Cenozoic history of the Himalayan-Bengal system: Sand composition in the Bengal basin, Bangladesh

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ABSTRACT

Stratigraphic sequences preserved in the Bengal basin provide detrital information that documents a significantly older history of the eastern Himalaya than that available from Ocean Drilling Program and Deep Sea Drilling Project cores recovered from the Bengal fan. The Bengal basin, formed as a result of the Himalayan collision, is located at the juncture of the Indian craton to the west, the Shillong massif and the Himalayan belt to the north, and the Indo-Burman ranges to the east. Modal analyses of Eocene and Oligocene sandstones of the Cherra, Kopili, and Barail Formations document compositions that are dominated by subangular monocrystalline quartz grains with scarce to no feldspar grains, and few lithic fragments (Cherra and Kopili: $Qt_{99}F_1L_0$; Barail: $Qt_{90}F_3L_7$; Qt—total quartz, F—feldspar, L—lithic fragments). These compositions are similar to sands derived from the Indian craton, suggesting that they underwent intense chemical weathering, likely in a source with low relief and considerable transport. Himalayan tectonism during this time was probably significantly more distant from the Bengal basin than at present.

Sandstones of the Miocene Surma Group (Bhuban and Boka Bil Formations) are rich in feldspar grains, argillite, and very low-grade metamorphic lithic fragments (Bhuban: $Qt_{66}F_{15}L_{19}$; Boka Bil: $Qt_{57}F_{23}L_{20}$) relative to older sandstones, suggesting onset of uplift and erosional unroofing in the eastern Himalaya, and initiation of stream systems supplying orogenic detritus to the Bengal basin. Sands of the upper Miocene to Pliocene Tipam Group and the Pliocene–Pleistocene Dupi Tila Sandstone contain abundant argillitic and low- to medium-grade metamorphic lithic fragments and feldspar grains (Tipam: $Qt_{61}F_{19}L_{19}$; Dupi Tila: $Qt_{70}F_{13}L_{17}$), suggesting continued orogenic unroofing. These younger sands are rich in potassium feldspar (P/F = 0.30, 0.20) relative to plagioclase (P)-rich Bhuban and Boka Bil sandstones (P/F = 0.66 and 0.48), suggesting a granitic source, probably the Miocene leucogranites of the High Himalayan Crystalline terrane.

These results document for the first time contrasts in orogenic history recorded in the Bengal system vs. western Himalayan foreland basins. Sands deposited in the Bengal basin are generally more quartzose and less lithic than those from the western Himalayan foreland basins, and pre-Miocene strata in the Bengal system show little to no evidence of orogenic activity. In part, this probably reflects west to east progression of the Himalayan collision, but it probably also results from sedimentary systems propagating southward, ahead of the advancing mountain belt as it has been consuming the remnant ocean basin trapped between the Indian craton and the Burmese block.

INTRODUCTION

The collisional history of the Himalayan mountain chain, developed along a region once occupied by the west-northwest–south-southeast Tethys ocean, is recorded in sediments deposited in subsiding foreland basins to the south (Burbank et al., 1996), including the Bengal basin of Bangladesh (Fig. 1). This basin is predominantly a huge delta complex, covering about 144 000 km^2 onshore and 63 000 km^2 offshore, and contains as much as 16 km of synorogenic Cenozoic sequences derived from the eastern Himalayas and the Indo-Burman ranges.

The timing of initial collision of the Indian plate with Eurasia has been debated (Cochran, 1990; Butler, 1995). Suggestions range from the Cretaceous-Tertiary boundary, on the basis of paleomagnetic work (Klootwijk et al., 1992), to various times in the Eocene (Rowley, 1996). An early Eocene collision between Asia and sedimentary rocks of the leading edge of India (a so-called "soft" collision) at about the time of magnetic anomaly 22 at 53 Ma is suggested on the basis of a 50% decrease in spreading rates in the central Indian Ocean (Sclater and Fisher, 1974). A middle Eocene date is based on the similarity of mammalian fossils between India and Mongolia (Sahni and Kumar, 1974), and on paleomagnetic data and plate motions (Dewey et al., 1988). A late Eocene collision has been proposed on the basis of radiometric dating of plutonic rocks of the Trans-(Tethys) Himalaya, inferred to represent the end of subduction of oceanic crust at the leading edge of India (Honeggar et al., 1982; Petterson and Windley, 1985). Beck et al. (1995) suggested, on stratigraphic grounds, that initial collision occurred between 66 and 55.5 Ma; there is firm evidence of collision by 49 Ma (early–middle Eocene time). This is considerably earlier than the middle Miocene age, originally postulated by Gansser (1964), for initial uplift of the Himalaya.

The collision between India and Eurasia did not take place simultaneously along the entire Himalayan belt (Dewey et al., 1989; Burchfiel, 1993). From 45 Ma to the present, India has rotated 33° counterclockwise, the motion relative to Asia having changed from predominantly northeast to more northerly, accompanied by a 50% reduction in velocity. Most geological information constraining the timing of collision has been produced from the western portion of the system. The stratigraphic record of the collision has been studied in some detail in the western Himalaya, beginning with the classic study of Krynine

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GSA Bulletin; April 1998; v. 110; no. 4; p. 497–511; 11 figures; 2 tables.

(1937); relatively few hard data on collisional timing have been reported from the eastern Himalayan foreland basin. Distal eastern equivalents of the Siwalik sequences have been studied in the Bengal fan (Fig. 1), in seismic surveys (Curray, 1991), and on two drilling legs (Deep Sea Drilling Project [DSDP] Leg 22 and Ocean Drilling Program [ODP] Leg 116; Ingersoll and Suczek, 1979; Cochran, 1990; Amano and Taira, 1992). Drilling has recovered strata as old as about 18 Ma, and detrital geochronology and isotopic studies of these strata indicate that orogenesis had begun prior to this time (e.g., Copeland et al., 1990; France-Lanord et al., 1993, 1994).

The Bengal basin, the land pathway that links the Himalaya to the Bengal fan, is a modern collisional foreland basin that contains both pretectonic and syntectonic stratigraphic sequences. These sequences provide detrital information on the eastern Himalaya and record a significantly older history than that available from ODP and DSDP cores recovered from the Bengal fan. Because of its location between the eastern Himalaya and the Indo-Burman ranges, Bengal basin sequences contain detrital sediments that yield information potentially relating to the uplift and unroofing history of both orogens. However, few detailed provenance studies have been carried out on the sediments of the Bengal basin. Quantitative analyses of sands derived from the developing mountain belt may help to evaluate the initiation and evolution of orogenic uplift and consequent exhumation in this active continental collision.

This paper reports the results of a petrographic investigation of Eocene through Pleistocene sand and sandstone of the Bengal basin, in order to interpret the tectonic history of the eastern Himalayas and the Indo-Burman ranges. Specifically, this paper addresses the following questions. (1) How has the composition of Bengal basin sandstones varied through Cenozoic time, and what do the changes observed suggest about orogenic processes? (2) What source-rock types are suggested by sandstone composition? (3) Can sandstone modal data help constrain the unroofing history of the eastern Himalaya, in particular the early stages of orogenesis, predating the record obtained from the Bengal fan?

BORDERING OROGENS

The 2500 by 300 km east-west Himalaya and the 1500 by 230 km north-south Indo-Burman ranges formed as India collided with Eurasia and the Burma platelet. The Himalayan belt is made up of four longitudinal lithotectonic units, juxtaposed along generally north-dipping thrust faults (Fig. 1). The lithologic and tectonic characteristics of these belts remain constant over long distances along strike (e.g., Gansser, 1964; Windley, 1983). From south to north, these units are (1) the Sub-

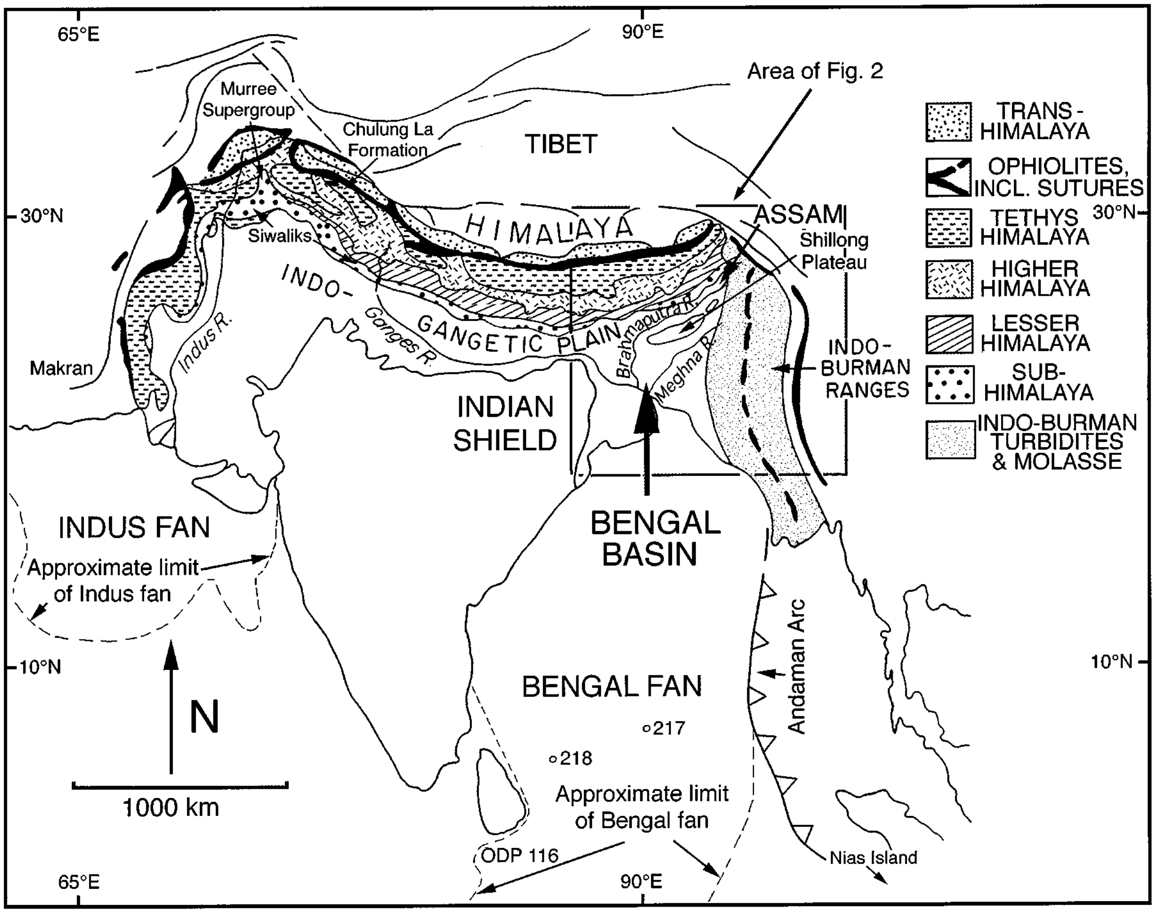

Figure 1. Location map of Bengal basin and adjacent regions, showing lithotectonic belts of Himalayan and Indo-Burman orogens and locations of units discussed in the text. Indian shield and Shillong Plateau expose Precambrian crystalline rocks. Deep Sea Drilling Project Sites 217 and 218 and area drilled by Ocean Drilling Program Leg 116 are shown on Bengal fan. Modified from Sengupta et al. (1990), Critelli and Garzanti (1994), and Uddin and Lundberg (1998).

Himalaya, representing the Miocene to Pleistocene molasse deposits of the Siwaliks, separated from the Indo-Gangetic Plain by the Main Frontal thrust; (2) the Lower, or Lesser, Himalaya, which represent southward-directed thrusts and nappes composed of Precambrian and Paleozoic sedimentary rocks, crystalline rocks, and granites; (3) the Higher Himalaya, located north of the Main Central thrust, composed of schists, gneisses, and granites, and located across the Indus-Tsangpo suture; and (4) the Tethys Himalaya and Trans-Himalaya, representing fossiliferous Cambrian to Eocene sedimentary rocks (shallow-water deposits, such as limestone, calcareous sandstone, and dolomite), batholiths, and volcanic rocks. The suture between India and Asia is marked by ophiolitic rocks, and is located south of the Trans-Himalaya and locally adjacent to the Precambrian Central Gneiss of the Higher Himalayas (Jain and Kanwar, 1970).

The Indo-Burman ranges are made up mainly of Cretaceous to Eocene pelagic strata overlain by thick Eocene to Oligocene turbidites and upper Miocene to Pleistocene molasse (Fig. 2; Brunnschweiller, 1966; Ni et al., 1989). Several authors (e.g., Fitch, 1970; Ni et al., 1989; Sengupta et al., 1990; Mitchell, 1993) have suggested that the Indo-Burman ranges are trench deposits containing ophiolite melanges scraped off the subducting Indian plate. East-west crustal compression is still active in the Indo-Burman ranges, as evidenced by north-trending folds of Pliocene–Pleistocene strata (Le Dain et al., 1984). Studies of focal mechanisms suggest that the basement of the Indian plate below the Indo-Burman ranges is moving north with respect to the rest of Asia (Ni et al., 1989; Chen and Molnar, 1990), producing right-lateral slip along the Sagaing and other faults located east of these ranges (Fig. 2; Le Dain et al., 1984).

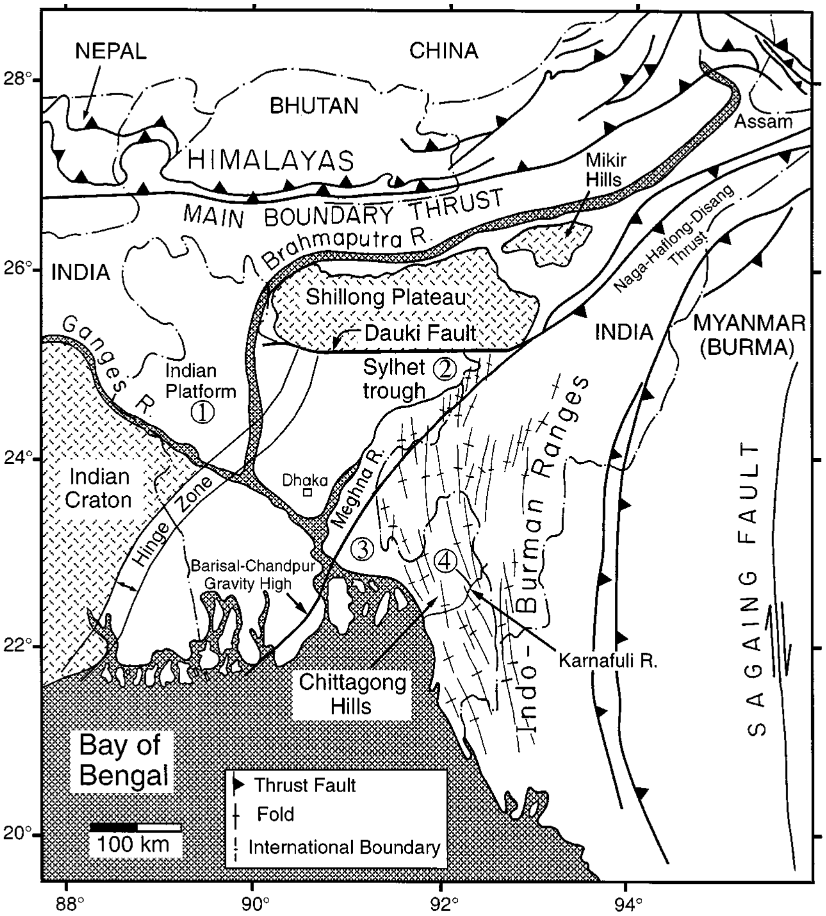

Figure 2. Regional tectonic map showing tectonic elements of the Bengal basin. Hinge zone separates the shallow "Indian platform" area from the region of thicker sediment accumulation. The Barisal-Chandpur gravity high represents the boundary between continental crust to the west and oceanic crust to the east. Modified from Johnson and Nur Alam (1991) and Uddin and Lundberg (1998). Circled numbers 1, 2, 3, and 4 represent approximate locations of the stratigraphic columns shown in Figure 3.

GEOLOGICAL FRAMEWORK OF THE BENGAL BASIN

The Bengal basin contains the confluence of two of the great river systems of the world, the Ganges, flowing from the west, and the Brahmaputra, flowing from the north; both originate in the Himalaya. Major streams from the Indo-Burman ranges also join this system in Bangladesh, including the Meghna, which flows from the northeast, and the Karnafuli, which enters Bangladesh from the southeast. The basin is bounded by the Indian craton to the west; the Shillong Plateau (a Precambrian massif) to the adjacent north; and is open on the south, extending into the Bay of Bengal, a remnant-ocean basin (Graham et al., 1975; Ingersoll et al., 1995) containing the Bengal deep-sea fan (Figs. 1 and 2).

The Bengal basin has two broad divisions: (1) the "Indian platform" (also known as the "stable shelf" area) to the northwest and west, and (2) the area known as the "Bengal foredeep," a region of much thicker sediment accumulation (Fig. 2). The Bengal foredeep includes the Sylhet trough (also known as the Surma basin) in the northeastern Bengal basin and the Chittagong Hill Tracts in eastern Bangladesh, which contain some of the best studied sequences of the Bengal basin.

The present sediment fill of the Bengal basin is asymmetric, the greatest thicknesses being near its northern and eastern margins. Seismic-reflection studies (Curray, 1991) show that sedimentary and metasedimentary rocks beneath the Bangladesh continental shelf are at least 22 km thick; 16 km are inferred to be collisional deposits that overlie 6 km of precollisional strata interpreted as buried continental rise and pelagic deposits.

STRATIGRAPHY

The stratigraphic framework of the Bengal basin was originally established on the basis of exposures along the eastern fold belts, exploration drilling conducted in the 1930s, and by lithostratigraphic correlation to type sections in Assam, in northeastern India (Figs. 1 and 2). This work has been refined by palynological (Chowdhury, 1982; Wallid, 1982; Uddin and Ahmed, 1989; Reimann, 1993; and unpublished reports by Bangladesh Petroleum Exploration, Inc. [BAPEX]), micropaleontological (Ahmed, 1968; Ismail, 1978; and unpublished reports by Petrobangla), and seismic-stratigraphic studies (Salt et al., 1986; Lindsay et al., 1991).

The pre-Tertiary stratigraphy of the Bengal basin is known only from the northwest part of the basin (Figs. 2 and 3). An ~1-km-thick

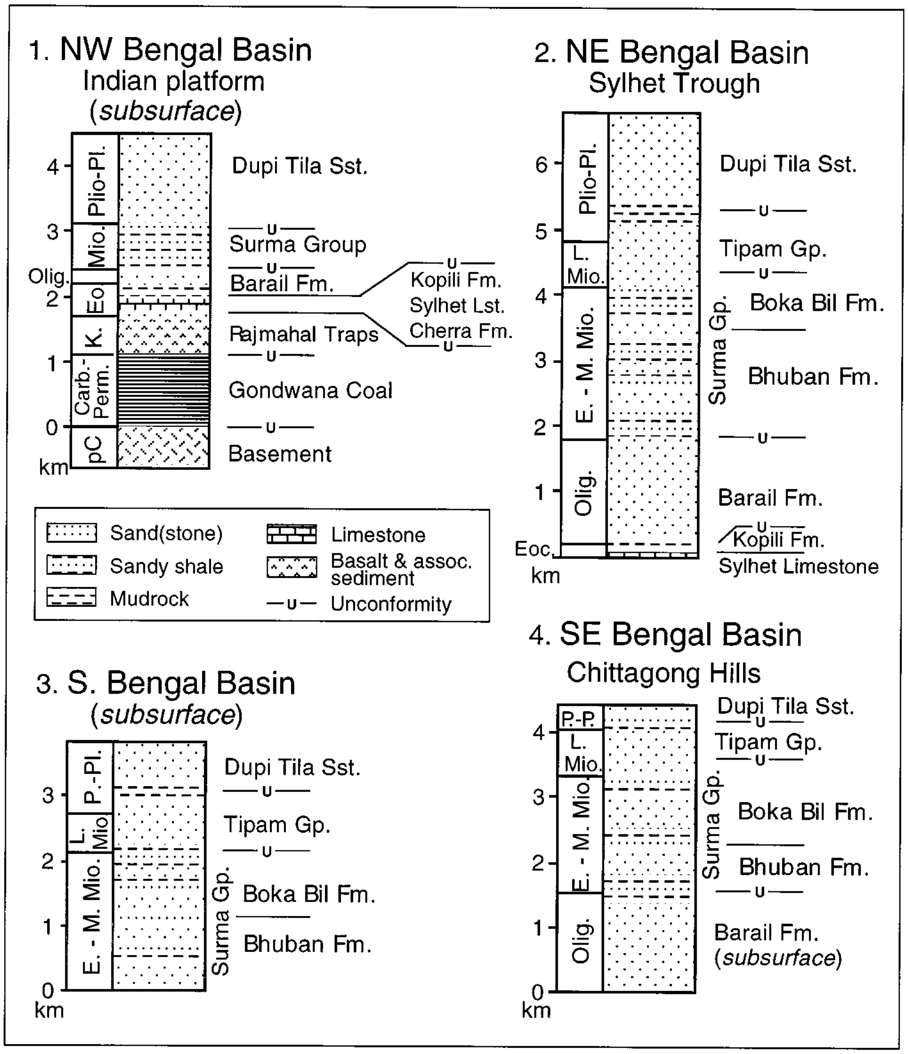

Figure 3. Summary stratigraphic sections in four areas of the Bengal basin. Approximate locations of the stratigraphic columns are shown in Figure 2. Most of the samples for this study were collected from the Sylhet trough and Chittagong Hill Tracts in eastern Bangladesh.

TABLE 1. RECALCULATED SANDSTONE MODAL PARAMETERS USED IN THIS STUDY

1. Primary parameters (after Graham et al., 1976; Dickinson and Suczek, 1979; Dorsey, 1988)

Qt = Qm + Qp, where
Qt = total quartzose grains
Qm = monocrystalline quartzose grains
Qp = polycrystalline quartz grains, including chert grains
F = P + K, where
F = total feldspar grains
P = plagioclase feldspar grains
K = potassium feldspar grains
L = Ls + Lv + Lm = Lsm + Lvm = Ls + Lv + Lm$_1$ + Lm$_2$ = Lt - Qp, where
Ls = sedimentary lithic fragments, mostly argillites
Lv = volcanic lithic fragments
Lm = metamorphic lithic fragments
Lsm = sedimentary and metasedimentary lithic fragments
Lvm = volcanic, hypabyssal, metavolcanic lithic fragments
Lm$_1$ = very low- to low-grade metamorphic lithic fragments
Lm$_2$ = low- to intermediate-grade metamorphic lithic fragments
Lt = total aphanitic lithic fragments

2. Secondary parameters (after Dickinson, 1970)

P/F = plagioclase/ total feldspar grains
Lv/L = volcanic / lithic fragments

Permo–Carboniferous Gondwana bituminous coal, inferred to have formed in intracratonic, fault-bounded basins, overlies Precambrian basement, and is overlain by about 500 m of the Cretaceous basaltic Rajmahal–Sylhet Trap (equivalent to the Deccan Traps).

Shallow-marine strata of the Paleocene to lower Eocene Cherra (or Tura) Formation consist mostly of clastic rocks and some carbonaceous material and impure limestones; they were penetrated by drill holes in the northwest platform area, and range in thickness from 169 to 360 m (Fig. 3). Marine transgression followed deposition of this unit, leading to deposition of the widespread middle Eocene nummulitic Sylhet Limestone. This limestone reaches a thickness of about 250 m in the Bengal basin, and is interbedded with sandstone, some of which is exposed in the Sylhet trough. The Sylhet Limestone is overlain by the 40–90-m-thick upper Eocene Kopili Formation, which consists mostly of argillaceous and fossiliferous materials, and represents a paralic transitional stratigraphic unit between middle Eocene carbonate facies and mainly arenaceous Oligocene sequences. The Oligocene Barail Formation was deposited during a marine regression. The 800–1600 m Barail Formation is composed of dominantly massive to thickly bedded sandstone interpreted by Banerji (1984) as estuarine and deltaic deposits. These upper Eocene and Oligocene strata are exposed in the Sylhet trough.

The Miocene Surma Group, consisting of the Bhuban and Boka Bil Formations, was deposited during repeated transgressions and regressions. This unit is well developed in the eastern fold belts and deeper parts of the basin, and is about 4.5 km thick in the northern Chittagong Hill Tracts and in the Sylhet trough (Fig. 3). In the northwestern stable shelf area, the Surma Group is represented by the much thinner (150 m to 1.3 km) Jamalganj Formation (Khan and Muminullah, 1980). The Bhuban Formation is composed mainly of sandstone, siltstone, shaly sandstone, and mudstone; the Boka Bil Formation is generally composed of shale, siltstone, and sandstone. A shaly upper member of the Boka Bil Formation was designated by Holtrop and Keizer (1970) as the "Upper Marine Shales," representing the last Miocene transgression.

The Surma Group is unconformably overlain by the upper Miocene to Pliocene Tipam Group, consisting of the Tipam Sandstone Formation and Girujan Clay Formation. The Tipam Sandstone Formation, which is locally as thick as 2.5 km, is composed mostly of weathered, medium- to coarse-grained, cross-bedded massive sandstone, and has been interpreted to have been deposited in bedload-dominated braided-fluvial environments (Johnson

TABLE 2. NORMALIZED MODAL ANALYSES OF SAND AND SANDSTONE FROM THE BENGAL BASIN, BANGLADESH

Sample number	QtFL (%)			QmFLt (%)			QmPK (%)			QpLsmLvm (%)			LsLvLm (%)			$LsLm_1Lm_2$ (%)			P/F
	Qt	F	L	Qm	F	Lt	Qm	P	K	Qp	Lsm	Lvm	Ls	Lv	Lm	Ls	Lm_1	Lm_2	
Dupi Tila Sandstone																			
BNDR-14	64	11	25	56	11	33	84	5	11	23	77	0	46	0	54	46	37	17	0.32
BNDR-17	61	29	10	53	29	18	65	3	32	44	56	0	62	0	38	62	20	18	0.08
SNGR1-1	84	2	14	66	2	32	97	0	3	56	44	0	44	0	56	44	36	20	0.13
INANI-16	68	10	22	57	10	33	85	5	10	34	66	0	54	0	46	54	30	16	0.35
INANI-19	75	12	13	67	12	21	85	2	13	40	60	0	37	0	63	37	45	18	0.15
Mean	70	13	17	60	13	27	83	3	14	39	61	0	49	0	51	48	34	18	0.20
Std. Dev.	9	10	6	6	10	7	12	2	11	12	12	0	10	0	10	10	9	1	0.12
Tipam Group																			
STPR-1	58	17	25	54	17	29	76	0	24	11	89	0	66	0	34	66	26	8	0.00
STPR-2	50	25	25	47	25	28	65	2	33	10	90	0	82	0	18	82	13	5	0.07
STPR-9	53	29	18	50	29	21	63	23	14	16	84	0	67	0	33	67	29	4	0.62
BNDR-10	60	17	23	49	17	34	76	4	20	31	68	1	61	2	37	62	26	12	0.18
NHILA-6b	67	18	15	60	18	22	78	13	9	24	69	7	46	9	46	50	31	19	0.59
SKND-7	65	14	21	58	13	29	81	4	15	26	74	0	46	0	54	46	42	12	0.22
SKND-9	54	27	19	44	27	29	62	6	32	33	67	0	48	0	52	48	42	10	0.17
SKND-11	57	22	21	51	22	27	70	14	16	22	76	2	36	2	62	37	47	16	0.46
SKND-14	63	14	23	56	14	30	80	2	18	22	77	1	54	1	45	55	27	18	0.11
INANI-2	63	19	18	54	19	27	73	10	17	35	64	1	44	1	55	44	39	17	0.37
INANI-6	68	13	19	56	13	31	81	6	13	39	61	0	34	0	66	34	51	15	0.33
INANI-9	82	11	7	73	12	15	86	2	12	56	42	2	37	4	59	39	40	21	0.15
Mean	61	19	20	54	19	27	74	7	19	27	72	1	51	2	47	53	34	13	0.30
Std. Dev.	9	6	5	7	6	5	8	7	7	13	13	2	15	3	14	14	11	5	0.19
Boka Bil Formation																			
STPR-4	47	33	20	42	33	25	56	20	24	20	78	1	72	1	27	73	16	11	0.46
BNDR-6	55	29	16	49	29	22	63	17	20	30	63	7	58	10	32	65	23	12	0.46
OL-70/68	48	29	23	45	29	26	61	27	12	10	81	9	66	10	24	73	20	7	0.68
OL-71/118	57	22	21	50	23	27	69	10	21	24	69	7	61	8	31	66	27	7	0.33
NHILA-2	56	34	10	47	33	20	58	23	19	48	51	1	66	3	31	68	24	8	0.55
NHILA-3	52	28	20	41	28	31	60	14	26	34	61	5	62	7	31	67	23	10	0.36
NHILA-5	53	26	21	51	26	23	67	29	4	7	90	3	47	4	49	49	39	12	0.87
SSR-7	66	5	29	58	5	37	92	3	5	22	78	0	34	0	66	34	53	13	0.39
SSR-13	47	15	38	41	15	44	74	3	23	14	84	2	64	3	33	66	20	14	0.11
HRGJ-3	62	22	16	50	22	28	69	9	22	42	47	11	26	19	55	32	32	36	0.29
HRGJ-4	63	19	18	53	19	28	74	11	15	35	57	8	35	13	52	41	47	12	0.41
HRGJ-8	63	17	20	58	17	25	77	9	14	23	76	1	37	1	62	38	46	16	0.39
HRGJ-12	42	38	20	37	38	25	50	32	18	19	73	8	51	10	39	56	29	15	0.65
HRGJ-15	61	21	18	54	21	25	73	11	16	30	70	0	54	0	46	54	32	14	0.41
SNGR1-3	65	23	12	54	23	23	70	25	5	48	51	1	49	1	50	49	31	20	0.84
SKND-6	75	10	15	62	10	28	87	5	8	47	51	2	46	4	50	48	37	15	0.41
Mean	57	23	20	50	23	27	69	15	16	28	68	4	52	6	42	55	31	14	0.48
Std. Dev.	9	9	7	7	9	6	11	9	7	13	13	4	13	5	13	14	11	7	0.20
Bhuban Formation																			
BNDR-2	54	29	17	48	29	23	62	16	22	27	68	5	59	7	34	63	29	8	0.42
OL-37/13	49	41	10	42	41	17	51	34	15	39	52	9	55	14	31	64	29	7	0.69
OL-29/78	51	38	11	42	38	20	53	30	17	45	50	5	67	8	25	73	19	8	0.63
PA-11	65	22	13	50	22	28	70	23	7	53	46	1	56	1	43	57	24	19	0.78
HRGJ-1	70	16	14	67	16	17	81	14	5	20	76	4	67	4	29	71	24	5	0.74
KMTA1-23	72	7	21	65	7	28	90	3	7	27	71	2	34	3	63	36	46	18	0.30
SNGR1-4	82	4	14	79	4	17	96	4	0	18	80	2	83	0	16	83	12	5	0.91
SNGR1-5	86	1	13	80	1	19	99	1	0	32	67	1	69	2	29	70	22	8	0.67
ATGM1-5	64	2	34	52	2	46	97	2	1	26	73	1	49	2	49	50	33	17	0.75
ATGM1-6	68	2	30	54	2	44	96	2	2	33	64	3	41	5	54	43	47	10	0.50
ATGM1-8	71	2	27	60	2	38	97	2	1	29	71	0	49	0	51	49	39	12	0.67
ATGM1-9	62	12	26	58	12	30	85	13	2	15	84	1	60	0	40	61	32	7	0.90
PATH5-1	78	11	11	57	11	32	84	13	3	67	32	1	58	1	41	59	34	7	0.83
PATH5-4	65	17	18	56	17	27	77	12	11	33	62	5	43	8	49	47	36	17	0.51
PATH5-6	54	30	16	47	30	23	61	24	15	30	70	0	52	1	47	52	34	14	0.62
Mean	66	16	18	57	15	28	80	13	7	33	64	3	56	4	40	58	31	11	0.66
Std. Dev.	11	14	7	12	14	9	17	11	7	14	14	3	12	4	12	13	10	5	0.17
Barail Formation																			
JA-1	84	2	14	80	2	18	97	3	0	24	76	0	63	0	37	63	28	9	1.00
JA-2	97	0	2	91	0	9	100	0	0	49	51	0	64	0	36	64	28	8	0.00
JA-3	88	0	12	86	0	13	99	1	0	20	80	0	72	0	28	71	22	7	1.00
SNGR1-6	96	2	2	92	2	6	98	2	0	39	61	0	80	0	20	80	18	2	1.00
ATGM1-10	87	10	3	84	10	6	89	6	5	17	83	0	63	0	37	63	30	7	0.55
Mean	90	3	7	87	3	10	97	2	1	30	70	0	68	0	32	69	25	6	0.71
Std. Dev.	6	4	6	5	4	5	4	2	2	14	14	0	7	0	7	7	5	3	0.44
Cherra and Kopili Formations																			
BOGRA2-1(Ko.)	97	2	1	94	2	4	98	0	2	70	30	0	61	0	39	61	29	10	0.00
BOGRA2-2 (Ko.)	92	8	0	76	8	16	90	2	8	98	2	0	100	0	0	100	0	0	0.23
BOGRA2-7 (Ch.)	99	1	0	97	1	2	99	0	1	100	0	0							0.00
Mean	96	4	1	89	4	7	96	1	3	89	11	0	80	0	20	80	15	5	0.06
Std. Dev.	4	4	1	12	4	8	5	1	4	17	17	0	28	0	28	28	21	7	0.11

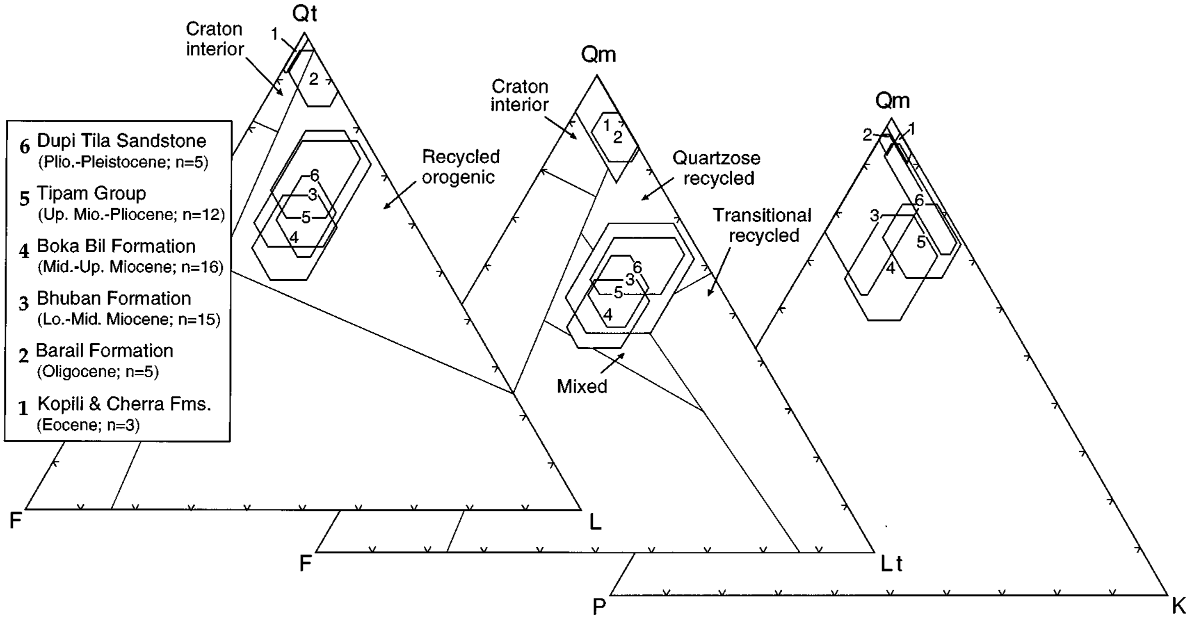

Figure 4. Ternary diagrams showing overall sandstone modes (QtFL and QmFLt plots) and light monocrystalline components (QmPK plot) of sand (see Table 1) in Bengal basin samples, showing means (indicated by numbers 1–6) and standard-deviation polygons for each stratigraphic unit. Provenance fields (QtFL and QmFLt plots; see Table 1) are from Dickinson (1985). QtFL plot: Note that Eocene–Oligocene sands plot near the quartz pole. These sands are compositionally different from the Miocene and younger sands, which plot in the "recycled orogenic" field. QmFLt plot: Chert and other polycrystalline quartz grains are included in the total lithic counts (see Table 1). QmPK plot: Following an early shift from almost pure quartz to a moderately feldspar-rich composition, plagioclase content decreases through Pliocene–Pleistocene time. Although standard deviations are not strictly valid statistically for constant-sum, constrained compositional data, polygons are shown to indicate ranges of values.

and Nur Alam, 1991). The Girujan Clay is locally as thick as 1 km, and is composed dominantly of mottled clay deposited in lacustrine, flood-plain, and overbank environments (Khan and Muminullah, 1980). These units are overlain unconformably by the Pliocene–Pleistocene Dupi Tila Formation, comprising mostly massive trough–cross-bedded coarse to pebbly sandstone, which reaches a maximum thickness of at least 2.3 km in the Sylhet trough. The Dupi Tila Formation contains alternating channel and flood-plain deposits, and has been interpreted as a meandering-river deposit (Johnson and Nur Alam, 1991).

METHODS

We collected 111 samples of sand and sandstone, ranging from early Eocene through Pleistocene in age, from surface sections and subsurface cores in the Bengal basin. Surface samples are from sections exposed in northern and southeastern Bangladesh, whereas subsurface cores are from wells drilled by Petrobangla in the northwest, northeast, and central parts of the basin. Unconsolidated sand was sieved, and the fractions coarser than 0.063 mm were epoxied into plugs for thin-section preparation. We selected 56 representative samples for modal analysis on the basis of appropriate grain size and low degree of alteration. Petrographic analyses were conducted following the Gazzi-Dickinson method, counting sand-sized minerals included in lithic fragments as the mineral phase rather than the host lithic fragment (Dickinson, 1970; Ingersoll et al., 1984). All thin sections were stained for plagioclase and potassium feldspar, following techniques modified from Houghton (1980). At least 300 framework points were counted per sample; 400 framework points were counted for samples that had greater compositional diversity. In order to quantify lithic components, at least 300 lithic-fragment framework points were counted per sample, with the exception of the lithic-poor Eocene samples, which were excluded from this analysis. Selected thin sections were also counted a second time and by a different person in order to minimize operator error. Point-counting parameters and recalculated parameters are defined in Table 1. Because of the potential importance of the metamorphic grade of abundant metasedimentary lithic fragments, we have distinguished between very low- to low-grade (Lm_1) vs. low- to intermediate-grade (Lm_2) metasedimentary fragments, following Dorsey (1988). Lm_1 fragments include slate, slaty siltstone, and quartzite, whereas Lm_2 fragments are quartz-mica tectonites, including phyllite, schist, and phyllitic quartzite.

PETROGRAPHY

Eocene to Pleistocene sand and sandstone of the Bengal basin varies from highly quartzose to quartzolithic and quartzofeldspathic; aphanitic lithic fragments are dominated by sedimentary and metasedimentary rock types. In general, older sandstone (Eocene and Oligocene) contains more quartz, although Miocene and younger sand also typically contains more than 50% quartz. Older sandstone exhibits more angular grains than does sand in younger units, in which grains range broadly from subangular to rounded. Many sandy units, both exposed and drilled, are unconsolidated, whereas others are strongly indurated. Modal analyses of the major stratigraphic units are presented in Table 2, and depicted graphically in Figures 4 and 5. Polygons surrounding mean values are calculated as sample standard deviations; although these do not represent true standard deviations for constrained-sum

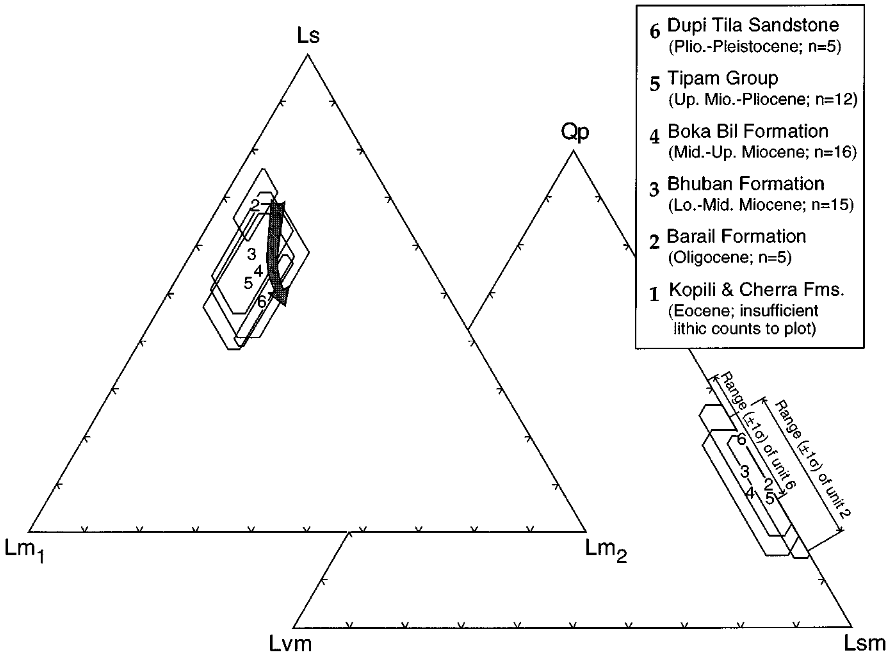

Figure 5. Ternary diagrams showing lithic fragment compositions ($LsLm_1Lm_2$ and QpLvmLsm plots; see Table 1) of sand in Bengal basin samples, showing means (indicated by numbers 1–6) and standard-deviation polygons for each stratigraphic unit. $LsLm_1Lm_2$ plot: Lithic fragments suggest an unroofing trend from sedimentary to metamorphic components over time (filled arrow). Although the polygons plotted for the Miocene to Pliocene Bhuban, Boka Bil, and Tipam sands (units 3, 4, and 5) largely overlap, the compositions of the Oligocene sandstones (unit 2) and the Pliocene–Pleistocene Dupi Tila sands (unit 6) show a temporal increase in higher-grade metamorphic lithic fragments derived from the orogens. QpLvmLsm plot: volcanic and metavolcanic fragments are absent in Eocene–Oligocene and Pliocene–Pleistocene samples. Polygons depicted show variability between polycrystalline quartz and metasedimentary lithic fragments. LsLvLm plots show no additional distinctions, as a result of the very low volcanic lithic components, and so are not shown. Although standard deviations are not strictly valid statistically for constant-sum, constrained compositional data, polygons are shown to indicate variability of values.

data (see Ingersoll, 1978), they are shown to indicate the variability of values for each group. Principal results are summarized in the following for the various stratigraphic units, from oldest to youngest.

Cherra and Kopili Formations

The single available sample of the Paleocene to lower Eocene Cherra (or Tura) Formation, from the Bogra–2 well in the stable shelf area, yields a quartz-arenite (orthoquartzose sandstone) composition. Framework grains are 99% quartz ($Qt_{99}F_1L_0$ [quartz, feldspar, lithic fragments]). Many of the quartz grains are coarse, and most are subangular to angular. Almost all are monocrystalline grains that exhibit undulatory extinction; there are very minor polycrystalline grains (elongate metamorphic lithic fragments). Many quartz grains are broken and exhibit irregular fractures, apparently induced during compaction. Of the rare feldspar grains, all are potassium feldspars, including both orthoclase and microcline. This rock contains considerable recrystallized clay matrix, and has been partially cemented by patchy micritic calcite cement.

Two samples of the upper Eocene Kopili Formation, from the Bogra–2 well of northwestern Bangladesh, have subfeldspathic ($Qt_{91}F_8L_1$) and quartz-arenite ($Qt_{97}F_2L_1$) compositions. Quartz grains are mostly monocrystalline, and most exhibit undulatory extinction. The sparse feldspar is mostly potassium feldspar and is predominantly orthoclase. Lithic fragments are overwhelmingly sedimentary, including mainly iron-rich mudrocks and siltstones; metamorphic fragments are scarce, and there is no identified volcanic detritus. One sample contains minor glauconite and abundant zeolite cement. For comparisons of temporal trends, the three samples of Cherra and Kopili Formation sandstones, all of which are Eocene in age and quartzose, are combined on ternary diagrams (Fig. 4).

Although we analyzed only three Eocene samples that are of appropriate grain size and alteration for point counting, we include them here due to their potential importance in constraining the early detrital record of the Bengal basin; future studies are planned to sample more fully these units.

Barail Formation

Five samples from the Oligocene Barail Formation have sublitharenitic ($Qt_{84}F_2L_{14}$) to quartz-arenitic ($Qt_{97}F_0L_3$) compositions; the average composition is $Qt_{90}F_3L_7$. Four samples are from the Sylhet trough (Tamabil-Jaintapur Road and Atgram-IX well), and the other sample is from northwest Bangladesh (Singra–1 well). There is no obvious difference in detrital composition between the samples from these two areas. The abundant quartz grains are dominantly monocrystalline grains that exhibit undulatory extinction, as in the older sandstones. Quartz grains are also generally subangular to angular (Fig. 6A), as in the Eocene sandstones. Polycrystalline quartz grains include chert and both foliated and nonfoliated metamorphic types. Of the sparse feldspar grains, plagioclase (P) is more common than potassium feldspar (P/F = 0.71). Of the relatively sparse lithic fragments, sedimentary rock types are more abundant than low-grade metamorphic fragments (Ls/L = 0.68); there are very rare medium- and high-grade metamorphic fragments, and virtually no volcanic lithic fragments. The sample from Atgram-IX contains abundant large intrabasinal limestone fragments and ooids. Grains are moderately sorted and subangular to subrounded.

Bhuban Formation

The 15 sandstone samples from the lower to middle Miocene Bhuban Formation, from locations across the basin, contain more feldspar grains and lithic fragments than the underlying stratigraphic units (Table 2 and Fig. 6B). These sands are sublithic to subfeldspathic ($Qt_{66}F_{15}L_{19}$), although some are nearly quartz arenites. Most quartz grains are monocrystalline (Qm) grains that exhibit undulatory extinction (Qm/Qt = 0.86), and plagioclase is generally more abundant than potassium feldspars (P/F = 0.66). Lithic components are dominated by sedimentary fragments (Ls/L = 0.56), and metamorphic lithic fragments are mostly low grade (Lm_1/Lm = 0.74). Volcanic lithic fragments, although not common, are present in this unit, in contrast to older units. Volcanic fragments average about 4% of lithic fragments, but are somewhat more

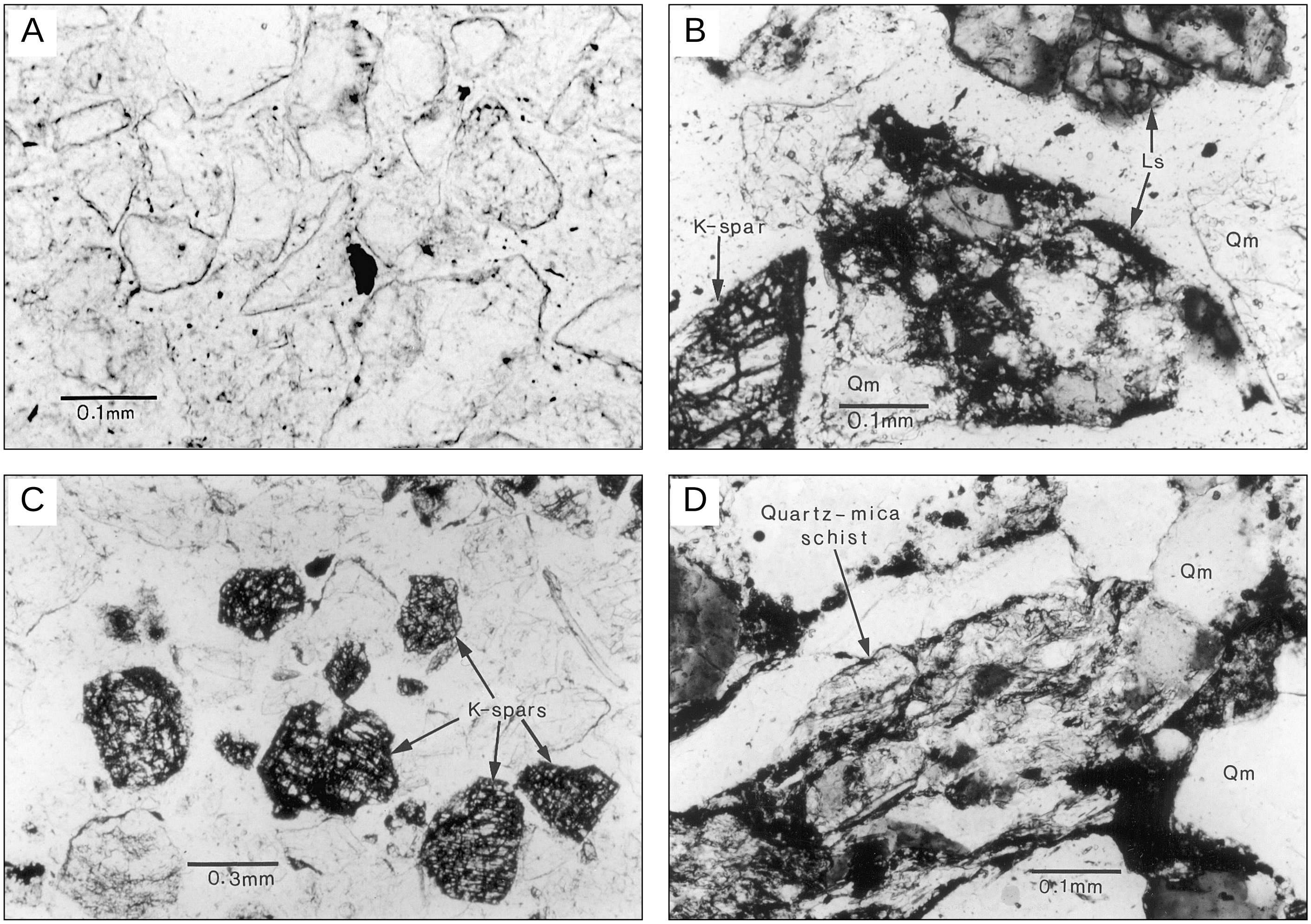

Figure 6. Representative photomicrographs of sandstones from the Bengal basin. (A) Oligocene Barail Formation: framework grains are all quartz, many of which are subangular. (B) Miocene Surma Group: sedimentary lithic fragments (Ls) and feldspar (K-spar) present in this unit are virtually absent in the Eocene–Oligocene sandstones. (C) Upper Miocene to Pliocene Tipam Group: potassium feldspar is relatively abundant, unlike in Oligocene to middle Miocene units. (D) Pliocene–Pleistocene Dupi Tila Sandstone: low- to intermediate-grade metamorphic lithic fragments (Lm_2), like the quartz-mica schist fragment shown here, are more abundant than in older units.

abundant in sandstones from the eastern sections (e.g., Olahtaung in the Chittagong Hill Tracts). Phenocryst phases and textures indicate mostly mafic to intermediate compositions for volcanic fragments.

Boka Bil Formation

The 16 sand samples from the middle to upper Miocene Boka Bil Formation have more diverse compositions than the older units, averaging $Qt_{57}F_{23}L_{20}$. These subarkosic and sublithic arenites are somewhat less quartzose than older units, but are also composed dominantly of quartz, mainly monocrystalline quartz exhibiting undulatory extinction. Plagioclase and potassium feldspars are equally abundant (P/F = 0.50). Sedimentary lithic fragments dominate the lithic populations (Ls/L = 0.51). Volcanic lithic fragments (mostly andesitic) compose to about 6% of the lithic fragments, and are more abundant in sands from the eastern fold belts (e.g., from the Harargaj anticline in the southeastern Sylhet trough). Intermediate-grade metamorphic fragments are more abundant in sands from this unit compared to those of the underlying Bhuban Formation. Micas are relatively abundant, averaging about 5% of framework grains, and are dominated by biotite (not depicted on ternary diagrams).

Tipam Group

The 12 sand samples from the upper Miocene to Pliocene Tipam Group reveal relatively uniform compositions, and contain moderate amounts of feldspars and lithic fragments. Mean QtFL values for Tipam sandstones ($Qt_{61}F_{19}L_{19}$) are very similar to those of the combined Surma Group (Bhuban and Boka Bil formations), but they show much less variation (Fig. 4). Monocrystalline quartz is the major grain type; most of the grains (87%) exhibit undulatory extinction. Potassium feldspar is more abundant (Fig. 6C) than plagioclase (P/F = 0.30), and most potassium feldspar grains show no twinning. Lithic fragments are dominated by sedimentary types (Ls/L=0.52), but also include lowest-grade metamorphic (Lm_1) and low- to intermediate-grade metamorphic lithic fragments (Lm_2). Volcanic lithic fragments are also less abundant (2% of lithic fragments) in Tipam sands than in Surma sandstones.

Dupi Tila Sandstone

Five sand samples from the Pliocene–Pleistocene Dupi Tila Sandstone contain somewhat more quartz and less feldspar than do the two immediately underlying units. Quartz grains in these sublithic to subfeldspathic quartz arenites ($Qt_{70}F_{13}L_{17}$) are mostly monocrystalline quartz grains that show undulatory extinction, as in older units, but feldspars are overwhelmingly dominated by potassium feldspar (P/F = 0.20), in contrast to the immediately subjacent units. Lithic fragments include roughly equal amounts of sedimentary and metamorphic fragments, but low- to intermediate-grade metamorphic lithic fragments (Lm_2; Fig. 6D) are more common (Lm_2/Lsm = 0.18) than in older stratigraphic units. These sands contain no identified volcanic lithic fragments.

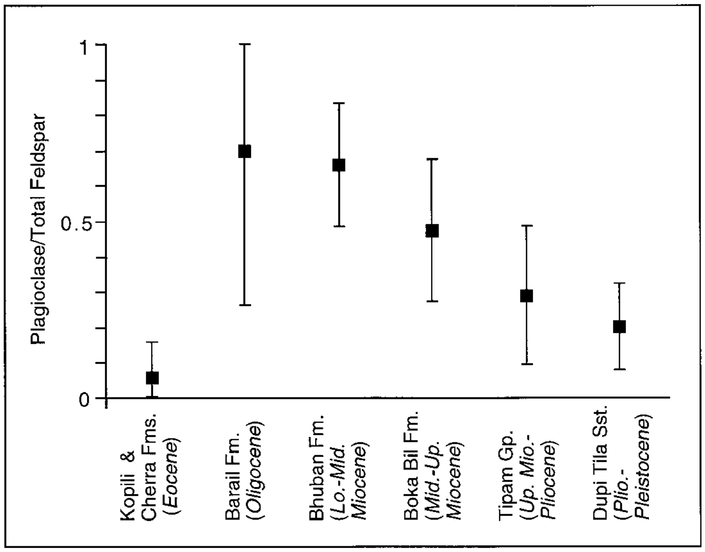

Figure 7. Ratios of plagioclase to total feldspar (P/F) in sand and sandstone from the Bengal basin, showing mean and standard deviation for each stratigraphic unit. Note that P/F ratio for Eocene samples is not statistically robust, as a result of very low feldspar content.

INTERPRETATION OF SANDSTONE MODES

In order to visualize the variations in sand composition and to help interpret the tectonic provenance of sands and sandstones from the Bengal basin, we constructed ternary diagrams of the major components, the monocrystalline grains, and the phaneritic lithic fragments (e.g., Dickinson, 1985). In order to evaluate unroofing trends in source mountain belts, we also plotted specific lithic components that are most likely to show useful variations in these dominantly phyllarenitic sandstones (e.g., Dorsey, 1988); i.e., sedimentary lithic (Ls), very low- to low-grade metamorphic lithic (Lm_1), and low- to medium-grade metamorphic lithic fragments (Lm_2).

The highly quartzose Cherra and Kopili samples plot in "craton interior" provenance fields of QtFL and QmFLt diagrams (Fig. 4; Dickinson, 1985). Barail sandstone samples, almost as quartzose and lacking significant chert or other polycrystalline quartz, plot as "craton interior" on a QtFL diagram and as "quartzose recycled orogenic" on a QmFLt diagram. All samples of Miocene and younger sands and sandstones plot as "recycled orogenic" on a QtFL diagram. On a QmFLt diagram, Bhuban and Dupi Tila samples plot in the "quartzose recycled" provenance field, whereas the slightly more feldspathic Boka Bil and Tipam samples plot in the "mixed" provenance field.

In terms of monocrystalline light components (QmPK, K = potassium feldspar), sands from the Bengal basin have a complicated temporal pattern (Figs. 4 and 7). Monocrystalline quartz is abundant relative to feldspar in all samples analyzed, but this is especially true for Eocene and Oligocene samples. The rare feldspars in the Eocene samples are mainly potassium feldspar, whereas those in Oligocene samples are mainly plagioclase. Miocene and younger samples contain higher and more variable amounts of feldspar than do the older samples. Most important, the abundance of potassium feldspar relative to plagioclase systematically increases over time in these post-Oligocene samples, which we interpret to reflect unroofing of deeper crustal levels in the source areas.

Volcanic components (Fig. 5) are generally scarce in Bengal basin sediments; there is a peak in abundance of only 2% of total framework grains (Lv/L = 0.06) in Boka Bil sands, and mean abundances are even lower in both older and younger units. This is similar to abundance patterns of heavy minerals analyzed in Bengal basin sands. Boka Bil sands show peak abundances of blue-green amphibole, probably indicative of arc volcanic sources, as well as sparse chromite, suggestive of ophiolitic sources (Uddin and Lundberg, 1998).

Lithic components are overwhelmingly sedimentary and metasedimentary; these are subdivided on the $LsLm_1Lm_2$ plot (Fig. 5), which suggests unroofing from Oligocene to Pliocene–Pleistocene time. Although the ranges plotted for the Miocene to Pliocene Bhuban, Boka Bil, and Tipam sands largely overlap, the compositions of the Oligocene sandstones and the Pliocene–Pleistocene Dupi Tila sands show a temporal increase in higher grade metamorphic lithic fragments derived from the orogens.

PETROFACIES EVOLUTION AND COLLISION HISTORY

Eocene sandstones analyzed from the Bengal basin, although very few in number, are extremely quartzose and predate significant input of collisional detritus. Assuming that these are representative, lower Eocene sand from the Cherra Formation is quartz-arenitic, comprising almost 100% quartz. The abundance of subangular to angular, coarse monocrystalline quartz grains reflects little abrasion and relatively brief transport, whereas the conspicuous lack of feldspar suggests either intense chemical weathering or a source terrane of quartz-rich sedimentary rocks. The Cherra Formation directly overlies the basement complex of the Indian shield in the northwestern part of the Bengal basin, and was sampled from an area not more than 200 km from present exposures of the Indian shield to the west (Fig. 2). Upper Eocene sandstones from the same locality, stratigraphically overlying the regionally extensive mid-Eocene nummulitic limestone, contain small amounts of feldspars and lithic fragments. Authigenic chert and glauconite suggest a slightly reducing environment. The dominance of monocrystalline, subangular to subrounded quartz grains, the presence of minor potassium feldspar and very little to no plagioclase, and the paucity of lithic fragments suggest derivation from continental sources rather than collisional orogenic terranes. These units were likely derived from the adjacent Indian craton and deposited on the eastern segment of the northeastern passive continental margin of India,

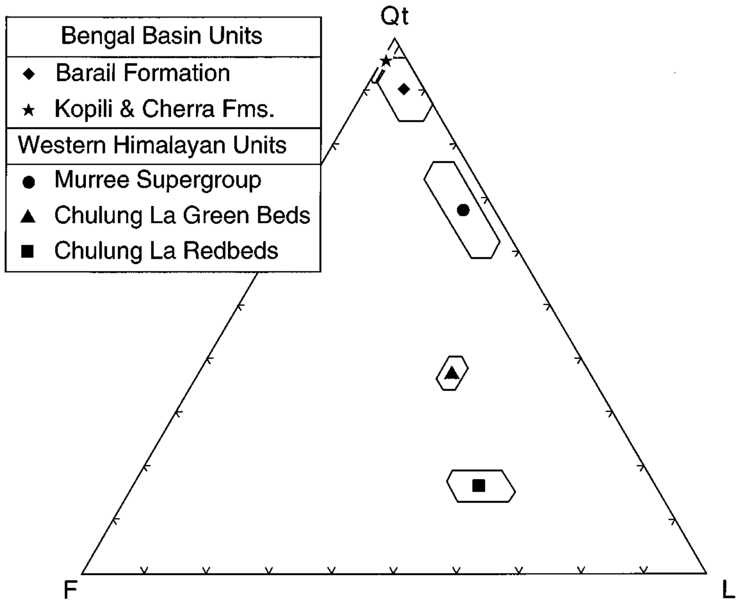

Figure 8. QtFL plot (see Table 1) showing means and standard-deviation polygons of Eocene–Oligocene sandstone of the Himalayan foreland basins, comparing sand compositions in the Bengal basin with those in the western Himalaya. Eocene–Oligocene sandstones of the Bengal basin are dramatically more quartzose than those of the western foreland basins. Western Himalayan Eocene–Oligocene data are from Critelli and Garzanti (1994) and Critelli and Ingersoll (1994).

which at that time was near the equator (Lindsay et al., 1991).

Oligocene sands of the Barail Formation are also mostly quartzose, and contain only minor sublitharenites. The abundance of quartz and the scarcity of both feldspar grains and lithic fragments suggest a source terrane with low relief and considerable transport, and intense chemical weathering. Given sufficiently intense chemical weathering, we cannot rule out the possibility that these quartzose sandstones were derived from proto-Himalayan sources. Johnsson et al. (1988) analyzed the composition of first-cycle quartz arenites in the Orinoco River basin of Venezuela and Colombia, and documented that river sands from the Andean foreland basin increase markedly in compositional maturity with increasing distance from the mountains, evolving to quartz arenites over transport distances of 200 to 300 km. River samples from the lowland portion of the Guayana shield are also strongly quartzose; some are pure quartz arenites. They suggest that intense chemical weathering and long residence time in flood plains and gentle slopes can produce first-cycle quartz arenites, irrespective of their tectonic origin. Kroonenberg (1994) studied upper Pleistocene river terraces of the Caqueta River in the Colombian Amazons, and found that tropical weathering is capable of destroying the provenance signature of source rocks in 30 to 40 k.y. Thus, a proto-Himalayan orogen could have supplied detritus that underwent intense chemical weathering to supply the quartzose Eocene–Oligocene strata of the Bengal basin.

A Himalayan source seems unlikely for the Eocene–Oligocene deposits of the Bengal basin, however, in light of the great distance to the Himalaya at the time, especially compared with the proximity of the Indian craton, which is also a potential source terrane. Tectonic activity at this time in both the eastern Himalaya and the Indo-Burman ranges was relatively distant from the present Bengal basin. Because the Bengal basin formed on the downgoing (Indian) plate, it has been steadily approaching the sites of plate convergence represented now by the southward-advancing Himalayan front and the westward advancing Indo-Burman ranges. During Eocene and Oligocene time, the Himalaya must have been more than 1500 km to the north of the Bengal basin (e.g., Le Fort, 1996), across an intervening region that has since been almost entirely subducted, or underthrust beneath the Himalaya. We know very little about this intervening region, except that adjacent oceanic terrane has been subducted eastward below what is now the Indo-Burman ranges. We speculate that during Eocene to Oligocene time, orogenic detritus from initial uplifts of the eastern Himalayan orogen was transported to the Indian Ocean somewhere to the east of the Bengal basin, in the region that has since been subducted beneath the Indo-Burman ranges. In contrast to the great distance to the Himalaya, the Bengal basin is directly adjacent to and in part overlies plutonic and metamorphic rocks of the Indian craton. In light of this proximity, and the location of the Bengal basin on the continental margin of eastern India, we believe that the simplest explanation of Eocene and Oligocene sandstones of the Bengal basin is derivation from the Indian craton to the west.

The abrupt increase in feldspar grains and lithic fragments in lower Miocene sands represented by compositions of Surma Group sandstone (Bhuban and Boka Bil Formations) marks the first clear signal of delivery of orogenic detritus to the Bengal basin. This may represent the actual initiation of collisional uplift and erosional unroofing in the eastern Himalaya; however, more likely it records the initiation or simply migration (to this area) of stream systems that supplied orogenic detritus to the Bengal basin. Stratigraphic reports (Rao, 1983) from Assam, immediately northeast of the Bengal basin, document extremely thick Oligocene sequences, including both marine and continental deposits, overlain by Miocene fluvial sequences similar to the Pliocene strata in the Bengal basin (and lithostratigraphically correlated, called the Tipam Group). This suggests that orogenic activity began in the eastern Himalaya by Oligocene time, as indicated by radiometric dating of metamorphism by Hodges et al. (1994), and migrated southward relative to Indian crust as it developed; large stream systems evolved to funnel voluminous detritus into the remnant ocean basin of Bangladesh by earliest Miocene time. It appears that the bulk of deltaic accumulation migrated from Assam in Oligocene time and through Bangladesh since early Miocene time. Today, the extreme southern portions of Bangladesh represent the delta plain of the Bengal delta.

Uplift and erosion apparently had not unroofed mid-crustal levels prior to Miocene time, however. The feldspathic to lithic arenites in the oldest Miocene strata in the Bengal basin contain abundant monocrystalline quartz, sedimentary lithic fragments and plagioclase, and minor volcanic lithic fragments, compositions that would be expected during initial unroofing of continental-margin terranes that are dominated by cover sedimentary units and areally minor volcanic terranes. During late early Miocene time (ca. 20 Ma), a large wedge of hot Indian crust was rapidly uplifted and carried hundreds of kilometers southward along the Main Central thrust in the Himalaya (Hubbard et al., 1991). Erosion of these uplifted granitic rocks probably contributed to the temporal increase in feldspar content we observe in Miocene sandstones. The ratio of potassium

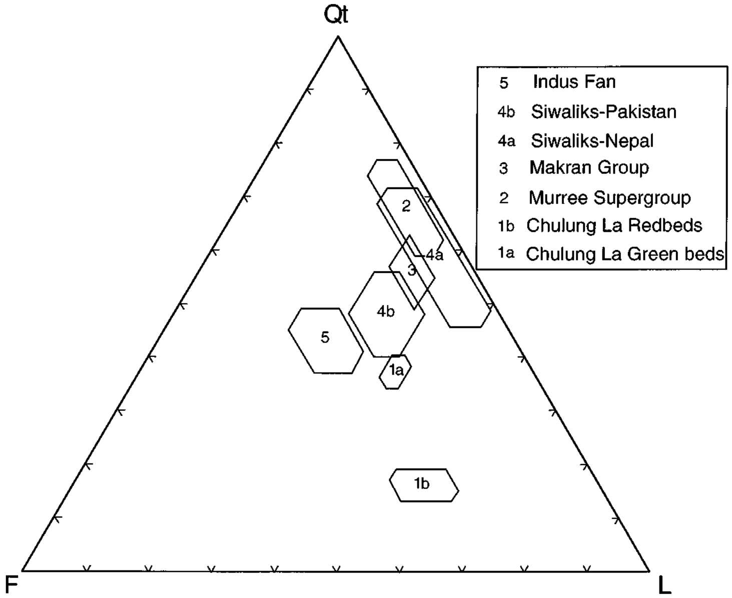

Figure 9. QtFL plot (see Table 1) showing means and standard-deviation polygons of Eocene through Neogene sand and sandstone from the western Himalayan foreland basins. Data are from Suczek and Ingersoll (1985), Critelli et al. (1990), Critelli and Garzanti (1994), and Critelli and Ingersoll (1994). Units numbered 1 through 5 are in chronological order (1 is the oldest).

feldspar to plagioclase is higher in upper Miocene (Boka Bil Formation) and younger strata than in Oligocene and lower to middle Miocene deposits (Fig. 7), and is one of the striking features of these sands (Fig. 6C; Uddin et al., 1994). This is probably not due to changes in the intensities of chemical weathering alone, because the abundance of potassium feldspar in these younger strata is high (as a percentage of total framework grains) relative to older units.

Volcanic and ophiolitic detritus in these sands may have been derived from the Indo-Burman ranges to the east. The negligible amount of such debris in lowest Miocene sands suggests that arc volcanic terranes developed on the Asian margin were shielded from the Bengal basin by the growing mountain belt, or that any volcanic detritus was weathered relatively completely prior to deposition here. Pliocene and younger units have sparse volcanic detritus as well, suggesting a lack of significant volcanic terranes. Volcanic terranes of the Indo-Burman ranges had likely been displaced southward by right-lateral strike-slip faults, and the plutonic roots of these terranes may now be represented by granites exposed in the Andaman islands (Mitchell, 1993). The Indo-Burman ranges expose two belts of ophiolites, representing sources for chromite in Bengal basin sands, but both belts are currently located east of the modern drainage divide (Sengupta et al., 1990). Volcanic and ophiolitic sources also exist in the Himalaya, but the fact that our easternmost samples are richer in volcanic detritus and contain chromite suggests that sources in the Indo-Burman ranges to the east are more likely to have provided the volcanic and ophiolitic components.

Sands in the younger Neogene units, the upper Miocene to Pliocene Tipam Group and Pliocene–Pleistocene Dupi Tila Formation, contain appreciable amounts of low- to intermediate-grade metamorphic lithic fragments (Lm_2), in contrast to older strata, suggesting unroofing of deep crustal levels in the orogens. These two units are also rich in untwinned potassium feldspar, relative to the plagioclase-rich sandstones of the Surma Group, suggesting a plutonic source, and/or an increase in mechanical weathering relative to chemical weathering in the source areas (Mack, 1978). Miocene leucogranites of the High Himalayan Crystalline terrane (France-Lanord et al., 1993) are apparently the principal source of these feldspars (Harrison et al., 1993; and many others).

The Shillong Plateau, which was uplifted in Pliocene time along the northern margin of the Bengal basin, provided another source for detritus of the Tipam Group and younger units proximal to the uplift (Johnson and Nur Alam, 1991), contributing sand especially rich in sedimentary lithic fragments eroded from cover units. Much of this recycled detritus is likely to have been derived from the same ultimate sources, but during earlier time periods, than the orogenic sediment with which it has mixed. Lithic populations in sands that accumulated in areas farther removed from the Shillong Plateau do not show a late pulse of sedimentary lithic fragments.

COMPARISON TO PETROFACIES OF THE WESTERN HIMALAYA

Our results on sand composition in the Bengal basin can be compared to abundant available data on sequences to the west in order to compare records of orogenic timing and erosional history. The synorogenic sequences in the western Himalaya have been studied in some detail, beginning with the classic study of Krynine (1937). Many studies have focused on the Miocene to Pleistocene Siwalik deposits of Pakistan, northwest India, and Nepal (Raju, 1967; Johnson and Vondra, 1972; Chaudhri, 1975; Parkash et al., 1980; Abid et al., 1983; and many others). Critelli and Garzanti (1994), Critelli and Ingersoll (1994), and Garzanti et al. (1996), however, reported new modal analyses of sandstones from a number of units in the western Himalayan foreland basins, including Paleogene strata.

The precollisional Upper Cretaceous to Paleocene clastic deposits from the Indus forearc in the western Himalaya are lithofeldspathic, and contain abundant microlitic and felsitic volcanic lithic fragments and granitoid detritus derived from an undissected magmatic arc (Garzanti et al., 1996). The upper Paleocene to lower Miocene synorogenic sediment that began to fill the evolving foreland basins that developed ahead of the southward-advancing Himalaya in the west comprise terrestrial sediments of the lithofeldspathic Chulung La Formation ($Qt_{24}F_{26}L_{50}$) and quartzolithic tidal-flat to fluviatile deposits of the Murree Supergroup ($Qt_{68}F_5L_{27}$; Bossart and Ottiger, 1989; Critelli and Garzanti, 1994). These units contain abundant metasedimentary, volcanic, and sedimentary lithic fragments and ophiolitic detritus (Figs. 8 and 9; Critelli and Ingersoll, 1994; Critelli and Garzanti, 1994).

The Tertiary clastic deposits of the Himalayan foothills of northern India include the pre-Siwalik Subathu and Dharmsala Sandstones and the Miocene–Pliocene Siwaliks. The Subathu contains a basal oligomictic conglomerate layer that includes subrounded quartz and chert pebbles, suggesting transgressive beach deposition, overlain by quartz arenites with minor lithic fragments and insignificant feldspar (as much as 5% of framework grains; Raju, 1967). The Dharmasala Sandstone consists of limestone conglomerates and sands, the sand containing 45% to 55% quartz and 15% to 25% lithic fragments, including sericite and chlorite schist fragments, quartzites, limestones, and chert, along with micas, chlorite-sericite matrix and carbonate cement; feldspar is rare to absent (Raju, 1967).

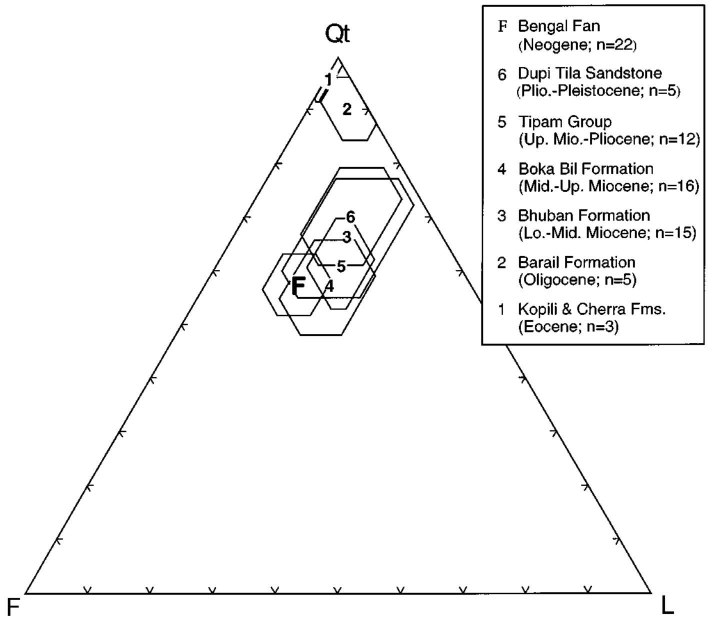

Figure 10. QtFL plot (see Table 1) showing means and standard deviation polygons of sands and sandstones from the eastern Himalayan foreland, including the Bengal basin and the Bengal fan (F). Data for the Bengal fan are from Ingersoll and Suczek (1979).

Raju suggested that derivation of these sediments was from low-grade metamorphic (greenschist facies) terranes in the Himalaya. Dewey et al. (1988) suggested derivation from the Indian shield to the south, however, assigning a late Oligocene age to the Murree sediments of the Indo-Gangetic basin. The Miocene–Pliocene Siwalik sandstones of Pakistan and Nepal are quartzolithic and contain two distinct petrofacies, a more feldspathic petrofacies ($Qt_{48}F_{18}L_{34}$) in Pakistan to the west, and a more quartzose petrofacies ($Qt_{59}F_6L_{34}$) in Nepal, both derived from Himalayan terranes (Critelli and Ingersoll, 1994; Critelli and Garzanti, 1994).

Lower Miocene to lower Pliocene sandstones from the Makran accretionary wedge in southwest Pakistan (Fig. 1) show mainly quartzolithic composition ($Qt_{56}F_{10}L_{34}$), and a temporal evolution toward more quartzose compositions (Fig. 9; Critelli et al., 1990). Lithic components in these sandstones distinguish two contrasting petrofacies; accreted abyssal-plain turbidites reflect a provenance of sedimentary and metasedimentary Himalayan terranes, and slope and shelf facies sediments record volcanic sources, inferred to represent upper Mesozoic volcanic terranes in northern Pakistan and early to middle Miocene andesitic volcanic centers in northern Makran.

The peak abundance of volcanic lithic fragments and the appearance of blue-green amphiboles in the Boka Bil Formation, the upper of the two Miocene units, suggests erosion of arc rocks from the Himalaya and/or the Indo-Burman ranges. Blue-green amphiboles are also present in strata of similar ages in Siwalik sandstones in the Potwar Plateau of the Pakistan Himalaya (Johnson et al., 1985; Cerveny et al. 1989) and in cores from ODP Leg 116 sites on the distal Bengal fan (Yokoyama et al., 1990; Amano and Taira, 1992).

Neogene sand from the Indus fan ($Qt_{43}F_{30}L_{27}$) (Suczek and Ingersoll, 1985) is more feldspathic than the Siwalik and pre-Siwalik sandstones (Fig. 9). Differences in feldspar content may be related to uplift of crustal blocks in the Himalayan zone (Copeland et al., 1990, Amano and Taira, 1992), and/or to uplifted granitoid rocks of the Indian shield (Critelli and Ingersoll, 1994).

Following the initial collision of India with Eurasia and Burma in early Tertiary time, large amounts of siliciclastic detritus built synorogenic wedges in the foreland and in remnant-ocean basins, including the development of very large deltas and submarine fans on the downgoing plate ahead of the collision zone. Increasingly precise foraminiferal biostratigraphic dating suggests that initial collision in the western Himalaya began by 57 ± 1 Ma (Beck et al., 1995). In contrast, the biostratigraphic age of the earliest orogenic sandstones from the Bengal basin suggests a somewhat later initiation of collision in the eastern Himalaya.

Other data from the eastern Himalayan foreland basins substantiate this trend. Along the Java-Sumatra trench to the southeast, sandstone of upper Oligocene to lower Miocene trench deposits are inferred to have been derived from the eastern Himalaya (Moore, 1979). These sandstones, which are now part of the Oyo complex, a tectonic melange exposed on Nias Island (Fig. 1), are very quartzose for trench deposits ($Qt_{72}F_8L_{20}$) (Moore, 1979). This suggests a mixed sedimentary-metasedimentary-volcanic source terrane in the Himalaya to the north, draining through the Bengal fan and reaching this subduction complex (Moore, 1979). Likewise, Neogene sands from the Bengal fan ($Qt_{57}F_{28}L_{14}$) are very similar in composition to sands of the same age in the Bengal basin (Fig. 10; Ingersoll and Suczek, 1979).

CENOZOIC HISTORY OF THE HIMALAYAN-BENGAL SYSTEM

The detrital record of the Himalayan collisional orogen preserved in the Bengal basin is distinctly different from the much better known record left in the Indus syntaxial foreland basin to the west. A synthesis of the contrasting evolution of these two regions is shown by schematic paleotectonic and paleogeographic diagrams in Figure 11. Eocene to Oligocene precollisional to syncollisional sediments in the Indus basin include both quartzose detritus from the Indian block and lithofeldspathic detritus from the developing suture on the Asian margin, whereas correlative deposits in the Bengal basin are overwhelmingly quartzose. The compositions and textures of Eocene and Oligocene sandstones in the Bengal basin do not suggest derivation from Himalayan or Indo-Burman orogenic sources, but rather point toward the low-relief, crystalline Indian craton adjacent to the west. Intense chemical weathering has also been suggested for Paleogene sediments in the Bengal basin because of their quartzose composition. This suggests strongly that the continental collision was diachronous overall, and that orogenic uplift, and consequently foreland-basin evolution, initiated earlier in the western Himalaya and propagated eastward over several tens of millions of years. This is consistent with the considerable (33°) counterclockwise rotation of India inferred for this time interval (Dewey et al., 1989).

Miocene sandstones of the Surma Group yield a clear record of unroofing of the eastern Himalaya and/or the Indo-Burman ranges. The source rocks from which these sands were derived were dominated by supracrustal rocks, which produced detritus rich in monocrystalline quartz and sedimentary to low-grade metamorphic lithic fragments. These supracrustal sources included Lesser Himalayan sedimentary and metasedimentary rocks that were thrust southward along the Main Boundary thrust (Mascle et al., 1986). Lithofacies maps of the thickest ac-

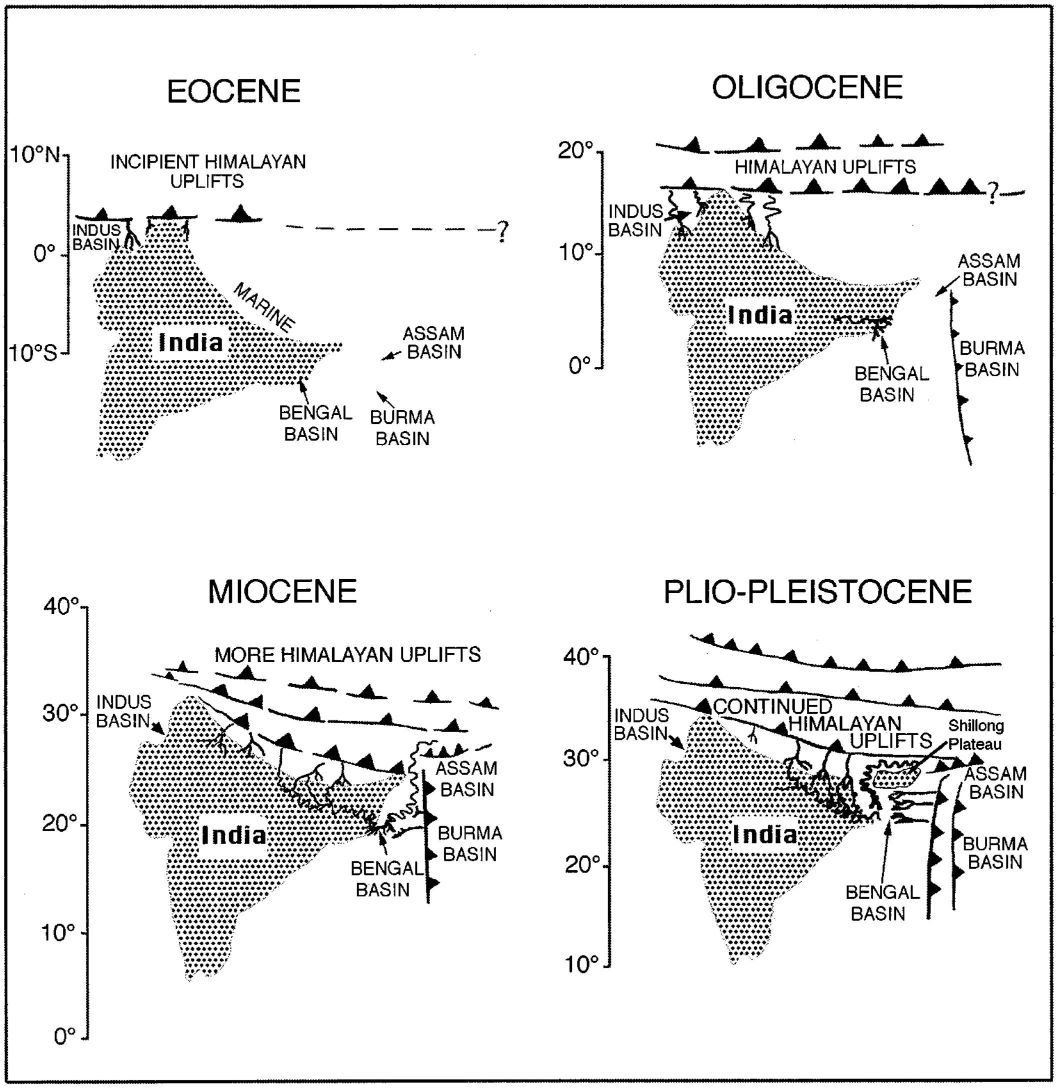

Figure 11. Schematic paleogeographic reconstructions of the Himalayan foreland and surrounding areas from Eocene to Pleistocene time, suggesting provenance evolution and eastward propagation of Himalayan collision. Modified from various sources, but mainly from Molnar and Tapponnier (1975), Johnson and Nur Alam (1991), and Lindsay et al. (1991).

cumulations of Miocene sediments in Bangladesh, however, suggest transport from the immediate east, suggesting input from the Indo-Burman ranges as well (Uddin and Lundberg, 1995). The initial input of Himalayan detritus to the Bengal basin was in early Miocene time, predating samples recovered from the Bengal fan, although current stratigraphic resolution precludes a more precise assignment than near the Oligocene-Miocene boundary (ca. 25 Ma).

Increases in the relative abundance of potassium feldspar in Bengal-basin sands during late Miocene to Pliocene time record unroofing of plutons in the eastern Himalayas. This was not likely due to exhumation of the Indo-Burman ranges, because there are no granitic terranes in the proximate (northern) Indo-Burman ranges, although it is possible that such terranes were present at that time. The sedimentation rate in the Bengal fan increased during this time, perhaps due to the increased rate of unroofing. Lithic-fragment populations are dominated by sedimentary rock types, and there is a temporal increase in the abundance of higher-grade metasedimentary lithic types in the Pliocene–Pleistocene strata relative to the Oligocene strata, suggesting orogenic unroofing. The course of the Brahmaputra River changed during Pliocene time, probably due to uplift of the Shillong Plateau (Johnson and Nur Alam, 1991). This represents a dramatic southward advance of the deformation front of the eastern Himalaya, whereas the deformation front of the Indo-Burman ranges has probably advanced more gradually westward, progressively encroaching on the Bengal basin.

Hodges et al. (1994) suggested a late Oligocene “Eohimalayan” metamorphic event on the basis of U-Pb data from leucogranites obtained from central Nepal. Results from our study of sand deposited in the Bengal basin, however, do not indicate obvious orogenic activity during Eocene–Oligocene time in the eastern Himalaya. This might be due to the greater distance from the orogenic belt to the Bengal basin depocenters prior to Miocene time; or, pre-Miocene drainage systems may have transported orogenic detritus elsewhere, perhaps east of the preserved portion of the Bengal basin, where it would have been either subducted or incorporated into the Indo-Burman orogen. The “Neohimalayan” episode (early to middle Miocene time; Hodges et al., 1994), however, during which intense deformation took place in most of the lithotectonic belts of the Himalaya and metamorphic core complexes underwent peak metamorphism and anatectic melting, is recorded clearly in the sediments of the Bengal basin. Isotopic analyses of sediment of the Bengal fan also suggest early Miocene unroofing of the Higher Himalaya (France-Lanord et al., 1993), and similar strong deformation and uplift may also have taken place in the Indo-Burman ranges during early to middle Miocene time. The results of this study are consistent with the hypothesis that the collision between India and Asia was diachronous (Dewey et al., 1989; Burchfiel, 1993; Rowley, 1996). Abundant data indicate that collision began near the western syntaxis by at least Eocene time, but it apparently did not begin until considerably later (although by earliest Miocene time) in the east.

Our petrographic results document, for the first time, detailed sand compositions of the Bengal basin, allowing evaluation of contrasts with sand deposited in the western Himalayan foreland basins. Sand in the Bengal basin is generally more quartzose and less lithic than that in the basins to the west, and pre-Miocene strata in the Bengal system show little to no evidence of orogenic activity. This likely reflects in part the diachronous west to east propagation of the Himalayan collision, but it also probably results from sedimentary systems migrating southward ahead of the evolving mountain belt.

CONCLUSIONS

The Bengal basin of Bangladesh comprises voluminous deltaic deposits in the heretofore little-studied eastern segment of the Himalayan foreland, providing a key link between orogenic sediment source terranes and the deep-sea deposits of the Bengal fan. Stratigraphic sequences preserved on land in the Bengal basin provide erosional information for the eastern Himalaya and the Indo-Burman ranges that records significantly older history than that available from Ocean Drilling Program and Deep Sea Drilling Project cores recovered offshore.

1. The quartzose nature of Eocene–Oligocene sediments suggests intense chemical weathering prior to deposition of the Eocene–Oligocene sediments. Sediment sources may have included incipient uplifts, presumably then quite distant, of the proto-Himalaya to the north and the early Indo-Burman ranges to the east. The subangular nature of quartz grains in these sediments, however, indicates that much of this detritus was more likely derived from relatively nearby sources, most likely the Indian craton immediately to the west.

2. Miocene and younger sandstones show an orogenic provenance; lithic populations indicate progressive unroofing through time. In particular, the abundance of potassium feldspar in the younger (Pliocene–Pleistocene) sand, relative to plagioclase-rich sand from the Miocene Surma Group, indicates a granitic source, probably derived at least in part from the Miocene leucogranites of the High Himalayan Crystalline terrane.

3. Petrographic analyses of Tertiary sand from the Bengal basin of Bangladesh suggest that dramatic tectonism began considerably later in the eastern Himalaya than has been documented near the western syntaxis, and there was detrital input to the Bengal basin from bordering orogens beginning in early Miocene time. This may also be due to southward propagation of sedimentary systems, advancing ahead of the southward-migrating mountain belt. Overall, this study is consistent with the hypothesis that the Himalayan collision was diachronous, having begun near the western syntaxis by at least Eocene time and beginning much later in the easternmost Himalaya, although by earliest Miocene time.

ACKNOWLEDGMENTS

Supported by National Science Foundation grants INT-9300295 and EAR-9419086, Total Oil Company, the Geology Department of Florida State University, the Geological Society of America, and Sigma Xi. We thank the former Minister of Energy and Mineral Resources of the Government of Bangladesh, Bangladesh Oil, Gas, and Mineral Corporation (BOGMC), and BAPEX for logistical help in Bangladesh and for access to borehole samples, and Monirul Hoque for helpful discussions. Thanks to Aminul Islam, Jasim Uddin, Manowar Ahmed, Nazim Ahmed, and M. Baqi for assistance during sample collection. We also thank Roy Odom, Jim Tull, and Paul Ragland for their comments on an earlier version of this manuscript, Suvrat Kher and Jiun-Yee Yen for help during sample analysis and drafting, Ray Ingersoll, Salvatore Critelli, and Eduardo Garzanti for providing data from the western Himalayas, and Paul Heller, Ray Ingersoll, and Mark Johnsson for constructive and thoughtful reviews.

REFERENCES CITED

Abid, A. I., Abbasi, I. A., Khan, M. A., and Shah, M. T., 1983, Petrography and geochemistry of the Siwalik sandstone and its relationship to the Himalayan orogeny: Geological Bulletin of the University of Peshawar, v. 16, p. 65–83.

Ahmed, S. T., 1968, Cenozoic fauna of the Cox's Bazar coastal cliff [Master's thesis]: Dhaka, Bangladesh, University of Dhaka, 68 p.

Amano, K., and Taira, A., 1992, Two-phase uplift of Higher Himalayas since 17 Ma: Geology, v. 20, p. 391–394.

Banerji, R. K., 1984, Post-Eocene biofacies, paleoenvironments, and paleogeography of the Bengal Basin, India: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 45, p. 49–73.

Beck, R. A., Burbank, D. W., Sercombe, W. J., Riley, G. W., Barndt, J. K., Berry, J. R., Afzal, J., Khan, A. M., Jurgen, H., Metje, J., Cheema, A., Shafique, N. A., Lawrence, R. D., and Khan, M. A., 1995, Stratigraphic evidence for an early collision between northwest India and Asia: Nature, v. 373, p. 55–58.

Bossart, P., and Ottiger, R., 1989, Rocks of the Murree formation in northern Pakistan: Indicators of a descending foreland basin of late Paleocene to middle Eocene age: Eclogae Geologicae Helvetiae, v. 82, p. 133–165.

Brunnschweiler, R. O., 1966, On the geology of the Indo-Burman ranges (Arakan coast and Yoma, Chin Hills, Naga Hills): Geological Society of Australia Bulletin, v. 13, p. 137–194.

Burbank, D. W., Beck, R. A., and Mulder, T., 1996, The Himalayan foreland basin, *in* Yin, A., and Harrison, M., eds., The tectonic evolution of Asia: New York, Cambridge University Press, World and Regional Geology Series, p. 149–188.

Burchfiel, B. C., 1993, Tectonic evolution of the Tibetan Plateau and adjacent regions: Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A-39.

Butler, R., 1995, When did India hit Asia? Nature, v. 373, p. 20–21.

Cerveny, P. F., Johnson, N. M., Tahirkheli, R. A. K., and Bonis, N. R., 1989, Tectonic and geomorphic implications of Siwalik Group heavy minerals, *in* Malinconico, L. L., Jr., and Lillie, R. J., eds., Tectonics of western Himalayas: Geological Society of America Special Paper 232, p. 129–136.

Chaudhri, R. S., 1975, Sedimentology and genesis of the Cenozoic sediments of the northwestern Himalayas (India): Geologische Rundschau, v. 64, p. 958–977.

Chen, W. P., and Molnar, P., 1990, Source parameters of earthquakes beneath the Shillong Plateau and the northern Indo-Burman ranges: Journal of Geophysical Research, v. 95, p. 12527–12552.

Chowdhury, S. Q., 1982, Palynostratigraphy of the Neogene sediments of the Sitapahar anticline (western flank), Chittagong Hill Tracts: Bangladesh Journal of Geology, v. 1, p. 35–49.

Cochran, J. R., 1990, Himalayan uplift, sea level, and the record of Bengal fan sedimentation at the ODP Leg 116 sites, *in* Cochran, J. R., Stow, D. A. V., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 116b: College Station, Texas, Ocean Drilling Program, p. 397–414.

Copeland, P., Harrison, T. M., and Heizler, M. T., 1990, ^{40}Ar/^{39}Ar single-crystal dating of detrital muscovite and K-feldspar from Leg 116, southern Bengal fan: Implications for the uplift and erosion of the Himalayas, *in* Cochran, J. R., Stow, D. A. V., et al., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 116b: College Station, Texas, Ocean Drilling Program, p. 93–114.

Critelli, S., and Garzanti, E., 1994, Provenance of the lower Tertiary Murree redbeds (Hazara-Kashmir syntaxis, Pakistan) and initial rising of the Himalayas: Sedimentary Geology, v. 89, p. 265–284.

Critelli, S., and Ingersoll, R. V., 1994, Sandstone petrology and provenance of the Siwalik Group (northwestern Pakistan and western-southeastern Nepal): Journal of Sedimentary Research, v. A64, p. 815–823.

Critelli, S., Rosanna D. R., and Platt, J. P., 1990, Sandstone detrital modes in the Makran accretionary wedge, southwest Pakistan: Implications for tectonic setting and long-distance turbidite transportation: Sedimentary Geology, v. 68, p. 241–260.

Curray, J. R., 1991, Possible greenschist metamorphism at the base of a ~22-km sedimentary section, Bay of Bengal: Geology, v. 19, p. 1097–1100.

Dewey, J. F., Shackleton, R. M., Chang, C., and Sun, Y., 1988, The tectonic evolution of the Tibetan Plateau: Philosophical Transactions of the Royal Society of London, v. 327, p. 379–413.

Dewey, J. F., Cande, S., and Pitman, W. C., 1989, Tectonic evolution of the India/Eurasia collision zone: Eclogae Geologicae Helvetiae, v. 82, p. 717–734.

Dickinson, W. R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, p. 695–707.

Dickinson, W. R., 1985, Interpreting provenance relations from detrital modes of sandstones, *in* Zuffa, G. G., ed., Reading provenance from arenites: Dordecht, Netherlands, Riedel, p. 333–361.

Dickinson, W. R., and Suczek, C. A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2164–2182.

Dorsey, R. J., 1988, Provenance evolution and unroofing history of a modern arc-continent collision: Evidence from petrography of Plio-Pleistocene sandstones, eastern Taiwan: Journal of Sedimentary Petrology, v. 58, p. 208–218.

Fitch, T. J., 1970, Earthquake mechanisms in the Himalayan, Burmese and Andaman regions and continental tectonics in central Asia: Journal of Geophysical Research, v. 75, p. 2699–2709.

France-Lanord, C., Derry, L., and Michard, A., 1993, Evolution of the Himalaya since Miocene time: Isotopic and sedimentologic evidence from the Bengal Fan, *in* Treloar, P. J., and Searle, M., eds., Himalayan tectonics, Geological Society [London] Special Publication 74, p. 603–621.

France-Lanord, C., Derry, L., and Michard, A., 1994, δ^{13}C of organic carbon in the Bengal Fan: Source evolution and transport of C3 and C4 plant carbon to marine sediments: Geochimica et Cosmochimica Acta, v. 58, p. 4809–4814.

Gansser, A., 1964, Geology of the Himalayas: London, Interscience, 289 p.

Garzanti, E., Critelli, S., and Ingersoll, R. V., 1996, Paleogeographic and paleotectonic evolution of the Himalayan range as reflected by detrital modes of Tertiary sandstones and modern sands (Indus transect, India and Pakistan): Geological Society of America Bulletin, v. 24, p. 631–642.

Graham, S. A., Dickinson, W. R., and Ingersoll, R. V., 1975, Himalayan-Bengal model for flysch dispersal in the Appalachian-Ouachita system: Geological Society of America Bulletin, v. 86, p. 273–286.

Graham, S. A., Ingersoll, R. V., and Dickinson, W. R., 1976, Common provenance for lithic grains in Carboniferous sandstones Ouachita Mountains and Black Warrior Basin: Journal of Sedimentary Petrology, v. 46, p. 620–632.

Harrison, T. M., Copeland, P., Hall, S. A., Quade, J., Burner, S., Ojha, T. P., and Kidd, W. S. F., 1993, Isotopic preservation of Himalayan/Tibetan uplift, denudation, and climatic histories in two molasse deposits: Journal of Geology, v. 101, p. 157–178.

Hodges, K. V., Hames, W. E., Olszewski, W., Burchfiel, B. C., Royden, L. H., and Chen, Z., 1994, Thermobarometric and ^{40}Ar/^{39}Ar geochronologic constraints on Eohimalayan metamorphism in the Dinggye area, Southern Tibet: Contributions to Mineralogy and Petrology, v. 117, p. 151–163.

Holtrop, J. F., and Keizer, J., 1970, Some aspects of the stratigraphy and correlation of the Surma Basin wells, East Pakistan: New York, United Nations, ECAFE Mineral Resources Development Series no. 36, p. 143–155.

Honegger, K., Dietrich, V., Frank, W. Gansse, A., Thoni, M., and Trommsdorf, V., 1982, Magmatism and metamorphism in the Ladakh Himalayas (the Indus-Tsangpo suture zone): Earth and Planetary Science Letters, v. 60, p. 253–292.

Houghton, H. F., 1980, Refined techniques for staining plagioclase and alkali feldspar in thin section: Journal of Sedimentary Petrology, v. 50, p. 629–631.

Hubbard, M. S., Royden, L. H., and Hodges, K. V., 1991, Constraints on unroofing rates in the High Himalaya: Tectonics, v. 10, p. 287–298.

Ingersoll, R. V., 1978, Petrofacies and petrologic evolution of the Late Cretaceous fore-arc basin, northern and central California: Journal of Geology, v. 86, p. 335–352.

Ingersoll, R. V., and Suczek, C. A., 1979, Petrology and provenance of Neogene sand from Nicobar and Bengal fans, DSDP Sites 211 and 218: Journal of Sedimentary Petrology, v. 49, p. 1217–1228.

Ingersoll, R. V., Bullard, T. F., Ford, R. L., Grimm, J. P., Pickle, J. D., and Sares, S. W., 1984, The effect of grain size on detrital modes: A test of the Gazzi-Dickinson point-counting method: Journal of Sedimentary Petrology, v. 54, p. 103–116.

Ingersoll, R. V., Graham, S. A., and Dickinson, W. R., 1995, Remnant ocean basins, *in* Busby, C. J., and Ingersoll, R. V., eds., Tectonics of sedimentary basins: Cambridge, Massachusetts, Blackwell Science, p. 363–391.

Ismail, M., 1978, Stratigraphic position of the Bogra limestone of the platform area of Bangladesh: Bangladesh Geological Society, Proceedings of the 4th Annual Conference, p. 19–25.

Jain, S. P., and Kanwar, R. C., 1970, Himalayan ridge in the light of the theory of continental drift: Nature, v. 227, p. 829.

Johnson, G. D., and Vondra, C. F., 1972, Siwalik sediments in a portion of the Punjab re-entrant: The sequence at Haritalyangar, District Bilashpur, H.P.: Himalayan Geology, v. 2, p. 118–144.

Johnson, N. M., Stix, J. Tauxe, L., Cerveny, P. F., and Tahirkheli, R. A. K., 1985, Paleomagnetic chronology, fluvial processes, and tectonic implications of the Siwalik deposits near Chinji Village, Pakistan: Journal of Geology, v. 93, p. 27–40.

Johnson, S. Y., and Nur Alam, A. M. N., 1991, Sedimentation and tectonics of the Sylhet trough, Bangladesh: Geological Society of America Bulletin, v. 103, p. 1513–1527.

Johnsson, M. J., Stallard, R. F., and Meade, R. H., 1988, First-cycle quartz arenites in the Orinoco river basin, Venezuela and Colombia: Journal of Geology, v. 96, p. 263–277.

Khan, M. R., and Muminallah, M., 1980, Stratigraphy of Bangladesh, in Petroleum and Mineral Resources of Bangladesh, Seminar and Exhibition: Dhaka, Government of the People's Republic of Bangladesh, p. 35–40.

Klootwijk, C. T., Gee, J. S., Pierce, J. W., Smith, G. M., and McFadden, P. L., 1992, An early India-Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121: Geology, v. 20, p. 395–398.

Kroonenberg, S. B., 1994, Effect of provenance, sorting and weathering on the geochemistry of fluvial sands from different tectonic and climatic environments, *in* Kumon, F., and Yu, K. M., eds., Sandstone petrology in relation to tectonics: Utrecht, Proceedings of the 29th International Geological Congress, p. 69–81.

Krynine, P. D., 1937, Petrography and genesis of the Siwalik Series: American Journal of Science, v. 34, p. 422–446.

Le Dain, A. Y., Tapponnier, P., and Molnar, P., 1984, Active faulting and tectonics of Burma and surrounding regions: Journal of Geophysical Re-search, v. 89, p. 453–472.

Le Fort, P., 1996, Evolution of the Himalaya, *in* Yin, A., and Harrison, M., eds., The tectonic evolution of Asia: New York, Cambridge University Press, World and Regional Geology Series, p. 95–109.

Lindsay, J. F., Holliday, D. W., and Hulbert, A. G., 1991, Sequence stratigraphy and the evolution of the Ganges-Brahmaputra Delta complex: American Association of Petroleum Geologists Bulletin, v. 75, p. 1233–1254.

Mack, G. H., 1978, The survivability of labile light-mineral grains in fluvial, aeolian and littoral marine environments: The Permian Cutler and Cedar Mesa Formations, Moab, Utah: Sedimentology, v. 25, p. 587–604.

Mascle, G., Herail, G., Van Haver, T., and Delcaillau, B., 1986, Structural evolution of the Himalayan episutural and perisutural basins: Centres Recherches Elf Aquitaine Bulletin, v. 10, p. 181–203.

Mitchell, A. H. G., 1993, Cretaceous-Cenozoic tectonic events in the western Myanmar (Burma)-Assam region: Journal of the Geological Society [London], v. 150, p. 1089–1102.

Molnar, P., and Tapponnier, P., 1975, Cenozoic tectonics of Asia: Effects of a continental collision: Science, v. 189, p. 419–426.

Moore, G. F., 1979, Petrography of subducted zone sandstones from Nias Island, Indonesia: Journal of Sedimentary Petrology, v. 49, p. 71–84.

Ni, J. F., Guzman-Speziale, M., Holt, W. E., Wallace, T. C., and Saeger, W. R., 1989, Accretionary tectonics of Burma and the three dimensional geometry of the Burma subduction zone: Geology, v. 17, p. 68–71.

Parkash, B., Sharma, R. P., and Roy, A. K., 1980, The Siwalik Group (Molasse-) sediments shed by collision of continental plates: Sedimentary Geology, v. 25, p. 127–159.

Petterson, M. G., and Windley, B. F., 1985, Rb-Sr dating of the Kohistan arc batholith in the Trans-Himalaya of north Pakistan and tectonic implications: Earth and Planetary Science Letters, v. 74, p. 45–57.

Raju, A. T. R., 1967, Observations on the petrography of Tertiary clastic sediments of the Himalayan foothills of North India: Dehra Dun, India, Bulletin of the Oil and Natural Gas Commission, p. 5–16.

Rao, A. R., 1983, Geology and hydrocarbon potential of a part of Assam-Arakan basin and its adjacent region: Petroleum Asia Journal, v. 6, p. 127–158.

Reimann, K.-U., 1993, Geology of Bangladesh: Berlin-Stuttgart, Gebruder Borntraeger, 160 p.

Rowley, D. B., 1996, Age of initiation of collision between India and Asia: A review of stratigraphic data: Earth and Planetary Science Letters, v. 145, p. 1–13.

Sahni, A., and Kumar, V., 1974, Paleogene palaeobiogeography of the Indian subcontinent: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 15, p. 209–226.

Salt, C. A., Alam, M. M., and Hossain, M. M., 1986, Bengal basin: Current exploration of the hinge zone of southwestern Bangladesh: Singapore, Proceedings of 6th Offshore Southeast Asia Conference, p. 55–67.

Sclater, J. G., and Fisher, R. L., 1974, The evolution of the east central Indian Ocean, with emphasis on the tectonic setting of the Ninetyeast Ridge: Geological Society of America Bulletin, v. 85, p. 683–702.

Sengupta, S., Ray, K. K., Acharyya, S. K., and de Smeth, J. B., 1990, Nature of ophiolite occurrences along the eastern margin of the Indian plate and their tectonic significance: Geology, v. 18, p. 439–442.

Suczek, C. A., and Ingersoll, R. V., 1985, Petrology and provenance of Cenozoic sand from the Indus cone and the Arabian basin, DSDP sites 221, 222, and 224: Journal of Sedimentary Petrology, v. 55, p. 340–346.

Uddin, A., and Lundberg, N., 1995, Miocene paleogeography of the Bengal basin, Bangladesh: Subsurface lithofacies analysis: Eos (Transactions, American Geophysical Union), v. 76, p. S279.

Uddin, A., and Lundberg, N., 1998, Unroofing of the eastern Himalaya and the Indo-Burman ranges: Heavy-mineral study of Cenozoic sediments from the Bengal basin, Bangladesh: Journal of Sedimentary Research, v. 68, p. 465–472.

Uddin, A., Kher, S., and Lundberg, N., 1994, Detrital record of the eastern Himalaya: Modal analysis of upper Cenozoic sandstones of the Bengal basin, Bangladesh [abs.]: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A-243.

Uddin, M. N., and Ahmed, Z., 1989, Palynology of the Kopili Formation at GDH-31, Gaibandha District, Bangladesh: Bangladesh Journal of Geology, v. 8, p. 31–42.

Wallid, K. M., 1982, Palynostratigraphy of the Tertiary sediments as exposed along the Jaflong-Tamabil-Jaintapur roadcut in Sylhet district, Bangladesh [Master's thesis]: Dhaka, Bangladesh, University of Dhaka, 105 p.

Windley, B. F., 1983, Metamorphism and tectonics of the Himalaya: Journal of Geological Society of London, v. 140, p. 849–865.

Yokoyama, K., Amano, K., Taira, A., and Saito, Y., 1990, Mineralogy of silts from the Bengal Fan, *in* Cochran, J. R., Stow, D. A. V., et al., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 116b: College Station, Texas, Ocean Drilling Program, p. 59–73.

MANUSCRIPT RECEIVED BY THE SOCIETY JULY 29, 1996
REVISED MANUSCRIPT RECEIVED SEPTEMBER 10, 1997
MANUSCRIPT ACCEPTED OCTOBER 15, 1997

Printed in U.S.A.