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Geochemistry of sandstone-mudstone suites of the Tipam Sandstone Formation, Surma Basin, Bangladesh

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Abstract

The geochemical study of the Tipam Sandstone Formation in the Surma Basin of the Bengal Basin reveals the tectonic setting, provenance in relation to composition, weathering history in source area and the climatic condition during deposition. The geochemical characteristics as shown by $CaO-Na_2O-K_2O$, Fe_2O_3-$MgO-TiO_2$ and $CaO-Na_2O-K_2O$ plots indicate with higher ratios of SiO_2/Al_2O_3, K_2O/Na_2O. This characteristics and Chemical Index of Alteration (CIA) highly support that the source rocks were dominated by old upper crustal granite and quartz monzonite. They also include recycled sedimentary rocks of the old continental foundation of active tectonic setting that subjected intensive weathering. Harker variation diagrams show positive correlation of K_2O and Na_2O, and negative correlation of CaO, Fe_2O_3 and MgO with SiO_2. This phenomenon indicates that the concentration of K_2O and Na_2O increase with increasing SiO_2 whereas CaO, Fe_2O_3 and MgO decrease with increasing SiO_2. This supports the derivation of the sediment from felsic igneous rocks i.e. from granitic rocks. SiO_2 content versus K_2O/Na_2O as well as SiO_2/Al_2O_3 versus K_2O/Na_2O diagrams, K_2O/Na_2O ratio and $(Fe_2O_3+MgO)-Na_2O-K_2O$ triangular plot indicate that the sediments were deposited in a basin along passive margin tectonic setting.

Key words: Geochemistry, Tipam Sandstone Formation, Surma basin, Provenance, Paleoclimate

Introduction

The present work has been made to focus on the nature of the source terrane, provenance, tectonic setting of depositional basin, paleoclimate and weathering history of the Tipam Sandstone Formation in the Surma Basin, Bangladesh on the basis of geochemical investigations of sandstone-mudstone suites. Provenance is critical for deciphering the tectonic history of ancient basins and has been applied to both terrane analysis and basin analysis. Provenance is also an important factor for finding petroleum reservoirs system within sedimentary basins.

The studied area is bounded within latitudes from 24°83′ to 24°88′N and longitudes from 92°07′ to 92°11′ E (Fig. 1) and is situated at about 30 km northeast of Sylhet town. The area includes Lalakhal Tea garden, Kamrangi, Nichinpur, Putikhal and Dighral areas of Jaintiapur upazila, which are in the northeastern part of Sylhet district, Bangladesh. The rocks of the Tipam Sandstone Formation are mainly composed of sandstones with intermittently alternation of sandstones and shales. On the basis of lithology, these rocks have been divided into the Lower Tipam Sandstone, the Middle Tipam Sandstone and the Upper Tipam Sandstone. The Lower Tipam Sandstone consists of yellowish brown to dark brown sandstone and occasionally of reddish brown conglomeratic sandstone, siltstone, mudstone and clay. Mudstone and clay, minor lithology are composed of gray, occasionally grayish black, massive clay or mudstone. The Middle Tipam Sandstone consists of grey colored parallel laminated silty shale with alternation of grayish white ripple laminated siltstone and fine-grained sandstone. The Upper Tipam Sandstone is composed of medium to very fine-grained sandstones with parallel laminated to ripple cross-laminated siltstone, laminated silty shale and unsullied shale. The thickness of the Late Mesozic and Cenozoic strata in the Surma Basin ranges from about 13 to 17 km (Evans, 1964; Hiller and Elahi, 1984) and much of these strata (Formations) are included Neogene age (Table 1).

The geochemistry of the sandstone and shale is a powerful tool to provide information about the provenance, tectonic setting, paleoclimate and weathering history. Recent and ancient detritus have been used to infer them by many workers (Condie, 1976; Le Maitre, 1976; Potter, 1978; Blatt *et al.*, 1980;

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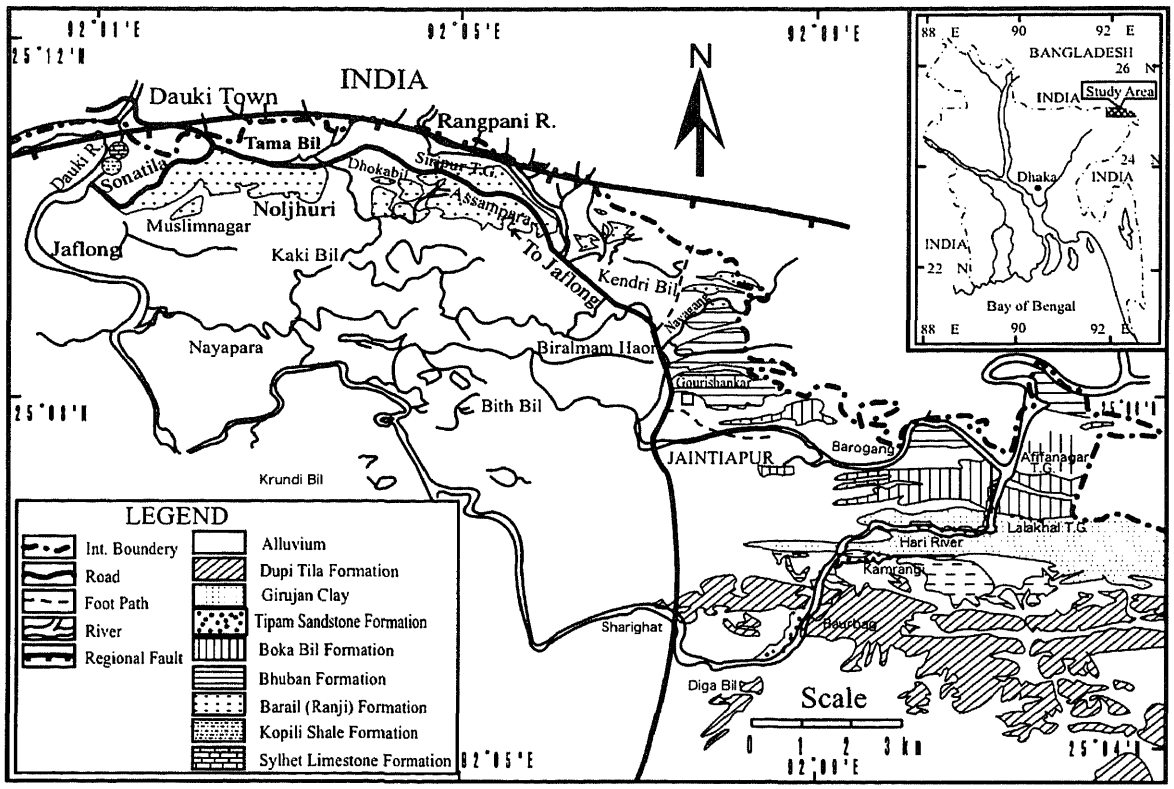

Fig. 1 Geological map of the study area showing the exposed Tertiary rock sequence.

Table 1. The stratigraphic succession of the Sylhet Trough (after Khan *et al.*, 1988).

Age	Group	Formation
Plio-Pleistocene	Dihing Group Dupi Tila Group	Upper Lower
Pliocene	Tipam Group	Girujan Clay Tipam Sandstone
Pliocene Miocene	Surma Group	Boka Bil Bhuban
Oligocene	Barail Group	Renji Jenam Laisong
Eocene	Jaintia Group	Kopili Sylhet Limestone Cherra.

Bhatia, 1983; Hiscott, 1984; Bhatia and Crook, 1986; Roser and Korsch, 1986, 1988; Suttner and Dutta, 1986; Nesbitt and Young, 1984; McLennan *et al.*, 1993). Roser and Korsch (1986) used the diagrams of SiO_2 vs. K_2O/Na_2O and SiO_2/Al_2O_3 vs. K_2O/Na_2O of published data from sandstone-mudstone suites to discriminate passive margin (PM), active continental margin (ACM), oceanic island arc (ARC) settings.

Geologic Setting

Tectonically the studied area in the Sylhet Trough, a sub-basin of the Bengal Basin in northeastern Bangladesh, is a complex province of the Bengal Basin. The Bengal basin lies on the eastern side of the Indian subcontinent and occupies most of Bangladesh and west Bengal of India as well as part of the Bay of Bengal (Alam, 1989). The Shillong Plateau bound

this Trough on the north, on the east and southeast by the Chittagong Tripura fold belt of the Indo-Burman ranges and on the west by the Indian Shield Platform, which is open to the south and southwest to the main part of the Bengal Basin (Johnson and Alam, 1991). The Surma Basin had its origin in the collision of India with Eurasia and Burma, building the extensive Himalayan and Indo-Burman ranges and thereby loading the lithosphere to form flanked sedimentary basins (Uddin and Lundberg, 1998). Johnson and Alam (1991) proposed that the Sylhet Trough has undergone a complex evolution recording the transition from a passive, rifted continental margin to a foreland basin on the margins of two mobile belts. The Sylhet Trough formed a portion of the foreland basin of the Himalaya orogen and the Indo-Burman Ranges (active continental margin). The Dauki fault system with huge vertical displacements represents the contact between the Surma Basin and Shillong Plateau (Hiller and Elahi, 1984; Johnson and Alam, 1991; Reimann, 1993). Johnson and Alam (1991) suggested that the Tipam Sandstone Formation has been formed in a bedload-dominated (probably braided) fluvial system. The garin size, shape, facies sequence, association, paleocurrent pattern and paleoslope indicates single source of sediment and the sediments deposited in a heavily loaded, low sinous and high sloped (16°–22°) braided river system (Roy *et al.*, 2006).

Sample and analytical methods

A number of sandstone and shale samples were collected from the Tipam Sandstone Formation along the Hari River section, in the Surma Basin, Bangladesh. Fresh 15 sandstone and 8 shale samples were randomly selected for the analysis of major element composition (SiO_2, Al_2O_3, K_2O, Na_2O, CaO, Fe_2O_3, MgO, P_2O_5, TiO_2 and MnO wt%). These samples were collected from Lower Tipam (LTS), Middle Tipam (MTS) and Upper Tipam Sandstone (UTS) Formation: ten samples of Lower Tipam, five samples of Middle Tipam and eight samples of Upper Tipam. First the samples were dried at 110°–120°C. Then dried samples were heated for two hours at 950°C endothermic peak temperature. Moisture loss was determined in the Soil Research Development Institute (SRDI), Rajshahi, Bangladesh. Then the crushed samples were used to determine the major element composition by XRF. Analyses were carried out with standard curves based on International Rock Standards (model Philips-2000) in the Glass and Ceramic Division of Bangladesh Council of Science and Industrial Research (BCSIR), Dhaka, Bangladesh.

Results

1. Major element geochemistry of sandstone

The major element compositions of 15 representative sandstone samples were selected for analyses (Table 2). Correlation between the elements is given in Table 3. The SiO_2 content varies from 40.1 to 75.8 wt% with an average of 67.9 wt%. It shows negative correlation with Fe_2O_3, TiO_2, CaO, MgO, MnO and ZrO_2 contents but significant with CaO (r = –0.93) and MnO (r = –0.83), whereas positive correlation exists with Al_2O_3, Na_2O and K_2O contents. Al_2O_3 varies from 9.0 to 21.4 wt%, with an average of 15.1 wt%. It shows high positive correlation only with K_2O (r = 0.854) and negative correlation significantly with CaO (r = –0.65) and MgO (r = –0.67). The studied sandstones contain small amount of Na_2O (0.1 to1.0%), with an average of 0.6 wt%. It shows negative correlation with K_2O (r = –0.57). The maximum value of K_2O is 3.2 wt% and the minimum is 1.9 wt% with the average value of 2.3 wt%. It shows positive correlation with SiO_2, Al_2O_3 and TiO_2. The total iron, expressed in Fe_2O_3, attains maximum value of 11.8 wt% and minimum of 3.5 wt% with an average of 5.4 wt%. The TiO_2 content ranges from 0.5 to 0.9 wt% with average of 0.6 wt%. It shows negative correlation with MnO (r = –0.85). CaO content varies from 0.3 to 36.4 wt% with average contents of 5.0 wt%. It shows positive correlation with MgO (r = 0.60) and MnO (r = 0.88). The MgO content varies from 0.4 to 2.6 wt% with an average of 1.4 wt%. It shows negative correlation with SiO_2 and Al_2O_3. MnO occurs in minor amounts, and shows maximum value of 1.0 wt% and minimum value of 0.1 wt% with an average content of MnO is 0.4 wt%.

2. Major element geochemistry of shale

Eight representative shale samples were selected for the major element analyses (Table 4). Correlation between the elements is given in Table 5. The SiO_2 content varies from 27.8 to 63.9 wt% with an average of 55.7 wt%. It shows positive correlation with Al_2O_3, Na_2O, K_2O and ZrO_2. Well correlations are with Al_2O_3 (r = 0.96), Na_2O (r = 0.86), K_2O (r = 0.90) and TiO_2 (r = 0.89). The Al_2O_3 content varies from 7.4 to 20.6 wt% with an average of 16.8 wt%. It shows high positive correlation with K_2O (r = 0.98), Na_2O (r = 0.86) and TiO_2 (r = 0.96) whereas negative correlation exists with CaO (r = –0.88). Low Na_2O content (0.2 to 0.6 wt%, with an average of 0.6 wt%) occurs in shale. It shows positive correlation with K_2O (r = 0.84). K_2O content varies from 1.2 to 3.8 wt% with an average of 2.9 wt%. It shows high positive correlation with TiO_2 (r = –0.96). The total iron, expressed in Fe_2O_3, attains

Table 2. Chemical composition (wt%) of sandstone, Tipam Sandstone Formation.

SAMPLE NO	SiO_2	Al_2O_3	Na_2O	K_2O	Fe_2O_3	TiO_2	CaO	MgO	MnO	P_2O_5	BaO	ZrO_2	Loss	Total
LTS-1	69.781	21.444	0.115	2.736	3.721	0.647	0.333	0.386	0.085	-	0.132	0.018	0.60	99.998
LTS-2	71.747	19.112	0.138	2.881	3.615	0.553	0.350	0.403	-	-	-	-	1.20	99.999
LTS-3	73.833	15.426	0.819	2.276	3.860	0.496	1.096	0.646	0.077	0.154	0.111	-	1.20	99.999
LTS-4	72.145	13.503	0.804	1.928	7.244	0.649	1.505	1.092	0.287	0.417	-	0.025	0.40	99.999
LTS-5	63.695	16.999	0.387	2.536	11.753	0.677	0.688	0.610	0.242	0.226	0.159	-	0.20	98.172
LTS-6	40.101	9.030	0.508	1.905	5.657	0.611	36.346	2.614	1.029	-	-	-	0.80	98.606
LTS-7	75.770	12.081	0.925	2.015	3.829	0.475	1.762	2.114	-	0.202	-	0.022	0.20	99.4
LTS-8	59.348	11.175	0.774	1.926	5.212	0.926	15.695	2.272	0.409	0.226	-	0.038	0.40	98.401
LTS-9	73.318	14.158	0.758	2.004	5.940	0.568	1.305	1.210	0.198	-	-	-	1.20	100.704
LTS-10	71.336	14.266	1.038	2.066	4.307	0.588	1.642	1.550	-	0.234	-	0.020	0.80	97.857
MTS-1	71.738	15.209	0.914	2.243	4.901	0.601	1.562	1.439	0.244	0.190	0.125	0.032	0.80	99.998
UTS-1	74.581	13.247	1.003	2.254	3.529	0.605	1.335	1.204	-	0.205	0.206	0.020	0.60	98.789
UTS-2	67.355	18.409	0.681	3.188	5.453	0.835	0.817	2.124	0.089	0.110	0.134	-	0.80	100
UTS-4	62.413	15.343	0.557	2.395	5.115	0.585	10.229	1.504	0.830	-	-	0.024	1.00	100
UTS-7	71.201	16.585	0.248	2.503	4.741	0.547	0.978	1.929	-	-	-	0.019	1.20	100.001

Table 3. Correlation matrix of different oxides of sandstone, Tipam Sandstone Formation.

	SiO_2	Al_2O_3	Na_2O	K_2O	Fe_2O_3	TiO_2	CaO	MgO	MnO	P_2O_5	BaO	ZrO_2
SiO_2	1.000	.435	.241	.185	-.275	-.354	-.937**	-.502	-.839**	.041	.083	-.594
Al_2O_3		1.000	-.599*	.854	-.026	-.016	-.650**	-.667**	-.665*	-.421	-.438	-.519
Na_2O			1.000	-.569*	-.136	-.002	-.051	.330	-.101	0.37	.233	3.14
K_2O				1.000	-.032	.164	-.415	-.341	-.438	-.622	-.193	-.530
Fe_2O_3					1.000	.283	.038	-.106	.008	.318	.110	.413
TiO_2						1.000	.213	.301	-.085	-.042	.096	.725*
CaO							1.000	.608*	.870*	.063	.160	.713
MgO								1.000	.605	-.233	.055	.461
MnO									1.000	.565	.530	.132
P_2O_5										1.000	5.35	-0.81
BaO											1.000	-.452
ZrO_2												1.000

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

the maximum value of 8.1 wt% and the minimum value of the 5.3 wt% with an average of 6.6 wt%. The TiO_2 content ranges from 0.6 to 1.1 wt% with average of 0.9 wt% for the shale samples. It shows negative correlation with MgO (r = –0.82). CaO varies from 0.8 to 44.7 wt%, with an average of 8.9 wt% of the shale samples. It shows high positive correlation with MnO (r = 0.99) and P_2O_5 (r = 0.90). The MgO content varies from 2.5 to 16.3 wt% with an average of 5.3 wt%. MnO shows low contents with maximum value of 2.0 wt% and minimum 0.1 wt% with an average of 0.6 wt%.

Discussion

1. Provenance

In general, geochemical approaches are equally applicable to coarse and fine-grained sedimentary rocks. This is not compatible with petrographical approaches where provenance studies for fine-grained as well as very coarse-grained sediments is difficult (McLennan *et al.*, 1993). There is growing evidence that even intimately associated sands and muds may be derived from quite different sources with different sedimentary histories and so both require their evaluation (e.g., McLennan *et al.*, 1990). Major

Table 4. Chemical composition (wt %) of shale, Tipam Sandstone Formation.

SAMPLE NO	SiO_2	Al_2O_3	Na_2O	K_2O	Fe_2O_3	TiO_2	CaO	MgO	MnO	P_2O_5	BaO	ZrO_2	Loss	Total
MTS-2	51.336	16.091	0.299	2.615	6.410	0.979	17.173	3.054	0.970	0.273	-	-	0.80	100
MTS-3	61.863	20.609	0.505	3.788	6.572	1.042	0.917	2.489	0.072	0.189	0.133	0.022	1.80	100.001
MTS-4	62.212	19.152	0.596	3.031	6.268	1.009	2.964	2.994	-	0.216	0.134	0.021	1.20	99.768
MTS-5	63.919	19.076	0.505	3.371	5.761	1.051	1.006	2.505	-	0.151	-	0.026	1.60	98.631
UTS-3	63.149	19.055	0.614	3.433	6.464	1.046	1.458	2.805	0.078	0.164	0.168	0.017	1.40	99.799
UTS-5	61.585	19.716	0.570	3.433	8.097	1.030	0.831	3.115	0.088	0.129	0.139	0.021	1.00	99.754
UTS-6	53.390	13.416	0.346	2.003	7.719	0.708	1.898	16.253	0.094	0.139	0.108	-	3.40	98.846
UTS-8	27.804	7.400	0.230	1.229	5.338	0.589	44.740	8.913	1.984	0.326	-	-	1.00	99.553

Table 5. Correlation matrix of different oxides of shale, Tipam Sandstones Formation.

	SiO_2	Al_2O_3	Na_2O	K_2O	Fe_2O_3	TiO_2	CaO	MgO	MnO	P_2O_5	BaO	ZrO_2
SiO_2	1.000	.958**	.857**	.908**	.407	.880**	-.964**	-.483	-.950**	-.798	.821	.303
Al_2O_3		1.000	8.59**	.798**	.329	.959**	-.871**	-.676	-.836*	-.659	.642	.085
Na_2O			1.000	.846**	.267	.794*	-.776*	-.576	-.794	-.667	.849	-.830
K_2O				1.000	.253	.954**	-.806*	-.730*	-.777	-.626	.685	.026
Fe_2O_3					1.000	.152	-.568	.263	-.766	-.682	-.443	-.333
TiO_2						1.000	-.732*	-.827*	-.666	-.492	.776	.194
CaO							1.000	.240	.995**	.894**	-.214	-.242
MgO								1.000	.128	-.001	-.742	-.488
MnO									1.000	.944**	-.576	-.047
P_2O_5										1.000	.134	-.119
BaO											1.000	-.986*
ZrO_2												1.000

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

element data can provide information on both the provenance composition and the effects of sedimentary processes, such as weathering and sedimentary sorting (McLennan *et al.*, 1993). It is recognized that sediment compositions have characteristics of certain assemblages of igneous/metamorphic/ sedimentary source rocks that have specific styles of sedimentary history (e.g. Dickinson, 1985, 1988). The provenance types do not precisely correspond to those recognized from petrographical approaches but instead provide a different perspective of the plate tectonic association (McLennan *et al.*, 1993). So, bulk chemical composition is one of the major factors in characterizing the provenance types. The analyzed sandstones are characterized by higher ratios of SiO_2/Al_2O_3. The maximum value is obtained from sample LTS-7 (6.3) and the lowest value from sample LTS-1 (3.3), with an average of 4.1. Shale samples are also characterized by higher value of SiO_2 and Al_2O_3 contents are suggestive of decent felsic phases for the provenance. The K_2O/Na_2O also shows high ratios both for sandstone and shale. The maximum values attain for the sandstone sample LTS-1 (27.8) and lowest value in LTS-10 (2.0). The average value of K_2O/Na_2O is 6.5 for sandstone and 6.3 for shale. Chemical Index of Alteration (CIA) values are also calculated for both sandstone and shale samples. CIA has been established as a general guide to the degree of weathering (Nesbitt and Young, 1984), although chemical changes resulting from other processes such as diagenesis and metamorphism have not been fully evaluated. Using molecular proportion CIA is shown as follows; $CIA=Al_2O_3/[Al_2O_3+K_2O+Na_2O+CaO] \times 100$ or abbreviating, $CIA=A/[A+K+N+C]\times 100$. However 3 sandstone samples (LTS-6, LTS-8, and UTS-4) and 2 shale samples (MTS-2, UTS-8) show high values of CaO. In the calculation of CIA for sandstone and shale, CaO is calculated as only residing in silicates minerals. But the values of CaO for those 5 samples are much higher concentration due to the post

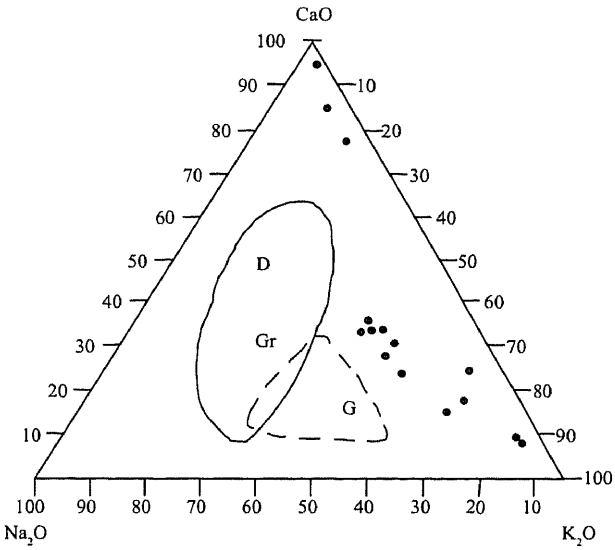

Fig. 2 $CaO-Na_2O-K_2O$ plots for the sandstones of the Tipam Sandstone Formation. Boundaries are after Le Maitre (1976). (D = dacite, Gr = granodiorite, G = granite).

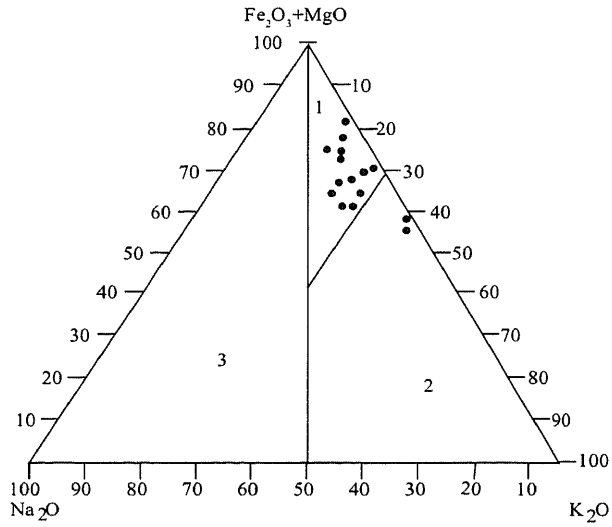

Fig. 3 $(Fe_2O_3+MgO)-Na_2O-K_2O$ plots showing the relation of major oxide for the sandstones of the Tipam Sandstone Formation. Boundaries are after Blatt *et al.* (1980). (1 = ferromagnesian-potassic sandstone, 2 = potassic sandstone, 3 = sodic sandstone).

depositional changes within the sediments. So, these 5 samples are to be avoided. Therefore the CIA value for the sandstone ranges from 71 to 87 with an average of 78, whereas those for shale from 74.4 to 80.3 with an average of 78. Usually the CIA values increase due to the increase in the degree of weathering. So, the value of CIA for sandstone and shale is moderate to higher.

Therefore, higher value of SiO_2/Al_2O_3, K_2O/Na_2O and CIA of sandstone and shale reflects a dominance of upper crustal granitic sources (e.g., Singo granite, Uganda from Nagudi *et al.*, 2003) and a relatively severe weathering (and recycling) history (McLennan *et al.*, 1993). So, the provenance is regarded as old upper continental crust (OUC). They include old stable cratons and the old continental foundation of active tectonic settings that contains recycled sedimentary and metasedimentary rocks. This type of provenance component constitutes old igneous, metamorphic and sedimentary terranes that have been influenced by intracrustal geochemical fractionation which include process of both intracrustal partial melting and or crystal fractionation (McLennan *et al.*, 1993). The geochemistry of sediments derived from these terranes are normally characterized by relatively consistent compositions, reflecting a broad and well mixed provenance (Potter, 1978) and the greater level of recycling expected for such environments (Veizer and Jansen, 1979, 1985).

Triangular plot of CaO, Na_2O and K_2O of the sandstone for focusing source rocks may be granite in nature (after Le Maitre, 1976) (Fig. 2), because most data are concentrated in the vicinity of the granite field. But three samples placed on the top of the diagram due to the high amount of CaO in the sediment caused by post depositional changes within the sediments. According to Blatt *et al.* (1980) $(Fe_2O_3+MgO)-Na_2O-K_2O$ triangular plot reveals that the sandstone samples are largely restricted to the ferromagnesian-potassic sandstone (Fig. 3). In the variation diagram $Fe_2O_3-MgO-TiO_2$ (after Condie, 1967), the geochemical data of sandstones fall near the fields of granite and quartz-monzonite (Fig. 4). Another approaches (Condie, 1967) for plotting the geochemical data of sandstones on the variation diagram $(CaO-Na_2O-K_2O)$ indicates that most of the source rock may be granite and monzonite (Fig. 5). Only three data show the affinity near the basalt and andesitic zone, due to the increase of $CaCO_3$ within the sediment due to post depositional changes.

Harker variation diagrams of sandstone samples (Fig. 6) show that the positive correlation exists between SiO_2 with K_2O, Na_2O and Al_2O_3 whereas negative correlation exists between SiO_2 with CaO, Fe_2O_3 and MgO. So the concentration of K_2O and Na_2O increases with increasing SiO_2 whereas the concentration of CaO, Fe_2O_3 and MgO decreases with increasing SiO_2 concentration. It seems that the derivation of the sediment from the felsic igneous fields i.e. from the granite rock, because SiO_2 contents

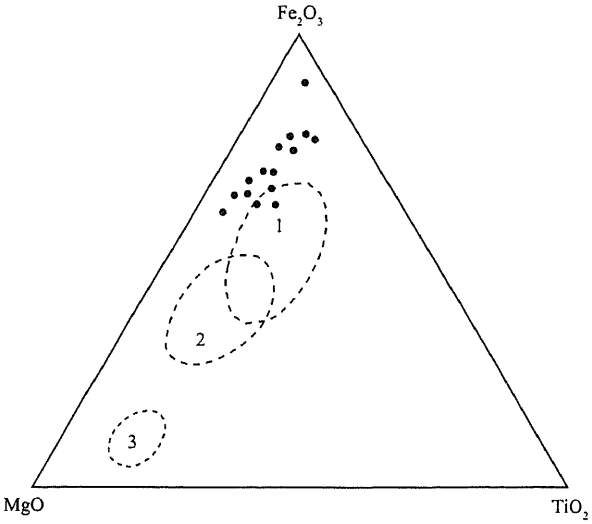

Fig. 4 Fe_2O_3-MgO-TiO_2 diagram (after Condie, 1967) showing the plots of sandstones of Tipam Sandstone Formation. (1. granite and quartz-monzonite, 2. quartz diorite and granodiorite, 3. basalt).

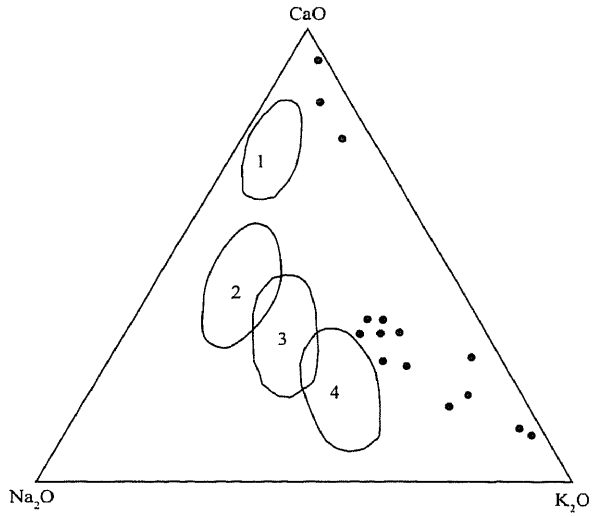

Fig. 5 CaO-Na_2O-K_2O diagram (after Condie, 1967) showing the plots of sandstones of Tipam Sandstone Formation. (1. basalt and andesite, 2. quartz diorite, 3. granodiorite, 4. granite and monzonite).

are relatively high (mostly 60–76%).

From above observations, the geochemical characteristics reveal that higher values of SiO_2/Al_2O_3, K_2O/Na_2O and CIA of sandstone and shale indicate the dominance of old upper crustal granitic source, including recycled sedimentary rocks of the old continental foundation of active tectonic settings. Triangular plots of (CaO-Na_2O-K_2O), (Fe_2O_3+MgO)-Na_2O-K_2O, (Fe_2O_3-MgO-TiO_2) and (CaO-Na_2O-K_2O) highly recommend that the source rocks are granite and quartz-monzonite and the samples are largely restricted to the ferromagnesian-potassic sandstone.

2. Tectonic setting of depositional basin

The tectonic setting of the depositional basin of the Tipam Sandstone Formation is formulated on the basis of major oxides of sandstone and shale by plotting different chemical variables on different bivariate diagrams. Roser and Korsch (1986, 1988) utilized mudstone in their work, and developed discrimination to cover the full range of grain size from sand to mud. In this study, geochemical data (major oxides) of both sandstone and associated shale (mudstone) have been applied to discriminate the tectonic setting of the depositional basin. Sandstone and mudstone of different tectonic setting are characterized by different chemical characteristics (major oxides). The different chemical parameters are used to evaluate the tectonic setting of the depositional basin. Major element geochemistry gives clues to the provenance types as well as weathering condition, both of which are controlled by the tectonic setting of the basin. Influence of diagenesis also depends on the tectonic setting of the area (Siever, 1979).

SiO_2 content versus K_2O/Na_2O (Fig. 7) as well as SiO_2/Al_2O_3 versus K_2O/Na_2O (Fig. 8) of sandstones and shales are used to discriminate tectonic setting (Roser and Korsch, 1986). Most of the data fall into the passive margin (PM) field. In the former diagram only three data fall within the active continental margin (ACM) boundary, being due to the higher amount of $CaCO_3$, the post depositional changes within the sediments. LTS-6 sample is to be avoided due to its very high content of $CaCO_3$. In the case of later diagram (Fig. 7), however, all the data of sandstone and shale fall into the passive margin field. According to Roser and Korsch (1986), PM sediments are largely quartz-rich sediments derived from plate interiors or stable continental areas and deposited in intracratonic basin or on passive continental margins. The geochemical characteristics of both sandstones and shales positively support it.

Many authors (Middleton, 1960; Crook, 1974; Maynard *et al.*, 1982; Bhatia, 1983) proposed that if the ratio of K_2O/Na_2O is greater than unity (K_2O/Na_2O > 1), a passive margin tectonic margin is supported for the sediments. Because that the value of K_2O/Na_2O is greater than unity for sandstone samples in this study. The sediment could be deposited in a basin along passive margin tectonic setting, which includes rifted

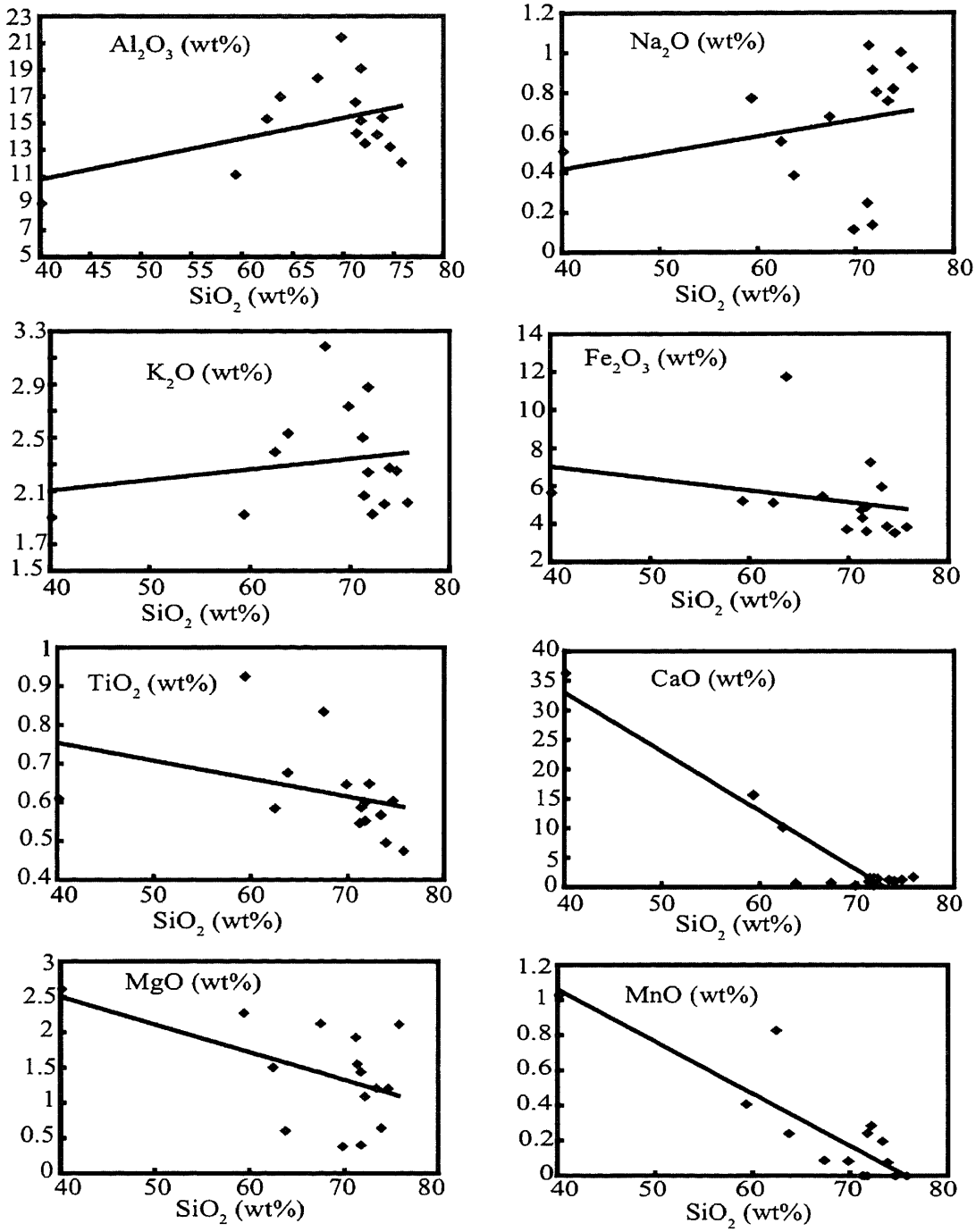

Fig. 6 Harker variation diagram of major elements for Sandstone of Tipam Sandstone Formation.

continental margin, intracratonic and rift bounded basins. Plots of some geochemical parameters in different bivariate diagrams K_2O/Na_2O vs. SiO_2 and SiO_2/Al_2O_3 vs. K_2O/Na_2O (Roser and Korsch, 1986) and K_2O/Na_2O ratio highly supports that the deposition of Tipam Sandstone occurred in a basin along passive continental margin setting (Fig. 7).

3. Paleoclimate and weathering

The effects of variable degrees of weathering in source areas can be important in influencing alkali and alkaline earth element (AE) contents of terrigenous sedimentary rocks (Nesbitt *et al.*, 1980; Schau and Henderson, 1983; Reimer 1985; Granstaff *et al.*, 1986). The degree of chemical weathering is a function of

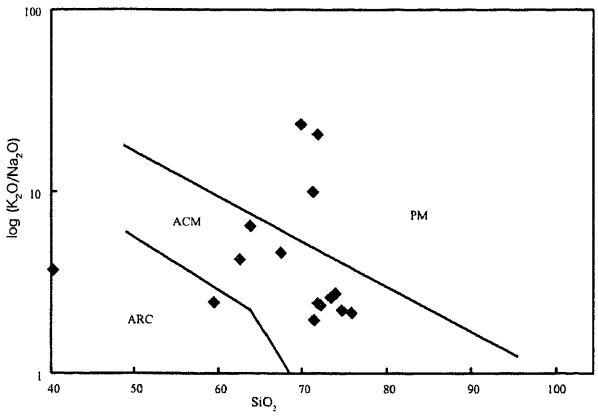

Fig. 7 K_2O/Na_2O-SiO_2 relations of sandstones-mudstones of the Tipam Sandstone Formation. Boundries are after Roser and Korsch (1986). (Abr. PM = passive margin, ACM = active continental margin, ARC = island-arc).

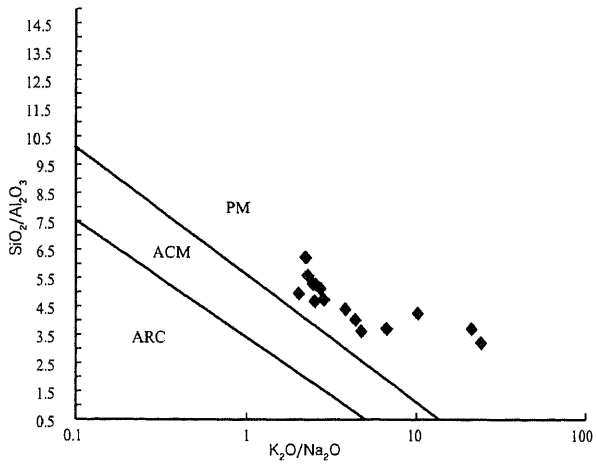

Fig. 8 SiO_2/Al_2O_3-K_2O/Na_2O relations of sandstones-mudstones of the Tipam Sandstone Formation. Boundaries are after Roser and Korsch (1986). (Abr. PM = passive margin, ACM = active continental margin, ARC = island-arc).

climate and erosion rate, the latter of which varies with the rate of tectonic uplift. The bulk chemical changes that take place during weathering have also been used to quantify the weathering history of sedimentary rocks, primarily to understand past climatic conditions (Nesbitt *et al.*, 1980; Nesbitt and Young, 1982, 1984). CIA value have been calculated for sandstone and shale samples. The CIA value for the sandstone ranges from 71 to 87 with an average of 78, whereas the CIA value for shale ranges from 74.4 to 80.3 with an average of 78. The CIA values increases due to the increase in the degree of weathering. Therefore, the value of CIA for sandstone and shale is moderately to highly suggest that the sediments were intense weathered in the source area. High values of SiO_2/Al_2O_3 and K_2O/Na_2O of sandstone and shale also reflect relatively severe weathering (and recycling) history of the Tipam Sandstone Formation (McLennan *et al.*, 1993). This is also suggested by high concentration of TiO_2, which is generally known as immobile species. The maximum concentration of TiO_2 attains for the sample LTS-8 (0.9 wt%) and the minimum concentration for the sample LTS-7 (0.5 wt%). The average concentration of TiO_2 in the sandstone is 0.6 wt%. Therefore, the high concentration of TiO_2 suggests that the sediment were subjected to intensive weathering in the source area. The concentration of Fe_2O_3 in the sandstone sample is comparatively high. The maximum concentration is 11.8 wt% and minimum concentration is 3.5 wt%, with an average value of 5.3 wt%. This high concentration of iron is indicative of oxidation, hydration and leaching processes involved during weathering of the Tipam Sandstone Formation (Schau and Henderson, 1983). Low contents of Na_2O (1 wt%) of sandstone and shale also indicate intensive to moderate weathering of the source rock. The ratios of $SiO_2/(Al_2O_3+K_2O+Na_2O)$ (Suttner and Dutta, 1986) express the climatic condition during the deposition of the sediments in the basin. The plot in SiO_2 vs. $(Al_2O_3+K_2O+Na_2O)$ diagram for the 15 sandstone samples indicates that the sediments deposited in the basin under semi-arid climatic condition (Fig. 9). Because the maximum data clustering in the semi-arid climatic zone instead of humid climatic zone, alumina/kaolinite decomposition and partial feldspar decomposition in the sandstone might occur as a result of decomposition after deposition. The concentration of alumina is relatively high due to the decomposition of feldspar. But it is very much interesting to fit this concept with the upheaval of Himalaya and with Asian monsoon. Because several workers have carried out a lot of works on sedimentology and petrography of Tipam Sandstone (Johnson and Alam, 1991; Roy *et al.*, 2006; Roy, 2003), and they concluded that from facies analysis and mineral association the sediments were deposited under humid to semi-humid climatic condition.

Therefore, extensive mechanical weathering, abundant alumina, high concentration of TiO_2 and iron that preserved in the ferric state, all indicate that the sediments in the source area were subjected by intensive weathering. The depositional conditions were under humid to semi humid climatic nature, because intensive weathering associated with mechanical and chemical disintegration that are related to the high

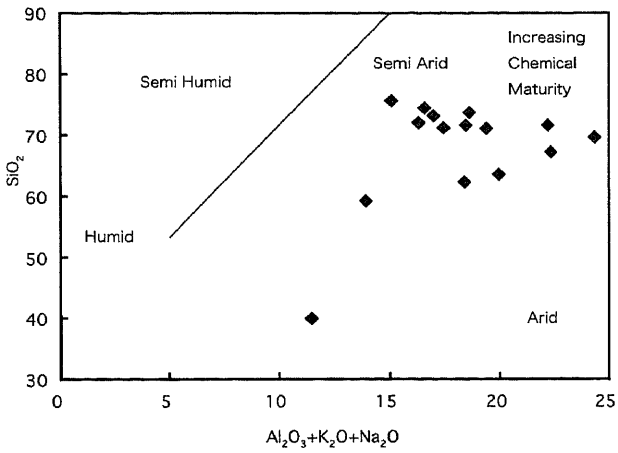

Fig. 9 Bivariate plots of SiO_2 (wt%) vs $Al_2O_3+K_2O+Na_2O$ (wt%) to discriminate climatic condition during the deposition of the Tipam Sandstones (after Suttner and Dutta, 1986).

rainfall, significant tectonic upliftment and high rate of erosion might occur. Those are only possible under humid to semi humid climatic conditions.

Conclusions

The sandstone samples are largely restricted to the ferromagnesian-potassic in nature. Harker variation diagrams support the derivation of sediment from felsic igneous field i.e from granite rock. Some variation diagrams, such as (CaO-Na_2O-K_2O), (Fe_2O_3-MgO-TiO_2) and (CaO-Na_2O-K_2O) along with high values of SiO_2/Al_2O_3, K_2O/Na_2O and CIA highly support that the source rocks were dominated by old upper crustal granite, quartz monzonite, including recycled sedimentary rocks of the old continental foundation of active tectonic settings. SiO_2 versus K_2O/Na_2O as well as SiO_2/Al_2O_3 versus K_2O/Na_2O diagrams of sandstones and shales along with K_2O/Na_2O ratio indicate that most of the sediment deposited in a basin along passive continental margin setting. The value of K_2O/Na_2O for sandstones being greater than unity also supports the tectonic setting. High value of SiO_2/Al_2O_3, K_2O/Na_2O and low value of Na_2O (1%) of sandstone and shale, and abundant alumina, high concentration of TiO_2 and iron that preserved in the ferric state, all suggest relatively severe weathering (and recycling) history of the Tipam Sandstone Formation.

From above observations it may be concluded that the sediments of Tipam Sandstone Formation seem to have been derived from the old upper crustal granite and quartz monzonite including recycled sedimentary rocks of the old continental foundation of the tectonic settings that deposited in a basin along passive continental margin setting. They might be under humid to semi-humid climatic condition due to the severe and intensive weathering (and recycling) history in the source area.

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