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Provenance of the Sawa Formation Sandstones, Vindhyan Super Group, Southeast Rajasthan, India

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Abstract

Integrated petrographical and geochemical analysis of Sawa Formation sandstones was analyzed to reconstruct their source area weathering, paleoclimate, tectonic setting and provenance conditions. Petrographically, quartz is dominant detrital mineral followed by feldspar, mica, rock fragments and heavy minerals. Sawa Formation sandstones have been classified as quartzarenite with subordinate sub-arkose and sub-litharenite type. Major oxide element abundances revealed the sandstones have high SiO_2 concentration, high K_2O/ Na_2O ratio, which is consistent with the petrographic data. These sandstones were derived mainly from stable cratonic with minor collision suture and fold thrust belt source and deposited in rifted continental margin basin setting, reflecting high maturity of sediments and high stability of the source area. The CIA, CIW and PIA values of these sandstones indicate high intensity of weathering condition in the source area under warm and humid climate.

Keywords: *Petrography, Geochemistry, Source area weathering, Paleoclimate, Tectonic setting*

Introduction

Siliciclastic sediment composition has been investigated to infer the provenance, weathering conditions, sediment transport, climate and tectonic environment (Taylor and McLennan 1985; Bhatia and Crook 1986; Johnsson and Basu, 1993; Cox et al. 1995; Nesbitt et al. 1996; Armstrong-Altrin, 2015). Variables including the nature of source rock, degree of weathering, transportation and diagenesis influences composition of clastic sediments (McLennan et al., 1993). However, the tectonic setting of the sedimentary basin may play a predominant role over other variables, because different tectonic settings can provide different type of source materials with variable chemical signatures (Bhatia and Crook 1986). The largest of Intracratonic Proterozoic sedimentary basins (Purana basins) is the Vindhyan Basin in the Indian subcontinent (Soni et al., 1987; Kale and Phansalkar, 1991). This sedimentary basin occurs as a large sickle shaped basin, covering an area of about 100,000 km^2 in Uttar Pradesh, Bihar, Madhya Pradesh and Rajasthan. The Vindhyan basin overlies the stable Bundelkhand craton of Archean-Palaeoproterozoic age (Roy, 1988; Chakraborty and Bhattacharya, 1996; Bose et al., 2001; Acharyya, 2003). An unmetamorphosed and undeformed sequence of Meso-Neoproterozoic sedimentary rocks about 4,500 m thick occupies mainly the northern fringe of peninsular India (Fig. 1). Thick Vindhyan Basin sediments show variably marine, aerially extensive, well exposed, lithologically variable, and largely unmetamorphosed successions (Chanda and Bhattacharya, 1982; Bose et al., 2001, 2015).

Geological Setting

The Meso-Neoproterozoic Vindhyan Super Group covers an area of about ~100,000 km^2 and a significant part of this Super Group is concealed below Deccan continental flood basalt traps and Indo-Gangetic alluvium (Venkatachala et al., 1996; Gopalan et al., 2013). The Vindhyan succession overlies the ~ 2.5Ga old Bundelkhand granite massif which is bounded to the northwest by the Great Boundary Fault and to the southeast by the Narmada-Son lineament (Fig. 1). The thick strata of Vindhyan Basin are subdivided into Lower Vindhyan sequence (the Semri Group) and the Upper Vindhyan sequence (the Kaimur, Rewa, and Bhander groups), separated by a major hiatus of unknown duration (Bose et al., 2001).

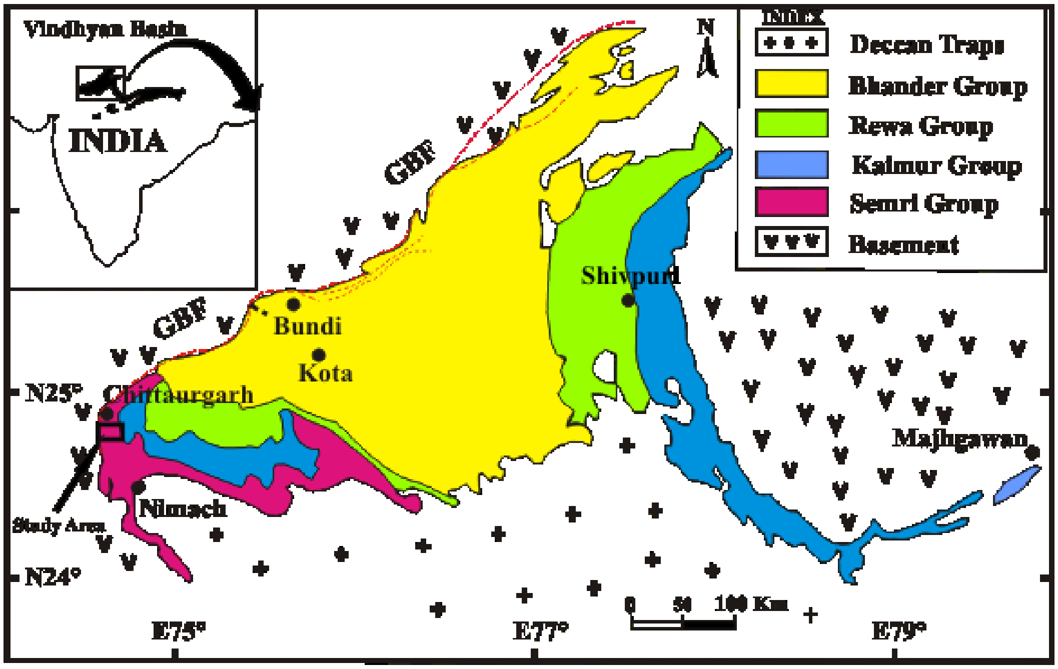

Fig. 1: Generalized regional geological map of Vindhyan Basin showing study area and lithological units (various groups) of Vindhyan Super Group (modified after Soni et al., 1987). GBT= Great Boundary Fault.

Table 1: Lithostratigraphic Succession of the Vindhyan Sequence, Southeastern, Rajasthan (after Prasad, 1984; Casshyap et al., 2001).

Group	Formation	Lithology	Thickness (m)	Age (Ma)
Upper Vindhyan	Kaimur	Sandstone, Conglomerate	20-70	
--------------------Unconformity---------------------				
Lower Vindhyan	Suket	Shale	120	
	Nimabhara	Limestone	100-150	
	Bari	Shale	45	
	Jiran	Sandstone	30-60	
	Binota	Shale	250	
	Palri	Shale	30-60	
	Sawa	Sandstone	30-60	1616±50 U-Pb (Zircon) (Shukla, 2011)
	Bhagwanpura	Limestone	30-50	
	Khardeola	Sandstone	70-200	
	Khairmala	Volcanic flows and tuffs	40-100	
----------------------Unconformity---------------------				
Basement comprises BGC, Quartzite, Phyllite, etc.				

The detailed geology of the area has been worked out by Prasad (1984). The stratigraphic succession of the Lower Vindhyan Group of southeastern Rajasthan is summarized in Table 1. The Sawa Formation comprises mainly of sandstones with conglomerate. The sandstone assemblage overlies Bhagwanpura Limestone Formation and crops out in narrow ridges of sandstone (Fig. 2).

Methodology

A total of thirty five sandstone samples were collected from Sawa Formation and thirty samples were selected for detailed petrographic investigations. In each thin section, 250–300 grains were counted using standard Gazzi–Dickinson method (Ingersoll et al., 1984). For petrofacies analysis, the detrital modes were recalculated to 100 percent by summing up of Qt, Qm, F, L and Lt following Dickinson's (1985) method. After useful thin section screening, ten representative samples were selected for geochemical analysis. Major element oxides were determined using standard X-ray Fluorescence (XRF) spectrometer (Philips PW-2440 Magix-PRO) at National Geophysical Research Institute (NGRI), Hyderabad. Moreover, the total iron is expressed as Fe_2O_3. Major oxide data were recalculated to an anhydrous (LOI-free) basis and adjusted to 100% before using them in various diagrams.

Results

Petrography

The modal composition and detrital petrofacies (based on Dickinson, 1985) of the Sawa Formation sandstones are given in Table 2. The average petrographic composition of the studied sandstones is quartz (97.23%) followed by feldspars (average 1.34%), micas (0.70%), rock fragments (0.54%) and heavy minerals (0.20%). Most of the quartz grains are monocrystalline (common quartz) and some polycrystalline grains (recrystallized and stretched quartz) (Plate 1a, b). Some monocrystalline quartz with undulation or non-undulation is characterized by inclusion of heavy minerals. Feldspar is present in the form of K- feldspar (microcline) (Plate 1a) and plagioclase feldspar (Plate 1c). K-feldspar is dominant variety than the plagioclase feldspar. Mica usually occurs as elongated muscovite due to mechanical compaction (Plate 1c) and inclusion of biotite in the monocrystalline quartz grain (Plate 1 d). The rock fragments comprise of chert (Plate 1e), granite, phyllite, schist and siltstone. Heavy minerals constitute minor component of the samples and include rounded zircon (indication of recycling) (Plate 1f), tourmaline, rutile, staurolite, epidote and opaque minerals. According to Folk's (1980) classification scheme, the studied sandstones are classified as quartzarenite with subordinate sub-litharenite and sub-arkose (Fig. 3).

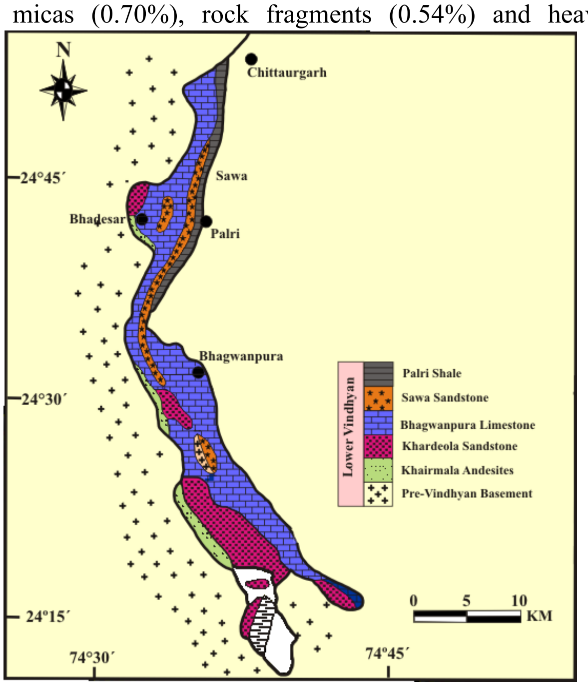

Fig. 2: Geological map of Sawa Formation and other sequences

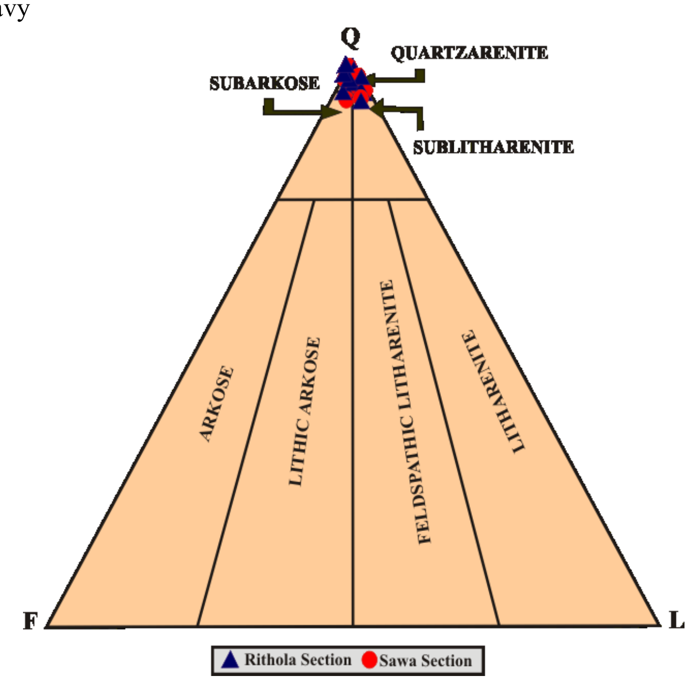

Fig. 3: Q-F-L diagram for the Sawa Formation sandstones (after Folk, 1980).

Major element concentrations

The major oxides in wt % for the Sawa Formation sandstones are listed in Table 3. The sandstones have higher SiO_2 content (>90 wt %) because of the presence of greater amount of quartz. The lower TiO_2 indicate smaller content of Ti-bearing minerals like ilmenite, titanite, etc. The low values of MgO and CaO also suggest the lesser presence of the calcitic components. K_2O shows more enrichment than Na_2O, (K_2O/Na_2O ranges from 6.00-6.50, average 6.23) (Table 3) suggesting dominance of K-feldspar over plagioclase feldspar which is also confirmed by the petrographic data. The extremely low concentration of P_2O_5 may be explained by the very low concentration of phosphates in the source rocks or their dissolution and mobilization during transport.

Table 2: Modal composition of the Sawa Formation sandstones, Vindhyan Super Group, Southeastern Rajasthan (after Suttner et al. , 1981; Dickinson et al. 1985)

Sample No.	Q	F	R	Qt	F	L	Qm	F	Lt	Qp	Lv	Ls	Qm	P	K
RS-1	94.34	2.07	3.58	96.48	2.07	1.45	90.35	2.06	7.59	73.70	0.00	26.30	97.53	0.43	2.03
RS-2	93.86	4.60	1.54	95.04	4.60	0.36	92.86	4.61	2.53	71.22	0.00	28.78	95.08	1.36	3.57
RS-3	99.16	0.84	0.00	99.16	0.84	0.00	96.03	0.84	3.13	100.00	0.00	0.00	99.10	0.26	0.64
RS-4	97.71	2.29	0.00	97.71	2.29	0.00	96.95	2.29	0.76	100.00	0.00	0.00	97.67	1.01	1.32
RS-5	99.09	0.91	0.00	99.09	0.91	0.00	95.74	0.91	3.35	100.00	0.00	0.00	99.03	0.13	0.84
RS-6	98.50	1.50	0.00	98.50	1.50	0.00	97.40	1.50	1.10	100.00	0.00	0.00	98.46	1.28	0.25
RS-7	96.14	1.11	2.75	97.62	1.11	1.27	92.21	1.11	6.68	78.20	0.00	21.80	98.71	0.40	0.89
RS-8	98.66	1.34	0.00	98.66	1.34	0.00	95.15	1.34	3.51	100.00	0.00	0.00	98.56	0.49	0.95
RS-9	99.88	0.12	0.00	99.88	0.12	0.00	98.76	0.12	1.12	100.00	0.00	0.00	99.88	0.00	0.12
RS-10	98.79	0.25	0.97	99.75	0.25	0.00	97.83	0.25	1.92	70.52	0.00	29.48	99.74	0.12	0.13
RS-11	98.96	0.31	0.73	99.32	0.31	0.37	97.81	0.31	1.88	80.65	0.00	19.35	99.68	0.15	0.16
RS-12	98.98	1.02	0.00	98.98	1.02	0.00	97.86	1.02	1.12	100.00	0.00	0.00	98.97	0.85	0.18
RS-13	98.40	1.60	0.00	98.40	1.60	0.00	97.11	1.60	1.29	100.00	0.00	0.00	98.36	0.37	1.27
RS-14	98.77	1.11	0.12	98.61	1.11	0.28	97.83	1.11	1.06	89.83	0.00	10.17	98.87	0.22	0.91
RS-15	99.48	0.52	0.00	99.48	0.52	0.00	98.31	0.52	1.17	100.00	0.00	0.00	99.47	0.16	0.36
RS-16	99.56	0.44	0.00	99.26	0.44	0.30	97.52	0.44	2.04	90.27	0.00	9.73	99.54	0.17	0.29
SS-1	98.15	1.26	0.59	98.15	1.26	0.59	97.56	1.26	1.18	100.00	0.00	0.00	98.71	0.38	0.90
SS-2	98.25	1.75	0.00	98.25	1.75	0.00	97.66	1.75	0.59	100.00	0.00	0.00	98.22	0.49	1.29
SS-3	99.63	0.37	0.00	99.63	0.37	0.00	99.63	0.37	0.00	100.00	0.00	0.00	99.63	0.13	0.24
SS-4	97.79	2.21	0.00	97.79	2.21	0.00	95.00	2.21	2.79	100.00	0.00	0.00	97.67	0.24	2.10
SS-5	98.72	0.30	0.98	98.72	0.30	0.98	97.85	0.30	1.85	100.00	0.00	0.00	99.69	0.19	0.11
SS-6	99.70	0.30	0.00	99.34	0.30	0.36	98.76	0.30	0.94	87.04	0.00	12.96	99.70	0.13	0.17
SS-7	99.58	0.42	0.00	99.58	0.42	0.00	99.21	0.42	0.37	100.00	0.00	0.00	99.59	0.17	0.24
SS-8	95.43	4.57	0.00	95.10	4.57	0.34	92.95	4.57	2.48	86.71	0.00	13.29	95.20	1.33	3.47
SS-9	97.45	2.55	0.00	97.45	2.55	0.00	95.61	2.55	1.84	100.00	0.00	0.00	97.35	1.32	1.32
SS-10	98.50	1.50	0.00	98.50	1.50	0.00	96.10	1.50	2.40	100.00	0.00	0.00	98.42	0.26	1.32
SS-11	98.38	1.15	0.47	98.50	1.15	0.35	95.84	1.15	3.01	95.68	0.00	4.32	98.77	0.19	1.04
SS-12	94.03	5.16	0.81	94.18	5.16	0.66	91.34	5.16	3.50	92.79	0.00	7.21	94.46	2.02	3.52
SS-13	95.98	4.02	0.00	95.98	4.02	0.00	95.16	4.02	0.82	100.00	0.00	0.00	95.92	1.18	2.90
SS-14	98.98	1.02	0.00	98.98	1.02	0.00	94.41	1.02	4.57	100.00	0.00	0.00	98.87	0.18	0.95

Q = Total quartz grain (Qm+Qp), where Qm = Monocrystalline quartz & Qp = Polycrystalline quartz.
F = Total feldspar (P+K), where P = Plagioclase & K = K-feldspar. R = Total rock fragments including chert.
L = total unstable lithic fragments (Lv+Ls), where Lv = volcanic/metavolcanic lithic fragments, Ls = sedimentary/metasedimentary lithic fragments

Discussion

Source area weathering

The chemical composition of the clastic rocks can provide useful information about weathering condition in the source area. The weathering indices like chemical index of weathering (CIW), chemical index of alteration (CIA) and plagioclase index of weathering (PIA) were widely used to infer paleo-weathering conditions in the source areas. CIA can be calculated following the equation using molecular proportion as proposed by Nesbitt and Young (1982): CIA = $[Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O] \times 100$, where CaO^* represents the amount of CaO incorporated in the silicate fraction of the studied sandstone samples. CIA values in sandstones range from 80.15 to 83.48 (average 81.04) (Table 3), which suggests that the source rocks were subjected to high degree of weathering under a warm and humid tropical climate conditions with abundant rainfall in the source area. CIW can be calculated following the equation using molecular proportion as proposed by Harnois (1988). CIW = $[Al_2O_3/ (Al_2O_3+CaO^*+Na_2O)] \times 100$, which ranges from 88.37 to 93.63 (average 91.65) (Table 3), suggests higher degree of weathering in the source area. PIA can be calculated following the equation using molecular proportion as proposed by Fedo et al. (1995): PIA = $[(Al_2O_3-K_2O)/$

$(Al_2O_3$+CaO*+$Na_2O-K_2O)]$ ×100. PIA values of the sandstones range from 87.07 to 92.35 (average 90.41) (Table 3) and suggests intense plagioclase weathering in the source area.

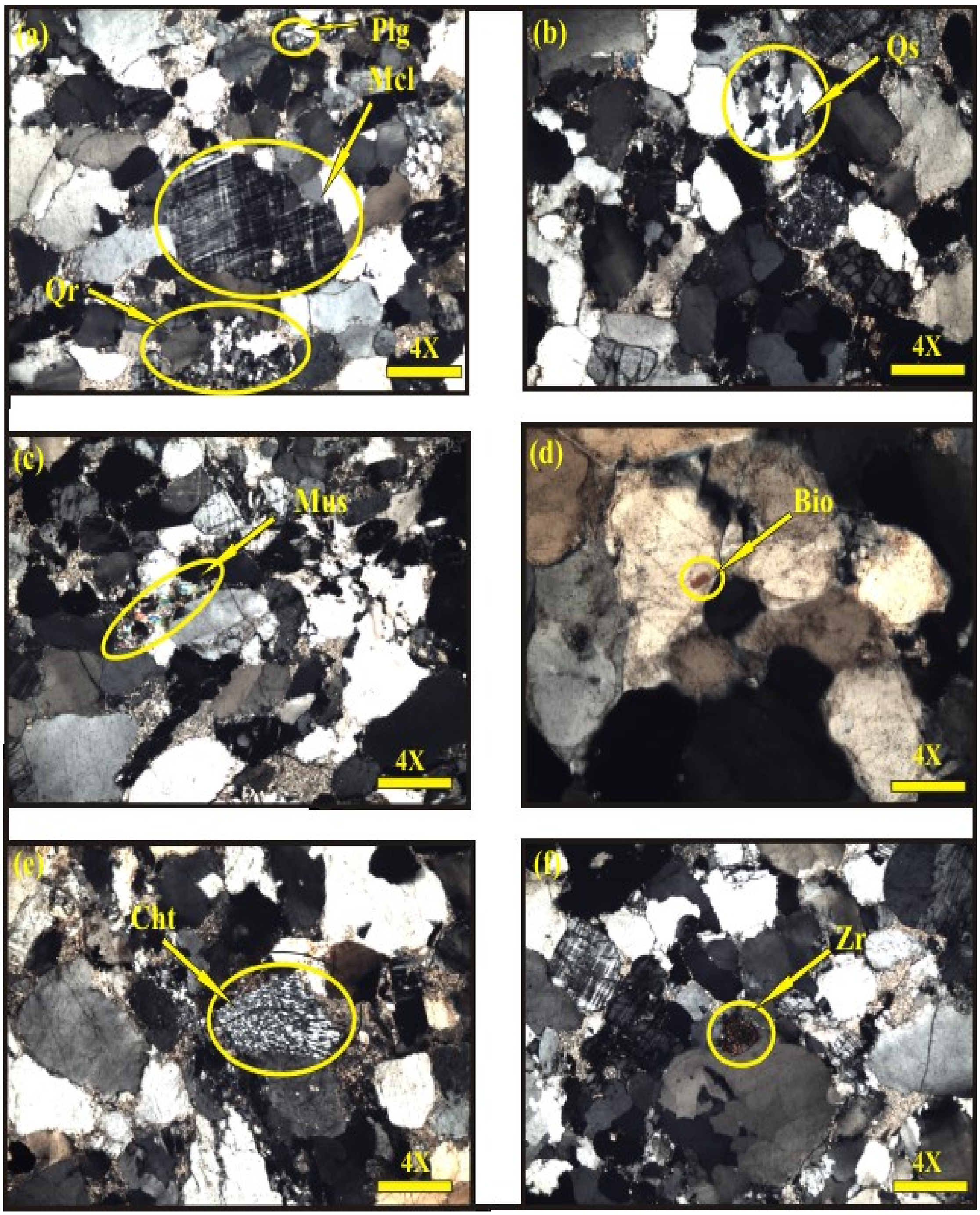

Plate 1: Photomicrograph showing (a) Recrystallized quartz (Qr), microcline (mcl) and plagioclase (plg), (b) Stretched quartz (Qs), (c) Muscovite, (d) Inclusion of biotite (bio) in quartz, (e) Chert (cht), (f) Rounded zircon (Zr).

Table 3: Major element concentrations (wt. %) for the Sawa Formation sandstones, Vindhyan Super Group, Southeastern Rajasthan

	RS-3	RS-8	RS-9	RS-13	RS-15	SS-2	SS-3	SS-7	SS-11	SS-12	Range	Average
SiO_2	94.89	95.92	95.98	96.02	93.47	94.12	95.12	96.16	96.13	93.98	93.47-96.16	95.18
Al_2O_3	1.68	1.79	1.36	1.91	1.75	1.75	1.87	1.14	1.78	2.14	1.14-2.14	1.72
Fe_2O_3	0.31	0.03	0.01	0.01	0.03	0.01	0.36	0.02	0.06	0.01	0.01-0.36	0.09
MnO	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00-0.01	0.00
MgO	0.53	0.38	0.41	0.42	0.43	0.35	0.47	0.26	0.64	0.42	0.26-0.64	0.43
CaO	0.11	0.12	0.11	0.11	0.12	0.10	0.11	0.13	0.11	0.11	0.10-0.13	0.11
Na_2O	0.03	0.05	0.04	0.02	0.03	0.04	0.05	0.02	0.06	0.06	0.02-0.06	0.04
K_2O	0.23	0.27	0.16	0.34	0.24	0.28	0.21	0.13	0.27	0.36	0.13-0.36	0.25
TiO_2	0.09	0.11	0.02	0.02	0.09	0.18	0.22	0.07	0.15	0.18	0.02-0.22	0.11
P_2O_5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.01-0.03	0.01
Total	97.88	98.69	98.10	98.87	96.18	96.84	98.42	97.94	99.21	97.29	96.18-99.21	97.94
LOI	2.12	1.31	1.90	1.13	3.82	3.16	1.58	2.06	0.79	2.71	0.79-3.82	2.06
CIA	81.95	80.27	81.44	80.25	81.78	80.65	83.48	80.28	80.18	80.15	80.15-83.48	81.04
CIW	92.31	91.33	90.07	93.63	92.11	92.59	92.12	88.37	91.28	92.64	88.37-93.63	91.65
PIA	91.19	89.94	88.89	92.35	90.96	91.30	91.21	87.07	89.88	91.28	87.07-92.35	90.41
K_2O/Na_2O	7.67	5.40	4.00	17.00	8.00	7.00	4.20	6.50	4.50	6.00	6.00-6.50	6.23

Palaeoclimate conditions

Climate might have been an important factor in the production of compositionally mature quartz-rich sandstones. The QFR ternary diagram of Suttner et al. (1981) indicates a metamorphic source rock in a humid climate (Fig. 4). The Palaeoproterozoic Pre-Aravalli metamorphic rocks are the basement of Vindhyan Supergroup so most of the sediments may have derived from this basement. However, this particular diagram can discriminate only sources of metamorphic and plutonic rocks (humid or arid conditions), and it does not discriminate between different tectonic settings. Humid climatic condition was also confirmed by bivariant plot of SiO_2 against total Al_2O_3+K_2O+Na_2O proposed by Suttner and Dutta in 1986 (Fig. 5).

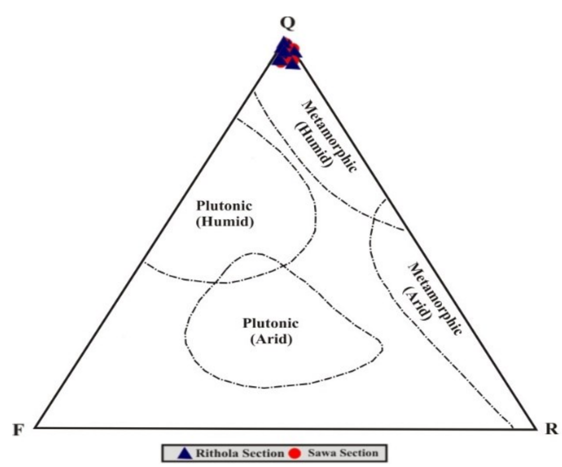

Fig. 4: Q-F-R ternary diagram for the Sawa Formation sandstones (after Suttner et al., 1981).

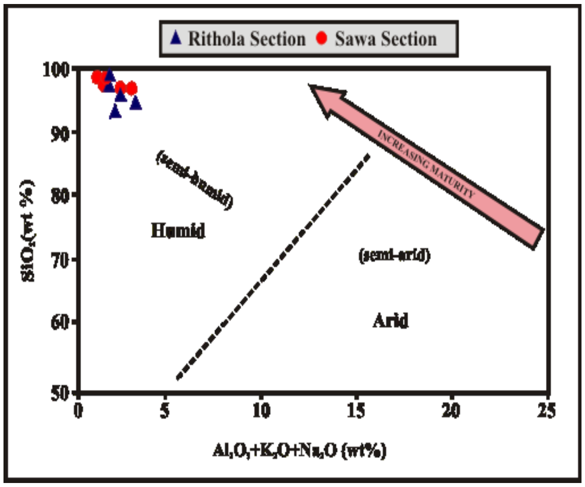

Fig. 5: SiO_2 versus $Al_2O3+K_2O+Na2O$ bivariate plot for the Sawa Formation sandstones (field after Suttner and Dutta, 1986).

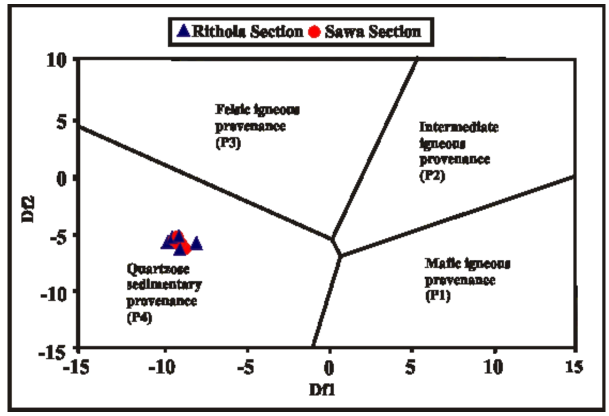

Fig. 6: Discriminant function diagram (after Roser and Korsch, 1988) for provenance of Sawa Formation sandstones. Df1 and Df2 refer to $-1.773TiO_2+ 0.607\ Al_2O_3+ 0.76\ Fe_2O_3- 1.500\ MgO+ 0.616\ CaO+ 0.509Na_2O- 1.224\ K_2O -9.09$ and $0.445\ TiO_2+ 0.070\ Al_2O_3- 0.250\ Fe_2O_3- 1.142\ MgO+ 0.438\ CaO+ 1.475\ Na_2O- 1.426\ K_2O-6.861$.

Provenance

Petrography gives the primary idea about the provenance of clastic rocks. The relative abundance of monocrystalline to that of polycrystalline quartz reflects the maturity of the sediments indicating a long distance transport and a distal provenance or recycling. Dominant medium to strong undulose monocrystalline quartz grains suggest metamorphic origin with slightly undulose to non undulose quartz grains suggest plutonic source (Basu, 1975; Potter, 1978a). Original polycrystalline quartz grains are disintegrated during high energy or long distance transport from the metamorphic source (Dabbagh and Rogers, 1983). The low percentage of feldspars and rock fragments indicates that the rock is chemically weathered and recycled. Euhedral zircon grains and flakes of muscovite indicate a plutonic source rock (Banerjee and Banerjee, 2010). The most probable source of Sawa Formation sandstone is the Palaeoproterozoic Pre-Aravalli metamorphic rocks and Berach granite.

Major element based discriminant function diagram (Roser and Korsch, 1988) is generally employed to distinguish between four fields of sedimentary provenance, namely: mafic igneous (P1), intermediate igneous (P2), felsic igneous (P3) and quartzose sedimentary or recycled (P4). In this diagram, the studied samples of the Sawa Formation sandstones plot in the quartzose sedimentary or recycled (P4) field (Fig. 6) indicating their derivation from granitic-gneissic terrain or mature polycyclic continental sedimentary source rocks.

Tectonic Setting

Tectonic setting of the Sawa Formation sandstone was determined by using detrital framework components plotted on standard ternary diagrams i.e., Qt-F-L, Qm-F-Lt, Qp-Lv-Ls and Qm-P-K (Dickinson, 1985). In Qt-F-L diagram, most of the samples plot in the stable, mature continental block provenance (Fig. 7a) suggesting their derivation from metasedimentary and sedimentary rocks which were originally deposited along former passive continental margins (Dickinson and Suczek, 1979; Dickinson, 1985). In Qm-F-Lt diagram, most of the samples fall in continental block provenance followed by recycled orogen provenance (Fig. 7b). In Qp-Lv-Ls diagram, most of the samples fall in rifted continental margin basin setting with minor contribution of collision suture and fold thrust belt setting (Fig. 7c) reflecting no contribution from the volcanic source. In Qm-P-K diagram, all the samples plot in the continental block basement uplift provenance (Fig. 7d) which reflects high mineralogical maturity of the sediments and high stability of the source area.

Using K_2O/Na_2O ratio and SiO_2, Roser and Korsch (1986) devised a binary tectonic discrimination diagram for the tectonic setting of terrigenous sedimentary rocks. The samples of Sawa Formation sandstones plot in the passive margin (PM) tectonic setting (Fig. 8) indicating that they are largely quartz-rich sediments derived from plate interiors or stable continental areas and deposited in stable intra-cratonic basin or on passive continental margins (Roser and Korsch, 1986).

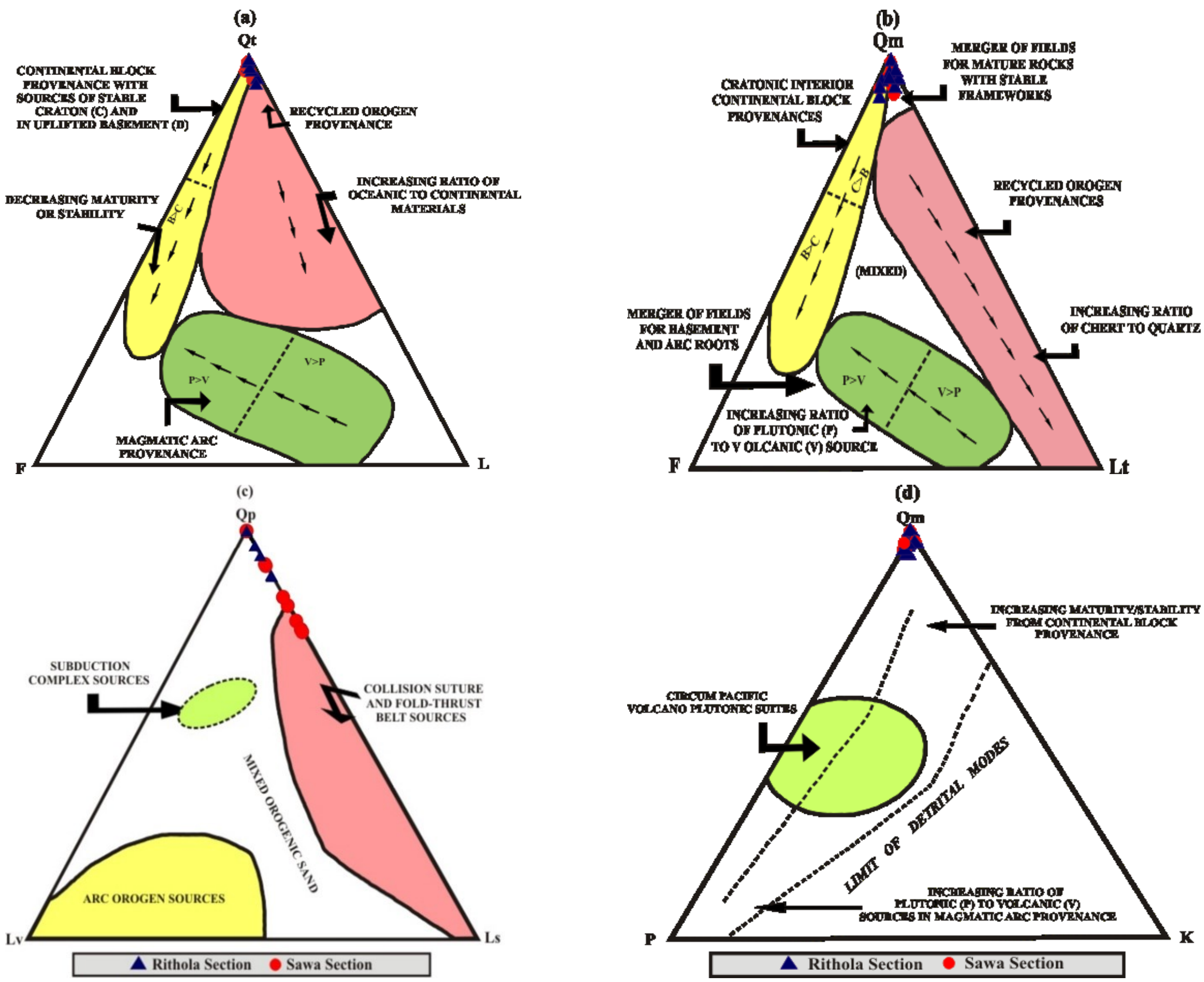

Fig. 7: (a) Qt-F-L (b) Qm-F-Lt (c) Qp-Lv-Ls (d) Qm-P-K ternary diagrams for the Sawa Formation sandstones (after Dickinson, 1985).

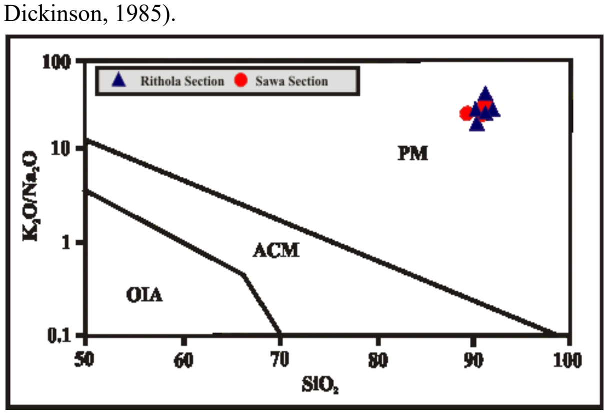

Fig. 8: SiO_2 versus K_2O/Na_2O tectonic discrimination diagram for the Sawa Formation sandstones (Roser and Korsch, 1986).

Conclusions

1. The detrital mineral composition of Sawa Formation sandstones is characterized by mainly quartz followed by feldspar, mica, rock fragments and heavy minerals. These sandstones are classified as quartzarenite with subordinate subarkose and sublitharenite.
2. The petrofacies analysis of these sandstone suggest that sediments were derived mainly from stable craton source and deposited mainly in rifted continental margin basin reflecting high maturity of sediments and high stability of source area.
3. Major oxide analysis revealed that these sandstones having high SiO_2 concentration, high K_2O/Na_2O ratio, were derived from granitic-gneissic terrain deposited in passive margin setting under warm humid tropical climate.
4. CIA, CIW, and PIA values indicate high degree of weathering condition in the source area.

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