	0.08	0.05	0.07	0.13	0.15	0.54	0.44	0.1	0.27
Yb	0.60	0.93	0.99	0.59	0.78	1.28	1.43	5.43	4.46	0.99	2.72
Lu	0.10	0.16	0.20	0.11	0.15	0.2	0.22	0.87	0.7	0.16	0.43
Nb	2.23	6.24	7.49	5.95	5.48	8.72	13.32	25.54	16.18	11.55	15.06
Ta	0.96	2.12	2.35	1.85	1.82	0.55	0.83	1.60	1.01	0.72	0.94
Ba	123.75	542.36	220.37	407.97	323.62	293.88	229.86	246.92	261.59	276.00	261.65
Th	3.18	13.28	18.66	10.85	11.50	20.88	13.19	40.20	42.92	32.12	29.86
U	0.68	3.23	4.51	1.72	2.54	8.88	8.83	15.98	13.72	10.78	11.64
Th/Sc	1.23	12.73	15.44	5.60	8.75	10.34	4.69	10.72	13.89	13.22	10.57
Th/U	4.64	4.11	4.13	6.29	4.79	2.35	1.49	2.52	3.13	2.98	2.49
La/Sc	4.06	7.08	10.55	7.25	7.24	10.40	4.50	11.89	15.73	11.73	10.85
Zr/Sc	27.13	64.20	57.68	44.89	48.47	10.34	4.69	10.72	13.89	13.22	64.16
CIA	74.48	50.12	50.47	49.03	56.03	66.33	66.50	66.38	65.45	69.05	66.74
CIW	80.11	57.33	65.51	55.57	64.63	74.87	75.87	76.87	77.87	78.87	76.87
$(La/Yb)_N$	12.50	5.69	9.17	17.01	11.09	11.77	6.35	5.89	7.82	20.65	10.50
Eu/Eu*	1.01	0.93	0.61	1.02	0.89	1.18	0.78	2.42	2.66	1.53	1.72

TABLE 1: Major (wt. %) and trace element concentrations (ppm), and the elemental ratios of the quartzites of the Bundelkhand (Raza and Mondal, 2018) and Aravalli Cratons.

rocks are more enriched in HSFE (Zr= 113-247.25 ppm, avg.183.45 ppm; Nb= 8.72 - 25.54 ppm, avg.15.06 ppm; Y= 17.44-62.78 ppm, avg.33.99 ppm) relative to BKB (Zr=67.02-87.04 ppm, avg.73.44ppm; Nb=2.23-7.49 ppm, avg.5.48 ppm; Y=5.64-8.55 ppm, avg.7.15ppm).

Large Ion Lithophile Elements (LILE)

LILE display large variation in their concentrations. For example Rb and Th concentrations are high in ARB samples (Rb = 208.94-387.30 ppm, avg. 278.82 ppm; Th=13.19-42.92 ppm; avg. 29.86 ppm) relative to those of BKB (Rb = 21.82-222.90 ppm; avg. 95.70 ppm; Th=3.18-18.67 ppm; avg. 11.50ppm). On the other hand, the Sr concentrations are high in BKB samples (Sr = 33.61-153.11 ppm, avg.72.10 ppm) than in ARB samples (Sr = 4.60-9.96 ppm, avg. 5.86 ppm). However, the concentration of Ba is comparable in samples of ARB (Ba = 229.86-293.88 ppm, avg. 261.65 ppm) and BKB (Ba = 123.75-542.36 ppm, avg. 323.62 ppm).

Transition Trace element (TTE)

Concentrations of TTE in studied rocks are highly variable. ARB quartzites are more enriched in Cr (15.19-19.10 ppm, avg. 16.87 ppm), Sc (2.02-3.75 ppm, avg. 2.82 ppm) and V (5.56-13.44 ppm, 8.59 ppm) in comparison to BKB quartzites (Cr = 4.05-6.37 ppm, avg. 4.70 ppm; Sc = 1.04-2.57 ppm, avg. 1.69 ppm; and V = 3.07-4.88 ppm, avg. 4.03ppm). However, BKB quartzites are more enriched in Co (18.24-27.37 ppm, avg. 23.24 ppm) relative to those of ARB quartzites (1.37-1.90 ppm, avg. 1.65 ppm).

Rare Earth Elements (REE)

REE Concentrations are high in ARB quartzites (∑REE = 58.44-253.36 ppm, avg. 156.02 ppm) in comparison to BKB quartzites (∑REE = 35.24-52.60 ppm, avg. 45.07ppm). Although, the total REE contents of ARB samples are comparable to those of BKB, they are depleted to that of Post-Archaean Australian Shales (PAAS; 147ppm) and Average Upper Continental Crust (AUCC; 127.38 ppm). The REE patterns of these two sequences of sedimentary rocks are similarly fractionated (Fig. 3 A and B), with comparable $(La/Yb)_N$ ratios (ARB=5.89-20.65, avg.10.50; BKB= 5.69-17.01, avg.11.09). High values of $(La/Yb)_N$ ratios (17.01 and 20.65 shown by samples N210 and JG5 of BKB and ARB respectively), suggest that the HREE may have been retained by garnet during the formation of source rocks, leaving them depleted in HREEs. This is a characteristic feature of TTG suites which are important constituents of the Archaean crust throughout the world. When average REE contents of these two groups of sedimentary rocks are compared, the ARB quartzites appear to be more enriched with prominent Eu-anomaly. However, both these sedimentary rock sequences display concave upward patterns of HREEs, which are characteristically shown by Archaean TTGs (Fig. 3C). The Eu-anomaly in clastic sedimentary rocks is a good fingerprint for source rock characterization. The ARB quartzites display more prominent Eu-anomalies (Eu/Eu* = 0.78- 2.66, avg. 1.72) relative to BKB quartzites (Eu/Eu* = 0.61-1.02, avg.0.89). Eu-anomalies have been of special interest in the provenance studies of Archaean rocks, because this feature indicates the presence of granitic rocks in the source terrain (Taylor and McLennan, 1985; Condie 1993; Gao and Wedepohl, 1995; Sugitani et al., 2006). Relatively low values of Eu/Eu* in BKB quartzites suggest that they did not experience zircon accumulation. If zircon accumulated in sediments of ARB during the processes of sediment recycling and sorting, the HREEs might have been increased in concentration by addition of zircon resulting substantial decrease in values of $(La/Yb)_N$ ratio.

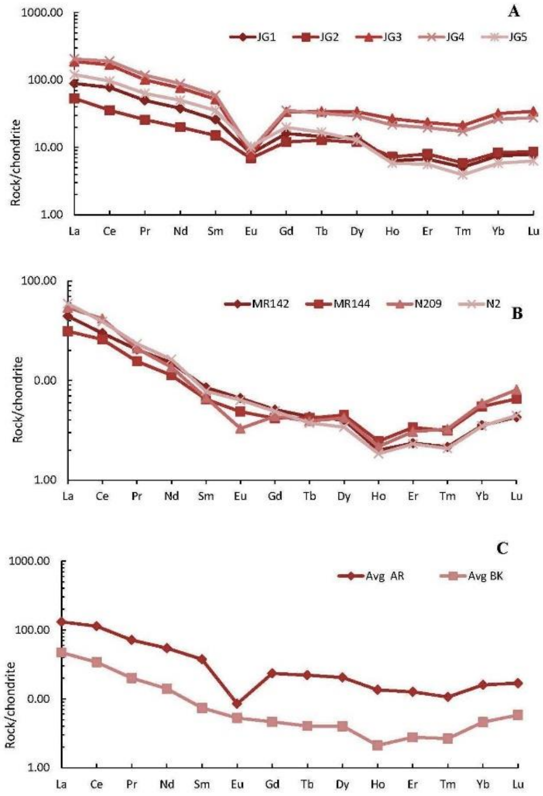

Figure 3: Chondrite normalized REE patterns of (A) Aravalli quartzite (B) Bundelkhand quartzite and (C) comparison of average of A and B. Normalizing values after McDonough and Sun (1995). Note concave upward patterns shown by HREE's.

Mineral Control on whole rock geochemistry

High concentration of SiO_2 in quartzites of BKB (~ 80%) in comparison to those of ARB (~ 75%) is due to presence of relatively higher amount of quartz in their mode. Higher values of SiO_2/Al_2O_3 ratio in BKB quartzites (~ 7) in comparison to ARB quartzite (~ 5) also suggest their more mature nature. The increasing trend of textural maturity in sandstones leads to an increase in the amount of quartz at the expense of primary clay size material (McLennan et al., 1993). Higher concentration of total alkalies in BKB quartzites (~ 7%) in comparison to ARB quartzites (~ 4%) may be due to more content of feldspars in their mode. The ARB quartzites are comparatively more enriched in TiO_2, V and Cr, which are mainly contained in phyllosilicates, possibly biotite. It is generally believed that clay minerals are the most common hosts of trace elements in clastic sedimentary rocks (Taylor and McLennan 1985). However, the importance of accessory minerals in trace element studies has also been discussed by many workers (e.g. Tripathi and Rajamani, 2003 and references therein). Heavy minerals normally accumulate the trace elements in clastic sedimentary rocks. In general, the most important heavy minerals are zircon, allanite and monazite. Among these, zircon preferentially incorporates HREE relative to LREE. Higher concentration of most of the trace elements including REEs in ARB quartzites comparative to BKB quartzites (Table 1) may be due to higher concentration of heavy minerals in their mode.

AUCC (Average upper continental crust) normalized multi-element patterns

Multi-element patterns, normalized to upper continental crust, of quartzites of ARB and BKB are plotted in Figure 4, A and B. In this diagram, the arrangement of the elements is in the order of increasing compatibility and represents a monotonic decrease of continental abundances with respect to primitive mantle (Hofmann, 1988, p 300).

The most incompatible elements are on the right and most compatible on the left side of the diagram. Since the elements Rb, Ba, K, Sr Na, and Ca are readily dissolved by aqueous fluids, they are relatively mobile during weathering. These elements are helpful for understanding weathering regimes and palaeo-environmental conditions (Nesbitt and Young 1982; Fedo et al., 1997). Rest of

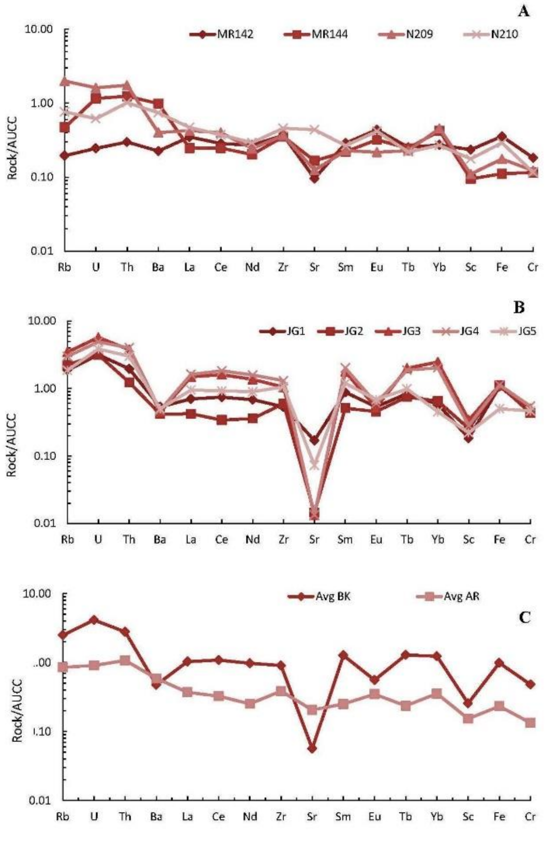

Figure 4: Average Upper Continental Crust (AUCC) normalized multi element spidergrams of **A**) Bundelkhand quartzite, **B**) Aravalli quartzite, **C**) comparison of average of A and B. Normalizing values are after Taylor and McLennan (1985).

the elements, on the other hand, resist dissolution and, are immobile, thus their depletion or enrichment relative to AUCC may reflect the provenance composition.

The analysed samples of BKB quartzites show relatively more variation in concentrations of various elements suggesting that the sediments are not well mixed. In comparison with AUCC, the sedimentary rocks of both of these groups show a general depletion in Sr, Ba and Sc, and enrichment in Th; other elements show small to large deviations from AUCC. A comparison of multi-element patterns of average BKB and ARB samples indicates that the patterns of these two are almost same (Fig. 4C). Very low AUCC-normalized values of Zr in BKB samples [$(Zr)_{AUCC}$ = 0.35-0.46, avg. 0.39] in comparison to those of ARB [$(Zr)_{AUCC}$ = 0.53- 1.30 avg. 0.91] suggest minor or no zircon accumulation in these rocks during sedimentary processes.

DISCUSSION

Assessment of sedimentary sorting and recycling

The chemical composition of the clastic sedimentary rocks is predominantly controlled by lithology of source terrain. However, some surface processes such as hydraulic sorting and palaeo-weathering may greatly modify the provenance memory (Lahtinen, 2000; Hofmann, 2005; Roddaz et al., 2006). In this regard, the sediment recycling is a common process which produces a buffering effect, where a small amount of new input can go unnoticed. Therefore, to determine the source area composition of sedimentary sequences, it is important to consider first the effect of these processes on the overall composition of sediments.

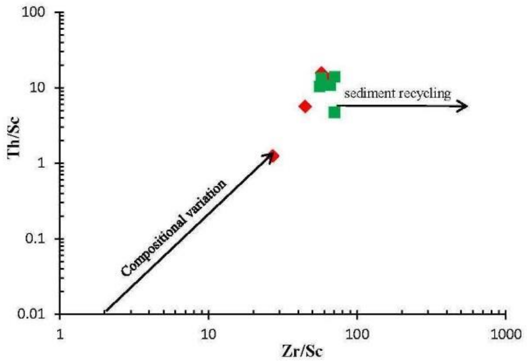

Figure 5: Zr/Sc-Th/Sc variation diagram (after McLennan et al. 1993) of the Aravalli quartzites (green squares) and the Bundelkhand quartzites (red diamonds).

The compositional variation and the degree of sediment reworking and heavy mineral sorting can be illustrated in Zr/Sc versus Th/Sc plot of McLennan et al., (1993). The Th/Sc ratio of sedimentary rocks characterizes the composition of their source rocks, whereas an increase in the Zr/Sc ratio alone would indicate the increase of zircon by sorting and recycling of sediments. Zircon enrichment in clastic sediments can be reflected by relationship between Th/Sc and Zr/Sc ratios (McLennan et al., 1993). On Th/Sc and Zr/Sc diagram, our samples of studied rocks fall on the general provenance-dependent compositional variation trend and no sample falls on the zircon addition trend (Fig. 5).

However, the ARB samples show relatively higher value of Zr/Sc (55.94-70.91, avg. 64.16) than those of BKB (27.13-64.20, avg. 48.47). Negative Eu- anomalies in the clastic rocks may be resulted due to accumulation of zircon in the sediments because zircon has a pronounced negative Eu-anomaly. Accumulation of zircon would lead to HREE enrichment and decrease in $(La/Yb)_N$ ratio, thus a negative correlation between Zr and $(La/Yb)_N$ ratios and positive correlation between Zr and ∑HREE contents would be expected. While ARB samples show strong positive correlation between Zr and ∑ HREE contents (r = 0.80), the BKB samples show negative correlation. (r = -72). While ARB samples show strong negative correlation between Zr and $(La/ Yb)_N$ ratios (r = -0.72), it is positive in case of BKB samples (r = 0.88). Zr and Yb show positive correlation in ARB samples (r = 0.85) and negative in BKB samples (r =0.63). These relationships suggest accumulation of zircon in sedimentary sequence of ARB but not in that of BKB. Large Eu-anomalies in the REE patterns of ARB samples also support Zr-accumulation. It has been observed that the sediments enriched in zircon due to grain size sorting may display significant Eu-anomalies (Sugitani et al., 2006). Lack of correlation between Th and $(La/Yb)_N$ (r = -0.01 in ARB and r = -0.42 in BKB) in our samples does not indicate the enrichment of monazite. The increasing trend of textural maturity in sandstones leads to an increase in amount of quartz at the expense of primary clay-size material. As a result, the SiO_2/Al_2O_3 ratio is increased and concentrations of other elements are decreased due to quartz-dilution. Therefore, the textural maturity of sandstone can be assessed by using SiO_2/Al_2O_3 ratio (McLennan et al., 1993). The analyzed samples have $SiO_2/Al_2O_3 < 10$ (BKB = 4.97-10.70, avg.7.24; ARB = 5.11-5.85, avg. 5.51), which indicate low maturity.

Source area weathering

The degree of chemical weathering may be quantified by using chemical index of alteration [CIA = $\{Al_2O_3/(Al_2O_3+CaO^*+Na_2O+K_2O)\} \times 100$], and chemical index of weathering [CIW = $\{Al_2O_3/(Al_2O_3+CaO^*+ Na_2O)\} \times 100$] values (Nesbitt and Young 1982; Fedo et al., 1995). CaO* represents Ca in silicate minerals. The CIA values of our ARB samples range from 65.45 to 69.05 (avg. 66.74) and those of BKB from 49.03 to 74.48(avg. 56.06). The CIW values of ARB samples are between 74.87 and 78.87, with an average of 76.87, and those of BKB samples are between 55.57 and 80.11, with an average of 65.51. These values are between unweathered clastic rocks (< 50) and moderately weathered rocks.

Th/U ratio of sedimentary rocks is expected to increase with increasing weathering due to oxidation and loss of uranium (Taylor & McLennan 1985). Th/U ratios above 4 are thought to be related to weathering history (McLennan et al. 1995). The Th/U ratio of these quartzites ranges from 1.49-3.13, avg. 2.49 in ARB samples and from 4.11-6.29, avg. 4.79 in BKB samples suggesting low degree of weathering in their respective source terrains. Low to moderate degree of chemical weathering may be the result of non-steady state weathering conditions, where active tectonism and uplift allow erosion of all soil horizons and rock surfaces (Nesbitt et al., 1997). Furthermore, the preservation of labile detrital minerals such as feldspar in association with quartz does not favour prolonged intense chemical weathering. Under these conditions, the terrigeneous debris would be derived both from erosion of uplifted blocks and also the region of low relief. Degree of weathering during the Archaean has been discussed by many workers. Several Archaean sequences have shown evidence of intense chemical weathering due to high surface temperature, CO_2-rich atmosphere and humid climate postulated for the Archaeans (Kasting, 1993; Sugitani et al., 1996, 2006). On the other hand, some workers believe low chemical weathering (e.g. Hofmann, 2005). The degree of chemical weathering is controlled by climate and rate of erosion. The low to moderate degree of chemical weathering in the source area of studied quartzites may thus reflect high erosion rate coupled with short distance and rapid sedimentation in a tectonically active basin.

As discussed above, the contents of U and Th in the quartzites of the Aravalli craton are more than those in the quartzites of the Bundelkhand craton. Furthermore, the Th/U ratio in the former is much less than that in the latter, with the values of the latter being comparable to the average crustal value.

These patterns indicate that the Aravalli craton is relatively more fertile for U, whereas the Bundelkhand craton is more or less barren. Indeed this is the actual case, since U-deposits like the albititisation-related hydrothermal metasomatic type (DhanaRaju, 2019) and a few other types are established by the AMD (Atomic Mineral Directorate) in the Aravalli craton, whereas no potential U-mineralization is established hitherto in the Bundelkhand craton.

Provenance composition

The geochemical composition of sedimentary rocks has been successfully used to evaluate the initial composition of source rocks (e.g. Naqvi et al. 1988; McLennan et al., 1995; Cullers, 2000; Raza et al., 2010a, b). Greater amount of plagioclase than alkali feldspar as observed in the petrography of these rocks suggests that they were most likely derived from a granodiorite-tonalite dominated source terrain. Variable amount of Eu-anomalies (Eu/ Eu* = 0.78-2.66) in the REE patterns and evidence of Zr-accumulation during sedimentation of ARB quartzites suggest presence of granite in their source. However, the geochemical characteristics of BKB quartzites do not show any evidence that may suggest large amount of granite in their source. The Al/Ti ratio of clastic sedimentary rocks is considered to be similar to their magmatic source rocks (Yamamoto et al., 1986; Hayashi et al., 1997); therefore, it can be used as an important indicator of source composition. In igneous rocks, Al resides mostly in feldspars and Ti in mafic minerals such as olivine, pyroxene, hornblend, biotite and illmenite. Therefore, the Al/Ti ratio of igneous rocks gradually increases from mafic to more felsic rocks. Usually the Al_2O_3/ TiO_2 ratio increase from 3 to 8 in mafic rocks, 8 to 21 in intermediate rocks and 21 to 70 in felsic rocks. The Al_2O_3/ TiO_2 ratio of studied sedimentary rocks is high (BKB = 81.5 - 361, avg. 174.18; ARB = 80.5-114.15, avg. 95.69). Relatively higher values of Al_2O_3/TiO_2 ratio in BKB samples indicates their derivation from a more felsic source region in comparison to source of ARB samples, which show relatively lower values of Al_2O_3/TiO_2 . These values suggest that the source region of BKB quartzites comprised predominately of felsic rocks. On the other hand, the source of ARB quartzites appears to be consisting of felsic rocks along with variable amount of mafic rocks. High values of $(La/Yb)_N$ ratios and concave upward patterns of HREEs, shown by studied quartzites further attest to the derivation of sedimentary debris from a source containing

TTG (e.g. Huang et al., 2010) that are thought to form above subduction zones (Drummond and Defant, 1990; Martin et al., 2005; Van Boening et al., 2008).

In recent years, simple mixing calculation have been performed by many workers (e.g. Osae et al., 2006; Roddaz et al.,2007; Absar et al., 2009; Raza et al., 2010a,b) using REE data. To constrain the contribution of various lithologies, the trace element modelling is attempted. Parameters of mixing calculations are same as given in Raza et al., (2010 a, b). The approach was to reach the best fit solutions which would closely reproduce the REE patterns. The ARB sedimentary rocks are best modelled with a mixture having 50% TTG, 40% Granite and 10% Mafic rocks (50 T : 40 G : 10M, Fig. 6A). REE pattern of Archaean Naharmagra quartzite of Aravalli craton (Raza et al., 2010) of the same age matches well with that of our samples of ARB and modelled mixture. The BKB sedimentary rocks are best modelled with a mixture having 80% TTG, 10% Granite and 10% Mafic rocks (80 T : 10 G : 10M, Fig. 6B). Although, the shapes of REE patterns of our samples closely match with that of modelled mixture, overall REE abundances are lower relative to modelled mixture. This is because of the fact that the REE abundances have been reduced, obviously due to sorting of clay fraction and quartz dilution. Although the modelling gives only an idea about the approximate contribution by possible end-members, it provides convincing evidence to distinguish the types of rocks which supplied the debris to the sedimentary basin. High values of $(La/Yb)_N$ ratio and concave upward patterns of HREEs, shown by both ARB and BKB quartzites suggest the derivation of studied sedimentary rocks from a source containing TTG that are thought to form

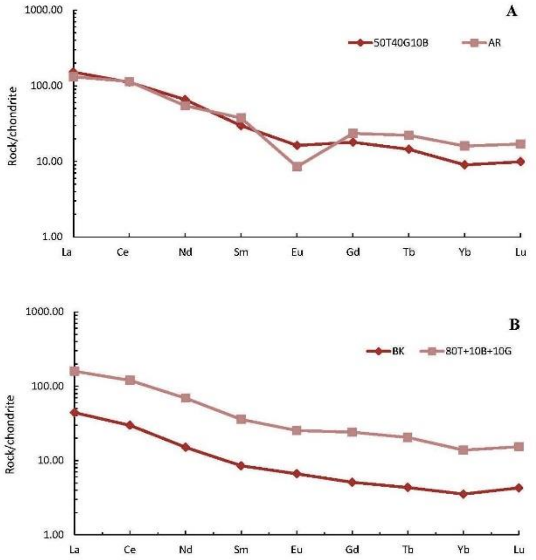

Figure 6: REE patterns of (**A**) average Aravalli quartzite compared with modelled provenance after mixing the end members in the proportions of 50%TTG, 40% granites, 10% basaltic rocks and **B**) average Bundelkhand quartzite compared with modelled provenance after mixing the end members in the proportions of 80%TTG, 10% basaltic rocks and 10% granites.

above subduction zones (Drummond and Defant, 1990; Martin et al., 2005; Van Boening et al., 2008). In view of the above discussion, it is inferred that the mixing of TTG and granite-derived material with smaller amount of mafic-derived debris explains the geochemical characteristics of these quartzites. However, the higher amount of TTG in the source area of BKB samples indicates the more primitive nature of continental crust in the Bundelkhand craton, in comparison to the Aravalli craton that had more evolved crust at the time of sedimentation of these Archaean sedimentary rocks. Presence of quartzites and greywacke (Raza and Mondal, 2018), along with subduction- related mafic volcanic rocks, both in the Aravalli (Upadhyaya et al., 1992) and Bundelkhand blocks (Raza and Mondal, 2019) of NIC, suggests that the sedimentary rocks were probably deposited on the margin of a young craton, consisting of newly accreted TTG and granite bodies.

CONCLUSIONS

This paper reports and discusses the results of geochemical and petrological study of quartzitic rocks that are the oldest known clastic sedimentary rocks of the Aravalli and Bundelkhand cratonic blocks of North Indian Shield. The rocks are mainly composed of quartz, followed by feldspar and biotite. The quartz varieties include common quartz with a few grains of recrystallized and stretched metamorphic quartz. Feldspar varieties include plagioclase and microcline. Plagioclase grains are more abundant in comparison to microcline. Mineralogical compositions suggest derivation of both of these sedimentary sequences from stable part of the craton.

Geochemically, the rocks are classified as ‘litharenite – arkose’. Trace element data, including REE characteristics, suggest accumulation of zircon in sedimentary sequence of ARB but negligible in that of BKB. Although, SiO_2/Al_2O_3 ratio of both the quartzites (BKB = 4.97-10.70, avg. 7.24; ARB = 5.11-5.85, avg. 5.51) is less than 10, indicating low maturity, the higher values of this ratio in BKB quartzites suggest that they are relatively more mature. Low to moderate degree of chemical weathering in the source area of studied rocks is indicated by CIA and CIW values, and Th/U ratio, which reflect high erosion rate coupled with short distance and rapid sedimentation in a tectonically active basin. The variation in the concentration of some of the major oxides, trace elements and REEs in quartzites of the two blocks of NIC may be due to difference in the composition of crustal segment from which they have been derived. The provenance analyses, based on geochemical characteristics, suggest the derivation of these sediments from a continental source terrain comprising Archaean TTG along with granites and mafic rocks in the different proportion. Provenance modelling indicates that the quartzites of BKB were derived from a terrain comprising 80% TTG, 10% Granite and 10% Mafic rocks (80T: 10G: 10M). On the other hand, the ARB quartzites can be best modelled with a mixture having 50% TTG, 40% Granite and 10% mafic rocks (50T: 40G: 10M). It is inferred that the mixing of TTG and granite-derived material with smaller amount of mafic-derived debris explains the geochemical characteristics of these quartzites. Higher amount of TTG in the source area of BKB samples indicates more primitive nature of continental crust in the Bundelkhand Craton in comparison to the Aravalli Craton at the time of sedimentation of these Archaean sedimentary sequences. Presence of sedimentary rocks, along with subduction-related mafic volcanic rocks within the Archaean basement complexes of Aravalli and Bundelkhand blocks of NIC, suggests that the sedimentary rocks were probably deposited on the margin of young cratons comprising newly accreted TTG and granite bodies.

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