Geochemistry of sandstones from the Miocene Surma Group, Bengal Basin, Bangladesh: Implications for Provenance, tectonic setting and weathering

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Twenty six sandstone samples from six wells penetrating the Miocene Surma Group in the Bengal Basin, Bangladesh, were analyzed by lithium metaborate/tetraborate fusion Inductively Coupled Plasma (ICP) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and by petrographic microscope. The framework grains of the Surma Group sandstones are rich in quartz followed by lithic grains, feldspar and mica (predominantly white mica). The sandstones are dominantly quartzolithic and quartzose one in composition with abundant low-grade metamorphic, sedimentary lithics, low feldspars and little volcanic detritus, indicating that the sands were derived from a quartzose recycled orogen province.

The Surma Group sandstones have moderate to high SiO₂ contents (64–85%; on average 77%), TiO₂ concentrations averaging 0.5%, Al₂O₃ contents of about 8.4%, and Fe₂O₃ (total Fe as Fe₂O₃) + MgO content of around 4.5%. Compared to the average sandstone value, the Surma Group sandstones are depleted in CaO (2.36%) and enriched in Al₂O₃, Fe₂O₃ and Na₂O. Geochemically, the sandstones are classified mainly as litharenites. The Chemical Index of Alteration (CIA) values for the Miocene Surma Group sandstones vary from 53 to 65 with an average of 59, indicating low to moderate weathering of the source areas. The average CIA value (59) is a little above than that (50) of the upper continental crust. The shales from the Miocene Surma Group show higher CIA (~70–78) values, indicating significant weathering in the source. The geochemical characteristics suggest an active continental margin to passive margin setting for the Surma Group sandstones, and preserve the signatures of a recycled provenance. The Eu/Eu* (~0.69), (La/Lu)_{cn} (~10.07), La/Sc (~3.98), Th/Sc (~1.44), La/Co (~3.84), Th/Co (~1.40), and Cr/Th (~9.48) ratios as well as chondrite-normalized REE patterns with flat HREE, LREE enrichment, and negative Eu anomalies indicate derivation of the Surma Group sandstones from felsic rock sources.

Keywords: Miocene Surma Group sandstones, Bengal Basin, geochemistry, provenance, tectonic setting

INTRODUCTION

This paper describes the geochemical composition of Miocene sandstones from the Surma Group of the Bengal Basin (Fig. 1) based on 26 core samples collected from six petroleum exploration wells: Bakhrabad-10 (BK), Fenchuganj-2 (FG), Kailas Tila-2 (KT), Titas-11 (TT), Shalda Nadi-1 (SN), and Shahbazpur-1 (SB) (Fig. 1). The Surma sandstones used in this study are encountered at depth ranges between 1571 m and 4249 m. Clastic sediments of the Surma Group have a thickness of 5000 m. The sedimentary succession comprises subequal proportions of alternating sandstones and shales. The sandstone framework components of the subsurface Surma Group are quartzolithic and quartzose, with abundant sedimentary and low-grade metamorphic grains, but lesser amounts of volcanic constituents (Rahman, 1999). These

compositions are diagnostic of a quartzose recycled orogen province (*sensu* Dickinson, 1985). The geochemistry of the sandstones is of similar importance, because such studies can give information about the provenance, tectonic setting and weathering history of the source rocks. The geochemical composition of terrigenous sedimentary rocks is a function of the complex interplay of various variables, such as provenance, weathering, transportation and diagenesis (Bhatia, 1983). Recent investigations on geochemical characteristics of ancient and modern detritus have been carried out in order to infer the source rocks, provenance and tectonic setting (e.g., Potter, 1978; Bhatia, 1983; Hiscott, 1984; Bhatia and Crook, 1986; Roser and Korsch, 1986, 1988; Dabard, 1990; McCann, 1991; McLennan *et al.*, 1993; Garver *et al.*, 1996; Nesbitt and Young, 1996; Hayashi *et al.*, 1997). The proposed major elemental geochemical parameters after Bhatia (1983), such as Fe₂O₃ + MgO%, TiO₂%, (Al₂O₃/SiO₂), (K₂O/Na₂O) and Al₂O₃/(CaO + Na₂O) are used to discriminate the plate tectonic setting of sedimentary basins. Bhatia (1983) indicates that the ratio Al₂O₃/

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Fig. 1. Major tectonic elements of the Bengal Basin (after Uddin and Lundberg, 1999). The map also shows the locations of petroleum exploration wells: Bakhrabad-10 (BK), Fenchuganj-2 (FG), Kailas Tila-2 (KT), Titas-11 (TT), Shalda Nadi-1 (SN) and Shahbazpur-1 (SB), from which the cores of Miocene Surma Group sandstones were analyzed in this study.

SiO_2 gives an indication of the quartz enrichment in sandstones. The ratio $\text{K}_2\text{O}/\text{Na}_2\text{O}$ is a measure of the potassium feldspar and mica versus plagioclase feldspar content in the rock, and $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O})$ parameter is a ratio of the most immobile to the most mobile element. Roser and Korsch (1986) used the ratio of $\text{K}_2\text{O}/\text{Na}_2\text{O}$ and SiO_2 content of published data from ancient sedimentary suites to define passive margin (PM), active continental margin (ACM) and oceanic island arc (ARC) settings. For sandstones and argillites of selected New Zealand terranes, Roser and Korsch (1988) used a discriminant function analysis of major elements (TiO_2 , Al_2O_3 , total Fe_2O_3 , MgO , CaO , Na_2O and K_2O) in discriminating four different provenance groups: (1) mafic, (2) intermediate-dominantly andesitic detritus, (3) felsic and plutonic and volcanic detritus and (4) recycled-mature polycyclic quartzose detritus.

The elements La, Ce, Nd, Y, Th, Zr, Hf, Nb, Ti and Sc are most suited for provenance and tectonic setting determinations because of their relatively low mobility

during sedimentary processes and their low residence time in sea water (Holland, 1978). These elements are transported quantitatively into clastic sedimentary rocks during weathering and transportation, reflecting the signature of the parent materials (Bhatia and Crook, 1986).

The Bengal Basin contains dominantly shallow-marine to continental clastic sediments and minor carbonates, reaching a thickness of about 18 km of mainly Tertiary to Recent sediments. The collision history of the Himalayan mountain chain, developed along a region once occupied by the west-northwest-south-southeast Tethys ocean, is likely recorded in sediments deposited in subsiding foreland basins, including the Bengal Basin. Sedimentary rocks are principal sources of information that may preserve detritus from orogenic settings. The composition of such clastic materials provides the only available clue to the composition of long-eroded source rocks, and thus is an invaluable tool in sediment source evolution.

The main purpose of this study is to evaluate the major and trace element geochemistry of the Miocene sandstones of the Surma Group from six petroleum exploration wells in the Bengal Basin in order to infer their provenance, tectonic setting and weathering signatures.

GEOLOGICAL SETTING

The Bengal Basin lies on the north-eastern part of the Indian subcontinent, between the Indian Shield to the west and north, and the Indo-Burman Ranges to the east, and occupies most of Bangladesh, parts of West Bengal and Tripura states of India and the Bay of Bengal (Alam *et al.*, 2003).

The Bengal Basin is well known for the development of a thick (± 22 km) Early Cretaceous–Holocene sedimentary succession (Curry, 1991; Curry and Munasinghe, 1991). The Cretaceous to Holocene Bengal Basin forms a “remnant ocean basin” (Mitchell and Reading, 1986) at the juncture of the Indian plate and the Burma platelet (Curry *et al.*, 1982).

The basin had its origin during the collision of India with Eurasia and Burma, building the extensive Himalayan and Indo-Burman Ranges and thereby loading the lithosphere to form flanking sedimentary basins (Uddin and Lundberg, 1998). Basin development began in the Early Cretaceous when the Indian plate drifted away from Antarctica. Since the Cretaceous Period, sedimentation in the Bengal Basin has been controlled by the movement of the Indian plate with the Burmese and Tibetan plates, and by the uplift and erosion of the Himalayas and Indo-Burmese mountain ranges (Alam, 1989). The onshore part of the Bengal Basin has been divided into platform or shelf, slope or “hinge”, and basinal facies (Fig. 1) (Evans, 1964; Salt *et al.*, 1986). Deposition in the Ben-

Fig. 2. Stratigraphic framework of the north-east and south-east Bengal Basin (after Uddin and Lundberg, 1999).

gal basin can be explained by two phases of sedimentation (Alam, 1989). The first major phase of sedimentation started with the Cretaceous marine transgression and continued up into the Oligocene period. The collision of the Indian plate with the Tibetan plate and the Burmese plate in the Miocene resulted in a rapid switch in sedimentation pattern in the Bengal Basin. With the Miocene collision of the Indian plate, there was a change from flysch to molasse sedimentation (Alam, 1989).

The Bengal Basin of Bangladesh contains one of the largest delta complexes in the world, covering an area of more than 200,000 km². It is filled mainly by orogenic sediments derived from the eastern Himalayas to the north and the Indo-Burman ranges to the east (Uddin and Lundberg, 1999) (Fig. 1). These deposits record uplift and exhumation of mountain belts formed by the ongoing India-Eurasia collision (Uddin and Lundberg, 1999). The bulk of the deltaic deposits are Miocene and younger (Fig. 2). Miocene sediments of the Surma Group comprise the early to middle Miocene Bhuban Formation and the middle to late Miocene Boka Bil Formation. These thick accumulations of mudstone and quartzolithic sandstones were derived from neighbouring orogenic belts, and were deposited during repeated transgression and regression. The Neogene Surma Group sediments reach a thickness of ≥ 4 km in the eastern fold belts and the deeper part of the basin (Uddin and Lundberg, 1999).

METHODS

Twenty thin sections of the Surma Group sandstones from the central and southeastern Bengal Basin

Fig. 3. QFL diagram for the Miocene Surma Group sandstones. Provenance fields after Dickinson (1985).

(Bakhrabad-10, Titas-11 and Shalda Nadi-1) (Fig. 1) were examined by the petrographic microscope, and the modal composition of Surma Group sandstones from the northeastern Bengal Basin (Rahman, 1999) was reviewed. Around 600 counts per thin section were made using the Gazzi-Dickinson point counting method as described by Ingersoll *et al.* (1984). In the case of coarse mineral aggregates, such as quartz-feldspar aggregates, individual minerals were counted as single grains.

Twenty six sandstone samples of the Miocene Surma Group from six petroleum exploration wells were analyzed for major and trace elements by Activation Laboratories Ltd. (code: 4Lithoresearch), Ontario, Canada. Major elements were analyzed by lithium metaborate/tetraborate fusion Inductively Coupled Plasma (ICP) and trace and rare earth elements (REE) by Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

RESULTS

Petrography

The Surma Group sandstones are rich in quartz followed by lithic grains, feldspar and mica (predominantly white mica). Quartz is the dominant framework grain, constituting on average 70% of the rock volume, and occurring as monocrystalline (most abundant) and polycrystalline grains. Feldspars constitute around 7% of the total framework grains of the sandstones. Both potassium (K) feldspar (~3%) and plagioclase (P) (~3.5%) are present in almost equal amounts. Next in abundance to quartz, lithic grains make up to 14% of the total framework grains. Lithic grains are dominated by sedimentary

Table 1. Chemical composition of the Neogene sandstones of the Surma Group encountered in six petroleum exploration wells in the Bengal Basin (for well locations see Fig. 1). BK-1 = Bakhrabad core 1, FG-5 = Fenchuganj core 5, KT-5 = Kailas Tila core 5, SB-1 = Shahbazpur core 1, SN-2 = Shalda Nadi core 2, TT-1 = Titas core 1, BL = Bhuban (lower part), BU = Boka Bil (upper part).

Sample	Bakhrabad-10			Fenchuganj-2			
	BK-1	BK-2	BK-3	FG-5	FG-10	FG-13	FG-15
Formation	BL	BL	BL	BL	BL	BL	BL
Major elements							
SiO ₂	81.26	82.14	79.82	84.06	76.16	76.10	75.59
TiO ₂	0.433	0.504	0.498	0.408	0.631	0.617	0.413
Al ₂ O ₃	8.02	7.64	8.85	7.66	10.31	9.96	9.88
Fe ₂ O ₃	3.39	3.24	3.55	2.06	4.15	4.01	3.71
MnO	0.033	0.038	0.043	0.025	0.043	0.052	0.083
MgO	0.95	0.85	1.07	0.56	1.21	1.23	1.20
CaO	0.45	0.51	0.67	0.55	0.60	0.94	1.97
Na ₂ O	1.24	1.24	1.41	1.39	1.88	1.93	1.97
K ₂ O	1.90	1.85	2.00	1.68	2.15	2.06	1.96
P ₂ O ₅	0.08	0.10	0.10	0.07	0.12	0.10	0.09
LOI	1.79	1.74	2.05	1.51	2.14	2.08	3.14
Total	99.55	99.85	100.06	99.97	99.39	99.08	100.01
Na ₂ O/K ₂ O	0.7	0.7	0.7	0.8	0.9	0.9	1.0
K ₂ O/Na ₂ O	1.5	1.5	1.4	1.2	1.1	1.1	1.0
Fe ₂ O ₃ + MgO	4.34	4.09	4.62	2.62	5.36	5.24	4.91
Al ₂ O ₃ /SiO ₂	0.10	0.09	0.11	0.09	0.14	0.13	0.13
CIA	63	62	62	61	62	59	53
Trace elements							
V	44	43	51	37	60	61	48
Cr	55	170	70	70	114	94	134
Co	9	8	9	7	12	11	10
Ni	26	22	26	23	31	36	43
Cu	18				11	11	13
Zn	36	35	36	31	55	42	39
Ga	11	11	12	10	15	15	13
Ge	1.5	1.5	1.5	1.3	1.6	1.5	1.4
Rb	76	73	80	62	92	88	76
Sr	76	85	88	104	110	145	139
Y	17.5	22.1	21.4	12.9	24.3	22.6	19.8
Zr	185	256	172	176	229	276	122
Nb	8.0	9.2	8.7	6.9	10.7	10.6	7.4
Sc	7	7	8	5	9	9	7
Cs	2.7	2.5	2.7	1.8	3.5	3.1	2.7
Ba	353	436	324	270	360	396	330
Be	2	2	2	2	2	2	2
La	30.1	33.8	32.9	21.7	41.0	39.4	29.0
Ce	62.5	69.9	69.1	44.0	84.3	80.7	61.0
Pr	6.48	7.26	7.30	4.45	8.84	8.31	6.44
Nd	24.3	26.8	27.1	16.3	32.4	30.9	24.0
Sm	4.95	5.42	5.65	3.28	6.77	6.21	5.09
Eu	0.998	1.06	1.14	0.628	1.31	1.16	1.13
Gd	4.03	4.43	4.59	2.52	5.53	4.90	4.40
Tb	0.72	0.79	0.84	0.45	1	0.87	0.8
Dy	3.79	4.3	4.43	2.53	5.18	4.63	4.21
Ho	0.69	0.81	0.81	0.48	0.94	0.86	0.78
Er	2.05	2.53	2.39	1.49	2.88	2.55	2.31
Tm	0.310	0.387	0.358	0.230	0.414	0.389	0.347
Yb	1.94	2.38	2.19	1.47	2.57	2.45	2.13
Lu	0.277	0.351	0.311	0.223	0.379	0.365	0.306
Hf	5.2	6.7	4.7	4.9	6.6	7.4	3.5
Ta	0.74	0.80	0.80	0.58	0.97	0.93	0.63
W	1.3	1.8	1.3	1.1	2.0	1.3	2.6
Tl	0.67	0.59	0.66	0.59	0.83	0.74	0.66
Pb	19	20	17	18	21	15	17
Bi	1.4	0.8	2.4	1.2	1.0	0.9	1.1
Th	9.20	11.80	10.60	10.30	13.20	13.90	8.69
U	1.57	2.00	1.68	1.92	2.38	2.45	1.51
ΣREE	143	160	159	100	194	184	142

Table 1. (continued)

Sample	Kailas Tila-2				Shahbazzpur-1				
	KT-5 BU	KT-8 BL	KT-9 BL	KT-10 BL	SB-1 BU	SB-2 BU	SB-3 BU	SB-5 BL	SB-6 BL
Major elements									
SiO ₂	72.92	80.50	85.23	84.31	76.71	70.06	85.09	79.38	75.34
TiO ₂	0.627	0.255	0.261	0.337	0.545	0.628	0.239	0.630	0.528
Al ₂ O ₃	10.35	6.66	6.59	6.51	9.26	11.16	6.89	9.03	10.07
Fe ₂ O ₃	4.98	2.27	2.28	2.54	3.96	5.02	2.54	3.62	4.26
MnO	0.085	0.163	0.023	0.037	0.039	0.066	0.020	0.040	0.046
MgO	1.69	0.61	0.56	0.60	1.33	2.12	0.53	1.20	1.57
CaO	1.25	2.96	0.64	0.75	0.80	2.10	0.50	0.80	0.90
Na ₂ O	1.40	1.25	1.24	1.18	1.61	1.76	1.31	1.62	1.86
K ₂ O	2.21	1.72	1.66	1.64	2.15	2.58	1.71	1.98	2.36
P ₂ O ₅	0.15	0.06	0.05	0.05	0.17	0.12	0.06	0.14	0.10
LOI	3.44	3.06	1.10	1.22	1.95	3.94	0.86	1.78	2.38
Total	99.10	99.51	99.63	99.17	98.52	99.55	99.75	100.22	99.41
Na ₂ O/K ₂ O	0.6	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8
K ₂ O/Na ₂ O	1.6	1.4	1.3	1.4	1.3	1.5	1.3	1.2	1.3
Fe ₂ O ₃ + MgO	6.67	2.88	2.84	3.14	5.29	7.14	3.07	4.82	5.83
Al ₂ O ₃ /SiO ₂	0.14	0.08	0.08	0.08	0.12	0.16	0.08	0.11	0.13
CIA	61	53	57	57	61	57	59	60	59
Trace elements									
V	66	30	29	33	57	69	30	52	52
Cr	104	103	104	42	163	61	102	101	86
Co	13	6	6	6	11	12	5	8	9
Ni	44				35	49			
Cu	20				16	22	12		
Zn	70				40	66			
Ga	16	9	8	8	13	16	8	11	9
Ge	1.4	1.0	1.0	1.0	1.6	1.4	1.0	1.3	1.3
Rb	103	58	53	54	90	126	57	75	76
Sr	124	166	115	113	121	123	115	115	112
Y	23.8	12.8	12.3	15.4	30.0	24.3	15.3	22.5	19.0
Zr	269	97	85	124	265	219	100	289	231
Nb	11.1	4.8	4.6	5.3	9.5	11.5	4.2	10.0	8.3
Sc	10	5	5	6	9	12	5	9	8
Cs	4.7	1.6	1.4	1.3	3.6	7.1	1.4	3.0	3.5
Ba	382	311	302	373	352	406	295	319	413
Be	2	1	1	1	2	2	1	2	2
La	37.6	19.5	19.5	25.2	39.3	37.2	21.6	36.6	26.2
Ce	77.6	39.3	40.0	52.5	81.9	75.9	45.4	76.2	53.4
Pr	8.17	4.10	4.20	5.50	8.70	7.86	4.80	8.09	5.52
Nd	29.8	15.5	15.4	20.3	34.0	29.2	18.3	28.9	20.3
Sm	6.11	3.27	3.28	4.16	7.33	6.05	3.84	5.91	4.07
Eu	1.20	0.749	0.778	0.850	1.50	1.19	0.838	1.08	0.785
Gd	5.02	2.70	2.74	3.37	6.39	5.04	3.18	4.57	3.23
Tb	0.92	0.46	0.48	0.6	1.2	0.93	0.56	0.84	0.6
Dy	4.88	2.59	2.64	3.21	6.34	4.89	2.91	4.39	3.28
Ho	0.92	0.47	0.46	0.59	1.15	0.93	0.53	0.82	0.62
Er	2.80	1.42	1.42	1.80	3.25	2.77	1.63	2.55	1.86
Tm	0.431	0.204	0.210	0.272	0.467	0.423	0.233	0.385	0.292
Yb	2.59	1.29	1.26	1.72	2.81	2.66	1.48	2.49	1.88
Lu	0.389	0.185	0.187	0.258	0.399	0.380	0.220	0.364	0.271
Hf	7.7	2.7	2.4	3.5	7.3	6.4	2.9	8.2	6.2
Ta	0.99	0.36	0.35	0.46	0.83	1.08	0.45	1.03	0.80
W	1.6	0.8	1.3	0.8	1.4	2.0	0.7	1.5	1.4
Tl	1.12	0.45	0.52	0.50	0.81	1.25	0.55	0.67	0.05
Pb	23	26	15	13	21	24	15	17	30
Bi	2.8	0.3	0.6	0.4	1.1	3.3	0.4	1.2	2.1
Th	12.70	5.28	5.26	7.25	13.50	12.40	6.69	18.30	11.50
U	2.54	0.98	0.98	1.19	2.17	2.35	1.28	2.87	2.02
ΣREE	178	92	93	120	195	175	106	173	122

Table 1. (continued)

Sample Formation	Shalda Nadi-1					Titas-11				
	SN-2 BU	SN-3 BU	SN-4 BU	SN-5 BL	SN-6 BL	TT-1 BL	TT-2 BL	TT-4 BL	TT-5 BL	TT-6 BL
Major elements										
SiO ₂	65.34	63.50	75.02	70.72	65.71	80.79	73.56	82.58	83.25	80.75
TiO ₂	0.485	0.409	0.559	0.376	0.311	0.552	0.497	0.648	0.439	0.409
Al ₂ O ₃	6.41	7.21	10.56	6.57	6.12	8.03	10.97	7.63	7.71	8.28
Fe ₂ O ₃	2.51	2.86	5.10	3.03	2.41	3.92	5.67	3.17	2.81	3.64
MnO	0.808	0.188	0.055	0.242	0.671	0.075	0.056	0.053	0.037	0.073
MgO	0.64	1.00	1.48	0.78	0.62	0.89	1.73	0.66	0.70	0.95
CaO	10.70	11.43	0.64	8.01	11.41	0.62	0.53	0.55	0.50	0.62
Na ₂ O	1.13	1.18	1.53	1.16	1.14	1.39	1.42	1.32	1.37	1.36
K ₂ O	1.39	1.69	2.33	1.44	1.40	1.72	2.67	1.57	1.75	1.94
P ₂ O ₅	0.09	0.09	0.12	0.07	0.07	0.08	0.08	0.07	0.07	0.10
LOI	9.89	10.57	2.66	7.52	10.04	1.48	2.73	1.33	1.36	1.82
Total	99.39	100.13	100.05	99.92	99.90	99.55	99.91	99.58	100.00	99.94
Na ₂ O/K ₂ O	0.8	0.7	0.7	0.8	0.8	0.8	0.5	0.8	0.8	0.7
K ₂ O/Na ₂ O	1.2	1.4	1.5	1.2	1.2	1.2	1.9	1.2	1.3	1.4
Fe ₂ O ₃ + MgO	3.15	3.86	6.58	3.81	3.03	4.81	7.40	3.83	3.51	4.59
Al ₂ O ₃ /SiO ₂	0.10	0.11	0.14	0.09	0.09	0.10	0.15	0.09	0.09	0.10
CIA	55	56	64	55	54	61	65	62	61	61
Trace elements										
V	32	36	63	33	28	45	60	50	37	42
Cr	67	97	69	120	35	142	53	138	53	87
Co	4	5	14	5	4	7	21	6	5	8
Ni	24		69	21		20	52			24
Cu			12				11			
Zn			45				51		34	
Ga	8	9	14	8	7	10	15	9	9	10
Ge	1.0	1.1	1.4	1.2	0.9	1.3	1.4	1.2	1.2	1.1
Rb	50	68	100	54	49	63	116	55	58	71
Sr	315	311	98	392	384	110	96	101	102	100
Y	23.7	21.9	22.8	19.0	14.0	16.6	16.7	24.0	15.9	16.1
Zr	313	195	176	157	108	234	127	230	188	141
Nb	7.7	7.8	10.0	6.8	5.4	9.1	9.4	10.3	7.2	6.8
Sc	6	6	10	5	5	7	10	8	7	8
Cs	1.7	2.8	4.9	1.8	1.5	2.1	6.1	1.6	1.8	2.6
Ba	238	286	365	235	233	307	395	312	496	336
Be	2	2	2	2	2	2	2	2	2	2
La	30.6	25.4	30.3	22.0	15.1	26.9	22.9	40.1	29.7	23.1
Ce	61.9	51.8	62.6	45.7	29.8	56.8	48.3	84.6	63.2	48.2
Pr	6.46	5.50	6.68	4.89	3.04	5.77	5.12	8.77	6.56	5.06
Nd	23.5	20.8	25.5	18.1	11.2	20.7	19.8	31.8	23.8	18.7
Sm	4.82	4.37	5.37	3.87	2.28	4.21	4.26	6.35	4.67	3.72
Eu	0.900	0.923	1.14	0.761	0.515	0.797	0.973	1.17	0.912	0.796
Gd	3.98	3.82	4.49	3.26	2.08	3.24	3.63	4.83	3.60	3.08
Tb	0.72	0.69	0.85	0.62	0.39	0.59	0.66	0.85	0.61	0.59
Dy	4.12	3.95	4.43	3.41	2.43	3.26	3.45	4.54	3.19	3.15
Ho	0.82	0.72	0.81	0.64	0.49	0.64	0.64	0.85	0.57	0.6
Er	2.50	2.21	2.45	1.99	1.50	1.99	1.96	2.65	1.77	1.82
Tm	0.392	0.319	0.358	0.307	0.235	0.316	0.280	0.404	0.272	0.277
Yb	2.43	1.99	2.17	1.91	1.44	2.05	1.71	2.57	1.71	1.74
Lu	0.354	0.290	0.327	0.284	0.205	0.314	0.256	0.378	0.246	0.262
Hf	8.9	5.2	5.0	4.4	3.1	6.5	3.7	6.3	5.1	4.1
Ta	0.71	0.75	0.87	0.59	0.46	0.90	0.88	0.89	0.64	0.61
W	0.9	15.8	2.3	0.8	0.8	1.3	1.8	1.3	1.0	1.1
Tl	0.49	0.65	0.95	0.57	0.41	0.68	1.06	0.54	0.60	0.80
Pb	15	18	19	22	15	24	27	17	22	30
Bi	0.5	0.9	0.6	2.2	1.6	4.7	5.0	0.9	3.5	5.8
Th	13.00	9.40	10.50	8.81	6.20	12.20	8.54	15.30	9.92	8.88
U	2.20	1.63	1.85	1.39	1.16	1.94	1.35	2.21	1.58	1.43
ΣREE	143	123	147	108	71	128	114	190	141	111

Major elements in wt.%, trace elements in ppm.

Fig. 4. Harker variation diagrams for major elements in the Surma Group sediments.

(mainly chert, shale) and low-grade metamorphic rocks (mainly fine-grained mica schist, quartz-mica schist and phyllites, partly graphite-bearing), along with a few volcanic rock fragments. Phyllosilicates constitute about 6% of the framework grains. White mica is generally more abundant (3.6%) than biotite (2.3%). Chlorite constitutes about 1.5% of the total framework grains. Calcite and dolomite are found both as detrital grains and as cements. Dolomite is predominant among the carbonate minerals, constituting about 1.1%, whereas calcite constitutes around 0.5%. Iron-bearing calcites are common.

The heavy mineral assemblage is characterized by predominance of garnet followed by apatite, tourmaline, epidote and staurolite.

The Surma Group sandstones have dominantly quartzolitic composition with predominance of quartz. Some feldspathic sandstones and quartz arenites are also recognized. The Surma sandstones contain abundant low-

Fig. 5. Chemical classification of the Miocene Surma Group sandstones (after Herron, 1986).

grade metamorphic, and sedimentary lithics, and little feldspar and volcanic detritus, indicating that the sands were derived from a quartzose recycled orogen province (Fig. 3).

Chemical composition

Averaged major and trace element analyses of the sandstones of the Surma Group from different wells are presented in Table 1.

Major elements The Surma Group sandstones have moderate to high SiO_2 contents (64–85%; on average 77%), TiO_2 concentrations averaging 0.5%, Al_2O_3 contents of about 8.4%, and Fe_2O_3 (total Fe as Fe_2O_3) + MgO content of around 4.5%. Compared to the average sandstone value proposed by Turekian and Wedepohl (1961), the Surma Group sandstones are depleted in CaO (2.36%) and enriched in Al_2O_3 , Fe_2O_3 and Na_2O . The samples show no marked differences in major chemical composition. The only exception is in their CaO content. Surma Group sandstones in the Shaldha Nadi well (SN in Fig. 1) are rich in CaO content which is agreement with petrographic observations. Most of the Shaldha Nadi sandstones are cemented with calcite. The linear relationship of TiO_2 , Al_2O_3 , Fe_2O_3 , MgO and K_2O with SiO_2 in the Surma Group sediments is conspicuous in the Harker variation diagrams, both lithologies (sandstones and shales) show similar linear trend (Fig. 4). The negative correlation of SiO_2 with most major elements is due to most of the silica being sequestered in quartz, as indicated by Osman (1996). In the present samples, TiO_2 concentrations increase with Al_2O_3 , suggesting that TiO_2 is probably associated with phyllosilicates especially with illite (Dabard, 1990); Fe_2O_3 + MgO are also well corre-

Fig. 6. Analysis of sandstones according to the richness of quartz of the Miocene Surma Group (after Crook, 1974).

lated with Al_2O_3 . The latter correlation implies that these oxides are associated with phyllosilicates, particularly in matrix chlorites (Dabard, 1990).

According to the diagram of Herron (1986) the sandstones are classified mainly as litharenites (Fig. 5). On the Na_2O – K_2O diagram (Fig. 6), the Surma Group sandstones data plot in the quartz-rich field.

Trace elements Trace element concentrations of the Surma Group sandstones are in concurrence with average upper continental crust (UCC) with the exception of Ni, Cr, Sr and Nb content (Fig. 7). In the present samples, Ni, Cr are enriched and Sr, Nb are depleted. The Cr enrichment (35–170 ppm) is related to the presence of chrome spinel which is reflected in the petrographic observation. The Sr content (76–392 ppm) of sedimentary rocks is variable because of the many influences on Sr in low temperature depositional environments (Fairbridge, 1972), e.g., the distribution of Sr can be affected by the presence of Ca, additional Sr can be incorporated in diagenetic carbonate, and fractionation of Sr can result from the weathering of feldspars, particularly plagioclase. Clear positive correlations between K contents and the abundances of Al, Cs, Ba, total REE, Th and U suggest that the concentrations of these trace elements are controlled by clay minerals and mica (after McLennan *et al.*, 1983). A significant correlation ($r^2 = 0.63$) between Ba and K_2O suggests that Ba is mainly associated with a feldspar component. High field strength elements (e.g., Zr, Nb, Hf, Y) generally show consistent inter-relationships, as do the ferromagnesian trace elements (Cr, Ni, V, Co, and Sc). These trace element relationships illustrate the chemical coherence and uniformity of the sediments. Cobalt and Sc abundances show significant positive cor-

Fig. 7. Multi-element normalized diagram for the Surma Group sandstones, normalized against upper continental crust (Taylor and McLennan, 1985).

Fig. 8. Chondrite-normalized rare earth element plots for the Surma Group sandstones. Chondrite values from Taylor and McLennan (1985).

relation with Ni, V and Al_2O_3 inferring that Co and Sc are partly controlled by chlorite and other accessory non-aluminous silicate minerals.

Rare Earth Elements REE concentrations of the Surma Group sandstones are shown as chondrite-normalized patterns in Fig. 8. The sandstones have (REE contents ranging between 71–195 with an average of 139, comparable to average UCC (143, Taylor and McLennan 1985). The sandstones show slight LREE-enriched and relatively flat HREE patterns with negative Eu anomalies.

DISCUSSION

Provenance and tectonic setting

Several classifications have been proposed to discrimi-

nate from various origins and tectonic settings (Maynard *et al.*, 1982; Bhatia, 1983; Bhatia and Crook, 1986; Roser and Korsch, 1986, 1988). To infer provenance, unstandardised discriminant function scores of the samples (F1 and F2) for major elements were plotted following the boundaries between fields (P1-P4), as proposed by Roser and Korsch (1988) (Fig. 9). The Surma Group sandstones and shales fall within the P4 field, which represents recycled mature polycyclic quartzose detritus. Recycled sources represent quartzose sediments of mature continental provenance, and the derivation of the sediments could be from a highly weathered granite-gneiss terrain and/or from a pre-existing sedimentary terrane as in the case of the Greenland Group of New

Fig. 9. Plot of discriminant functions F1 and F2 for the sandstones from the Miocene Surma Group of the Bengal Basin. Provenance fields are after Roser and Korsch (1988). P1 = mafic and lesser intermediate igneous provenance; P2 = intermediate igneous provenance; P3 = felsic igneous provenance and P4 = recycled-mature polycyclic quartzose detritus.

Zealand (Roser and Korsch, 1988). The recycled nature of the Surma Group is also reflected in the sandstone modal compositions (Fig. 3). The Surma Group sandstones in the Bengal Basin have dominantly quartzolitic composition with predominance of quartz, abundant low-grade metamorphic and sedimentary lithics, less feldspar and little volcanic detritus. The $^{40}\text{Ar}/^{39}\text{Ar}$ results for the Surma Group sandstones point to heterogeneous ages of the source region, which seems to be typical of the early stages of a rapidly uplifting collision orogen (Rahman and Faupl, 2003a). The narrow age range (cluster between 25 and 36 Ma) of the low temperature steps can be correlated with early cooling ages known from the High Himalayan crystalline basement (Rahman and Faupl, 2003a). The concentrations of Rb (mean ~74 ppm), Sr (~148), Sm (~5.0) and Nd (~23) in the Surma Group sandstones are in accordance with those of High Himalaya sedimentary series (France-Lanord *et al.*, 1993).

The high-field-strength elements (HFSE) such as Zr, Nb, Hf, Y, Th are preferentially partitioned into melts during crystallization (Feng and Kerrich, 1990), and as a result these elements are enriched in felsic rather than mafic sources. These elements are thought to reflect provenance compositions as a consequence of their generally immobile behavior (Taylor and McLennan, 1985). The REE and Sc also give indication of source compositions because of their relatively low mobility during sedimentation and their low residence times in sea water (Bhatia and Crook, 1986). REE and Th abundances are higher in felsic than in mafic igneous source rocks and in their weathered products, whereas Co, Sc, and Cr are more concentrated in mafic than in felsic igneous rocks and in their weathered products. Mafic and felsic source rocks differ significantly in the ratios such of Eu/Eu*, (La/Lu)_{cn}, La/Sc, Th/Sc, La/Co, Th/Co, and Cr/Th and hence provide useful information about the provenance of sedimentary rocks (e.g., Cullers *et al.*, 1988; Cullers, 1994, 2000; Cullers and Podkovyrov, 2000). In this study, Eu/Eu*, (La/Lu)_{cn}, La/Sc, Th/Sc, La/Co, Th/Co, and Cr/Th

Table 2. Range of elemental ratios of Miocene Surma Group sandstones in this study compared to elemental ratios in sediments derived from felsic rocks, mafic rocks, and in the upper continental crust

Elemental ratio	Surma Group sandstones (n = 26)	Ranges in sediments from felsic sources ¹⁾	Ranges in sediments from mafic sources ¹⁾	Upper Continental Crust ²⁾
Eu/Eu*	0.63–0.77	0.40–0.94	0.71–0.95	0.63
(La/Lu) _{cn}	7.65–11.28	3.00–27.0	1.10–7.00	9.73
La/Sc	2.89–5.01	2.50–16.3	0.43–0.86	2.21
Th/Sc	0.85–2.17	0.84–20.5	0.05–0.22	0.79
La/Co	1.09–7.65	1.80–13.8	0.14–0.38	1.76
Th/Co	0.41–3.25	0.04–3.25	0.04–1.40	0.63
Cr/Th	4.92–19.77	4.00–15.0	25–500	7.76

¹⁾Cullers *et al.* (1988); Cullers (1994, 2000); Cullers and Podkovyrov (2000).

²⁾McLennan (2001); Taylor and McLennan (1985).

Fig. 10. Distribution of K and Rb in the Miocene Surma Group sediments relative to a K/Rb ratio of 230 (=main trend of Shaw, 1968).

values of the Miocene Surma Group sandstones are more similar to values for sediments derived from felsic source rocks than to those for mafic source rocks (Table 2), suggesting derivation from felsic source rocks. The higher LREE/HREE ratios and negative Eu anomalies of the Surma Group sandstones also bears the characteristics of felsic source rocks (after Taylor and McLennan 1985; Wronkiewicz and Condie 1989). The Surma Group sediments have uniform K/Rb ratios that lie close to a typical differentiated magmatic suite or main trend with a ratio of 230 (Fig. 10) (Shaw, 1968). This characteristic reveals the chemically coherent nature of the sediments and derivation from rocks of acidic and intermediate compositions.

The ferromagnesian trace elements Cr, Ni, Co, and V show generally similar behavior in magmatic processes, but they may be fractionated during weathering (Feng and Kerrich, 1990). In the studied samples, Cr and Ni are enriched with respect to the average composition of the Upper Continental Crust (UCC). This enrichment in Cr and Ni may suggest some basic input from the source terrane.

The elevated values of Cr (>150 ppm) and Ni (>100 ppm) and a ratio of Cr/Ni between 1.3–1.5 are diagnostic of ultramafic rocks in the source region (Garver *et al.*, 1996). In comparison, Cr concentrations ranges from 35 to 170 ppm (average 94 ppm) and Ni concentrations ranges from 20 to 69 ppm (average 34 ppm). Cr/Ni ratios vary from 1.0 to 7.7, but are mostly less than 2.0. This comparison implies that the existence of widespread mafic/ultramafic rocks in the source region was most unlikely. The occurrence of only rare detrital chrome spinel (~0.3%) within the sandstones of the Surma Group, as revealed from heavy mineral data, is in good agreement with this finding.

Fig. 11. Tectonic discrimination diagram for Surma Group sediments. Boundaries are after Roser and Korsch, 1986. PM = passive margin, ACM = active continental margin, ARC = oceanic island arc margin.

Roser and Korsch (1986) established a discrimination diagram using $\log (K_2O/Na_2O)$ versus SiO_2 (Fig. 11) to determine the tectonic setting of terrigenous sedimentary rocks. SiO_2 and K_2O/Na_2O increase from volcanic-arc to active continental margin to passive margin settings. The Surma Group sandstones plot in the passive margin field, whereas the shale samples fall in the active continental margin field (Fig. 11). Discrimination of tectonic settings on the basis of major element data was also proposed by Bhatia (1983); these include oceanic island arc, continental island arc, active continental margin, and passive margin settings. Most of the Surma Group sandstones fall in the general area of active continental margin and passive margin fields of the Al_2O_3/SiO_2 versus $Fe_2O_3 + MgO$; K_2O/Na_2O versus $Fe_2O_3 + MgO$; $Al_2O_3/(CaO + Na_2O)$ versus $Fe_2O_3 + MgO$ (Fig. 12) but there is much scatter on plot the TiO_2 versus $Fe_2O_3 + MgO$ plot, with data spreading across three fields (active continental margin, continental island arc, passive margin).

Weathering in the source area

The Chemical Index of Alteration (CIA) gives an indication of the degree of weathering in the source region (Nesbitt and Young, 1982). CIA records the progressive alteration of plagioclase and potassium feldspars to clay minerals. The CIA index is calculated using molar proportions following the equation $CIA = [Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where CaO^* represents the amount of CaO incorporated in the silicate phases. Nesbitt and Young (1982) suggested a CIA value of nearly 100 for kaolinite and chlorite, and 70–75 for average shales. High values (i.e., 76–100) indicate intensive chemical

Fig. 12. Tectonic-setting discrimination diagrams for Surma Group sediments. Boundaries are after Bhatia (1983). A = Oceanic island arc margin; B = Continental island arc; C = Active continental margin; D = Passive margin.

Fig. 13. CIA ternary diagram, Al_2O_3 – $\text{CaO}^* + \text{Na}_2\text{O}$ – K_2O (after Nesbitt and Young, 1982); $\text{CaO}^* = \text{CaO}$ in silicate phase.

weathering in the source areas whereas low values (i.e., 50 or less) indicate unweathered source areas. CIA values for the Surma Group sandstones vary from 53 to 65, with an average 59 indicating the Surma sandstones were likely derived from the least weathered zones of soil profiles. The average CIA value (59) is a little above than

Fig. 14. Plots of (a) Th/U versus Th and (b) Th/Sc versus Zr/Sc for the Surma Group sandstones (after McLennan *et al.*, 1993).

that of the CIA value (50) of UCC. The calculated CIA values for the Surma Group sandstones are very similar to the CIA values of Yamuna River System sediments in the Himalaya (~51 to 69; average ~60) (Dalai *et al.*, 2002). The CIA values are also plotted in Al_2O_3 – $(\text{CaO}^* + \text{Na}_2\text{O})$ – K_2O (A–CN–K) diagram (Fig. 13). In the A–CN–K diagram the Surma Group sandstones plot a little away from the plagioclase–K-feldspar join line, indicating low to moderate chemical weathering of the source. Interbedded shales from the Surma Group show higher CIA values (~70–78) (Rahman and Faupl, 2003b) comparable to and a little higher than average shale CIA = 70–75, (Nesbitt and Young, 1982). The presence of plagioclase (~9%) in the shales (Rahman and Faupl, 2003b) may imply insignificant chemical weathering during sedimentation in the basin (Einsele, 1992, p. 364), but the CIA values of shales are clearly indicative of significant weathering in their source. The occurrence of abundant quartz, and small amounts of feldspar of the sandstones as well

as illite and chlorite rich clay assemblages of the shales (Rahman and Faupl, 2003a, b) implies that the minerals are predominantly detrital and reflect the character of their source material (after Weaver, 1958). The thick pile of interbedded sandstones and mudrocks may have been resulted from rapid erosion of fast rising orogens. Integrating the CIA values of both sandstones and mudrocks, it is most likely that the sediments of the Miocene Surma Group were derived from different zones of weathering in the source soil profiles.

Th/U in sedimentary rocks is of interest, as weathering and recycling typically result in loss of U, leading to an elevation in the Th/U ratio. The Th/U ratio in most upper crustal rocks is typically between 3.5 and 4.0 (McLennan *et al.*, 1993). In sedimentary rocks, Th/U values higher than 4.0 may indicate intense weathering in source areas or sediment recycling. Th/U ratios in the Surma Group sandstones range from 5.0 to 6.9, with an average of 5.9, indicating the derivation of these sediments from recycling of the crust. A Th/U versus Th plot for the Miocene Surma Group sandstones (Fig. 14a) shows a typical distribution similar to the average values of fine-grained sedimentary rocks reported by Taylor and McLennan (1985) and follows the normal weathering trend (McLennan *et al.*, 1993). Sedimentary sorting and recycling can be monitored by a plot of Th/Sc against Zr/Sc (McLennan *et al.*, 1993). First-order sediments show a simple positive correlation between these ratios, whereas recycled sediments show a substantial increase in Zr/Sc with far less increase in Th/Sc. The trend of increased Zr/Sc and almost constant Th/Sc can also be exhibited by first-cycle sediments if they are derived from largely plutonic sources, as described by Roser and Korsch (1999) in the case of the Torlesse terrane of New Zealand. On the Th/Sc versus Zr/Sc diagram, the Surma Group sandstones follow a general trend consistent with their direct derivation from igneous rocks (Fig. 14b). The Rb/Sr ratios of sediments also monitor the degree of the source-rock weathering (McLennan *et al.*, 1993). The Surma sandstones have average ratios of 0.50, higher than that of the average upper continental crust (0.32) but significantly lower than the average post-Archean Australian shale (0.80; McLennan *et al.*, 1983). However, the Neogene shales have higher Rb/Sr ratios (~1.3) than that of PAAS. The Rb/Sr ratios of the Surma Group sediments (sandstones and mudrocks) therefore indicate least to significant weathering in the source area soil profiles.

CONCLUSIONS

The Miocene Surma Group sandstones have dominantly quartzolithic composition and a more quartzose one although some feldspathic and quartz arenitic sandstones are also recognized. The Surma sandstones

contain abundant low-grade metamorphic, sedimentary lithics, low feldspar and low volcanic detritus, indicating that the sands were derived from a quartzose recycled orogen province.

The Surma Group sandstones have moderate to high SiO₂ contents. Compared to the average sandstone value proposed by Turekian and Wedepohl (1961), they are depleted in CaO and enriched in Al₂O₃ and MgO. Tectonic discrimination diagrams suggest an active continental margin to passive margin setting for the Surma Group sandstones.

Eu/Eu*, (La/Lu)_{cn}, La/Sc, Th/Sc, La/Co, Th/Co and Cr/Th ratios and the REE patterns indicate derivation of these sandstones from felsic source rocks. The existence of huge complexes of mafic/ultramafic rocks in the source region is most unlikely. CIA values for the Miocene Surma Group sandstones vary from 53 to 65 with an average 59, indicating derivation from the least weathered zones of soil profiles. The average CIA value (59) is a little above than that of the CIA value (50) of upper continental crust. Shales from the Surma Group show higher CIA (~70–78) values, indicating significant weathering in the source. Integrating the CIA values of the mudrocks, it is most likely that the sediments of the Miocene Surma Group were derived from the different zones of weathering in the source soil profiles, and likely from the rapid erosion of fast rising recycled orogens.

The geochemical characteristics preserve the signatures of a recycled provenance for the Miocene Surma Group sediments, in good agreement with framework mineralogy.

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