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Provenance of the Late Pleistocene -Holocene sediments of the Southeastern Coast of Bangladesh: Inference from detrital mode and Major element Geochemistry

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Abstract

The modal composition, heavy mineral study and major element geochemistry of the sand samples of the Late Pleistocene -Holocene sediments of the southeastern coast of Bangladesh reveal the tectonic setting, provenance and their relation to composition, source rock complex and evolution of temporal change of the source area and the climatic condition during deposition. The observation shows that the sands were derived from a quartzose recycled orogen provenance, such as fold-thrust belt and a collision suture. Geochemical discrimination analysis indicates the study area fall astride between passive margin to slightly active continental margin tectonic setting relating to recycled orogenic source which represents quartzose sediments of mature continental provenance, highly weathered granite-gneissic terrain and/ or a pre existing sedimentary terrain. The Chemical Index of Alteration (CIA) values for the Late Pleistocene – Holocene sands indicating chemical different zones low to significant weathering of the source area. The sands of the Late Pleistocene -Holocene sediments were likely deposited in semi-arid to humid climatic conditions. Existence of epidote, staurolite, tourmaline, sillimanite, amphibole, garnet and kyanite reveals the source rock as metamorphic terrain. The presence of sedimentary rock fragments and it is dominant, such as chert, shale and metamorphic lithic fragments, such as quartz mica schist, mica bearing quartz-schist, quartz-mica-graphic-schist suggest the sands of metamorphic as well as sedimentary source terrains. The existence of a granitoid source can be inferred from the occurrence of apatite, zircon (predominated mineral), tourmaline and rutile. Presence of K-feldspar and less content of plagioclase feldspar also suggests the plutonic source.

Keywords: Detrital Mode (modal composition, heavy mineral study), Major element Geochemistry, Late Pleistocene -Holocene sediments, Bengal Basin.

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Introduction

The study of sedimentary provenance includes the location and nature of sediment source areas, the pathways by which sediment is transferred from source to basin of deposition, and the factors that influence the composition of sedimentary rocks (e.g., relief, climate, tectonic setting) [19]. Sediment compositions are influenced by the character of the sedimentary provenance, the nature of the sedimentary processes within the depositional basin and the kind of dispersal paths that link provenance to basin. The key relations between provenance and basin are governed by plate tectonics, which thus ultimately controls the distribution of different types of sediments [14].

Detrital modes of sediments suites primarily reflect the different tectonic settings of provenance terranes [15]. Crooks(1974) and Schwab (1975) have observed that quartz rich rocks are associated with passive continental margin that quartz poor rocks mostly of volcanogenic derivation are of magmatic island arc origin and that rocks of intermediated quartz are associated mainly with active continental margin or other orogenic belts [13],[40]. In Bengal Basin, geochemical analysis mainly worked out on Miocene Surma group [34] based on core samples. Hossain (2010) made some petrography and whole-rock geochemistry of the Tertiary Sylhet succession northeastern Bengal Basin [21]. Bari et al., (2002) carried out for major and trace element geochemical composition of the Neogene sandstones and the beach sands collected from different locations across the Inani and Dakhin Nhila hill ranges and their adjacent paleobeach and beach areas covers the Cox's Bazar and Teknaf areas of Cox's Bazar district [6]. Otherwise, no detailed study on geochemical analysis has been carried out of the Bengal Basin, specially the exposed sediments (Late Pleistocene-Holocene) southeastern part of Bangladesh part of the Bengal Basin.

In the present study, an attempt has been made towards detrital mineralogy and major element geochemistry of Late Pleistocene-Holocene sediments to establish the provenance relationships and to reconstruct the relation between provenance and the depositional basin that are governed by plate tectonic setting.

Geological setting of the study area

A number of workers have been studied the tectonic and structural behavior of the Bengal Basin [1], [2], [3],[18], [28],[39],[26], [42]. According to these works, the tectonic framework of the Bengal Basin may be broadly divided into two main units (Figure 1): (1) the stable platform in the northwest and (2) The fore deep to the southeast. A narrow northeast-southwest trending zone called "Hinge Zone" separate the two units diagonally almost through the middle of the basin. The eastern portion of the foredeep is folded and exposes the Tertiary Chittagong- Tripura folded Belt (CTFB). The CTFB developed as a consequence of the Indo-Burman Ranges in the east. Bakhtine (1966) subdivided the CTFB into three zones in terms of the degree of folding intensity: (a) western quiet zone of box like structures; (b) middle zone of asymmetric thrust-faulted structures and (c) eastern highly compressed, narrow-ridge shaped structures [3]. The study area lies in the western quiet zone of Chittagong- Tripura Folded Belt (CTFB) and particularly around the Inani, Ukhia and Dakhin Nhila structures. So, the stratigraphic successions of these regions are the stratigraphic succession of the study area. The deposits of the Inani Anticline have been divided into Middle and Upper Boka Bil, Tipam sandstone, Girujan clay and Dupi Tila formations [4], on the other hand those of the Dakhin Nhila Anticline have been divided into Upper Bhuban, Lower and Middle Boka Bil and Tipam sandstone Formations [5].

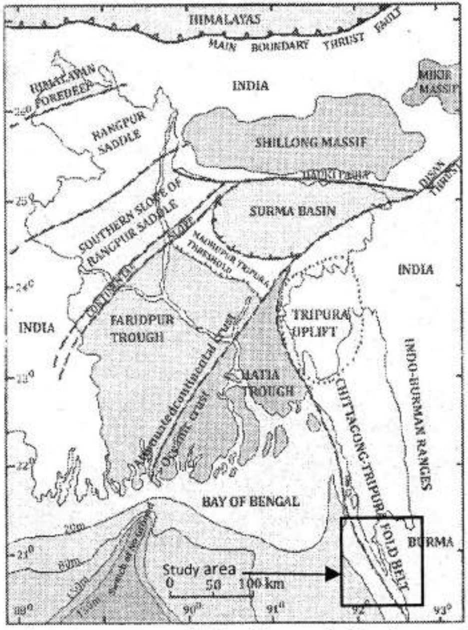

Figure 1. Major tectonic elements of the Bengal Basin and its adjoining areas in respect to the tectonic elements [18], [36].

Method

The mineralogical compositions of the sediments have been determined by petrographic microscope using point counting method. Among the framework grains only quartz, feldspar and lithic grains have been recalculated from Table 2 and shown in Table 3, Table 4 and Table 5. Different types of triangular diagrams such as QtFL, QmFLt, QpLvmLsm, LmLvLs plots, diamond diagram and bivariant log/ log plot of Qp/ (F+L) against Qt/ (F+L) are plotted [14],[15]. The selected powdered samples were subjected to hydrofluorization treatment [43] to determine Na, K, Ca, Mg, Al, Fe, Ti, Mn and P contents. Classical method was used to determine the silica content. Except K and Na, these were analyzed in the Analytical Chemistry branch of Geological Survey of Bangladesh (GSB) and ICSL, BCSIR, Dhaka by using EDXRF Analyzer (Table 6). The individual framework grains and heavy mineral composition also used as tools for interpreting source rocks.

Petrography (Results)

The grain types that are used by Dickinson (1985) and Ingersoll & Suczek (1979) for plotting QtFL, QmFLt, QpLvmLvs, and LmLvLs triangular diagrams are listed in Table 1 [14], [23]. These are also shown in Table 3 [12]. In these classifications intrabasinal grains, micas and chlorites are ignored. Extrabasinal carbonate grains or detrital limeclasts (Lc) are not recalculated with other lithic fragments because of their vastly different geochemical response during weathering and diagenesis, as well as the case of confusion with intrabasinal carbonate grains (intraclasts, bioclasts, ooliths, peloids) [15].

Table 1. Classification and symbols of sand grain types [15], [44].

Grain Types	Symbols
Quartzose Grains	
Total quartz grains (Qm+Qp+chert)	**Qt**
Monocrystalline quartz	**Qm**
Polycrystalline quartz	**Qp**
Feldspar Grains	
Total feldspar grains (P+K)	**F**
Potassium feldspar	**K**
Plagioclase feldspar	**P**
Lithic Grains	
Metamorphic lithic grains	**Lm**
Sedimentary lithic grains	**Ls**
Volcanic lithic grains	**Lv**
Volcanic and metavolcanic lithic grains	**Lvm**
Sedimentary and metasedimentary lithic grains	**Lsm**
Total unstable lithic grains (Lvm + Lsm)	**L**
Total lithic grains (Ls+Lm+Lv+chert)	**Lt**

Table 2. Framework composition of the Late Pleistocene - Holocene sands of the study area (expressed in percentage). **Borehole index**: KP=Kachubaniapara borehole, SC =Shonaichari borehole, SP = Shonarpara borehole. **Index:** Qm - monocrystalline quartz, Qmn – non-undulose monocrystalline quartz, Qmu – undulose monocrystalline quartz, Qp – polycrystalline quartz, F feldspar, K – potassium, P – plagioclase, Ls – sedimentary lithic grains, Lm – metamorphic lithic grains, Lv – volcanic lithic grains.

Sample no.	Depth (m)	Qm		Qp	chert	F		Mica		Chlorite	Ls	Lm	Lv	Carbonates	others
		Qmn	Qmu			K	P	White mica	Biotite						
Kachubaniapara borehole															
KP-1	3.51	48.2	7.9	5.4	6.1	4.9	5.4	2.9	5.2	1.6	10.1	0.7	0	0.7	1.1
KP-2	4.80	49.2	10.2	1.7	0.0	3.2	0.5	4.0	1.4	1.6	23.0	4.2	0	0.4	2.6
KP-3	4.88	46.5	7.7	3.1	2.7	4.4	3.5	6.0	14.4	2.7	4.9	2.9	0	0.9	0.4
Average		48.0	8.6	3.4	2.9	4.2	3.2	4.3	7.0	1.9	12.7	2.6	0	0.6	1.4
Shonaichari borehole															
SC-1	1.73	65.8	7.9	6.1	1.4	4.1	0.5	0.9	0	0	9.3	3.4	0	0	0.7
SC-2	6.40	44.2	7.2	4.3	6.8	4.5	2.9	1.4	4.3	0.8	12.7	7.2	0	0.6	3.1
SC-3	12.57	37.9	13.6	17.3	7.9	12.4	0.7	0.3	0	0	7.7	1.2	0	0.3	0.7
SC-4	14.17	83.9	2.3	3.6	0.0	3.1	0.5	0	0	0	4.0	0.7	0	0.2	1.8
SC-5	15.69	60.9	11.6	5.7	5.3	5.9	2.5	1.7	0.2	0.6	3.8	0.6	0	0	0.8
Average		58.5	8.5	7.4	4.3	6.0	1.4	0.9	0.9	0.3	7.5	2.6	0	0.2	1.4
Shonarpara borehole															
SP-1	1.73	63.4	13.8	6.0	5.8	0.7	0.9	0	0	0	7.4	0.7	0	0.2	1.2
SP-2	1.98	55.4	20.5	5.1	2.9	4.1	1.9	0	1.5	0	6.8	0.2	0	0	1.7
SP-3	3.15	53.7	11.0	16.5	4.0	5.9	3.3	0	1.3	0	3.7	0	0	0	0.7
SP-4	3.51	60.2	4.5	0.2	1.0	0.6	3.1	4.4	3.7	1.7	15.6	1.9	0	1.0	2.5
SP-5	4.78	47.6	6.6	19.0	2.9	8.4	1.1	2.0	1.8	0.2	7.1	1.1	0	0.9	1.3
SP-6	5.03	58.1	17.6	7.9	4.2	5.2	1.0	0	1.2	0	4.0	0	0	0.2	0.6
SP-7	6.4	51.8	10.6	7.3	6.2	6.6	4.5	1.4	0	0.7	6.4	2.1	0	0.7	1.9
SP-8	6.50	57.3	13.5	11.3	5.5	4.5	0.2	0	0	0	2.0	0.2	0	0.2	4.6
SP-9	6.55	1.2	17.1	9.0	1.0	6.6	2.9	1.5	1.0	0	5.4	2.2	0	0	2.2
Average		55.4	12.8	9.1	3.7	4.7	2.1	1.0	1.2	0.	6.5	0.9	0	0.4	1.8
Total average		55.0	10.8	7.6	3.7	5.0	2.1	1.6	2.1	0.6	7.9	1.7	0	0.4	1.6

Table 3. Recalculated parameters for assigned framework grains [12].

Framework grains	QtFL	QmFLt	QpLvmLsm	LmLvLs
Quartz(single crystal)	Qt	Qt		
Polycrystalline quartz	Qt	Lt	Qp	
Feldspar	F	F		
Phyllite	L	Lt	Lsm	Lm
Fine grained schist	L	Lt	Lsm	Lm
Slate	L	Lt	Lsm	Lm
Volcanic grain	L	Lt	Lvm	Lv
Shale	L	Lt	Lsm	Ls
Siltstone and fine grains sandstone	L	Lt	Lsm	Ls
Chert	Qt	Lt	Qp	Ls

Table 4. Recalculated modal framework composition of the Late Pleistocene – Holocene sands (recalculated from Table 2).

Sample no.	**Depth (m)**	**QtFL %**			**QmFLt %**		
		Qt	**F**	**L**	**Qm**	**F**	**Lt**
Kachubaniapara borehole							
KP-1	3.51	76.21	11.64	12.15	67.40	12.39	20.21
KP-2	4.80	66.41	4.01	29.58	65.77	4.08	30.14
KP-3	4.88	79.23	10.52	10.24	74.70	10.97	14.33
Shonaichari borehole							
SC-1	1.73	82.5	4.60	12.90	79.86	4.91	15.22
SC-2	6.40	69.57	8.23	22.20	60.09	8.65	31.25
SC-3	12.57	77.69	13.28	9.022	63.22	16.11	20.66
SC-4	14.17	91.55	3.65	4.80	91.23	3.79	4.97
SC-5	15.69	86.68	8.73	4.58	80.03	9.28	10.67
Shonarpara borehole							
SP-1	1.73	90.19	1.63	8.17	83.34	1.74	14.92
SP-2	1.98	86.60	6.22	7.19	82.71	6.56	10.73
SP-3	3.15	86.80	9.39	3.80	79.30	11.29	9.41
SP-4	3.51	75.59	4.30	20.11	74.38	4.31	21.31
SP-5	4.78	81.12	10.15	8.73	72.47	12.73	14.80
SP-6	5.03	89.61	6.36	4.02	84.10	6.92	8.98
SP-7	6.4	79.52	11.60	8.88	70.80	12.56	16.64
SP-8	6.50	92.71	4.99	2.31	85.16	5.66	9.18
SP-9	6.55	82.08	9.98	7.94	79.06	11.02	9.90

NOTE. KP = Kachubaniapara borehole, SC = Shonaichari borehole, SP = Shonarpara borehole.

Provenance Interpretation According to Modal Analysis QtFL and QmFLt Triangular Diagrams

Compositional fields characteristic of different provenances are shown on QtFL and QmFLt triangular diagrams (Figure 2A, 2B). These diagrams show nominal fields for discrimination of sands derived from various types of provenances in (1) continental block, for which sediment sources are on shields and platforms or in faulted basement blocks; (2) magmatic arc, for which the sources are within active arc orogens of island arcs or active continental margins and (3) recycled orogen, for which sources are deformed and uplifted strata sequences in subduction zones, along collision orogens, or within foreland fold-thrust belts [14],[15].Recalculated point count data are shown in Table 4, have been plotted on QtFL and QmFLt triangular diagrams (Figure 2). The QtFL plot of the Late Pleistocene- Holocene sands are characterized by high quartz content, low to moderate amounts of unstable lithic fragments and low feldspar which is indicative of recycled orogen provenance which shows similarity with sands of the Dupi Tila formation [47]. The QmFLt plot is dominated by high monocrystalline quartz, moderate to high total lithic grains and low feldspar which falls into the field of quartzose recycled orogene provenance which also shows the similarity with sand of Dupi Tila formation [47].

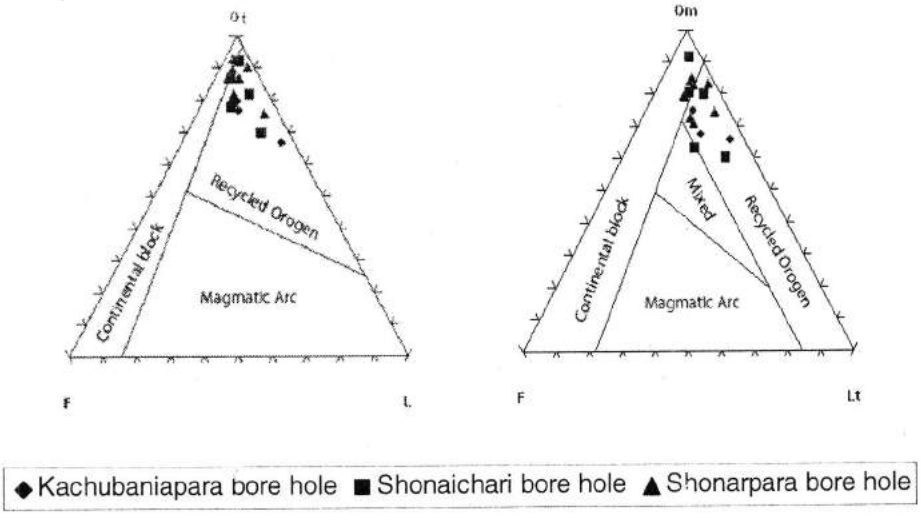

Figure 2. QtFL and QmFLt triangular diagrams for the Late Pleistocene-Holocene sands [15].

QpLvmLsm AND LmLvLm Triangular Diagrams

QpLvmLsm and LmLvLs triangular diagrams of lithic components are more indicative of provenance and tectonic setting. Both the plots are useful in differentiating sand derived from different tectonic settings such as suture belts, magmatic arcs and rifted continental margins [23]. Recalculated point-count data are shown in Table 5. The QpLvmLsm plot of the Late Pleistocene- Holocene sands (Figure 3A) shows high content of sedimentary and metasedimentary lithic grains and moderate to high content of polycrystalline quartz. The LmLvLs plot (Figure 3B) is dominated by sedimentary and low grade metamorphic lithic grains, but tow content of volcanic lithic grains content. Both the plots show that the Late Pleistocene-Holocene sands may be derived from collision orogens, i.e., suture belts and deposited in a remnant ocean basin.

Table 5. Recalculated point-count data for plotting QpLvmLsm and LmLvLs triangular diagrams of the Late Pleistocene- Holocene sands (recalculated from Table 2).

Sample no.	Depth (m)	QpLvmLsm%			LmLvLs%		
		Qp	Lvm	Lsm	Lm	Lv	Ls
Kachubaniapara borehole							
KP-1	3.51	44.32	0	55.68	6.23	0	93.77
KP-2	4.80	1.73	0	98.27	15.49	0	84.51
KP-3	4.88	18.05	0	81.95	37.16	0	62.84
Shonaichari borehole							
SC-1	1.73	16.23	0	83.77	26.79	0	73.21
SC-2	6.40	4.50	0	95.50	36.09	0	63.91
SC-3	12.57	64.57	0	35.43	13.92	0	86.08
SC-4	14.17	57.01	0	42.99	14.26	0	85.74
SC-5	15.69	70.42	0	29.58	14.29	0	85.71
Shonarpara borehole							
SP-1	1.73	54.08	0	45.92	8.56	0	91.44
SP-2	1.98	78.12	0	21.88	3.02	0	96.98
SP-3	3.15	100	0	0	0	0	100
SP-4	3.51	0.72	0	99.28	10.73	0	89.27
SP-5	4.78	70.77	0	29.23	13.55	0	86.45
SP-6	5.03	100	0	0	0	0	100
SP-7	6.4	35.13	0	64.87	25.03	0	74.97
SP-8	6.50	96.33	0	3.67	10.09	0	89.91
SP-9	6.55	43.29	0	56.71	29.06	0	70.94

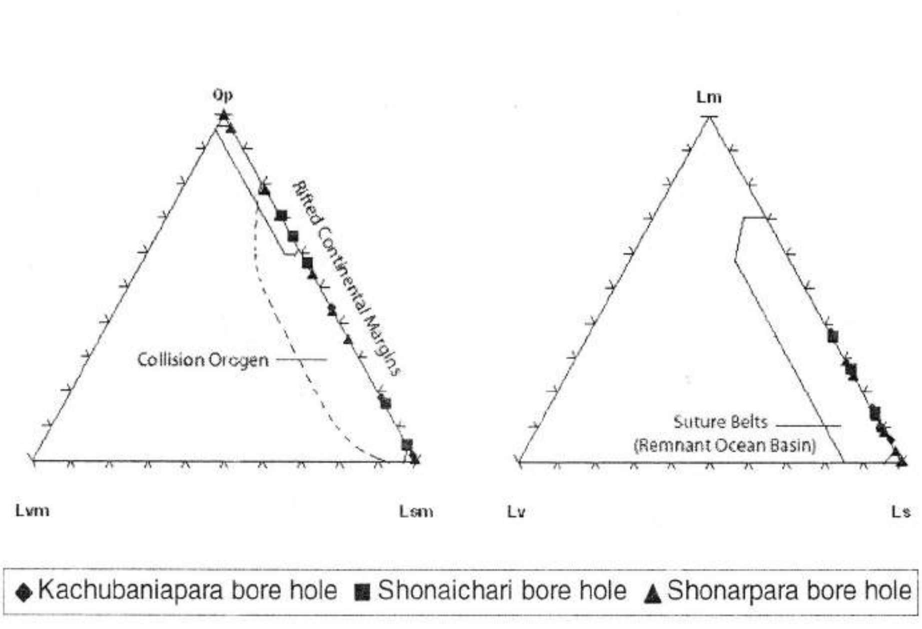

Figure 3. QpLvmLsm and LmLvLs triangular plots of Late Pleistocene-Holocene sands.

Source Rock Complexes

Polycrystalline quartz of metamorphic origin is common in these sediments of the study area as revealed from sutured boundaries between the crystals. Scholle (1979) suggested that polycrystalline quartz with ten or more individual crystals is an excellent indicator of metamorphic sources, whereas sand size polycrystalline quartz with five or more crystals is usually derived from gneisses [11], [41]. Polycrystalline quartz composed of two crystals with straight intercrystal boundaries indicating plutonic source also occurs but this type of polycrystalline quartz is common in the Late Pleistocene- Holocene sands. The presence of monocrystalline quartz could be the result of intense reworking of the sediments and/or may bear the character of high quartz content of the source material, whereas chert sources could be either radilarite or reworked chert nodules of the carbonate. A wide range of metamorphic source terrain is indicated by the presence of garnet, kyanite, epidote, staurolite, for the Late Pleistocene- Holocene sands (Figure 4A). As source rock, low grade metamorphic rocks are indicated by the presence of chloritoid, epidote, and chlorite [33]. Assemblage of epidote and staurolite is suggestive of dynamo-thermal metamorphic source rock [17], [25], [32].While garnet, rutile, and kyanite may be derived from varying grade of metamorphic rocks. The possible sources of garnet and staurolite are mica schist complexes [16]. According to Heinrich (1956), the presence of tourmaline and epidote is suggestive of derivation of the sediments from low to medium grade metamorphic provenance. Staurolites point to medium grade metamorphism [20].The ZTR index is consistent with high mineralogical maturity of sediments [22]. ZTR composition suggests the contribution of a significant proportion of the clastic sediments from crystalline sources. The possible sources of stable minerals such as zircon, tourmaline, rutile, and apatite are gneisses and granitoid rocks. Zircon-Tourmaline-Rutile triangular diagram (Figure 4B) shows predominance of Zircon in the Late Pleistocene- Holocene sands at the study area. The sub-rounded to rounded stable minerals particularly zircon and apatite present in this sands indicating multiple recycling of these minerals which suggest that these minerals may be derived from recycled sedimentary source terrains. Tourmaline grains are generally non-polycyclic with rarely polycyclic indicating a crystalline rock complex as a major source. Blatt et al., (1972) worked out a metamorphic provenance for brown and pale brown varieties of tourmaline. Tourmaline is known as low-grade metamorphic complex [10].

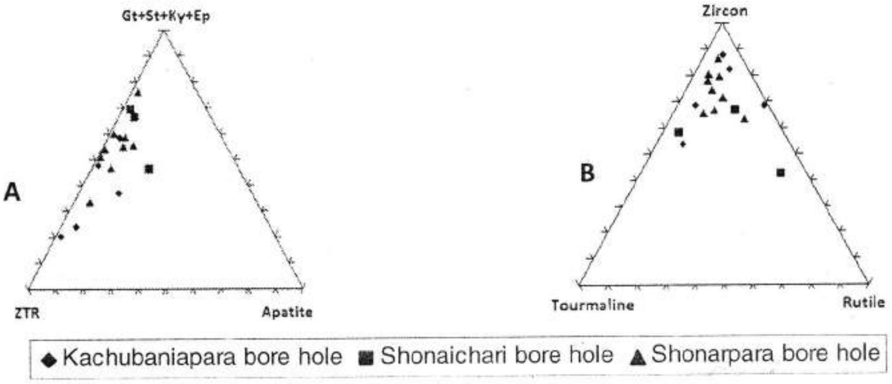

Figure 4(A). Triangular plot of Gt+St+Ky+Ep (Garnet+Staurolite +kyanite+ epidote)-ZTR (Zircon+Tourmaline+Rutile)-Apatite. (B) Zircon-Tourmaline-Rutile triangular plot of Late Pleistocene- Holocene sands of the studied area.

Provenance Interpretation According to Geochemical Analysis

Geochemical analysis of sediments may indicate the possible plate tectonic setting. Several classifications have been proposed to discriminate sediments from various origin and tectonic setting [8],[11],[27],[29],[37],[39]. The classification of Roser & Korsch (1988) is based on major element discriminate function and distinguished four provenance of tectonic setting. In this discriminant diagram (Figure 5A)[38], most of the Late Pleistocene-Holocene sands plot on P4 field which represents the recycled mature polycyclic quartose detritus shows similar in province field of the Dupi Tila Formation[9],[21]. From plot of K_2O/ Na_2O versus Fe_2O_3+MgO [38] of the samples indicate the recycled tectonic source which is in agreement with the known P4 tectonic setting of Greenland (New Zealand) (Figure 5B) which also shows similarity with the sands of Dupi Tila formation [9]. SiO_2 content versus K_2O/ Na_2O (Figure 6A) as well as SiO_2/ Al_2O_3 versus K_2O/ Na_2O (Figure 6B) of the samples were used to decipher the tectonic setting [38].The Late Pleistocene- Holocene sands of the study area fall astride between passive margin (PM) and active continental margin (ACM) which are in accordance with sands of Dupi Tila Formation [9].

Table 6 Major elements composition (wt.%) of the Late Pleistocene-Holocene sands of Reju khal (Shonarpara and Shonaichari borehole) Cox's Bazar and Kachubaniapara borehole, Teknaf.

Sample no.	Depth (m)	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	Na_2O	K_2O	CaO	MgO	P_2O_5	LOI	Total
Kachubaniapara borehole													
KP-01	1.98	76.8	7.95	5.39	2.17	0.14	0.96	1.08	0	2.4	0.21	1.2	98.3
KP-02	3.25	71.8	6.78	3.74	0.66	0.25	1.5	1.2	3.36	2.6	0.14	6.2	98.23
KP-03	3.51	83	7.23	1.65	0.19	0	0.78	1.38	0	2	0.09	2.4	98.72
KP-04	4.72	84.3	2.13	5.37	0.88	0.40	*	2.09	6.6	*	*	*	101.76
KP-05	4.8	68.76	7.4	5.65	0.48	0.44	*	1.74	15.35	*	*	*	99.82
Shonaichari borehole													
SC-01	12.57	79.6	5.12	3.63	0.11	0	0.54	0.72	0	0.6	0.1	8.8	99.22
SC-02	14.17	62.5	2.77	9.47	0.48	0.63	*	2.36	0.621	*	*	*	95.99
SC-03	15.7	72.2	7.78	10.34	0.29	0	0.42	1.2	0	1	0.29	5.8	99.32
Shoharpara borehole													
SP-01	1.73	83.8	3.83	5.5	0.64	0.0716	*	2.28	0.45	*	*	*	96.57
SP-02	1.98	89.2	4.12	1.1	0.22	0	0.48	0.78	0	0.8	0.05	1.6	98.35
SP-03	3.51	87.5	3.57	5.33	0.55	0.03	*	1.89	0.34	*	*	*	99.20
SP-04	4.78	89.51	2.38	5	0.34	0.07	*	1.19	0.89	*	*	*	98.31
SP-05	5.03	81.74	2.65	5.61	0.65	0.08	*	2.89	0.36	*	*	*	93.98
SP-06	6.4	92.94	2.41	2.48	0.33	0.03	*	1.24	0.52	*	*	*	99.95
SP-07	6.5	83.6	3.93	4.51	0.2	0.08	0.48	0.6	0	1	0.11	3.8	92.92
SP-08	6.55	84.46	2.25	8.96	0.416	0.20	*	1.95	1.17	*	*	*	99.40
Total Average		80.92	4.52	5.23	0.54	0.15	0.32	1.54	1.85	0.65	0.06	1.86	98.13

NOTE: KP = Kachubaniapara borehole; SP = Shonarpara borehole; SC = Shonaichari borehole; * = Value not detected (below detection limit 1).

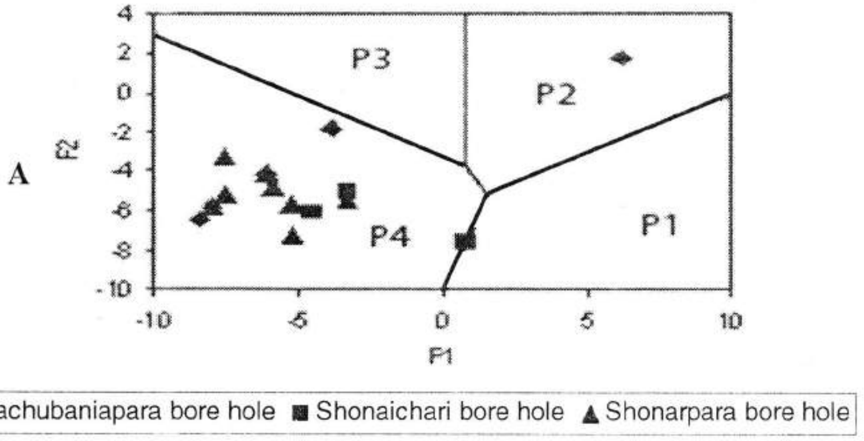

Figure 5 A. Plot of discriminant functions F1 and F2 for samples of the Late Pleistocene- Holocene sands of the Reju khal (Shonarpara and Shonaichari borehole) Cox's Bazar and Kachubaniapara bore hole, Teknaf. Provenance fields [38]; P1= dominantly basaltic, andesitic rocks; P2= dominantly andesitic rocks; P3= acid plutonic and volcanic rocks; P4= matured polycyclic continental sedimentary rocks.

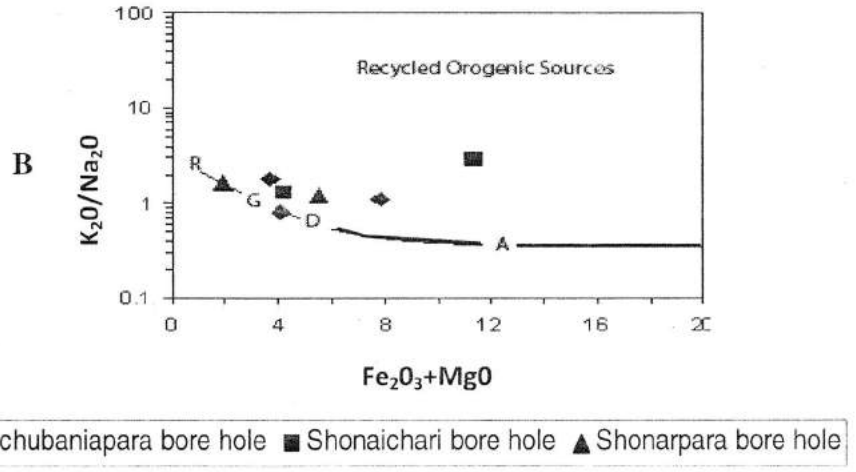

Figure 5 B. Plot of K_2O/ Na_2O versus Fe_2O_3 + MgO, where letters A, D, R and G mean andesite, dacite, rhyolite and granite respective from the southern Welsh Basin, edge (PM) of continents. The solid line connecting the letter A, D, R and G, is the average basalt (off scale at 48 % SiO_2). Samples above the line represent the recycled orogenic sources (known data from Green Land terrain [38].

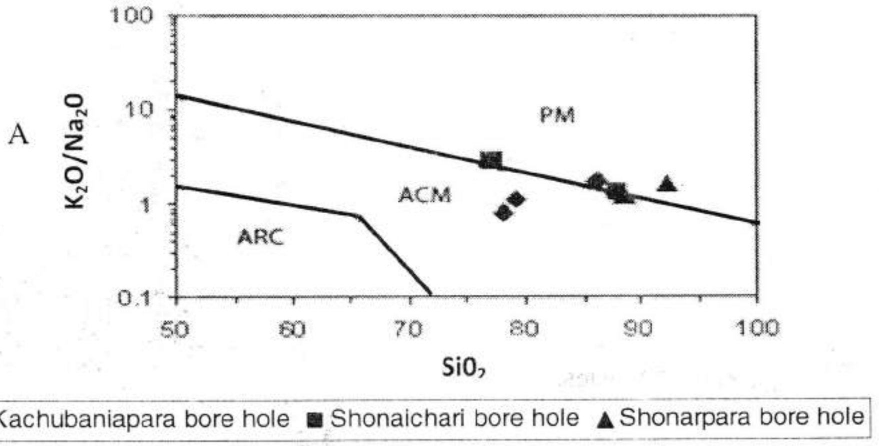

Figure 6A. Tectonic discrimination diagram of the Late Pleistocene-Holocene sands of Reju khal (Shonarpara and Shonaichari borehole) Cox's Bazar and Kachubaniapara borehole, Teknaf) based on K_2O/ Na_2O versus SiO_2. Where ACM = Active Continental Margin, ARC = Oceanic Island Arc and PM = Passive Continental margin [38].

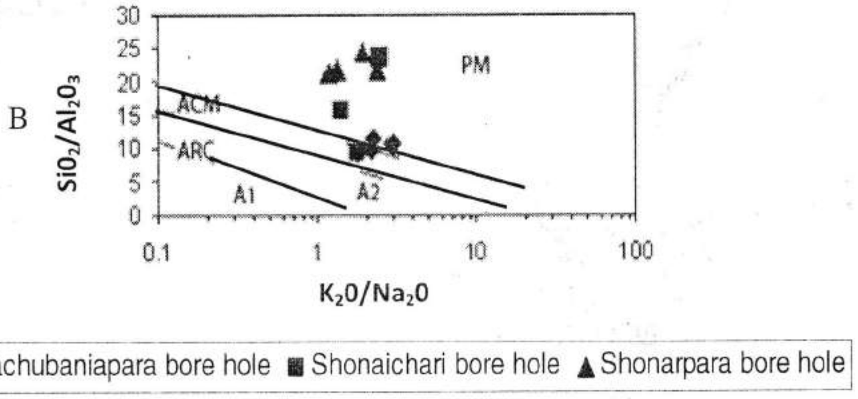

Figure 6B. SiO_2/ Al_2O_3 versus K_2O/ Na_2O relations of samples of the Late Pleistocene- Holocene sands. A1 = Arc setting, A2 = Evolved arc setting and PM = Passive margin [37].

Weathering in the source area

In deciphering the weathering of sedimentary rocks, Nesbitt & Young (1982) proposed the CIA value (Chemical Index of Alteration) (Table 7) using molecular proportion of some bulk elements [30]. The chemical index of alteration (CIA) monitors the progressive alteration of some plagioclase and potassium feldspars to clay minerals. The CIA value was calculated using equation,

$$CIA= [Al_2O_3/ (Al_2O_3 +CaO^*+Na_2O+K_2O]*100$$

Where CaO* represents the amount of CaO incorporated in the silicate phases. Nesbitt & 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 weathering in the source areas whereas low values (i.e., 50 or less) indicate unweathered source areas.

Table 7. Values of Al_2O_3 – CaO^* +Na_2O –K_2O for CIA (Chemical Index of alteration) ternary diagram.

Sample no.	**Depth(m)**	**CIA**	**CaO^*+Na_2O**	**Al_2O_3**	**K_2O**
KP-01	1.98	78	0.01	0.08	0.01
KP-02	3.25	42	0.08	0.07	0.01
KP-03	3.51	74	0.01	0.07	0.01
KP-04	4.72	13	0.12	0.02	0.02
KP-05	4.8	20	0.27	0.07	0.02
SC-01	12.57	78	0.01	0.05	0.01
SC-02	14.17	52	0.01	0.03	0.02
SC-03	15.7	86	0.00	0.08	0.01
SP-01	1.73	61	0.01	0.04	0.02
SP-02	1.98	73	0.01	0.04	0.01
SP-03	3.51	57	0.01	0.04	0.0
SP-04	4.78	45	0.02	0.02	0.01
SP-05	5.03	46	0.01	0.03	0.03
SP-06	6.4	51	0.01	0.02	0.01
SP-07.	6.5	77	0.01	0.04	0.01
SP-08	6.55	35	0.02	0.02	0.02

CIA values for the Late Pleistocene- Holocene sands of the study areas range from 13 to 86 with an average (~ 56). These wide ranges of CIA value indicate that the Late Pleistocene – Holocene sands of the study areas were derived from the least weathered to significant weathered zones of the source area. These CIA values also plotted in A-CN-K diagram which reveals that the samples are plotted on A-K edge that is indicating chemical different zones least to significant weathering of the source area (Figure 7). Hossain *et al.*, (2010) found that the average CIA value of sands of Dupi Tila Formation is (~ 67) whereas in the studied area the average value of CIA is (~ 56) indicating dominantly moderate chemical weathering of the source area [21].

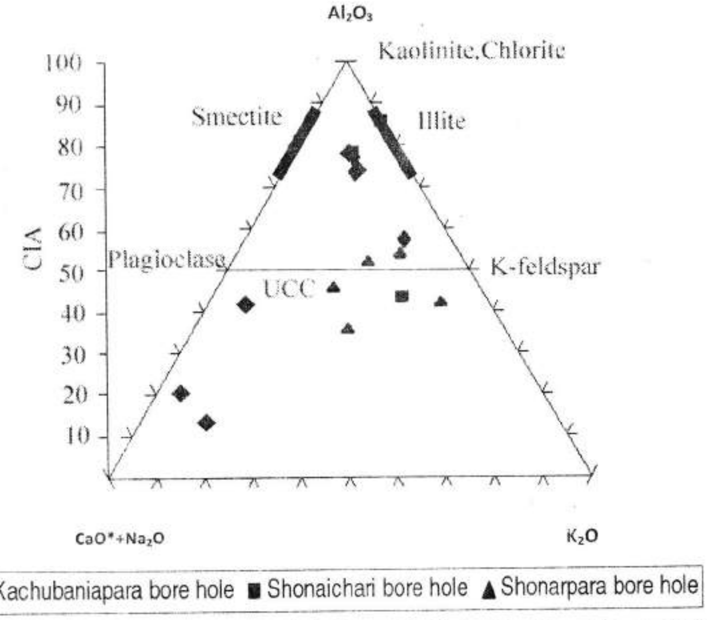

Figure 7. CIA ternary diagram, Al_2O_3 - CaO^*+Na_2O - K_2O [30]; CaO^* = CaO in silicate phase.

Paleoclimate of the provenance area

Climate affects sandstone composition through its influence on pedogenic processes which brings about parent rock destruction [46]. Yong *et al.*, (1975) and Basu (1976) have shown that if the same phaneritic crystalline parent rock is weathered in contrasting wet and dry climates, under comparable conditions of relief, the detritus produced will have a framework composition unique to the climate in which it is produced [7], [50]. They have demonstrated that ratios of feldspar plus lithic fragments to polycrystalline quartz or to total quartz are sensitive indicators of the climatic heritage of sand. This climatic signature will be preserved in the sands when they are deposited if such sands do not suffer sedimentary differentiation via long distance transport and deposition in high energy littoral environments [45]. The framework composition of the Holocene-Late Pleistocene sands QFL plot (Figure 8) shows that the climatic conditions during weathering in the source areas were semi-arid to humid. The bivariant log/ log plot of the ratio of polycrystalline quartz to feldspar plus rock fragments against the ratio of total quartz to feldspar plus rock fragments (Figure 9) reveals that the sands are weathered in the semi-arid to humid climatic conditions.

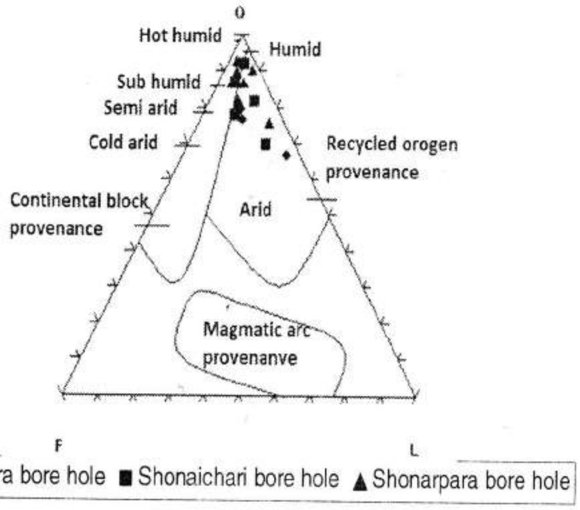

Figure 8. QFL triangular diagram for paleoclimate interpretation of the provenance areas of the Holocene-Late Pleistocene sands [46]. Provenance field boundaries are taken from [14].

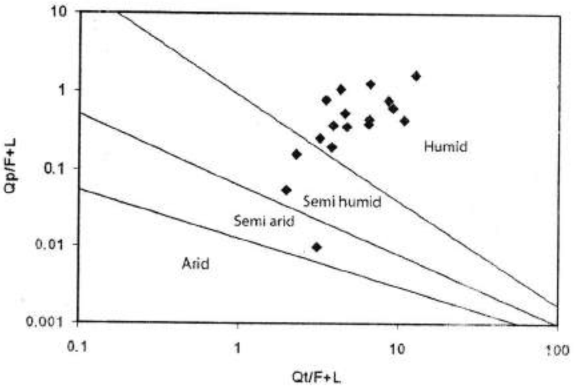

Figure 9. Bivariant log/ log plot of the ratio of polycrystalline quartz to feldspar plus rock fragments against the ratio of total quartz to feldspar plus rock fragments for the Holocene- Late Pleistocene sands [46].

Discussion and Conclusions

The QtFL and QmFLt triangular model plots reveal that the sediments may have a quartose recycled to craton interior composition. The QtFL shows high quartz content, low feldspar and low amounts of unstable lithic grains. The QmFLt plot shows high monocrystalline quartz, high total lithic grains and low feldspar. The QtFL and QmFLt mode represent quartose recycled orogen provenance although few also represent craton interior provenance which are in agreement with the sands of Dupi Tila Formation [9]. The LmLvLs and QpLvmLsm reveal high amount of sedimentary and metamorphic grains and low/ absence of volcanic lithic grains. They are indicative of recycled orogen province, such as fold-thrust province or a collision suture zone. All these characteristics suggest granitic as well as sedimentary and low grade metamorphic terrains and deposited in a remnant ocean basin [15]. The geochemical characteristics suggest the passive margin to slightly active margin tectonic setting for the Holocene- Late Pleistocene sands of the Reju khal, Cox's Bazar and Teknaf area. It preserves the signatures of recycled provenance field which have undergone least to significant chemical weathering. The CIA values of sands indicates that the Holocene- Late Pleistocene sands were derived from the least to significant zones of weathering in the source profiles and likely from the rapid erosion of fast rising recycled orogens. As revealed from the heavy mineral studies, medium to high-grade metamorphic terrains are reflected in the source area from the common occurrence of garnet, staurolite, kyanite as well as sillimanite. The presence of apatite, zircon, and rutile indicates the existence of granitoid source terrain. The high Himalayan tectonic unit is composed of various metamorphic rocks. The garnet, amphibole and epidote are the major constituents in the High Himalaya [49]. Based on petrographical data of metamorphic and granitic rocks from the Himalayas, garnet is a common mineral in both the biotite schist and gneiss, as well as calcic amphibole in the High Himalaya is predominantly a bluish-green hornblende [49]. The Lesser Himalayan crystalline basement is built up of low to medium (garnet + kyanite + staurolite) grade terrains. Kyanite is a typical marker of the High Himalaya Crystalline, but is also found locally in Lesser Himalaya [31]. In the Indo-Burman ranges, thick Eocene to Oligocene turbidite successions and Upper Miocene to Pleistocene molasse sediments [48] are the significant rocks successions, whereas crystalline rocks are uncommon [24]. The source rocks of these sands were dominantly supracrustal rocks. From the heavy minerals study, it appears that the blue-green amphiboles in the Miocene units in the Bengal Basin, suggests unroofing of arc and ophiolitic rocks from suture zones of the Himalayas and/or the Indo-Burman ranges [48]. Uddin & Lundberg (1998b) also concluded that the relative abundance of various aluminum silicates and epidote minerals in the Tipam and Dupi Tila

Formations indicate orogenic input from the erosion of low- to high-grade metamorphic rocks in the orogenic belts and further systematic unroofing of progressively deeper level units in the eastern Himalayas [48]. The heavy mineral suites reflect that the probable source of the clastics which have contributed to the study area of interest is located in the north, northwest and east-northeastern part of Bangladesh. These detrital grains could have been derived from crystalline and sedimentary deposits of the Himalayas, Rajmahal hills, Shillong Plateau and Indo-Burman Ranges [35].

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