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Provenance of the Mio-Oligocene Bhuban Sandstones, Surma Group of Kolasib District, Mizoram, India

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ABSTRACT

Mizoram is located in the Indo-Burmese tectonic collision zone in the easternmost corridor of the Indian subcontinent, bordering Myanmar to the east and south and Bangladesh to the west, resulting in a complex tectonic framework. The region geologically comprises Oligocene to Miocene sedimentary strata of the Surma basin, which are texturally and mineralogically immature. In order to enhance the current state of knowledge on the petrogenesis of the sedimentary terrain of this region, the present work deals with the provenance of the Mio-Oligocene Bhuban sandstone of the Bhuban Formation, Surma Group, around Kolasib in the northwestern section of Mizoram with the help of petrographic and geochemical analyses. Identification of detrital grains and mineral modes in thin section was carried out using LeicaDM4500 P polarizing microscope equipped with Leica DFC420 camera and Leica Image Analysis software (LAS- v4.6). A Gazzi-Dickinson point counting method was employed during modal analysis. Geochemical analyses include major-minor oxides, trace elements and REEs. Results of petrographic and geochemical analyses were plotted in various binary and ternary discrimination diagrams to find out the geological history of the rocks. Detailed petrographic examination indicates that the detrital quartz grains dominate the framework mineral, which was followed by rock fragments and feldspars. The classification indicated lithic to sub-lithic arenite of moderate to poorly sorted, fine- to very fine grains. The petrographic analysis eventually confirmed mineralogical and textural immaturity. Based on the petrographic and geochemical studies, rocks of the study area are derived from mixed sources ranging from igneous to metamorphic rocks and recycled sedimentary rocks, dominated by felsic igneous and low rank metamorphic sources, which are deposited under sub-humid climatic conditions in the geological past.

INTRODUCTION

The geological setup of Mizoram evolved during the late Tertiary Period owing to tectonic activities between the Indian plate and the Burmese Plate that brought about the present state of highly deformed geological structure (Ganguli, 1975; Nandy, 2017). As such, the region is geologically young and immature, and structurally very unstable due to high attitudes of the sedimentary beds. The tectonic framework of the region is very complex due to the subduction process, which is found to be active till today (Steckler et al., 2016). The age of rocks of Mizoram as a whole is only Oligocene to Recent alluvium, which is considered to be very young in terms of geological age**.** Several researchers have conducted numerous studies to elucidate sedimentary provenance with the help of petrographic analysis (Armstrong Altrin et al., 2009; Blatt et al., 1980; Girty et al., 1996; Bracciali et al., 2007; Shinjana et al., 2014; Srivastava and Pandey, 2011; Hauhnar et al., 2021). Recent research attempting to determine classification and provenance of sandstones from different parts of Mizoram include Chenkual et al. (2010), Lalmuankimi et al. (2011), Lalnunmawia and Lalhlimpuii (2014), Lalnunmawia et al. (2016, 2020-a,2020 b, 2021), Lalduhawma and Kumar (2014), Zoramthara et al. (2015), Bharali et al. (2017); Hauhnar et al. (2018), Hussain and Bharali (2019), Laltluanpuii et al. (2019) and Hauhnar et al. (2021). The present work deals with petrographic analysis of Mio-Oligocene sandstone of

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the Bhuban Formation, Surma Group, exposed around Kolasib town in Mizoram, to understand the provenance of the sandstone.

The analysis of major oxides (such as SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, and TiO_2) provides valuable insights into several aspects of sediment derivation and geological history. Major element geochemistry of sandstones is crucial for rock classification and nomenclature. The major element data are pivotal in constructing variation diagrams, which allow geochemical processes to be deduced.

STUDY AREA

Kolasib is the district capital of Kolasib District of Mizoram, which is located in the northwestern part of Mizoram, India. The geological formations in the entire district comprise mainly sandstone, siltstone and shale belonging to the Surma Group and Tipam Group, with a total thickness of about 560m. The study area is covered within the Survey of India Toposheet No. 83D/12 and falls within the coordinates of latitudes 24°15'N to 24°12'N and longitudes of 92°40'E to 93°41'E. Field studies of the area revealed the occurrence of pockets of calcareous sandstones besides the above major lithological components. The geological and location map of the study area is given in Fig. 1.

MATERIALS AND METHODS

Extensive geological fieldwork was carried out in the study area. From different locations of the study area, such as Rengtekawn, Zero point and Kolasib town, 30 sandstone samples were collected, among them 24 were selected for detailed analysis (17 from Kualmawi Quarry to Kolasib designated as RK, 5 from Rengtekawn to Zero Point designated as RB and 4 from the heart of Kolasib town designated as K). Out of these, 24 representative sandstones were prepared into thin sections using Petro-thin with a thickness of. 0.03 mm. Identification of detrital components of the rocks and modal analysis were carried out using a Leica DM2700-P Polarization Microscope equipped with motorized stepping stage, PetrogLite, image analysis software and microphotographic imaging system, which is installed at the Department of Geology, Mizoram University. During modal analysis, the Gazzi-Dickinson method (cf. Ingersoll et al., 1984) was followed. A minimum of 300 counts for each sample was taken for identification and textural classifications. The details of the laboratory analytical procedure are available in Roy et al. (2007). Sedimentological software used for data processing and plotting is OriginPro 9.0 32-bit software.

The analysis of major/minor oxides was done using Philips model PW2440 MagiX PRO wavelength dispersive X-ray Fluorescence spectrometry (WD-XRF) equipped with an automatic sample changer and software Super Q 3.0, installed at Wadia Institute of Himalayan Geology, Dehradun. The sandstones were manually powdered into a 200 ASTM mesh size. Pressed pellets were prepared using the powdered sandstone samples with the help of boric acid in collapsible aluminium cups, which were pressed at a pressure of 25 tonnes in two cycles (5 sec each). The pressed pellets were then analyzed using WD-XRF. In geochemical analysis of trace elements and REE, 0.05 g of powdered sandstone samples were put in a Savillex. An acid mixture of HF and HNO_3 in the ratio 7:3 was added. The Savillex vessels were closed and kept on a hot plate at 150 °C for 48 hrs. After 48 hrs, 1 to 2 drops of $HClO_4$ were added to each vessel and evaporated to near dryness. The remaining residues were dissolved by adding 10 ml of 1:1 HNO_3. After all the residues were dissolved, the sandstone samples were again heated on a hot plate for

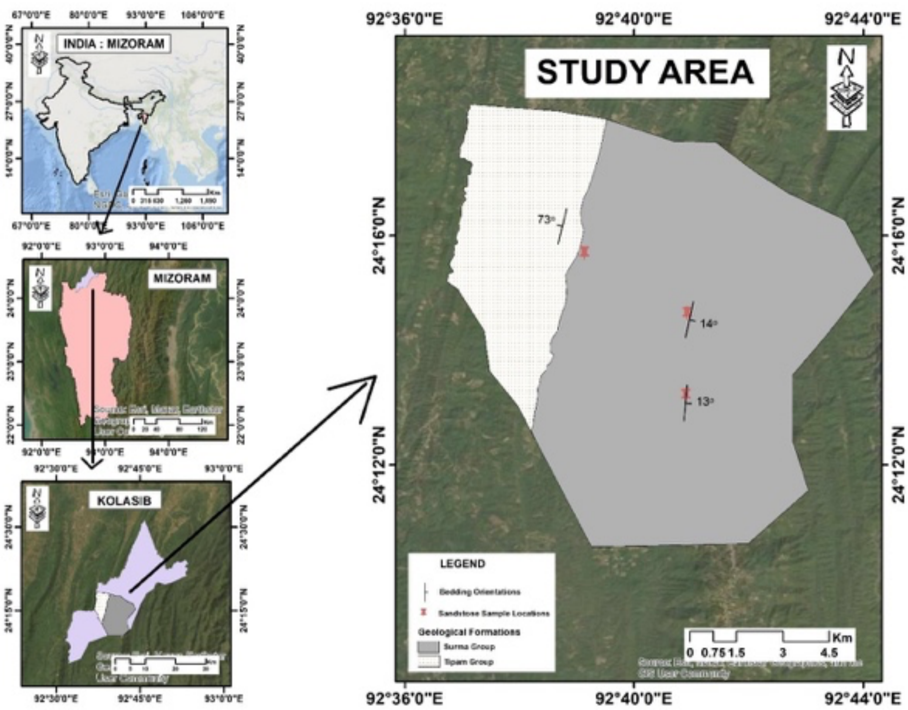

Fig.1. Geological map of the Study Area

40 min at 80 °C to dissolve all suspended particles and then transferred into a 250 ml standard flask. 10 ml of 1:1 HNO_3 and Rhodium (Rh) solution was added again to the standard flask with Millipore water. Here, Rhodium (Rh) solution is used as an internal standard. Finally, 5 ml was taken out from a 250 ml solution of the sandstone samples and the volume was made into 50 ml with Millipore water and the final solution was stored in Eppendorf tubes for High Resolution-ICPMS analysis. The HR-ICPMS was calibrated with the Chinese geochemical standard GSR-4. In the present study, two standards, i.e., GSR-4: Chinese sandstone standard GSR-4 (Geochemical standard reference for sandstone) after Xeujing et al., 2007 and Upper Continental Crust (UCC) after Rudnick and Gao (2003), values have been used for comparison.

RESULTS

In the present work, 24 sandstone samples were analyzed for petrographic modal analysis and geochemistry. The results of these analyses are shown in Table 1 and Table 2 (a, b and c) respectively.

Table 1: Data of modal analysis of Bhuban Sandstones in and around Kolasib, Mizoram

Sl. No.	Sample No.	Quartz (Total)	Feldspar	Rock Fragments	Sum (Qtot+F+RF)	Total Quartz (Recalculated %)	Feldspar (Recalculated %)	Rock Fragments (Recalculated %)
1	RK - 1	47.3	7.3	44.7	99.3	47.7	7.3	44.9
2	RK - 3	62.6	4.1	32.6	99.2	63.2	4.1	32.7
3	RK - 4	80.2	1.5	18	99.7	80.5	1.5	18
4	RK - 5	79.9	2.7	16.8	99.4	80.3	2.7	16.9
5	RK - 7	70.7	3.4	25.1	99.2	71.3	3.4	25.3
6	RK - 8	68.9	5.1	25.6	99.6	69.2	5.1	25.7
7	RK - 9	68.7	4.6	26.4	99.7	68.9	4.6	26.5
8	RK - 10	69.7	6	24	99.7	69.9	6	24.1
9	RK - 11	60	4	35.3	99.3	60.4	4	35.6
10	RK - 13	66.3	5	26.7	98	67.7	5.1	27.2
11	RK - 14	66.3	7.7	23	97	68.4	7.9	23.7
12	RK - 15	69.8	6.7	23.5	99.9	69.8	6.7	23.5
13	RK - 17	65.6	6.3	28	99.9	65.7	6.3	28
14	RK - 18	62.3	6.7	30	99	62.9	6.7	30.3
15	RK - 19	65.7	5	28.3	99	66.3	5.1	28.6
16	K - 1	64.3	6.7	28.7	99.7	64.5	6.7	28.8
17	K - 2	64.7	7	27.3	99	65.3	7.1	27.6
18	K- 3	66.3	11	21.7	99	67	11.1	21.9
19	K - 4	66.7	9	24.3	100	66.7	9	24.3
20	RB - 2	62.7	9.7	27.3	99.7	62.9	9.7	27.4
21	RB - 3	67.7	9.3	22	99	68.5	9.4	22.2
22	RB - 6	67	7.3	25	99.3	67.5	7.4	25.2
23	RB - 7	64.3	9.3	25.6	99.3	64.8	9.4	25.8
24	RB - 10	65	12.7	22	99.7	65.2	12.7	22.1

Table 2 (a): Table showing Major Oxides in terms of wt.%

Sl. No.	Sample	Na_2O %	MgO %	Al_2O_3 %	SiO_2 %	P_2O_5 %	K_2O %	CaO %	TiO_2 %	MnO %	Fe_2O_3 %
1	K1	0.7	1.9	16.3	62.8	0.2	2.9	0.4	0.8	0.1	6.5
2	K2	0.8	1.7	15.7	64.7	0.2	2.8	0.2	0.8	0.0	5.8
3	K3	1.7	2.1	12.9	70.9	0.1	2.3	0.7	0.6	0.0	4.1
4	K4	1.7	1.7	13.7	68.6	0.1	2.5	0.4	0.7	0.1	4.5
5	RB2	1.1	1.6	14.0	71.3	0.1	2.8	0.3	0.7	0.0	4.3
6	RB3	1.5	2.4	15.2	65.0	0.1	3.1	1.8	0.8	0.1	5.7
7	RB6	1.5	2.2	14.7	66.5	0.1	3.0	1.0	0.8	0.1	5.8
8	RB7	1.1	2.0	14.8	67.8	0.1	2.9	0.4	0.7	0.0	4.8
9	RB10	1.6	2.1	12.7	69.5	0.1	2.6	0.3	0.7	0.1	6.8
10	RK1	1.5	2.2	12.9	68.8	0.1	2.7	1.0	0.8	0.1	5.7
11	RK3	1.5	2.9	14.0	65.7	0.1	3.0	1.2	0.7	0.1	6.2
12	RK4	1.5	2.7	13.7	66.5	0.1	2.9	1.4	0.7	0.1	6.0
13	RK5	1.5	2.6	13.4	67.2	0.1	2.9	1.4	0.7	0.1	6.1
14	RK7	1.0	1.1	10.9	76.7	0.1	2.0	0.2	0.5	0.1	3.3
15	RK8	0.8	2.0	17.2	61.1	0.1	3.2	0.2	0.8	0.5	6.8
16	RK9	1.3	2.1	14.9	66.9	0.1	2.8	0.3	0.7	0.1	5.4
17	RK10	1.6	2.5	13.8	66.8	0.1	2.8	1.1	0.8	0.1	6.2
18	RK11	1.2	2.0	14.9	67.0	0.1	2.7	0.3	0.7	0.0	5.0
19	RK13	1.5	2.3	13.6	67.8	0.1	2.8	1.4	0.8	0.1	6.2
20	RK14	1.6	2.3	14.5	67.2	0.1	2.9	0.5	0.8	0.1	6.2
21	RK15	1.1	1.7	13.1	70.1	0.1	2.4	0.4	0.6	0.1	4.9
22	RK17	1.2	3.0	14.3	61.0	0.1	3.0	4.2	0.7	0.1	5.8
23	RK18	1.3	2.3	13.4	69.6	0.1	2.8	1.0	0.7	0.1	4.9
24	RK19	0.8	2.2	17.7	62.2	0.1	3.4	0.2	0.8	0.1	5.9

Table 2 (b): Table showing trace elements of Bhuban sandstones, Kolasib, in terms of ppm

Sample	Sc	Co	Ni	Cu	Zn	Ga	Pb	Th
K1	12	18	67	20	195	16	15	22
K2	12	18	58	20	169	16	17	20
K3	9	11	41	12	139	13	12	14
K4	8	34	37	33	85	15	14	16
RB2	10	171	40	21	70	15	16	20
RB3	11	64	48	19	73	16	15	18
RB6	9	59	42	39	94	15	15	17
RB7	11	107	59	20	69	16	20	18

RB10	9	20	70	26	88	15	29	15
RK1	11	14	47	13	207	14	13	19
RK3	10	16	81	19	136	16	15	16
RK4	10	16	68	18	272	15	15	17
RK5	10	14	64	18	204	15	14	17
RK7	6	10	45	10	243	11	12	14
RK8	13	20	102	29	263	19	25	17
RK9	12	12	64	17	150	17	14	17
RK10	9	14	48	14	242	16	11	17
RK11	9	11	59	18	129	16	15	17
RK13	9	14	49	18	154	15	16	21
RK14	10	15	55	18	127	16	15	18
RK15	9	11	60	17	213	14	16	17
RK17	11	13	49	19	169	15	16	16
RK18	10	15	49	19	228	16	17	18
RK19	14	15	67	28	182	20	20	18

Table 2(c): Table showing trace elements of Bhuban sandstones, Kolasib, in terms of ppm

Sample	**Rb**	**U**	**Sr**	**Y**	**Zr**	**Nb**	**Ba**	**Cr**	**V**
K1	136	5.18	76	40	387	13	505	213	104
K2	133	3.97	71	37	351	13	582	171	98
K3	97	BDL	84	25	239	11	393	81	70
K4	104	BDL	87	28	242	12	439	74	77
RB2	135	4.04	72	32	372	14	514	148	87
RB3	131	2.99	95	29	208	11	521	78	101
RB6	124	3.14	76	29	250	12	506	68	93
RB7	140	3.40	79	38	228	13	498	141	87
RB10	124	2.17	72	27	204	11	401	62	99
RK1	115	4.93	108	30	334	13	474	144	93
RK3	129	3.46	88	29	218	12	470	154	102
RK4	124	3.39	82	30	234	11	473	138	97
RK5	126	0.98	82	30	235	12	465	130	98
RK7	77	BDL	54	18	179	9	332	106	56
RK8	183	1.32	76	34	206	12	673	167	103
K9	142	2.39	84	33	256	14	488	133	89
RK10	122	4.91	93	29	234	12	485	77	98
RK11	128	2.61	81	34	252	14	533	189	84
RK13	122	4.08	91	32	347	14	494	114	99
K14	127	3.58	79	31	259	13	488	117	100
RK15	109	0.80	80	45	255	10	673	239	78
RK17	122	1.21	120	27	200	10	400	137	95
RK18	128	1.11	78	30	228	13	467	133	83
RK19	183	BDL	78	37	218	14	570	150	110

CLASSIFICATION OF BHUBAN SANDSTONES

Microscopic analysis revealed that the Mio-Oligocene Bhuban sandstones of the study area exhibit very fine- to fine-grained, moderately to poorly sorted and angular to sub-angular grains (Fig. 2 A-D), which are indicative of a low to moderate degree of transportation. The detrital grains are cemented together by ferruginous as well as calcareous cement. The framework grains of the sandstone comprise of monocrystalline and polycrystalline quartz (Q_m and Q_p) varieties, K-feldspars, plagioclase and rock fragments with accessory minerals. Modal analysis (Table 3) of the rock thin sections suggested that quartz dominates the framework grains, constituting an average of 67.02 % of the total framework grains. The basis for identification of quartz was based on the distinguishing properties of quartz itself, such as the presence of undulatory extinction, low relief, first-order birefringence, absence of cleavage and alterations. Monocrystalline undulatory quartz dominates over the polycrystalline quartz variety. The quartz grains show angular to subangular and subrounded shapes. Quartz grains show different variations, such as undulatory and non-undulatory monocrystalline variety (Q_m) and polycrystalline (Q_p) variety, having 2-3 sub-grains and those having more than 3 sub-grains. Suturing and fracturing of quartz grains were observed in some of the sandstone samples. Rock fragments constitute 25.81 % of the total framework grains and consist mostly of metamorphic fragments and uncommonly of chert. Feldspar, having the lowest percentage in terms of abundance, constituted an average of 6.56 % of the total framework grains. The variety of observed feldspars comprises of plagioclase, orthoclase and microcline.

Table 3: Modal Count of petrographic thin sections of Bhuban sandstones (where, Q_{Mu}: monocrystalline undulatory quartz, Q_{Mnu}: monocrystalline non undulatory quartz, Q_P: polycrystalline quartz, $Q_{P2\text{-}3}$: polycrystalline quartz with 2-3 grains per quartz, $Q_{P>3}$: polycrystalline quartz with >3 grains)

Sample No.	Quartz							Feldspar		Rock Fragments	Cement	Micas	Matrix	Chert	Opaque
	Q_{Mu}	Q_{Mnu}	Q_{Mt}	$Q_{P\,2\text{-}3}$	$Q_{P>3}$	Qpt	Total	$P_{Cax/Na}$	F_K						
SAS-1	12.3	21.8		0.8	5.1			4.1	0	6.1	0	13	0.6	5.1	6.6
SAS-3	8.7	29.3		2.2	0.9			1.9	0.4	4.9	0.5	17	19	2.1	4.24
RK - 1	56.7	5.6	62.3	4.7	3	7.7	70	4.3	3	22.67	1.6	2	2.5	1.67	0
RK - 3	47.92	7	54.92	7	0.7	7.7	62.62	3.1	1	32.46	1	2.5	2	1	0
RK - 4	66.62	6	72.62	5.6	2	7.6	80.22	1	0.5	18	2.3	4	2.2	1.05	0.6
RK - 5	66.38	7.9	74.28	4.6	1	5.6	79.88	1.5	1.2	16.85	1	2.5	2.5	1.95	0.7
RK - 7	59.94	5.4	65.34	3.4	2	5.4	70.74	4	1.4	25.08	1.1	1.7	1.9	0.33	0
RK - 8	58.71	4	62.71	3.9	2.3	6.2	68.91	3.2	1.9	25.641	2	1.5	2	1.75	0
RK - 9	61.93	4.5	66.43	2.3	0	2.3	68.73	3.3	1.3	26.384	0.6	1	3.2	0.33	0.3
RK - 10	56.17	5.9	62.07	3.3	4.3	7.6	69.67	5.8	0.2	24	1.2	1.6	1.5	1.8	0
RK - 11	45.6	6.8	52.4	7	0.6	7.6	60	3.7	0.3	35.33	2	1.1	1.9	2	0.3
RK - 13	54	5.43	59.43	6.3	0.6	6.9	66.33	4.7	0.3	26.67	1.3	1.3	2.5	1.95	0
RK - 14	53.63	4.8	58.43	7.6	0.3	7.9	66.33	4.8	2.9	23	0.3	1.1	3.5	1.5	0.5
RK - 15	58.48	6.4	64.88	4.3	0.6	4.9	69.78	3.9	2.8	23.5	0.3	1.5	1.5	2.2	0
RK - 17	59.15	3.9	63.05	2.3	0.3	2.6	65.65	3.7	2.6	28	1	2.5	4	1.8	0.3
RK - 18	54.63	5.1	59.73	2.6	0	2.6	62.33	4.7	2	30	0.4	1	3.3	1.33	0
RK - 19	56	7.07	63.07	2.6	0	2.6	65.67	3.2	1.8	28.33	5.3	2.5	2	0.75	0
K - 1	51.83	6.9	58.73	4	1.6	5.6	64.33	4.5	2.2	28.67	1.3	2.5	2.5	0.75	1.6
K - 2	55.17	4.9	60.07	3.3	1.3	4.6	64.67	3	4	27.33	1.3	3	2.5	1.75	0.3
K- 3	52.53	5.5	58.03	7.3	1	8.3	66.33	6.7	4.3	21.67	0.3	3	2	1.33	0
K - 4	51.17	5.9	57.07	9	0.6	9.6	66.67	4	5	24.33	0.1	2	5	0.75	0
RB - 2	50	4.77	54.77	6.6	1.3	7.9	62.67	4	5.7	27.33	2.3	1.3	2.5	0.33	1.7
RB - 3	55.9	3.87	59.77	6.3	1.6	7.9	67.67	5.3	4	22	0.6	1.3	4.5	0.75	0.75
RB - 6	53.9	4.9	58.8	7.6	0.6	8.2	67	4.3	3	25	1	0.6	4.2	0.33	0.75
RB - 7	50.3	4.03	54.33	9	1	10	64.33	5	4.3	25.65	1	2.6	5.3	0.75	0.75
RB - 10	54	4.1	58.1	6.3	0.6	6.9	65	7	5.7	22	1.3	2.3	2.7	1	0

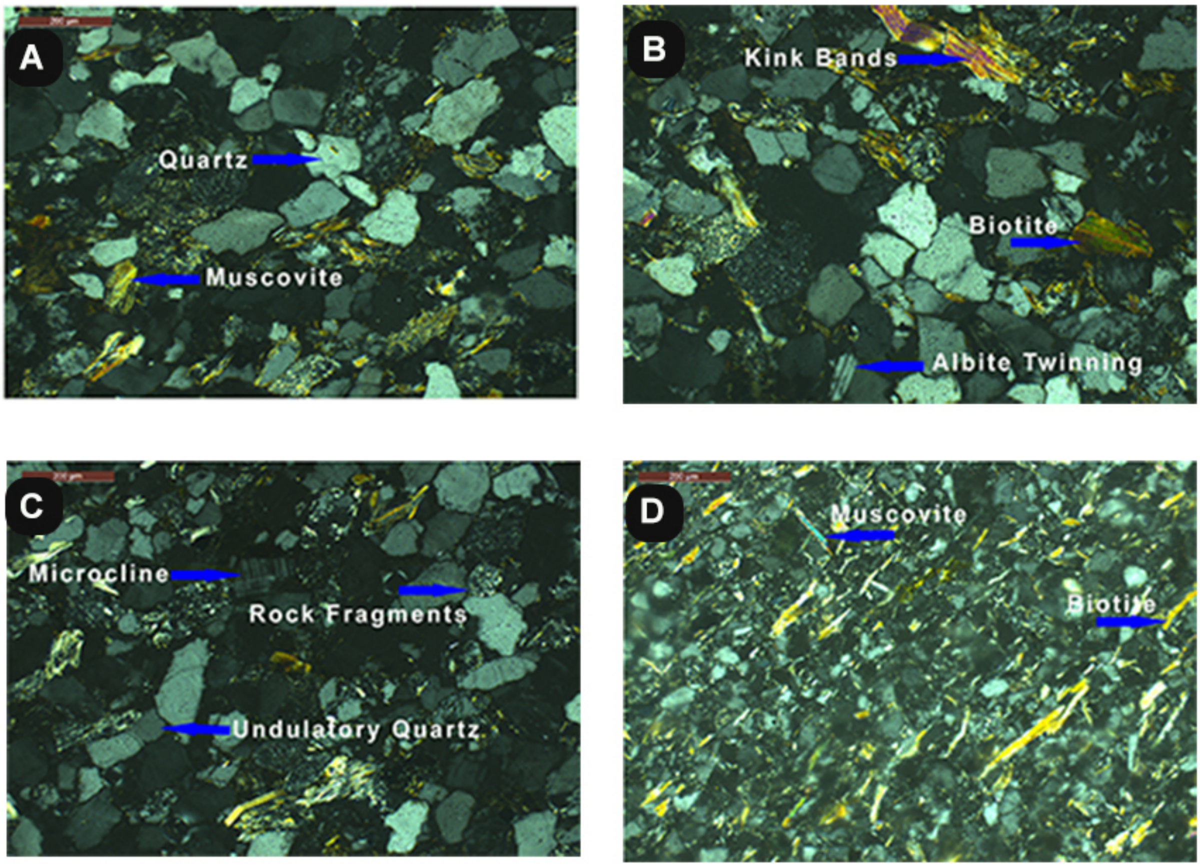

Fig. 2. Thin section photomicrograph of Bhuban sandstones, Kolasib district, Mizoram

The grains are mainly angular with a few sub-angular shapes. Plagioclase prevails over other feldspar varieties and was distinguished from others by its characteristic lamellar twinning. Microcline and orthoclase rarely occurred in the collected sandstone samples.

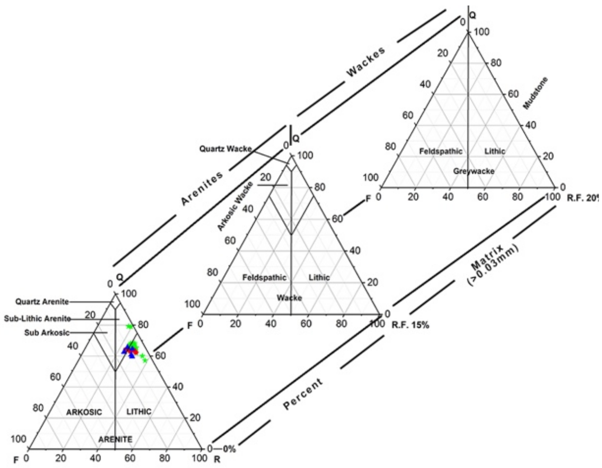

Fig. 3. Classification of Bhuban Sandstone of Kolasib District, Mizoram, India (after Pettijohn et al., 1972)

The trends of percentages among the detrital grains in the sandstone do not deviate much, although slight variations were observed. The predominance of detrital quartz grains was observed in all the sandstone samples collected from different beds of sandstones of the study area, followed by rock fragments and feldspar being the least dominant grain. Detrital framework grains such as

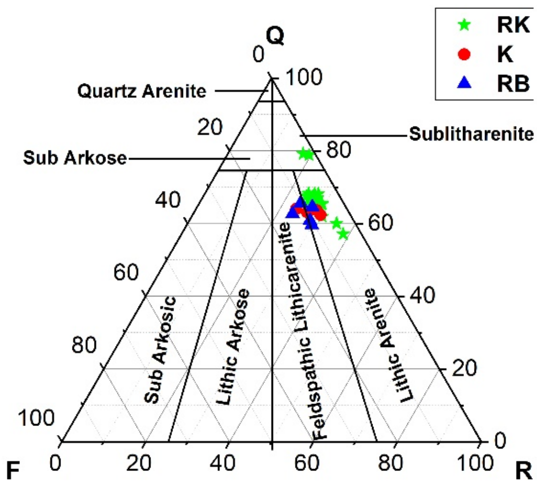

Fig. 4. QFR diagram for Classification of Bhuban Sandstone of Kolasib District, Mizoram, India (after Folk, 1980) biotite and muscovite having kink band structure were commonly observed, with a few occurrences of cherts and opaque minerals. Among all the detrital materials, special interest was given to detrital grains of quartz, feldspar and rock fragments as they constituted the elemental parameters in the classification of sandstones, the determination of source rocks and the tectono-provenance of the sandstones.

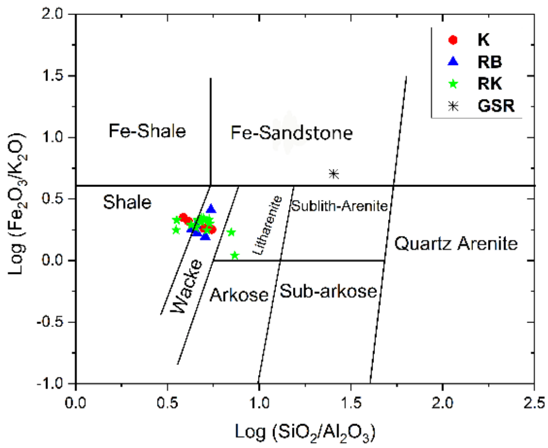

Fig. 5. Log $SiO_2Al_2O_3$ vs $Fe_2O_3K_2O$ after Herron (1988)

Petrographic data were utilized for the purpose of sandstone classification of the investigated rocks using Pettijohn et al. (1972) and Folk (1980), as shown in Fig. 3 and Fig. 4, respectively. These schemes of classification indicate that the Mio-Oligocene sandstones of the Bhuban Formation indicate that the sandstone samples are somewhat dispersed equally, straddling both the sub-lithic arenite and lithic arenite fields without much variation.

Geochemical classification based on Herron (1988) diagram (Fig. 5) shows that the sandstones mainly fall into the wacke category, with some sandstone samples plotting in the litharenite and shale fields. Based on this observation, several of the sandstone samples can be geochemically classified as predominantly wackes and shales, with minor representation of litharenite (Fig. 5), when plotted on Herron (1988) chemical classification diagram (Fe_2O_3/K_2O vs. SiO_2/Al_2O_3). While, according to the geochemical classification based on Pettijohn et al. (1972), the samples are distributed across the litharenite and arkosic fields (Fig. 6).

GEOCHEMICAL COMPOSITION

The major and trace element composition of 24 sandstone samples from the Bhuban Formation in the Kolasib district is presented in Table 2 (a) and (b). The major element data reveal that the Bhuban sandstones contain a moderately elevated level of SiO_2 (average 67.14 wt. %) in comparison to the Upper Continental Crust (UCC). Additionally, SiO_2 (67.14 wt. %), Al_2O_3 (14.26%), and MgO (2.14%) are present in higher concentrations than in the UCC, while elements like Fe_2O_3, K_2O, and Na_2O are noticeably lower. The generally low levels of Na_2O and CaO suggest a limited amount of plagioclase in the samples. In contrast, the relatively high average K_2O/Na_2O ratio (2.32) points to a considerable presence of K-feldspar.

The average concentrations of oxides constituting more than 1 wt. % include SiO_2 (67.14 wt. %), Al_2O_3 (14.26 wt. %), Fe_2O_3 (5.53 wt. %), K_2O (2.79 wt. %), MgO (2.14 wt. %) and Na_2O (1.30 wt. %). Oxides having concentrations between 1 and 0.1 wt. % includes TiO_2 (0.72 wt. %), CaO (0.85 wt. %) and P_2O_5 (0.11wt. %). Manganese oxide (MnO) makes up the least amount, accounting for less than 0.08 wt. % (0.04 wt. %). The loss on ignition (LOI) varies from 2.96–6.97 wt. % with a mean of 4.88 wt. %. The weight percentage concentrations of SiO_2, Fe_2O_3 and TiO_2 are higher than those of the upper continental crust (UCC), whilst other oxides show significantly lower values relative to the UCC (Taylor and McLennan, 1985). The concentration of K_2O/Na_2O (2.32) is higher than that of the UCC, which is 0.86. Clastic sedimentary rocks typically consist of varying compositions of aluminous clay (Al_2O_3) and quartz (SiO_2). Sediments with higher quartz concentration are plotted towards the apex of SiO_2, where Al_2O_3 concentration is the lowest. Sediments with high concentrations of clay minerals like muscovite, illite and chlorite are plotted towards the peak of Al_2O_3, where SiO_2 is the least (Raza et al., 2012). Bhuban sandstones exhibit a positive correlation (r = 0.40) trend in the diagram of SiO_2 vs Al_2O_3. The investigated sandstones comprise a sediment mixture made up of quartz and K-feldspar with accessory minerals, like mica and lithic fragments.

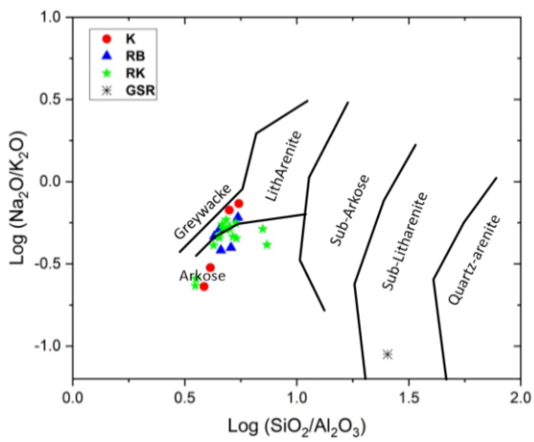

Fig. 6. Log $SiO_2Al_2O_3$ vs Na_2OK_2O after Pettijohn (1972)

This further implies moderate weathering in the provenance, leading to limited concentrations of Al_2O_3 in the depositional environment. To assess the influence of

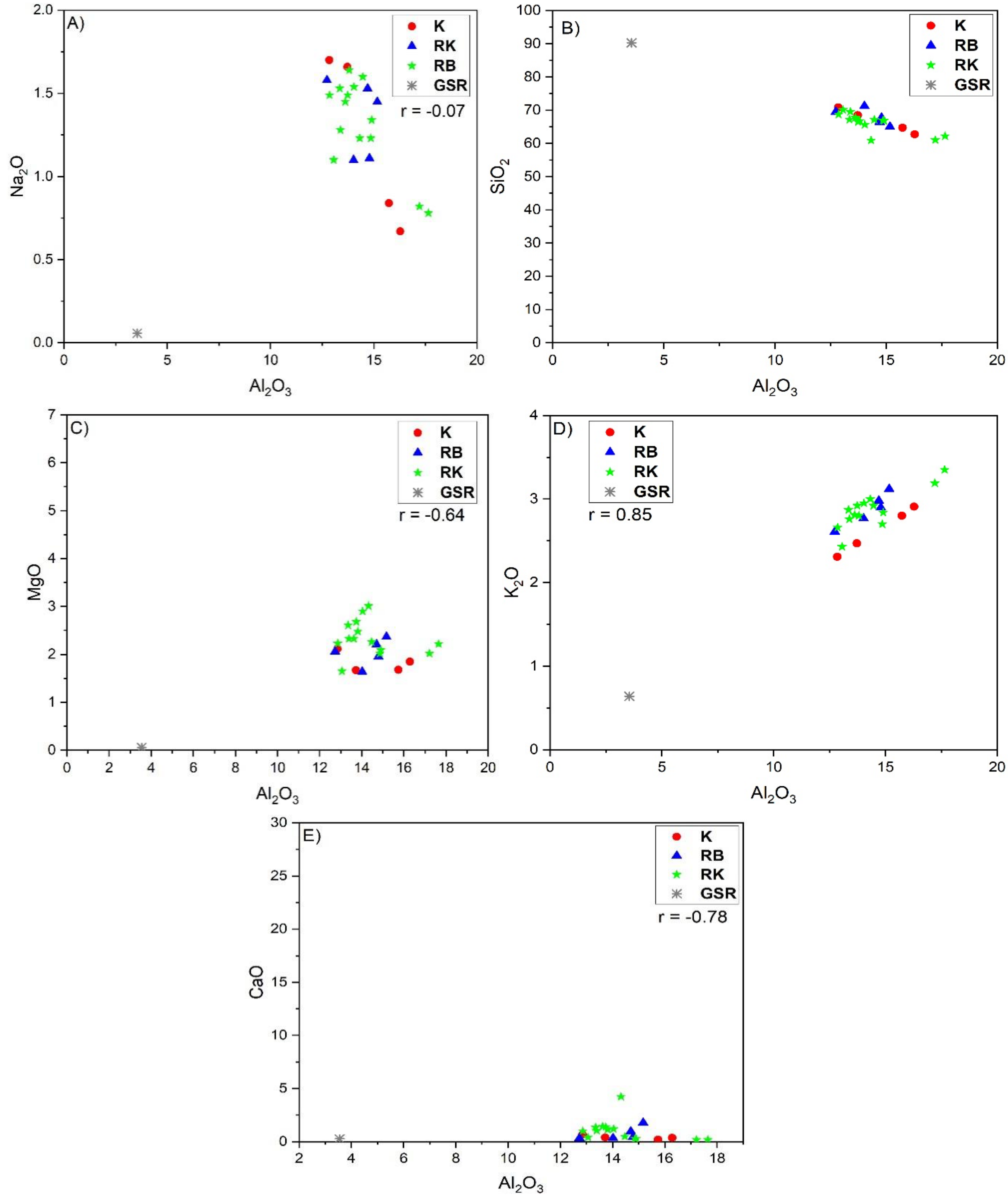

Fig. 7 (A-E). Correlation between various Major Oxides of Bhuban Sandstones, where RK designates sandstone samples taken from Kualmawi Quarry to Kolasib, RB designates sandstone samples taken from Rengtekawn to Zero Point and K designates sandstone samples taken from Kolasib Town. GSR designates the Geochemical Standard Reference of sandstone and UCC designates the Upper Continental Crust

clay minerals on the overall major elemental variations in the Bhuban sandstones, major oxides such as SiO_2, CaO, K_2O, MgO and Na_2O are plotted against Al_2O_3 using the Harker variation diagram and correlation coefficient values are presented in Fig. 7 (A-E). Binary plots of Al_2O_3 with MgO exhibit negative correlations (r = - 0.64). Positive correlation of oxides like Al_2O_3 and K_2O (r = 0.85) indicates the control of clay minerals such as illite and/or the presence of alkali feldspar in the sandstone samples, which is supported by the presence of orthoclase in the sediments.

A positive relationship between K_2O and Al_2O_3 indicates that K-bearing minerals significantly affect the distribution of aluminium, suggesting that the relative concentrations of these elements are largely governed by the presence of clay minerals (McLennan et al., 1993).

The contents of large ion lithophile elements (LILE) such as Sr (average: 84.24 ppm) and Ba (average: 481.88 ppm) are much lower compared to the Upper Continental Crust (UCC), whereas U (average: 2.98 ppm), Rb (average: 123.88 ppm), and Th (average: 11.28 ppm) are comparatively higher than UCC values.

comparable to that of other rare earth elements (REE) even though it is not highlyenriched (McLennan, 1989). The negative correlation of Sr with Al_2O_3, along with the depletion of CaO, indicates that calcic plagioclase is being removed during diagenetic processes, leading to a reduced abundance of this mineral — a feature also observed in thin section analyses. The positive correlation of Nb suggests an association of both elements with the same mineral phase, likely clay minerals (Fig. 8 (F). A positive

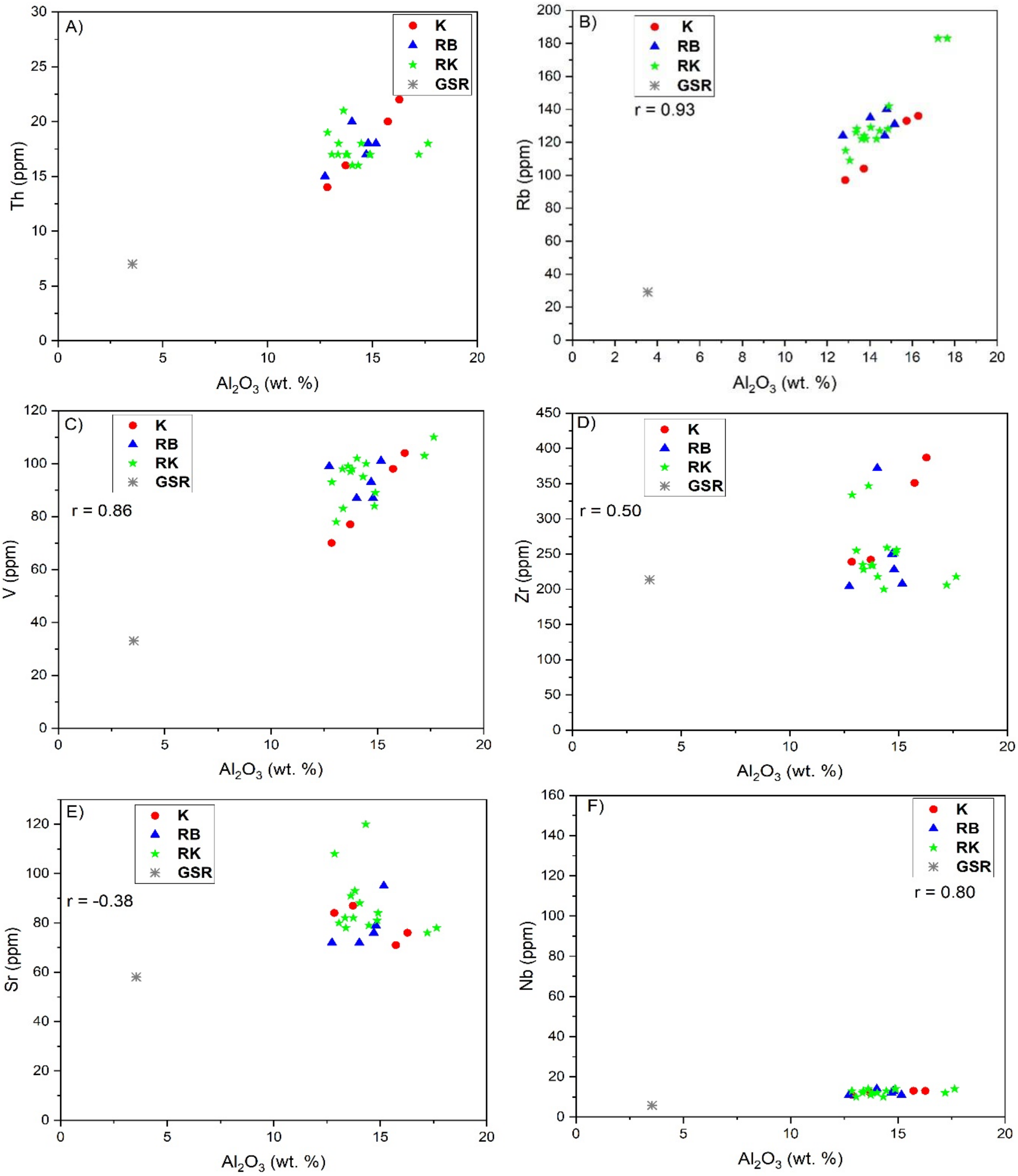

Fig. 8(A-F). Correlation of Al_2O_3 with respect to various trace elements (Pearson, 1896)

Rb (r = 0.01) and Zr (r = 0.93) exhibit positive correlations with Al_2O_3, while Sr (r = –0.38) exhibits a weak negative correlation with Al_2O_3. Sr retains a provenance signature correlation between Rb and K_2O is an indicator of the presence of K-bearing clay minerals such as illite and kaolinite.

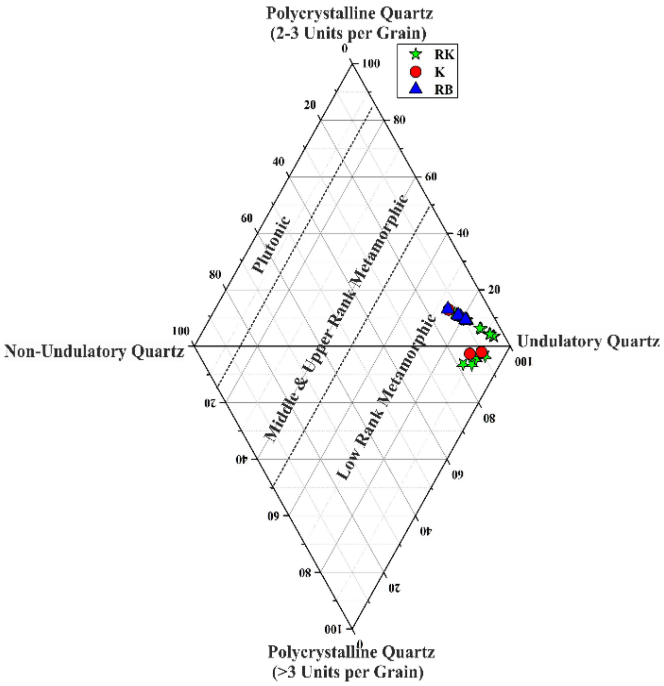

Fig. 9. Diamond Plot for Provenance after Basu et al. (1975)

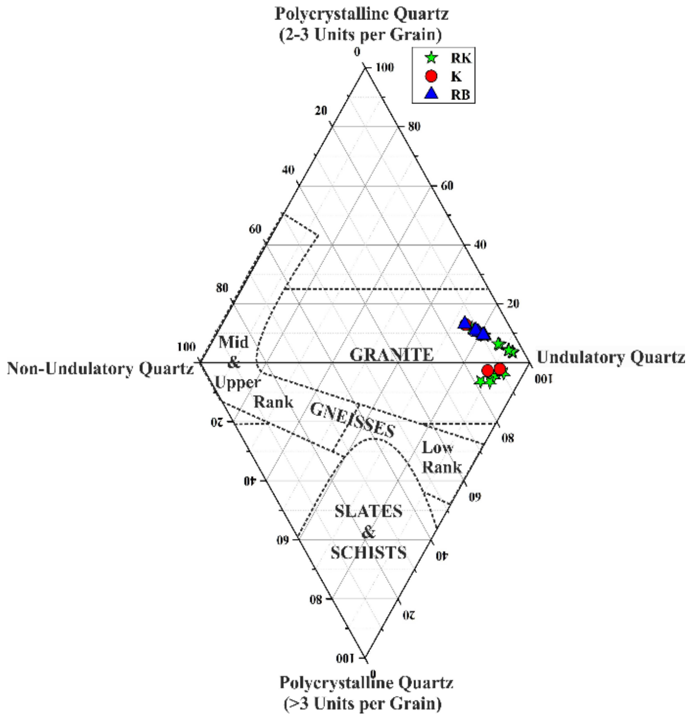

Fig. 10. Diamond Plot for Provenance after Tortosa et al. (1991)

PROVENANCE

The significance of various petrographic analyses is that typical detrital grains could be indicative of source rock provenance. The common occurrences of monocrystalline quartz are primarily indicative of plutonic and recycled sedimentary sources, while polycrystalline quartz is indicative of recrystallized metamorphic sources. The sandstones, being dominated by high percentages of monocrystalline quartz, are a clear indication that the sandstones were mostly derived from a low rank metamorphic source (Basu et al., 1975) as shown in Fig. 9.

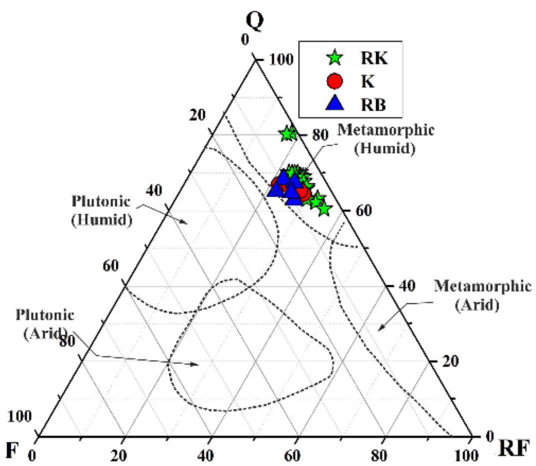

Fig. 11. Ternary diagram showing source rock provenance and environment of deposition after Suttner et al. (1981)

The characteristic undulatory extinction and inter-crystalline suturing in monocrystalline and polycrystalline quartz are also significant indicators of metamorphic source (Blatt and Christie, 1963).

The abundance of micas like biotite and muscovite also implies metamorphic schist as one of the source rocks in the provenance. The modal data of the various quartz varieties, such as non-undulatory quartz, undulatory quartz, polycrystalline quartz (2-3 units per quartz grain) and polycrystalline quartz (>3 units per grain) are systematically recorded and utilized for the determination of lithological provenance by plotting in a double triangular diagram after Basu et al. (1975). This diamond diagram discloses that detrital grains of the sandstones are derived from low rank metamorphic provenance. The modified diamond diagram of Basu et al. (1975) prepared by Tortosa et al. (1991) was also employed to determine the provenance. The diagram revealed that the sediments were found to be derived from a granitic source as well (Fig. 10). These observations are suggestive of mixed source rocks for the investigated sandstones.

The combined parameter to find out source rock provenance and environment of deposition is offered by the ternary plot of Suttner et al. (1981) as shown in Fig. 11. The diagram suggests that the detrital grains are derived from metamorphic provenance deposited under sub-humid climatic conditions. This can be attributed to the high percentage of quartz with lesser amounts of rock fragments and feldspar minerals.

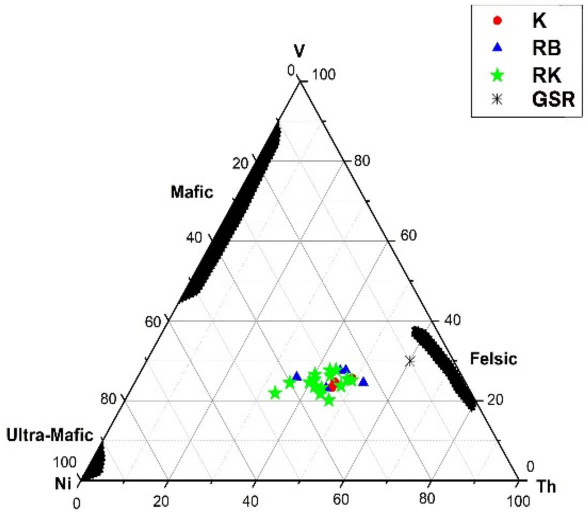

Fig. 12. Provenance plot of V-Ni-Th X 10 after Bracciali et al. (2007)

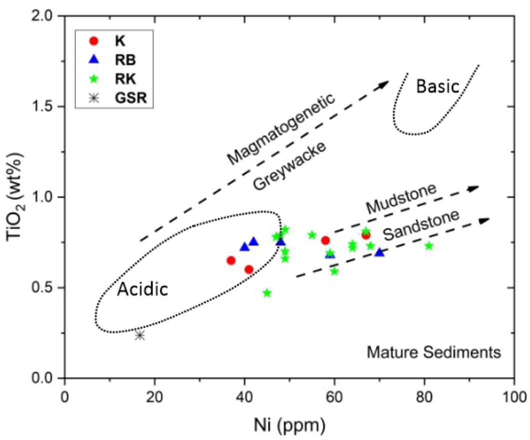

Fig. 13. Provenance plot of Ni Vs TiO_2 after Floyd et al. (1989)

Geochemical compositions of clastic sediments have been used to determine the source area by various workers (Roser and Korsch, 1988; McLennan et al., 1993; Pandey and Parcha, 2017; Hussain and Bharali, 2019). Ternary plot after Bracciali et al. (2007) shows that the Bhuban sandstones of the area are rich in Th and Ni at the same time depleted in V, thus resulting in the concentration of the samples near the felsic field (Fig. 12). Plotting of the samples of the study area using bivariate plot of TiO_2 Vs Ni after Floyd et al. (1989) represents a mildly acidic as source (Fig. 13). Based on the ratio of TiO_2/Zr (Hayashi et al. 1997) the Bhuban sandstone of the study area depicts felsic source (Fig. 14). The ternary plot of La-Th-Sc proposed by Jinliang and Xin (2008) represent intermixing of source sediments essentially for sandstones by intermixing between Granite and Granodiorite (Fig. 15).

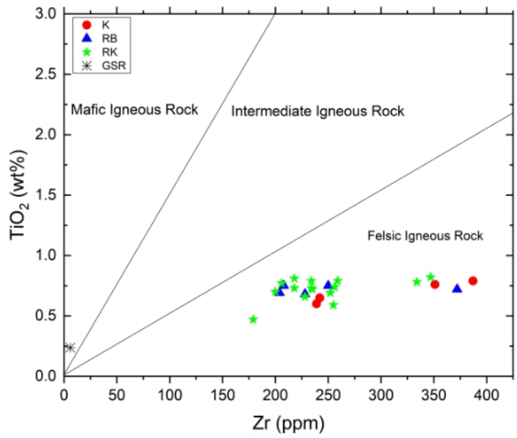

Fig. 14. Zr Vs TiO_2 bivariate provenance plot after Hayashi et al. (1997)

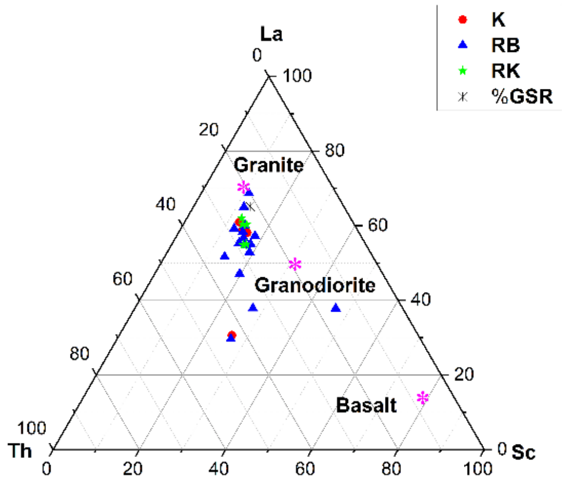

Fig. 15. Ternary provenance plot of La-Th-Sc after Jinliang and Xin (2008)

WEATHERING AND RECYCLING

The Chemical Index of Alteration (CIA), introduced by Nesbitt and Young (1982), is one of the most commonly applied methods for quantitatively assessing the extent of chemical weathering experienced by rocks in the source area of clastic sediments, and has been utilized in this study. This index is calculated from the molar proportions of oxides by the formula: CIA = $[(Al_2O_3/(Al_2O_3+CaO^*+Na_2O+K_2O)]$ X 100, where Cao* is the amount of CaO in fraction only. The average shale has a CIA value ranging from 52 to 77, which indicates a moderately weathered source. Highly weathered rocks, which produce residual clays like kaolinite and gibbsite-rich shales, typically exhibit CIA values approaching 100, whereas unweathered granitic or upper continental crustal rocks have values around 50 (Fedo et al., 1996). To determine the paleo-weathering of the source area, alkali and alkaline earth elements are used (Nesbitt and Young, 1982; Armstrong-Altrin et al., 2013; Pandey and Parcha, 2017; Madhavaraju et al., 2018). In the present work, the chemical index of alteration (CIA) after Nesbitt and Young (1982) and the plagioclase index of alteration (PIA) after Fedo et al. (1996) are employed and the values are shown in Table 4. The investigated sandstones have an average CIA value of 81.59, which indicates intense chemical weathering in the source area (Nesbitt and Young, 1982; Fedo et al., 1995).

Table 4: Geochemical weathering parameters of Bhuban Sandstones (where, CIA: Chemical Index of Alteration after Nesbitt and Young, 1982; PIA: Plagioclase Index of Alteration after Fedo et al., 1995; CIW: Chemical Index of Weathering after Harnois, 1988; WIP: Weathering Index of Parker after Parker, 1970; ICV: Index of Chemical Variability after Cox et al., 1995; where, GSR-4: Chinese Sandstone Standard from Xeujing et al., 2007 and UCC: Upper continental crust after Rudnick and Gao, 2003, 2005)

Litho-Unit	Sample	CIA	PIA	CIW	WIP	ICV
Bhuban Sandstones	K1	76.78	88.09	90.17	36.93	0.81
	K2	76.72	87.92	90.02	36.67	0.77
	K3	66.29	71.96	76.11	42.87	0.90
	K4	69.11	76.16	79.87	41.90	0.84
	RB2	72.10	81.95	85.24	39.05	0.78
	RB3	62.77	67.72	72.96	50.93	1.00
	RB6	66.20	72.83	77.45	47.98	0.97
	RB7	71.95	81.61	84.92	41.39	0.81
	RB10	67.94	75.69	80.01	43.23	1.11
	RK1	64.27	70.04	75.08	45.02	1.08
	RK3	63.97	69.70	74.86	50.30	1.11
	RK4	62.80	68.00	73.40	49.47	1.11
	RK5	62.25	67.25	72.79	49.14	1.14
	RK7	72.85	81.91	84.91	29.23	0.74
	RK8	77.04	89.14	91.12	40.68	0.83
	RK9	71.96	81.24	84.51	42.97	0.86
	RK10	63.96	69.40	74.40	48.62	1.09
	RK11	73.02	82.29	85.26	40.60	0.80
	RK13	62.87	67.89	73.13	47.32	1.11
	RK14	68.40	76.25	80.42	47.03	0.99
	RK15	71.65	80.44	83.74	36.35	0.85
	RK17	52.46	53.22	59.54	55.92	1.26
	RK18	65.72	72.24	77.01	44.31	0.97
	RK19	77.12	89.70	91.64	42.22	0.76
	Average	81.59	90.72	95.43	50.33	1.14
Standard	GSR-4	73.26	82.58	85.48	6.83	1.28
	UCC	50.17	50.22	55.81	69.91	1.19

The A-CN-K triangular diagram (after Nesbitt and Young, 1982) in Fig. 16 shows that the composition of Al_2O_3 is comparatively higher and the sandstones trend in a direction parallel to the A-CN. Moreover, illitic composition of the clay reveals moderate weathering, suggesting that chemical weathering was not extreme, with a relatively short degree of transportation and possible felsic source rock. In terms of CIA, the studied samples suggest moderate weathering. The PIA values of the Bhuban sandstones show an average of 82.58, which is higher than that of the UCC, clearly indicating that the sediments have undergone intense chemical weathering in the source rock.

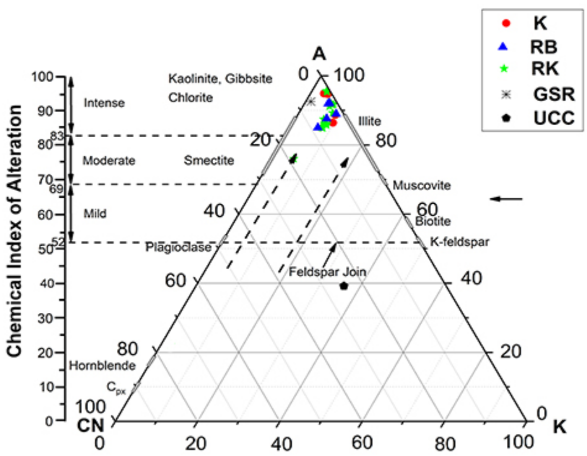

Fig 16. A-CN-K plot after Nesbitt and Young (1982) for Bhuban Sandstone

CONCLUSION

The sandstones of the Mio-Oligocene Bhuban Formation of the Surma Group are fine to very fine-grained, moderately to poorly sorted of litharenite to feldspathic litharenite. The detrital components are primarily of quartz, rock fragments and feldspar and slightly micaceous in nature. Observance of kink bands in the rock fragments indicates the compaction of the rocks due to compressional forces. The majority of the studied sandstone samples belong to the wacke field, with a few samples falling in the field of litharenite and shale. Provenance studies using geochemical data indicate the source rock to be of felsic origin. The negative correlation of Sr with Al_2O_3, along with the depletion of CaO, indicates the removal of calcic plagioclase. The detrital sediments of the study area are derived from mixed source rocks ranging from igneous to metamorphic rocks and recycled sedimentary rocks, dominated by felsic igneous and low rank metamorphic sources, which were deposited under sub-humid climatic conditions in the geological past. The Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA) and Chemical Index of Weathering (CIW) suggest intense weathering conditions in the source area.

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CONFLICT OF INTEREST:

The authors declare that there is no conflict of interest.

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