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Geochemistry of the Archaean metasedimentary rocks of the Bundelkhand Mauranipur-Babina greenstone belt, central India: Implications for provenance characteristics

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Abstract: Metasedimentary rocks occurring as minor components of Mauranipur- Babina greenstone belt of the Bundelkhand craton were analyzed for major oxides and trace elements to constrain the composition and weathering history of their provenance and the tectonic setting prevailing at the time of deposition. On the basis of mineralogy and geochemical compositions, two types of lithologies are identified. First, a texturally immature, medium to coarse grained, light-coloured rock distinguished as Arkose. Second, a fine grained, dark coloured metapelitic rock containing adequate amount of mafic minerals, identified as greywacke. CIA (chemical index of alteration) and CIW (chemical index of weathering) values and Th/U ratios suggest that the source area of these sedimentary rocks had only been weekly weathered. ICV (Index of compositional variability) values of these rocks are <<1, suggesting that the sediments are generally immature. Low degree of weathering in their source region, immature nature and minor sorting influence on the detritus are the features which suggest high rate of erosion, rapid sedimentation, potentially marked relief and short distance transportation of the debris, derived from a tectonically active source region. Th- Sc- Zr systematic suggests insignificant degree of recycling. Assessment of provenance composition using Al_2O_3 - TiO_2, Sc-Th/Sc and (CaO+MgO) - SiO_2 – (Na_2O_+ K_2O), variation diagrams, REE patterns and (La/Yb)n ratios suggest that the studied sedimentary rocks were derived from mixing of debris of felsic and mafic composition in different proportions. The provenance modelling using REE data indicates that the arkoses can be best modelled with an 80% TTG and 20% granite mixture. On the other hand the greywacke can be best modelled with a mixture having 50% TTG, 40% basaltic rocks and 10% granite. It is 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.

Key words: Bundelkhand, metasediments, geochemistry, provenance.

Introduction

Compositional characteristics of source rocks are generally preserved in the sedimentary products and thus provide valuable information about nature of their source terrain (Van de Kamp and Leake, 1985; Armstrong-Altrin et al., 2004; Armstrong-Altrin and Verma, 2005; Sinha et al., 2007; Nagarajan et al., 2007; Maravelis and Zelilidis, 2009). Many studies have revealed that the chemical composition of the clastic sedimentary rocks is controlled by various factors including source rock composition, the extent and duration of weathering, mode of transportation and post depositional processes such as diagenesis (Taylor and McLennan, 1985, McLennan et al., 1993; Hayashi et al., 1997; Purevjav and Roser, 2013). Therefore, the elemental compositions of sedimentary rocks have been widely used to determine the provenance characteristics of sedimentary rocks and the tectonic conditions prevailing at the time of their deposition (Nesbitt, 1979; 1994; Cullers et al., 1987, 1988; McLennan et al., 1990, 1993; Wronkiewicz and Condie, 1990; Condie et al., 1995; Cox et al., 1995; Cullers and Podkovyrov, 2000*;* Cullers 2000; Condie 2001; Hofmann 2005; Manikyamba, et al., 2008; Absar et al., 2009; Raza et al., 2010; Absar and sreenivas, 2015; Fatima and Khan, 2012). In recent years, the origin of the continental crust has received wide attention amongst the Precambrian geologists (Taylor and McLennan, 1985; Windley, 1995 and Condie, 1997). To understand the origin of continental crust it is important to know the composition of early crust. Clastic sedimentary rocks have been demonstrated to represent the average chemical composition of exposed crust from which they were derived (Taylor and McLennan, 1985). Therefore, the geochemical characteristics of the sedimentary formations, particularly those from Archaean greenstone belts, may provide important clues to estimate the composition of the early crust (Wronkiewicz and Condie, 1987; McLennan, 1989; Cullers, 2000; Condie, 2001; Hofmann, 2005; Absar et al., 2009; Raza et al., 2010). Most of our present knowledge regarding composition and evolution of early crust is based on geochemical and isotopic composition of Precambrian sedimentary records.

Sedimentary successions comprising clastic sedimentary rocks are important components of Archaean greenstone belts of the Indian shield. Although enough amount of Precambrian sedimentary record is available in Indian shield, the application of sediment geochemistry to the crustal evolution studies did not catch up widely. Despite early beginning by Naqvi and his co-workers (Naqvi and Hussain, 1972; Naqvi and Rogers, 1987 and references therein) in the field, comprehensive work on the geochemical aspects of the Archaean sedimentary rocks of the Indian shield are lacking. In this shield area, most of the work on the geochemistry of sedimentary rocks has been carried out on the Archaean sequences of Dharwar craton of south Indian shield (Naqvi et al., 1983; Naqvi and Rogers, 1987 and references therein; Naqvi et al., 2002). The present work deals with the major and trace element geochemistry of clastic sedimentary rocks of an Archaean greenstone belt, referred to as Mauranipur- Babina greenstone belt of the Bundelkhand craton occurring to the north of Central Indian Shear Zone (CISZ) in the central part of the Indian shield.

Although the geochemistry of mafic rocks of the Archaean greenstone belt of this area has been examined (Malviya et al., 2006), the geochemical data on associated sedimentary rocks are not available in literature. The Bundelkhand craton thus remains unrepresented in any model proposed for the evolution of the Archaean continental crust. The present study is the first, to report major and trace element (including REE) characteristics of previously unrecognized clastic sedimentary rocks from volcanic-sedimentary sequence of greenstone belt occurring in the Mauranipur-Babina section of the Bundelkhand Craton. Our aims are to report and utilize the textural and geochemical data of these Archaean sedimentary rocks to constrain the composition and weathering history of their source terrain. This would also help to understand the tectonic scenario prevailing during the Archaean in this part of the Indian Shield.

Geological setting and field occurrence of the studied sedimentary rocks

Bundelkhand cratonic block

The Bundelkhand cratonic block, occurring in the central part of the Indian Shield, covers an area of about 29,000km^2, and is bounded by the Great Boundary Fault (GBF) in the west and the Central Indian Tectonic Zone in the south. It consists predominantly of Proterozoic granites containing linear slivers of gneisses of tonalite-trondhjemite- granodiorite composition

(TTG) and volcanic-sedimentary sequences of Archaean age. The western, eastern and southern margins of the craton are marked by the presence of Proterozoic basins hosting sedimentary successions of Bijawar Group and Vindhyan Supergroup. (Fig.1). The Bundelkhand craton experienced multiple phase of mafic and felsic magmatism during the Archaean and Proterozoic time. The dominant magmatic event was the emplacement of a series of Proterozoic granitoids exposed at various places within the craton. The TTG magmatism in the Bundelkhand craton occurred from ~3.59 Ga to ~2.6 Ga (Verma et al., 2016; Saha et al., 2015; Kaur et al., 2014; Mondal et al., 2002). Based on various associated magmatic events the lithological units of the Bundelkhand massif can be divided into: 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 Bundelkhand linear Tectonic Zone (BTZ). This lineament is a major brittle ductile shear zone extending along Mauranipur-Babina section and iii) undeformed younger granitoids including hornblende granitoids, biotite granitoids and leucogranitoids (Mondal and Zainuddin, 1996). These granitoids are intrusive in nature within Archaean gneisses and metamorphosed supracustal rocks. NE-SW trending quartz reefs (2.0- 1.8 Ga, Pati et al., 2007) and NW-SE trending dolerite dykes (2.0-0.9Ga, Rao et al., 2005) have also been observed within massif (Basu, 1986). Dolerite dykes cut across the quartz reefs, suggesting it to be the youngest magmatic phase of the Bundelkhand craton. Based on the structural analyses three generation of deformation within Muaranipur supracrustal rocks were suggested (Malviya et al., 2006). The D_1 deformation phase is marked by moderately plunging tight to isoclinal fold (F_1), the second generation of deformation is marked by refolded fold and the formation of pucker lineation on S_1 plane and the third generation of deformation are represented by low amplitude broad warps.

Mauranipur-Babina Greenstone belt

Although, coharent greenstone belts similar to those of Dharwar craton are not found in the Bundelkhand block, the sporadic occurrences of volcanic-sedimentary sequences, along linear zones within the gneissic complex, are considered as greenstone belts (Basu, 1986; Prasad et al., 1999; Ramakrishnan and Vaidyanadhan, 2010). Two east-west trending zones comprising many greenstone sub- belts 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 Mauranipur- Babina greenstone belt consists of metamorphosed assemblages of mafic and felsic volcanics, banded iron formations and minor sedimentary components. The samples for present study were collected from Naugao, Jugalpur and Baruasagar where the metasedimentary rocks are associated with basaltic to basaltic andesitic rock (Malviya et al., 2006) and constitutes a small portion of the Archaean greenstone belt in the major shear zone along Mauranipur-Babina section. Two distinct metasedimentary rocks were identified based on their mineralogical and textural characteristics; immature medium to coarse grained gritty quartzite dominantly composed of quartz and feldspars and fine grained dark coloured metapelitic rocks with abundant mafic components in addition to quartz grains.

Field Occurrences of clastic sedimentary rocks

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) and constitutes a small portion of the Archaean greenstone belt in the major shear zone along Mauranipur-Babina section. Two distinct metasedimentary rocks were identified based on their mineralogical and textural characteristics. These are: (i) fine grained metapeletic rocks consisting predominantly of mafic minerals in association with quartz grains and (ii) medium to coarse grained, quartzites consisting predominantly of quartz and feldspars.

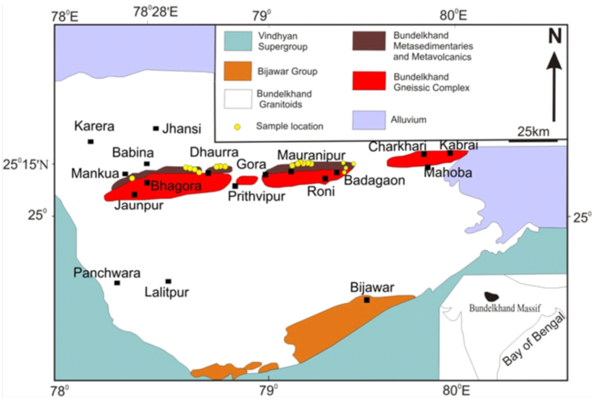


Figure1: Generalized geological Map of the Bundelkhand massif, illustrating marginal basins and East-West trending Bundelkhand tectonic zone (after Ramakrishnan and Vaidyanadhan, 2010)

Sampling procedures and Analytical Techniques

In the present study samples were collected from the isolated outcrops of the volcano-sedimentary successions of the greenstone belt of the Bundelkhand craton from Dhaurra, Prithvipur, Naugao, Baruasagar, Badagao and Mauranipur areas (Fig.1).

Bundelkhand metasediments								
			Greywacke			Arkose		
Sample Name	M 219	M 220	M 221	N 205	MR 142	MR 144	N 209	N 210
SiO₂	64.55	58.47	58.71	58.37	87.18	82.04	76.65	73.53
TiO₂	0.51	0.67	0.65	0.73	0.1	0.03	0.09	0.14
Al₂O₃	15.78	13.02	12.39	14.63	8.15	10.83	13.38	14.78
Fe₂O₃ T	3.37	5.32	5.42	7.68	1.6	0.5	0.79	1.31
CaO	9.68	14.34	10.22	5.53	0.66	0.27	0.38	1.61
MgO	3.17	5.1	8.82	5.15	0.06	0.08	0.09	0.29
Na₂O	0.97	1.44	2.01	4.2	0.5	4.6	3.86	5.4
K₂O	1.37	1.4	1.56	3.52	0.71	2.51	5.62	3.28
MnO	0.41	0.33	0.2	0.06	0.03	0.01	0.02	0.03
P₂O₅	0.11	0.11	0.09	0.33	0.02	0.01	0.02	0.04
Sum	99.92	100.2	100.07	100.2	99.01	100.88	100.9	100.41
Sc	5.261	9.142	9.769	4.691	2.579	1.044	1.209	1.939
V	31.537	51.571	56.618	35.773	4.881	3.07	3.453	4.708
Cr	7.837	19.917	24.762	5.883	6.379	4.054	4.286	4.075
Co	20.425	28.495	32.872	20.084	21.9	18.247	25.43	27.378
Ni	11.357	35.043	43.839	14.202	7.528	5.621	3.21	3.114
Cu	1.051	1.163	1.051	3.354	1.327	1.33	0.718	0.919
Zn	41.981	57.551	68.666	28.149	11.132	17.141	13.84	9.115
Ga	13.267	11.125	11 .123	12.307	3.738	5.445	11.22	13.621
Rb	54.383	38.858	57.981	71.247	21.821	52.66	222.9	85.419
Sr	72.052	65.577	61.853	440.59	33.617	58.189	43.48	153.11
Y	28.423	23.868	20.926	17.363	5.642	8.068	8.554	6.345
Zr	238.61	161.18	142.317	140.89	69.971	67.02	69.73	87.044
Nb	12.756	7.289	6.584	5.284	2.236	6.249	7.49	5.957
Cs	1.636	0.825	0.881	0.824	0.221	0.206	1.186	1.2
Ba	202.58	160.02	100.469	891.99	123.75	542.36	220.3	407.97
La	32.73	21	16.921	42.821	10.474	7.392	12.75	14.063
Ce	61.052	40.532	33.986	83.065	18.226	15.804	25.54	23.89
Pr	6.178	4.235	3.614	11.243	1.94	1.478	1.99	2.214
Nd	23.245	16.441	14.353	44.955	7.037	5.259	6.337	7.612
Sm	4.587	3.364	3.155	6.949	1.301	0.994	1.028	1.197
Eu	0.96	0.686	0.666	1.844	0.385	0.282	0.191	0.368
Gd	4.024	3.226	2.832	4.939	1.046	0.859	0.899	1.009
Tb	0.697	0.564	0.508	0.632	0.162	0.157	0.146	0.14
Dy	4.663	4.067	3.574	3.332	1.019	1.143	1.068	0.864
Ho	0.545	0.467	0.402	0.353	0.113	0.139	0.123	0.104
Er	1.795	1.591	1.374	1.202	0.388	0.558	0.506	0.381
Tm	0.226	0.201	0.178	0.137	0.055	0.08	0.083	0.053
Yb	2.231	2.013	1.823	1.401	0.601	0.932	0.998	0.593
Lu	0.355	0.338	0.293	0.225	0.109	0.166	0.205	0.113
Hf	6.59	4.601	4.013	4.012	2.013	2.639	3.08	3.008
Ta	1.737	0.946	0.922	0.562	0.961	2.124	2.353	1.85
Pb	10.857	7.851	8.126	12.674	9.21	15.141	21.89	21.551
Th	12.541	6.73	5.824	8.143	3.185	13.289	18.66	10.853
U	2.84	2.047	1.557	2.51	0.687	3.236	4.515	1.725

Table 1: Major (wt%) and Trace element concentra for metasedimentary rocks of the Bundelkhand gre (BGB)

Samples were collected from fresh and unweathered outcrops to avoid weathering and alteration effects. All the samples were examined petrographically. In order to Obviate grain size compositional dependence of coarse grain metasedimentary rocks modal analysis was carried out by counting more than 500 points per thin sections using the Dickinson-Gazzi point counting methods (Dickinson, 1970). For geochemical studies samples were powdered to -200 mesh size by using agate pulveriser. Major element oxides were determined by X-Ray fluorescence Spectrophotometry (XRF) technique in geochemical laboratory of Wadia Institute of Himalayan Geology, Dehradun. The accuracy and precision was ± 1-3%. Trace element and REE 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 (Roy et al., 2007). International rock standards SCo-1 and GSR-4 were also analyzed and the results agree with the reported values (Govindaraju, 1994). The precision is better than 10% RSD. The data are given in Table 1.

RESULTS

Petrography

The collected samples of metasedimentary rocks of the Mauranipur- Babina greenstone belt are of two distinct types. First, the texturally, immature medium to coarse grained, light-coloured sedimentary rocks appearing as quartzite. Another set of metasedimentary rocks are fine grained volcaniclastic type sediments containing adequate amount of mafic minerals along with quartz. The frame work grains of our medium to coarse grained, light coloured samples of metasedimentary rocks are dominantly feldspars (plagioclase + microcline) and quartz among which monocrystalline quartz (Q_m) are in abundance than polycrystalline quartz (Q_p). In contrast, the fine grained, dark coloured samples of the metasediments are rich in pyroxenes (Table 2). Since first type of sediments are medium to course grained they were studied under the microscope to determine their modal compositions. The QFR classification diagram (Folk, 1980) defines arkosic nature of these sediments (Fig. 2B). The mineralogical compositions were also plotted in triangular diagrams in accordance with Dickinson (1985) scheme. In QtFL diagram our samples are plotted in the field of uplifted basement provenance (Fig. 2A). It can thus be suggested that an uplifted basement complex can be the source for these metasedimentary rocks.

Samples	Qt	Qm	Qp	F	L
N210	210	150	60	313	0
N209	207	177	30	401	0
MR144	220	190	30	375	0
MR142	200	156	64	405	0

Table 2: Framework modes (after Dickinson,1985) of the metasediments of the Bundelkhand greenstone Belt (BGB). Qt, Total quartz; Qm, Monocrystalline quartz; F, Total feldspar grains; Lt, total lithic fragments

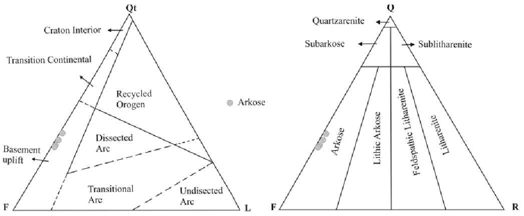


Figure 2: Studied metasediments plotted in (**A**) Basement uplift field in Dickinson and Suczek, (1979), framework mode diagram discriminating between different tectonic depositional settings Qt= total quartz (monocrystalline and polycrystalline); F= feldspar (plagioclase and K-feldspar); L= lithic fragments. (**B**) Arkose field in Folks's classification (1980) of sandstone based on QFR ternary diagram (Q= total quartz; F= total feldspar; R= total rocks fragments including chert.

Geochemistry

Because most of the rocks under study have undergone metamorphism up to the amphibolite facies, it is possible that some or many of the major and trace elements will have been variably remobilized (Taylor & McLennan 1985; Tarney & Weaver 1987; Barovich & Patchett 1992; Pearce 1996; Tran *et al.* 2003). The alteration of original composition, if any, would obviously reduce the effectiveness of the geochemical parameters. The degree of mobility during high grade metamorphism is controversial. It is generally agreed that major changes in composition of sedimentary rocks can occur even before the onset of granulite facies metamorphism (e.g. Taylor & McLennan 1985). However, some studies have suggested that elemental mobility in high grade rocks is insignificant (Ferry 1983; Roser & Korsch 1986; Passchier et al., 1990). In recent years, various studies have shown that REEs, high field strength elements (HFSEs) and even transition elements are not generally affected even beyond amphibolite facies metamorphism (Barovich & Patchet 1992; Crichton & Condie, 1993; Payne et al., 2006). However, large ion lithophile elements (LILE) are expected as being variably mobile during metamorphism. The elements Rb, Sr and Ba are highly mobile during secondary processes (Nesbitt et al., 1980), and thus the abundance of these elements in sedimentary rocks does not always represent the composition of their source rock. Th is considered immobile during sedimentation and weathering and has very low residence time in seawater (McLennan et al., 1980).

Many authors have suggested the use of immobile or relatively immobile elements as discriminant tools (Cann, 1970; McLennan, 1989; Taylor and McLennan, 1985). These elements include Al_2O_3, TiO_2, HFSE such as Zr, Y, Nb, Hf, Ta and Ga and transition 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 tools in igneous discrimination and sedimentary provenance characterization studies.

Although exceptions occur (Cullers, 1994), the REE are generally regarded as immobile. The smoothness and parallel nature of REE patterns (Fig. 3) and multielement profiles (Fig. 4) of the studied rocks together with the facts that the samples are from different parts of the belt, suggest that REE and other elements have not been affected significantly during the process of metamorphism. The similarity in the patterns is maintained over a large range of composition (SiO_2=58.37-87.18%). In the present study, although all the

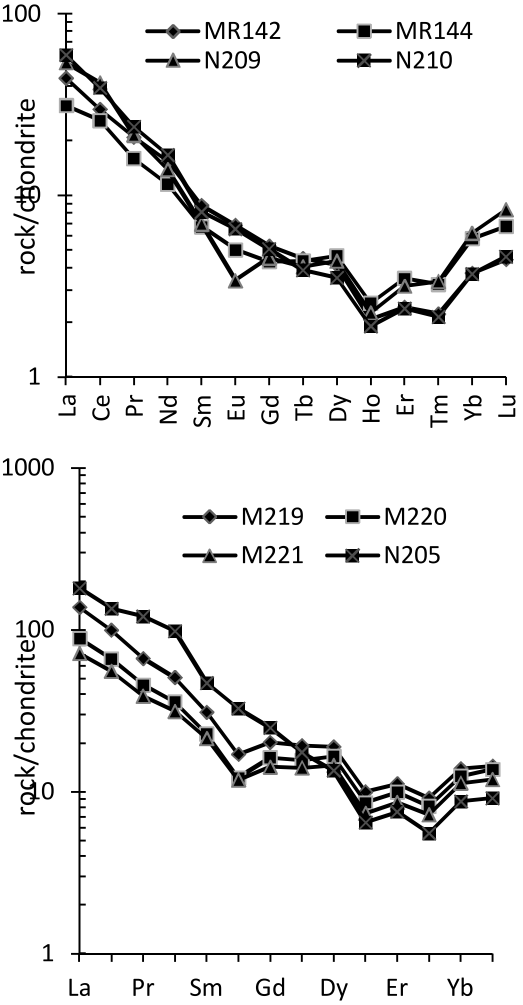


Figure 3: Chondrite- normalized rare earth elements (REE) pattern. Normalizing values after McDonough and Sun (1995) (**A**) Greywacke with fractionated REE pattern and slight negative Eu anomaly and enriched Heavy rare earth elements (HREE). (**B**) Arkose with fractionated REE pattern and no to negligible Eu anomaly.

elements analyzed are used for geochemical characterization of metasediments, more weight is given to the immobile elements. In the present study, with the exception of a few major element fingerprints, our interpretations and conclusion heavily rely on the immobile or less mobile trace elements.

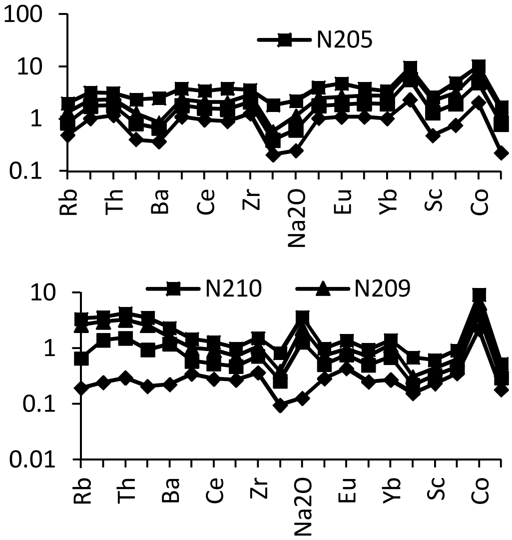


Figure 4: Average Upper Continental Crust (AUCC) normalized multielement spidergram of (**A**) greywackes and (**B**) Arkose from Mauranipur- Babina greenstone belt of the Bundelkhand craton. Normalized values after Taylor and McLennan (1985).

Geochemical classification

Major and trace element contents of our samples show large variations. Many of the geochemical differences between the samples of fine grain metapelites and medium to course grained quartzites of Mauranipur-Babina belt are due to different mineralogy of the two types of the sediments. On SiO_2/ Al_2O_3 versus K_2O /Na_2O bivariant diagram (Fig. 5) our samples are plotted within or very near to the field of Archaean greenstone shale. However the samples of metapelites show more restricted range of SiO_2/ Al_2O_3 than those of quartzites.

Geochemical composition of clastic sedimentary rocks has been widely used to distinguish the rock types (e.g. Pettijohn et al., 1972; Herron, 1988). On chemical classification diagram of Herron (1988), the analysed samples of metapelites plot in the field of greywacke and those of quartzite in the field of arkose (Fig. 6). On this diagram the samples, identified as greywacke appear to show heterogeneous geochemical signatures in comparison to homogenous composition of arkose samples. Taking into consideration the above mentioned diagrams, the studied clastic sedimentary rocks of Mauranipur-Babina greenstone belt are described herein as greywacke and arkose in our further discussion.

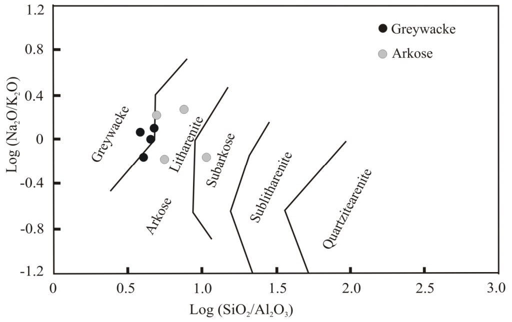


Figure 5: Chemical classification scheme diagram of Pettijohn (1972), analysed samples are plotted within or very near to the field of greywacke and arkose.

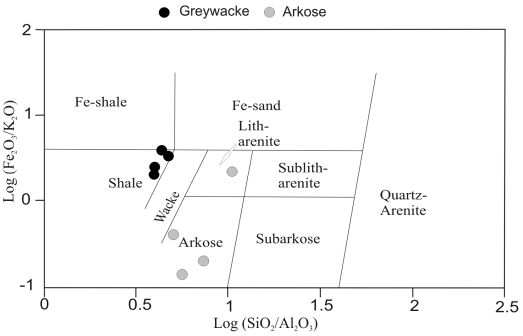


Figure 6: Chemical classification diagram of Herron (1988), the analysed samples of metapelites are plotted in the field of greywacke and those of quartzite in the field of arkose

Geochemical characterization

Comparison of major elements composition between the greywacke and arkose samples indicates that the latter are enriched in SiO_2 (avg.~80%) and depleted in Al_2O_3 (avg. ~12%) relative to the former (~60% and 14% respectively). However MgO and CaO contents of the greywacke (avg. 5.56% & 9.94% respectively) are greater than those of arkose (avg. 0.13% & 0.73 respectively). Greywacke are also enriched in TiO_2 (avg. 0.64%) relative to arkose (avg.0.09%). Other major elements do not show much variation. The SiO_2 contents of greywacke and arkose show a strong negative correlation with Al_2O_3 (r = - 0.76; - 0.99 respectively). Such correlation is expected, because in sedimentary rocks the Al_2O_3 and SiO_2 contents are controlled by aluminous clay and quartz contents respectively. The strong positive relationship between Al_2O_3 and K_2O (r = 0.77) is shown by samples of arkose, indicating illite control. Such a relationship is not exhibited by the samples of greywacke (r= 0.23). It is observed that 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. As a result, the SiO_2/Al_2O_3 ratios are increased and concentrations of other elements are decreased due to quartz dilution. Therefore, the maturity of sandstone can be assessed by using SiO_2/Al_2O_3 ratios (McLennan et al., 1993). The average SiO_2/Al_2O_3 ratio of studied arkoses and greywacke are lower > 10 (7.2 and 4.3 respectively), thus suggesting that they are immature sediments. However the greywacke appear to be more immature than the samples of arkose.

The studied greywacke are relatively more enriched in ferromagnesian trace elements such as (Avg. Ni= 26 ppm; Cr= 15ppm; V= 44ppm and Sc= 7ppm) relative to arkose (Avg. Ni=5 ppm; Cr= 5 ppm; V=4 ppm and Sc= 2 ppm) indicating a significant proportion of mafic material in their source terrain. Similarities and dissimilarities among various samples of greywacke and arkose in major and trace elements are shown in multi element spidergrams in Fig. 4. In this diagram, the arrangement of the elements is in the order of increasing compatibility from left to right. In comparison with average upper continental crust (AUCC), the greywacke are enriched in MgO, CaO and TiO_2 and depleted in Na_2O, K_2O and P_2O_5. On the other hand the arkose are generally depleted in TiO_2, CaO, Fe_2O_3, MgO and P_2O_5 (Table 1). Enrichment of MgO, CaO and TiO_2 in the former can be attributed to the higher amount of mafic minerals as shown by petrographic study. In comparison with AUCC, the samples greywacke are generally depleted in almost all the elements except in Large Ion Lithophile Elements (LILE) Rb, Th, U and K which show more concentration in arkose.

The overall total REE concentrations as shown by our samples of arkoses vary from 35 ppm to 53 ppm with an average of 46 ppm. The greywacke samples are more enriched in total REE showing variation from 84 ppm to 203 ppm with an average of 132 ppm. However, the total REE contents of arkose as well as greywacke remain lower than that of AUCC (~ 143 ppm; Taylor and McLennan, 1985). Chondrite- normalized REE patterns of our greywacke and arkose samples are sub-parallel, characterized by LREE enrichment and no to minor Eu anomalies (Fig. 3). These rocks also exhibit concave- upward REE patterns between Dy and Lu, This feature is more prominent in the REE patterns of arkose samples. Such type of REE patterns are characteristically shown by TTG (e.g. Huang et al., 2010) and considered as a characteristic feature of arc magma (Van Boening and Nabelek, 2008).

Discussion

Weathering history of the source terrain

The degree of weathering in the source area of sedimentary rocks can be quantified by using geochemical indices such as chemical index of alteration

[CIA= {Al_2O_3 / (Al_2O_3+CaO* + Na_2O + K_2O)}X 100] (Nesbitt and Young, 1982) and chemical index of weathering [CIW= {Al_2O_3 / (Al_2O_3+CaO* + Na_2O)}X 100] (Cullers, 2000) where all the major oxides are expressed in molecular proportions and CaO* is the content of CaO incorporated in silicate fraction. The CIA values of greywacke are lower (30- 43; avg 37) than those of arkoses (49- 74; avg. 56). Similarly the CIW values of greywacke (31-46; avg 40) are lower than those of arkoses (56-80; avg 65) (Table 3). Collectively these values are intermediate between those of unweathered igneous rocks and typical shales (i.e. <50 and 70-75 respectively) and therefore suggest that the source area of these sedimentary rocks had only been weekly weathered.

Elements Ratio	**Bundelkhand Metasediments**		**Mixing end members (Condie 1993)**			**Mixing result for Greywacke**	**Mixing result for Arkose**
	Greywacke	**Arkose**	**TTG**	**Basalt**	**Granite**	**T60:B40:G10**	**T80:G20**
La$_N$	119.6	47.13	126.58	31.65	210.97	150.8439	143.4599
Ce$_N$	89.16	34.03	91.35	31.05	155.23	110.8731	104.1289
Nd$_N$	54.15	14.35	48.14	23.55	98.50	65.82591	58.21225
Sm$_N$	30.49	7.63	22.97	19.61	41.18	29.91786	26.61367
Eu$_N$	18.45	5.44	17.76	17.24	14.66	16.4672	17.14063
Gd$_N$	18.87	4.79	14.97	15.86	22.73	18.16384	16.52491
Tb$_N$	16.62	4.18	12.47	14.71	17.38	14.65515	13.44823
Yb$_N$	11.59	4.85	6.21	13.53	11.76	9.164414	7.321885
Lu$_N$	12.30	6.02	6.91	14.96	12.60	9.990718	8.04814
Eu/Eu*	0.73	0.89	-	-	-	-	-
(La/Lu)$_N$	10.44	8.49	-	-	-	-	-
La/Sc	4.84	7.23	-	-	-	-	-
Th/Sc	1.36	8.75	-	-	-	-	-
La/Co	1.24	0.47	-	-	-	-	-
Th/Co	0.35	0.50	-	-	-	-	-
Cr/Th	2.13	0.72	-	-	-	-	-
(La/Sm)$_N$	3.88	6.18	-	-	-	-	-
(Gd/Yb)$_N$	1.71	1.06	-	-	-	-	-
(La/Yb)$_N$	11.03	10.50	-	-	-	-	-
Th/U	3.67	4.79	-	-	-	-	-
Zr/Sc	26.89	48.47	-	-	-	-	-
CIA	37	56	-	-	-	-	-
CIW	40	65	-	-	-	-	-
ICV	13.9	11.8	-	-	-	-	-

Table 3: Average values of elemental ratios of the greywacke and arkose metasedimentary rocks of the Bundelkhand craton and mixing calculation of the Archaean rocks (Condie 1993).

The weathering history of source area of sedimentary sequences can also be evaluated by using their Th/U ratios. The Th/U ratios of sedimentary rocks are increased with increasing weathering due to oxidation and loss of U (Taylor and McLennan, 1985; McLennan et al., 1995). The average Th/U ratio of Upper crustal rocks is around 3.8 (Taylor and McLennan, 1985). Th/U ratios above 4 are considered to be related to weathering history. The Th/U ratios of studied samples range from 3.24 to 6.29 and averages at 4.2. The average Th/U ratio of greywackes is lower (3.67) than that of arkose (4.79) (Table 3). In Figure 7(A), Th/U is plotted against Th abundances (McLennan et al., 1993). Most of the samples of greywacke plot below the value for upper continental crust (UCC), only one sample (N220) plot slightly above the line representing UCC. The samples of arkoses plot slightly above the line. The plot of greywacke near the field of depleted mantle sources indicates their derivation from non-recycled arc magmatic rocks. As a whole the Th/U values of studied rocks suggest that these sediments were derived from source rocks with weak weathering and/or from debris which suffered least recycling. This result is consistent with interpretation drawn from CIA and CIW values.

A number of studies carried out on Archaean sedimentary sequences indicate severe chemical weathering of their source areas (McLennan et al., 1983; Wronkiewicz and Condie, 1987; Kasting, 1993; Fedo et al., 1996; Hofmann et al., 2003; and Hofmann, 2005). Elevated surface temperature, CO_2– rich atmosphere and humid climate during the Archaeans are the factors which have been related to intense weathering during that period (Kasting, 1993; Knauth and Lowe, 2003; Hessler et al., 2004). The intensity of chemical weathering is mainly controlled by source rock composition, duration of weathering, climate and tectonic conditions (Wronkiewicz and Condie, 1987). The rate of erosion and the climate are the main control of weathering. If rate of erosion is high it will not leave enough time for severe chemical weathering. Therefore, low degree of weathering in the source region of our samples may be due to high rate of erosion, rapid sedimentation and short distance transportation of the debris in a tectonically active setting of sedimentation. These conditions are compatible with non-steady state weathering where active tectonism and uplift allow erosion of all soil horizons and rock surfaces.

Provenance

Although overall composition of source region essentially controls the chemical composition of the clastic sedimentary rocks, there are certain surface processes such as sediment recycling, hydraulic sorting and palaeoweathering which may greatly modify the provenance memory (Lahtinen, 2000; Hofmann, 2005; Roddaz et al., 2006). Therefore, to identify the source of sedimentary sequences it is important to consider first the effect of these processes on the overall composition of sediments. The Th/Sc-Zr/Sc variation diagram is a useful measure to assess the contribution of pre-existing sedimentary sources. A Th/Sc ratio >1 of sedimentary rocks reflects input from fairly evolved crustal igneous rocks (Taylor and McLennan, 1985). Th/Sc ratio <0.8 indicates source of the sedimentary rocks other than the typical continental crust, probably a mafic source or input from mature or recycled source if coupled with higher ratio of Zr/Sc (>10). Average values of Th/Sc and Zr/Sc ratios of our samples are low (greywacke= 1.36 and 26.9; arkose= 8.75 and 48.47 respectively, Table 3). 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 to sediments. Our samples of Greywacke and arkose, both display a positive linear correlation between Zr/Sc and Th/Sc (r= 0.98; 0.92 respectively), that is consistent with provenance dependent igneous differentiation trend. 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). In Zr/Sc versus Th/Sc diagram (Fig. 7B) the studied samples are plotted along linear trend, suggesting insignificant degree of recycling.

The major element composition of pelitic rocks can be used to suggest their detrital mineralogy (Cox et al., 1995). The index of compositional variability [ICV = $(Fe_2O_3+K_2O+Na_2O+CaO+MgO+TiO_2)/Al_2O_3$] has been effectively used in this regard (Cox et al., 1995). Basic idea behind the calculation of this parameter is that the non-clay minerals have higher ratios of the major cations to Al_2O_3 than clay minerals, so the non-clay minerals have higher ICV values. For example ICV decreases in the order of pyroxene and amphibole (~10-100)-biotite (~8)-alkali feldspar (~0.8-1)-plagioclase (~0.6)-muscovite and illite (~0.3)-montmorillionite (~0.15-0.3), and kaolinite (~0.03-0.05) (Cox et al., 1995). Immature shales with high percentages of non-clay silicate minerals will thus have ICV values greater than one. Such shales are often found in tectonically active settings in first cycle deposits (Van de Kamp and Leake, 1985). In contrast, more mature mud rocks rich in clay minerals ought to have lower ICV values of less than one (Cox et al., 1995). Such shales are derived from stable cratons with quiescent environments (Weaver, 1989). Low ICV values have also been found, however, in some first cycle material that was intensely weathered (Barshad, 1966). The average ICV values of studied greywacke (13.9; range- 12.39-15.78) and those of arkoses (11.78; range- 8.15-14.78) are >>1, thus suggest that these sediments are generally immature, derived from a tectonically active source region.

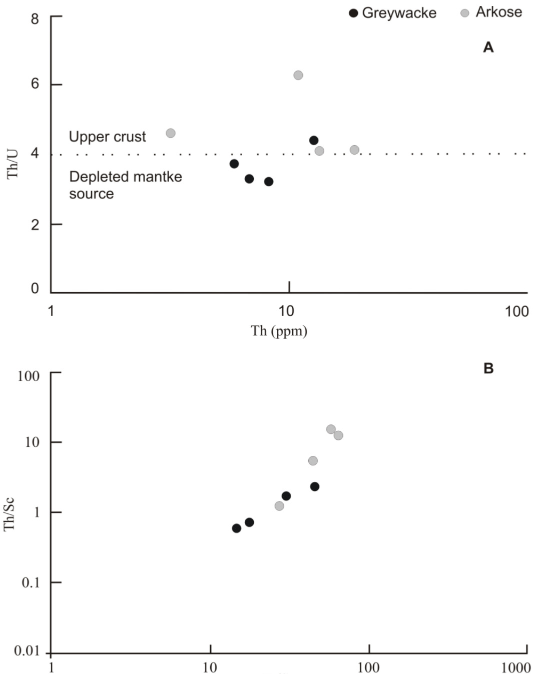


Figure 7: Discrimination diagram illustrating weathering and recycling; (**A**) Th/U vs Th diagram after McLennan et al., (1993), (**B**) Th/Sc vs Zr/Sc diagram after McLennan et al. (1993).

The geochemical composition of clastic sedimentary rocks is primarily related to that of their source terrain. Therefore, the major and trace element compositions are widely used to determine the composition of their source region (Roser and Korsch, 1988; Fedo et al., 1997; Culler, 2000; Gu et al., 2002; Roddaz et al., 2007; Manikyamba, 2008; Absar et al., 2009; Raza et al., 2010; Absar and Sreenivas, 2014). It is observed that Ti and Al remain essentially immobile and behave similarly during weathering and fluvial transport (Nesbitt and Young, 1982; Sugitani et al., 1996; Chen et al., 2010, 2013). 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 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 ilmenite). Therefore, the Al/Ti ratio of igneous rocks gradually increases from mafic to more felsic rocks. The Al_2O_3/ TiO_2 ratio of our samples of greywacke varies from 19.06 to 30.94 and averages at 22.36, therefore suggest their derivation from source of mafic to intermediate composition. The average value of Al_2O_3/ TiO_2 of studied arkose samples is 174.18 (range 81.50- 361.00) reflecting a felsic source. In Al_2O_3 - TiO_2 diagram (Fig. 8**),** the studied samples of arkose are plotted near the granite field and those of greywacke near the basalt field with an inclination towards granite field. This relationship indicates the derivation of our greywacke samples from a source region comprising a mixture of mafic and felsic rocks. On the other hand the studied arkose samples appear to have been derived from a source of predominantly felsic composition. On the (CaO+MgO) - SiO_2 – (Na_2O+ K_2O) ternary diagram (Taylor and McLennan, 1985), our samples of greywacke and arkose again plot near the fields of basalt and granite respectively (Fig. 9) thus indicating the derivation of debris from sources of contrast composition.

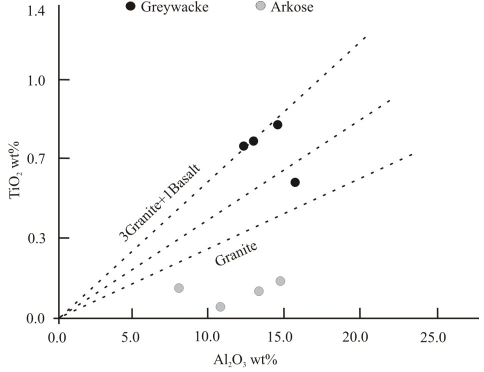


Figure 8: TiO_2 wt% versus Al_2O_3 wt% bivariate diagram (after McLennan et al., 1980). The 'granite line' and '3granite+ 1basalt' line are after Schieber (1992).

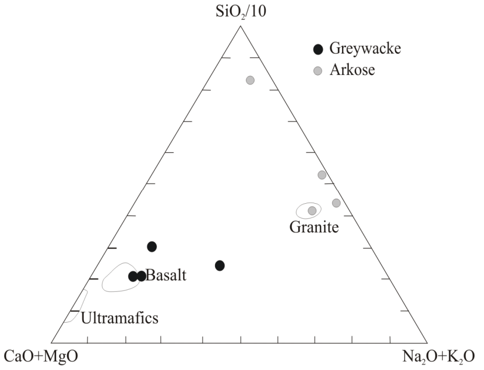


Figure 9: $SiO_2/10$- CaO+MgO- Na_2O diagram after Taylor and McLennan (1985), analyzed greywacke and arkose samples occupying basalt and granite field respectively.

REE and their ratios are most sensitive geochemical parameters influenced by source rock composition. The REE patterns are the most reliable indicators of sedimentary provinces (Taylor & McLennan, 1985). The degree of LREE vs HREE enrichment may be accessed through the $(La/Yb)_N$ values. The degree of differentiation of LREE from HREE is a measure of proportion of felsic to mafic rocks in the provenance. All of our samples reveal LREE enrichment with $(La/Yb)_N$ ratio ranging from 6.30 to 20.73 in greywacke and from 5.38 to 16.11 in arkose. The $(La/Yb)_N$ ratios, as shown by some of our samples e.g. N205 of greywacke and N210 of arkose are very high (20.73-16.11 respectively) in comparison to North American Shale Composite (NASC= 7.17; Gromet et al., 1984) and Post- Archaean Australian Shales (PAAS= 8.2). Amongst older crustal components, Tonalite-Trondhjemite-Granodiorite (TTG) and adakite suites are characterized by high $(La/Yb)_N$ ratios (TTG=42, Martin, 1994; Adakite= 24, Defant et al., 1991). Therefore, the high values of $(La/Yb)_N$ ratio as shown by some of our samples point towards a possible TTG/adakite component in their source terrain.

The negative Eu anomaly is a reflection of recycled crustal material characterizing evolved crustal cratons (Gao and Wedepohl, 1995; Meinhold et al., 2007). REE patterns of studied rocks do not exhibit significant negative Eu anomalies. They exhibit either minor Eu anomalies with (Eu/Eu*= 0.64-0.68) or no Eu anomalies with Eu/Eu* values ranging from 0.61 to 1.02. Out of four samples of arkose three samples show no Eu anomalies (Eu/Eu*= 0.93-1.02) and one sample show minor Eu anomaly (Eu/Eu*= 0.61). Amongst the greywacke samples, one sample shows no Eu anomaly (Eu/Eu*= 0.96) and rest of the three samples show minor Eu anomaly (Eu/Eu*= 0.64-0.68).

Significantly the samples of greywacke (N205) and arkose (N210) having high values of Eu/Eu* (0.96 and 1.02 respectively) also have high values of $(La/Yb)_N$ ratios (21.92 and 17.01). These relationships could indicate the contribution of TTG ($\{La/Yb)_N = 0.97$; Condie, 1993) source for both of the sedimentary types. The large variation in Eu/Eu* (greywacke: 0.64-0.96; arkose: 0.61-1.02) together with more mafic nature of greywackes and more felsic nature of arkose could be explained by invoking mixing of TTG, granite and mafic rocks in different proportions. It appears that the studied sedimentary rocks were derived from mixing of debris of felsic composition from distal sources to that of mafic composition from local sources, probably derived from a magmatic arc. These characteristics suggest the derivation of debris from young undifferentiated arc material (McLennan et al., 1990).

With the identification of mafic rocks, granite and TTG as possible source rocks of studied sedimentary sequence, an attempt can be made to constrain the contribution of these components. 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, 2010b) using REE data. To determine the relative contribution of these end members to overall composition of studied Greywackes and arkoses, simple mixing calculations are performed. The purpose is to search for best fit solution to reproduce the observed REE patterns of these rock types. The greywacke samples are best modelled with a mixture of 50% TTG, 40% basalt, and 10% granite (Fig. 10). To constrain the contribution of various source rocks, the trace element modelling is attempted, also for the studied arkose samples. The shape of trace element pattern (Fig. 11) of average arkose samples is closely similar to that of modelled pattern. However, the overall trace element abundances are lower in arkose relative to modeled mixture. This is because of the fact that the trace element abundances have been reduced due to 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. Our modelling suggests that minor amount of granitic (or Rhyolitic) material must have been in existence during the time of deposition of sedimentary rocks of Mauranipur-Babina greenstone belt.

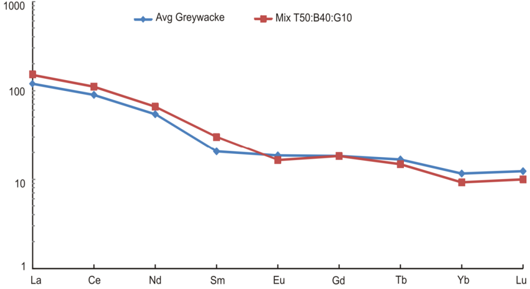


Figure 10: Chondrite –normalized REE patterns of greywacke from Mauranipur-Babina greenstone belt of the Bundelkhand craton compared with estimated best- fit source composition (Mixing results : 50%TTG, 40% basaltic rocks, 10% granites) See table 3.

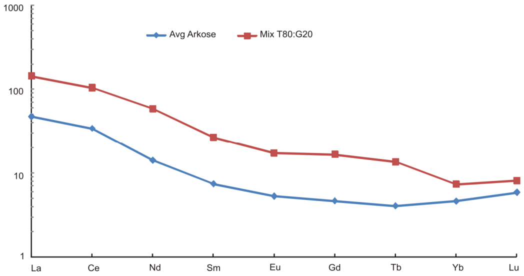
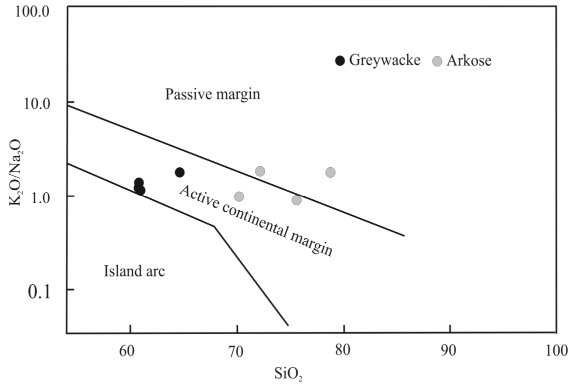


Figure 11: Chondrite –normalized REE pattern of Arkoses from Mauranipur-Babina greenstone belt of the Bundelkhand craton compared with estimated best- fit source composition (Mixing results : 80%TTG and 20% granites), See table 3.

Tectonic setting

The immature nature of studied rocks, low degree of weathering in their source region and minor sorting influence on the detritus are the features which suggest high rate of erosion, rapid sedimentation, potentially marked relief and short distance transportation of the debris. These features indicate a tectonically active setting of sedimentation where the sedimentary basin received detritus from terrains that were actively being eroded during the entire period of sedimentation. According to K_2O/ Na_2O versus SiO_2 diagrams (Fig.12) of Roser and Korsch (1988) and Th-Sc-Zr/10 triangular diagram (Fig.13) of Bhatia and Crook (1986), our samples appear to have been deposited predominantly in an active continental arc setting. High values of $(La/Yb)_N$ ratios and concave upward patterns of HREEs, shown more prominently by the samples of arkoses, further attest the derivation of studied sedimentary rocks from a source containing TTG (e.g Huang et al., 2010) that are thought to form above subduction zones (Drummond and Defant, 1990; Van Boening et al., 2008).



Roser and Korsch (1988), the analysed greywacke and arkose sediments of the Bundelkhand craton predominantly occupies active continental arc settings.

These features lead to suggest that the basin evolved through contemporaneous sedimentation of immature sediments derived from 1) A young craton evolved through accretion and tectonic amalgamation of continental arcs consisting TTG and granitic batholiths and 2) Mafic volcanic rocks derived from syn-depositional volcanic centres in an active tectonic environment.

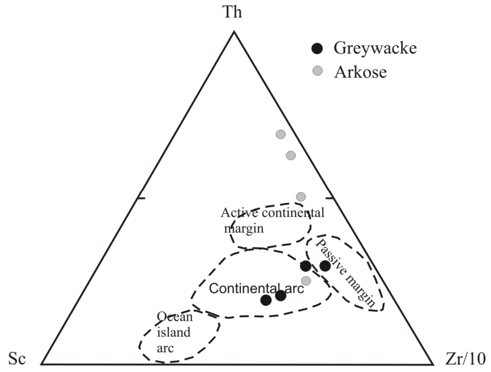


Figure 13: Th-Sc-Zr/10 after Bhatia and Crook (1986), the analysed greywacke and arkose sediments of the Bundelkhand craton predominantly occupies active continental arc settings.

Conclusions

The Archaean clastic sedimentary rocks, occurring in parts of Mauranipur-Babina greenstone of the Bundelkhand craton of the central India are geochemically classified as greywacke and arkose.

The source terrain suffered low degree of weathering indicative of non steady weathering conditions where active tectonism and uplift lead erosion of all soil horizons and rock surfaces. These trends indicate high erosion rate coupled with short distance rapid sedimentation in a tectonically active basin.

The provenance analyses based on geochemical characteristics suggest the derivation of greywacke from a terrain comprising 50%TTG, 40% mafic volcanic rocks and 10% granite. The arkose were derived from a source region consisting 80%TTG and 20% granite.

The basin experienced contemporaneous sedimentation of immature detritus derived from a young craton consisting TTG and granitic batholiths and syn-depositional volcanic centres in an active tectonic environment.

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