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Miocene sedimentation and subsidence during continent–continent collision, Bengal basin, Bangladesh

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Abstract

The Bengal basin, a complex foreland basin south of the eastern Himalayas, exhibits dramatic variability in Neogene sediment thickness that reflects a complicated depositional and tectonic history. This basin originally formed as a trailing margin SE of the Indian continental crust, complicated by convergence with Asia to the north and oblique convergence with Burma to the east. Newly compiled isopach data and previously reported seismic data show evidence of thickening of basin fill toward the south, opposite of the pattern typically seen in foreland basins. This is presumably due to sedimentary loading of voluminous deltaic sediments near the continent–ocean boundary and basinward downfaulting analogous to that in the Gulf of Mexico. Isopach data show that there is considerable vertical relief along the base of the Miocene stratigraphic sequence, probably due to down-to-the-basin faulting caused by focused deltaic sedimentation and associated crustal flexure. In contrast, when viewed in east–west profile, basin shape is more typical of a foreland basin, with strata thickening eastward toward the Indo–Burman ranges, which reflects east–west convergence with Southeast Asia.

Comparison of the lateral and vertical extent of the Bhuban and Boka Bil Formations with the Bouguer anomaly map of Bangladesh suggests that considerable subsidence of the Sylhet trough (in the northeastern part of the Bengal basin), which has the lowest gravity value of the region, had not taken place by the end of the Miocene. This post-Miocene subsidence is attributed to tectonic loading from southward thrusting of the Shillong Plateau along the Dauki fault. Relatively uniform Miocene isopachs across the Sylhet trough confirm that this began in the Pliocene, consistent with results of recent research on sediment provenance. In the northwest, in the region south of the Siwalik foreland basin, continental crust has not as yet been loaded, allowing relatively little accommodation space for sediment accumulation. The Miocene here is very thin. Deltaic progradation across most of Bangladesh during the Miocene followed earlier, more proximal progradation across Assam, immediately northeast of the Bengal basin, and has been followed by continued progradation into the southern Bangladesh coastal and offshore region.

Keywords: Bengal basin; Bangladesh; Himalayas; Isopach maps; Surma Group

1. Introduction

The Bengal basin is a composite basin with a varied tectonic history. Other than minor Carbonifer-

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ous coal measures preserved at least locally on Precambrian continental crust, the main phase of deposition in this basin began following the separation of India from Antarctica at about the beginning of Late Cretaceous time (Sclater and Fisher, 1974; Molnar and Tapponnier, 1975). The motion of the Indian continent slowed markedly from the Early Eocene to Early Oligocene and then resumed in a north–northwesterly direction (Sclater and Fisher, 1974). Thick Tertiary deposits accumulated in the Bengal basin beginning in the Late Eocene, with deposition accelerating with the arrival of clearly orogenic sediments in the earliest Miocene (Uddin and Lundberg, 1998a). The Bengal basin is a large basin occupied dominantly by the Ganges–Brahmaputra delta. From at least Miocene to the present, the Ganges–Brahmaputra and associated or ancestral rivers have been transporting clastic sediments to the Bengal basin.

Exploration for gas and oil by several national and international oil companies has been continuing in the Bengal basin since about 1910. The Bangladesh part of the Bengal basin is rich in natural gas deposits. Proven reserves of natural gas exceed 13 trillion ft^3 (Murphy, 1988), and production is currently being used for domestic and industrial purposes. Most of the gas fields are characterized as structural traps located in the Sylhet trough of northeastern Bangladesh. There is at least one well that is producing oil in the Sylhet trough (Murphy, 1988). The major hydrocarbon producing sediment horizon is the Boka Bil Formation, an Upper Miocene unit that comprises the upper portion of the Surma Group. Exploration efforts here have produced a number of data sets that are useful in helping to decipher the paleogeography of the Bengal basin, with most data focusing on strata of the Miocene.

Proximal deposition of a portion of the orogenic sediment from the eastern Himalaya and the Indo–Burman uplifts has built a thick sequence (~ 20 km) of deposits in the Bengal basin. These deposits hold considerable potential for recording the erosion of and thus the tectonic events in the Himalayan and Indo–Burman mountain belts. Although the Himalayan belt and the sediments along its northwestern foothills have been studied for a number of years, and drill cores from distal portions of the Bengal deep-sea fan have been recovered by several drilling cruises, the deltaic sediments of the Bengal basin, through which the orogenic detritus is transported to reach the deep-sea fan, have not been studied in detail.

Isopach maps have been drawn from electric logs obtained from oil and gas exploration in the region, and gravity data have been compiled, in an effort to study the Miocene sedimentation patterns in the Bangladesh part of the Bengal basin and fundamental issues of paleogeography during the critical time periods immediately prior to and following the Miocene. The purpose of this paper is to address questions about basin-scale patterns of subsidence and sedimentation. The fundamental question addressed here is the following: what are the overall patterns of subsidence across the Bengal basin, and what do they imply about the history of basin development and regional tectonic events? Also, when did the considerable subsidence of the Sylhet trough take place, and what does this mean for the evolution of the prograding delta?

2. Regional geology

Bangladesh constitutes the eastern continuation of the central broad Indo–Gangetic plains of India, which serve to physiographically divide the Peninsular (shield) area to the south from the extra-Peninsular region (Himalayan mountain ranges) to the north and northeast (Fig. 1). The Bengal basin is located primarily in Bangladesh, with a lesser part in the West Bengal State of India, and lies roughly between 20°34′ to 26°38′N and 88°01′ to 92°41′E. The basin is surrounded by India on three sides. The Shillong Plateau of Assam lies to the immediate north, and the Himalayas to the distant north. The Indo–Burmese Arakan-Chin uplifts lie to the east and the Indian shield to the west. The area is open toward the south and drains into the Bay of Bengal in the northern Indian Ocean (Fig. 1). Sediment carried by three major rivers, the Ganges, the Brahmaputra, and the Meghna, is distributed to the Bengal deep-sea fan by turbidity currents through the 'Swatch of No Ground' (Curray and Moore, 1971; Kuehl et al., 1989), a submarine canyon. The Bay of Bengal has been identified as a remnant ocean basin (Curray et al., 1982; Ingersoll et al., 1995) because the basin has been closing by easterly subduction beneath the Indo–Burman ranges and the Andaman and Sunda Arcs.

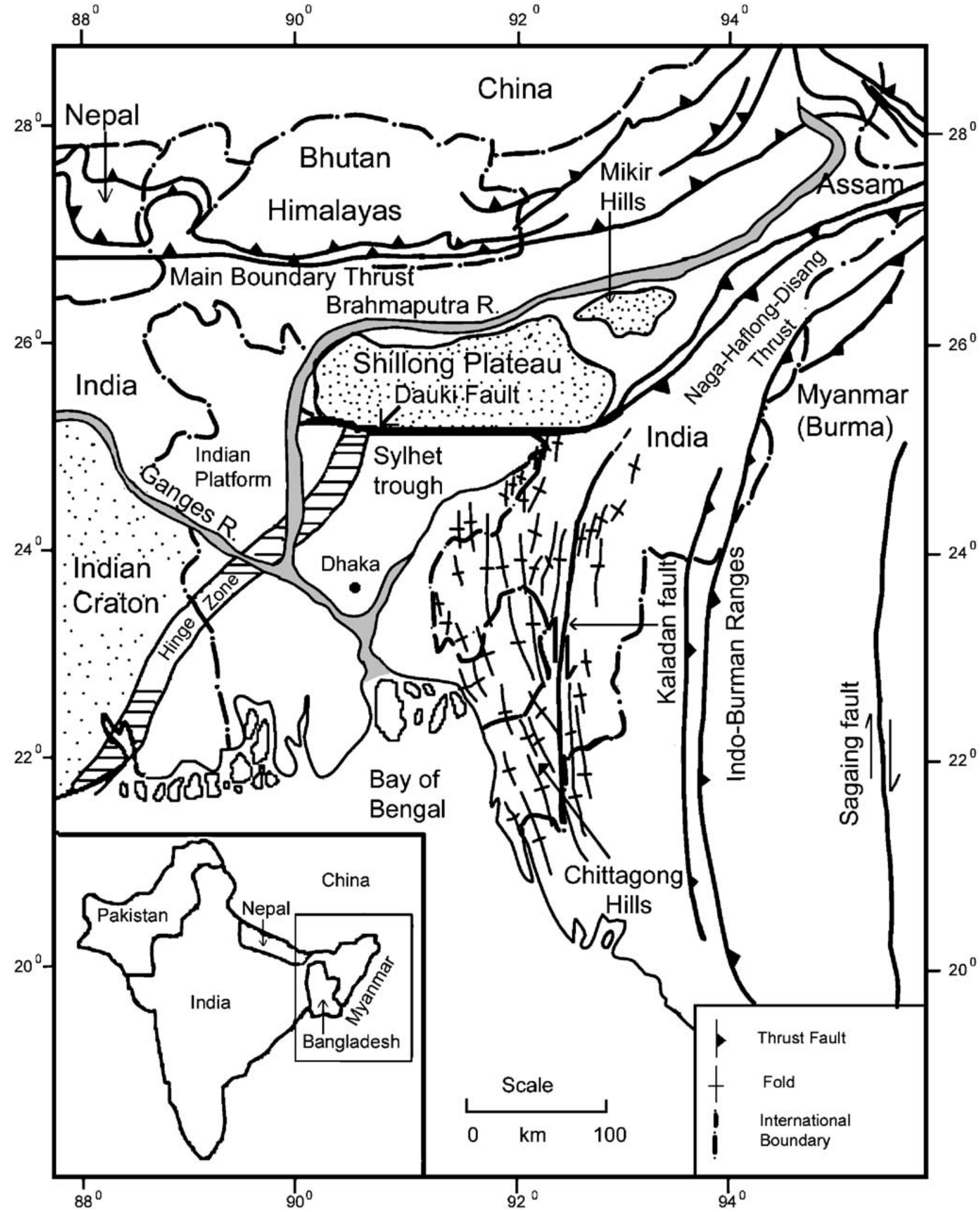

Fig. 1. Map showing major tectonic elements in and around the Bengal basin. Hinge zone demarcates the deeper basin from the Indian Platform area. Right-lateral N–S faults (e.g., Kaladan fault) are in the east. The Dauki fault separates the Sylhet trough from the uplifted Shillong Plateau at the north (after Uddin and Lundberg, 1998b).

The Shillong Plateau and the Mikir Hills to the north are underlain by Precambrian continental crust (Fig. 1). Previously, it was suggested that the Shillong Plateau was the result of right-lateral shear faulting having detached a block of Indian crust some 250 km eastward from the Rajmahal hills of India (Evans, 1964). More recently, vertical or dip-slip uplift has been suggested for the origin of the Shillong Plateau (Fig. 2a; Desikachar, 1974; Hiller and Elahi, 1984). The plateau appears presently as a horst block, bor-

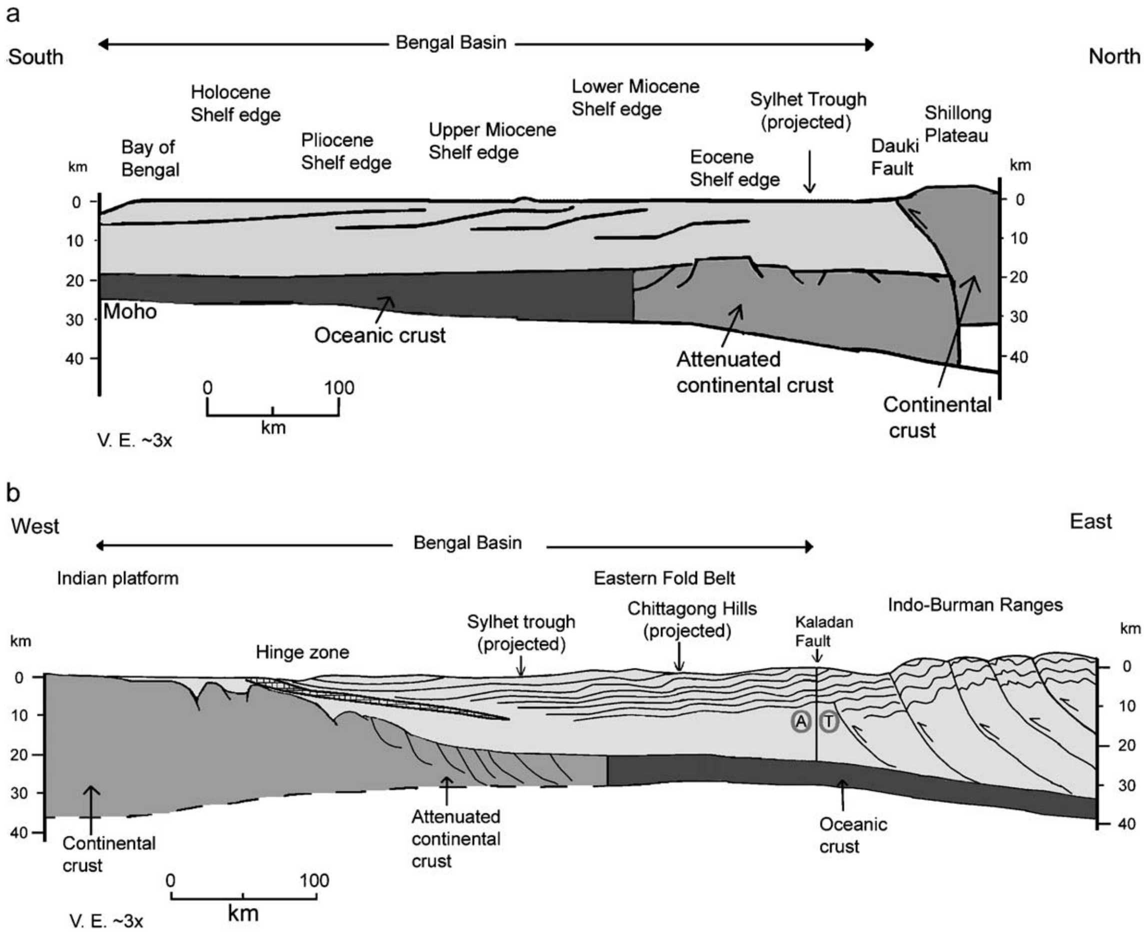

Fig. 2. Schematic cross-section of the Bengal basin; (a) N–S, through the Shillong Plateau; (b) E–W, through the northern Chittagong Hill region, after Murphy (1988). These show sediment thickening toward the south and east, respectively.

dered on all sides by faults (Khandoker, 1989) and drained by the Brahmaputra River on the north and west. The southern margin of the plateau is a south-dipping monocline, truncated by the prominent E–W trending Dauki fault, which marks the northern boundary of the Bengal basin (Fig. 1). Molnar (1987), based on interpretations of the seismotectonics of the region, interpreted the Dauki fault as an overthrust. Johnson and Nur Alam (1991) also suggested that the Dauki fault is a thrust fault, with a dip similar to that of other frontal Himalayan thrusts (i.e., 5–10°; Molnar, 1987) and indicated that a few tens (28–80) of kilometers of horizontal tectonic transport would be required to carry the Shillong Plateau to its present elevation. Uplift of the Shillong Plateau also led to a 300 km westward shift of the Brahmaputra after the Miocene (Johnson and Nur Alam, 1991).

2.1. Tectonic setting

The Bengal basin is asymmetric; the thickness of the sediments increases toward the south and east to more than 16 km (Fig. 2a and b; Curray and Moore, 1971; Murphy, 1988). Interpretations of the tectonic setting of the basin are varied and rather convolute. Desikachar (1974) proposed a plate tectonic model of the region. He considered the Bengal basin as a pericratonic basin of the Indian plate. His proposition suggests that the deeply subsided central portion of the Bengal basin forms part of the Indian plate, whereas the eastern basin margin is actually part of the Burmese plate. In his view, the Burmese plate has moved toward the Indian plate beginning in the Miocene, and just east of the Ninety-East ridge (or its northern extension), where he inferred maximum subsidence, the Burmese plate overrode the Indian plate to form a subduction zone between the two plates. Today most authors agree that convergence between India and Burma has resulted in subduction of oceanic crust beneath Burma, with the trailing margin of India currently passing obliquely into the foreland of the Indo–Burman ranges (Murphy, 1988; Mukhopadhyay and Dasgupta, 1988; Alam et al., 2003). This convergent margin has been complicated by right-lateral strike-slip motion (e.g., Kaladan fault, Sagaing fault; Fig. 1), possibly throughout the history of the collision (e.g., Ni et al., 1989).

Tectonically, the basin has two broad divisions: (1) the 'Indian platform' (also known as the 'Stable shelf' region) to the northwest and west, underlain by Precambrian continental crust, and (2) the deeper part of the basin in the south and east. The 'Hinge zone' (Sengupta, 1966) separates the two structural provinces. The basement of the 'Indian platform' slopes to the northwest and southeast from a central ridge, which has the shallowest occurrence (~ 140 m) of Precambrian rocks in Bangladesh. These basement rocks are generally considered to be an eastward subsurface continuation of rocks of the Indian Shield. From the Hinge zone, the southeastern slope of the Precambrian basement steepens rather abruptly (from 2–3° to 6–12°), and then dips more gently (1–2°) again in the deeper (SE) part of the basin. The narrow (25–100 km) 'Hinge zone' has also been known as the 'Calcutta–Mymensingh gravity high' (Sengupta, 1966; Khandoker, 1989), although more recent data (Khan and Agarwal, 1993) suggest that this term is somewhat misleading. The Hinge zone runs in a NE–SW direction (Fig. 1) between the Naga–Haflong–Disang thrust zone of Assam in the northeast to the Indian part of the Bay of Bengal, off the east coast of India to the south (Fig. 1).

The deeper part of the Bengal basin, a zone of very thick sedimentary strata lying over deeply subsided basement, is subdivided, based on gravity studies, into a northwestern platform flank, just east of the Hinge zone, and an eastern folded flank that includes the Chittagong Hills and the Sylhet trough in the northeastern part of the Bengal basin (Khandoker, 1989; Khan, 1991). The platform flank shows small-amplitude, isometric or geographically equant anomalies, whereas the folded flank exhibits large-amplitude, linear or elongate anomalies (Bakhtine, 1966). The Sylhet trough is a conspicuous trough of thick sedimentary fill along the northeastern part of the Bengal basin, and has been studied extensively as a result of successful petroleum exploration (Holtrop and Keizer, 1970; Woodside, 1983). The Sylhet trough is a depositional low located just south of the crystalline Shillong Plateau with a structural relief of about 20 km between the trough and the neighboring plateau (Murphy, 1988; Johnson and Nur Alam, 1991). The folded flank of the deeper basin is composed of elongated folds of north–northwest to south–southeast trend. Structural complexity of the folded flank increases from west to east and merges into the Indo–Burman ranges farther east (Khan, 1991). Strata exposed in the folded flank are broadly similar to those exposed along the length of the Sub-Himalayan belt of the Himalayas.

2.2. Stratigraphy

The stratigraphy of the basin (Fig. 3) is incompletely known because of thick sequences of alluvium cover and relative paucity of fossils. Comparative lithologic studies have been the only means to establish and to interpret the stratigraphy. The nomenclature and classification of the stratigraphy of the Bengal basin is established on the basis of type sections in the Assam basin (northeast India) (Khan and Muminullah, 1980). Stratigraphically, only the Tertiary rocks are exposed in the folded flank of the Bengal basin (Chittagong Hills and flanks of the Sylhet trough; Fig. 1) and the Permo–Carboniferous Gondwana coals are the oldest Phanerozoic sediments at the holes drilled into the Precambrian 'Indian platform' tectonic zone in northwest Bengal basin. These intracratonic, fault-bounded Gondwana coal deposits are exposed at the western fringe of the Bengal basin, in the Bihar State of India. There are also subsurface occurrences of volcanic rocks, equivalent to the Rajmahal traps of India, followed by trap-wash sediments

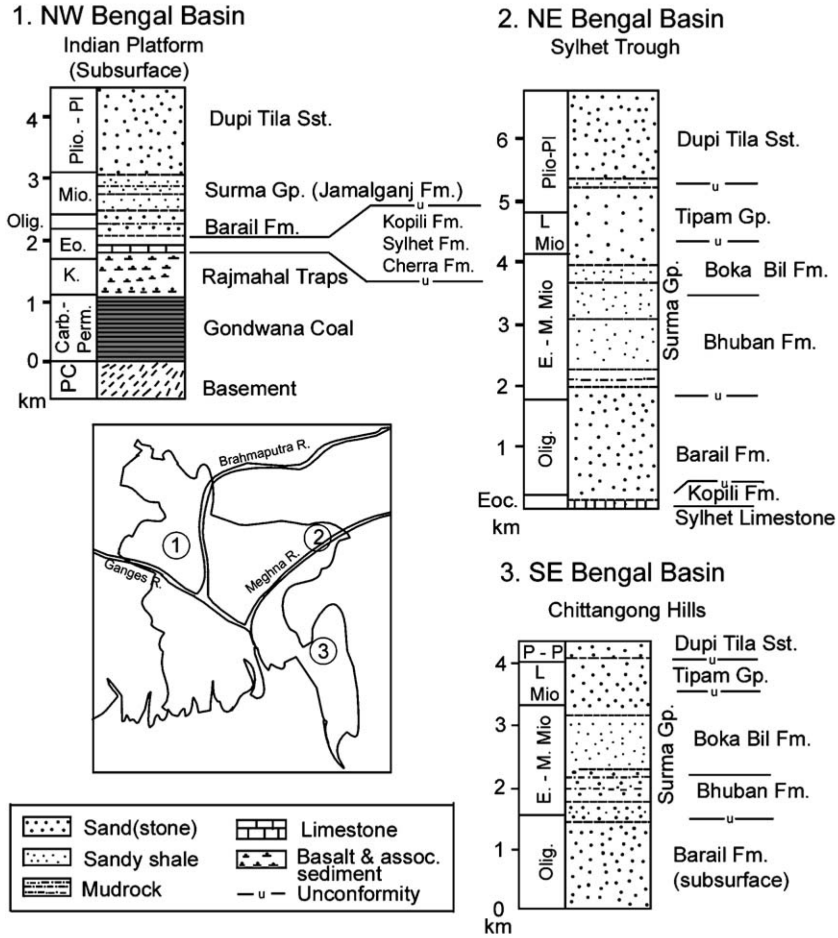

Fig. 3. Stratigraphic framework of the Bengal basin. Miocene sediment thickness is much lower near the Indian platform in the northwestern part of the basin. This shelf area of the basin is floored by continental crust (after Khan and Muminullah, 1980; Uddin and Lundberg, 1999; and many other sources).

present above the Gondwana coal formations at the NW of the Bengal basin.

Repeated submergence and emergence of the Bengal basin must have taken place in the shelf region during Late Cretaceous–Middle Eocene time, when the deeper parts of the Stable shelf of West Bengal, Bangladesh and Assam were invaded by the sea, whereas freshwater sedimentation of sandstone and carbonaceous mudrocks continued in most of the shallow shelf regions (Hoque, 1974; Banerji, 1981; Reimann, 1993). In the Bengal foreland and Indo–Burman ranges, sedimentation took place in a marine environment and turbidites probably played an important role in sedimentation (Graham et al., 1975). The Eocene interval is marked by an extensive marine transgression caused by conspicuous basin-wide subsidence. Clastic sediment input on the 'Stable shelf' was reduced and the shelf became the site of deposition of shallow, clear water, open marine, limestone. These limestones, commonly known as the Sylhet Limestone, are very rich in fossil nummulites. This limestone is exposed at the northern fringe of the Sylhet trough on the south slope of the Shillong plateau.

The Oligocene to Earliest Miocene time was characterized by a major marine regression exposing most of the 'Stable shelf.' The Bengal basin is bounded from the Burma basin to the east by the Indo–Burman ranges. The Oligocene clastic rocks (Barail Group) are exposed in part of the Sylhet trough and drilled in some holes (Holtrop and Keizer, 1970; Reimann, 1993).

The Miocene Surma Group is a diachronous unit consisting of a succession of alternating mudrock, sandstone, siltstone and sandy shales with occasional thin conglomerates (Imam and Shaw, 1985). Overlying the Surma Group, the Upper Marine Shale represents a regional marine transgression in the region (Holtrop and Keizer, 1970). By Early Miocene time, a major phase of sedimentation started and huge amounts of clastic sediment were funneled into the basin from the northeast and the major Mio–Pliocene delta complex started to build from the northeast (Uddin, 1990). A considerable amount of sediment was also coming into the basin from the northwest and small deltas were building on the western side of the basin (Alam, 1989). Sedimentation was in deltaic and open-shelf environments along the basin margins, whereas turbidites were controlling the sedimentation in the central and southern areas (Alam, 1989). Deltaic sedimentation during the Miocene has been documented based on extensive studies of lithofacies (e.g., Alam, 1989; Uddin and Lundberg, 1999), and fossil assemblages (mostly palynology; as cited in Reimann, 1993), confirmed by studies of seismic reflection character (Salt et al., 1986; Lindsay et al., 1991). Many investigations of lithofacies have reported mainly coastal to shallow water deposits, with some reports of deep marine strata in SE Bangladesh (e.g., Reimann, 1993; Gani and Alam, 1999). Tests of foraminifers and hystrichospherids from the more shaly sequences in the Chittagong Hills also indicate brackish to marine environments. Remains of gastropods, lamellibranchiats, echinoids and burrows discovered in cross-bedded sandstone of the Bhuban Formation indicate nearshore depositional environments (Reimann, 1993). A paleogeographic reconstruction of the Bengal basin in the Miocene (Alam, 1989) shows several deltaic complexes prograding from the northeast, east, west and northwest into the basin. Strata of the overlying Tipam Formation were laid down under continental fluviatile conditions (Alam, 1989). During this time, strata along the eastern margin of the Bengal basin began to be actively deformed, producing a distinct mobile belt (folded flank of the deeper part of the basin) known as the Chittagong folded belt.

The Late Miocene–Pliocene time was a period of intense deformation and uplift in the mobile belts of the Bengal basin, contributing to widespread regression of the sea (Hoque, 1974). A regression during the Late Miocene (the Messinian) has also been seen in seismic reflections recorded far offshore in the Bay of Bengal (Curray and Moore, 1971). West-directed compression propagated westward, deforming strata in the area of the Chittagong Hill tracts. Deposition of fluviatile and deltaic sandstones and conglomerates (Dupi Tila Sandstone and Dihing Formation) took place in the eastern fold belt and in the Sylhet trough (Holtrop and Keizer, 1970).

The Quaternary in the Bengal basin was marked by a general regression presumably due to voluminous sediment influx from the highlands, although glacioeustatic oscillations have also been recorded (Morgan and McIntire, 1959). Much of the present geomorphic landscape of the Bengal basin and the regions surrounding it developed during this time (Hoque, 1974). Pleistocene and Holocene deposits are represented on land by three areas of red clay deposits, a coastal coral bed and several small sand bodies, but voluminous deltaic deposits of this age are restricted to the offshore regions of the Bay of Bengal.

3. Methods

The Miocene Surma Group is the stratigraphic interval that is of particular interest from the perspective of hydrocarbon occurrence in Bangladesh, because all natural gas pay zones are found in this group. Because these strata are well represented in the deeper parts of the basin, petroleum exploration has produced a wealth of subsurface data. Electric logs obtained during hydrocarbon exploration were analyzed to measure thicknesses of the Miocene units (the Bhuban and Boka Bil Formations) in 18 wells (Table 1). These Miocene units are bounded below by a basal-Miocene unconformity, and bounded above by a distinctive seismic reflector known as the “Upper Marine Shale” (Reimann, 1993). The contact between these two units is transitional, identified mainly on the basis of lithology and supported by palynomorphs and some foraminifers (Reimann, 1993). Related subsurface data were also studied to compare and decipher

Table 1
Thickness of two Miocene units (Bhuban and Boka Bil Formations) of the Surma Group in the Bengal basin in various wells of Bangladesh

Tectonic location: Major	Tectonic location: Important subdivision	Wells	Thickness of Boka Bil Formation (in meters): From	To	Total	Thickness of Bhuban Formation (in meters): From	To	Total
Shelf		Bogra-1	217	782	565	782	1593	811
		Kuchma-X1	340	1090	750	1090	1606	516
		Singra-IX	1290	1600	310	1600	1880	280
Hinge zone		Hazipur-1	1393	2247	854	2247	3130	883
Deeper basin	Surma basin (=Sylhet trough)	Chattak-1	626	1081	456	1082	2134	1052
		Sylhet-2	1240	1915	675	1915	2818	903
		Atgram-IX	1085	2256	1171	2256	4178	1920
		Kailastila-1	2150	2900	750	2290	4138	1238
		Beani Bazar-IX	2631	3640	1009	3640	4109	469
		Rashidpur-2	1036	2710	1674	2710	3851	1141
		Habiganj	1165	2326	1161	2326	3506	1180
		Kamta-1	1030	2740	1710	2740	3614	874
		Titas-1	832	2362	1531	2362	3758	1396
		Bakhrabad-1	560	1770	1210	1770	2838	1068
		Begumganj-1	1480	2580	1100	2580	3656	1076
		Muladi-1	750	2590	1840	2590	4395	1805
		Feni-1	1300	2440	1140	2440	3200	760
	Folded belt	Semutang-1	250	1530	1280	1530	3500	1970
		Jaldi-3	500	1380	880	1380	2930	1550
	Offshore	Kutubdia	1713	3606	1792	not drilled		

paleogeography. Gravity data (Brunnschweiler, 1980; Rahman et al., 1990; Khan and Agarwal, 1993) have been analyzed to interpret overall basin geometry in light of Miocene stratal variations. Most of the Miocene strata in the northwestern part of the Bengal basin are limited to very thin, mostly undifferentiated sequences and are not included in this study.

4. Depositional patterns

An isopach map of the lower to middle Miocene Bhuban Formation (Fig. 4) shows dramatic thickening of strata toward the south and toward the east. In the northwest part of the study area, Bhuban thicknesses generally range from about 500 to 900 m, with one area of reduced thickness (Singra well). This overall pattern is varied by a region of anomalously thin strata extending from the Bakhrabad well southeastward to the Jaldi well. Although we have no data in the Tripura area of India, there is an apparent offset of the isopachs of Bhuban strata between northeastern Bangladesh and the region to the south, called the Chittagong Hills.

An important observation about the Bhuban strata is that the maximum thicknesses in the south and along the eastern parts of the basin are the same (~ 1800 m), suggesting that crustal type and accommodation space were similar across these areas. The very regular pattern of thickening toward the south and toward the east, from 500 to 1800 m thick, suggests deltaic deposition prograding southward and eastward. This further suggests deeper marine sedimentation beyond the deltaic deposits to the south and east. This is certainly true in southeast Bangladesh where turbidites are reported in the Bhuban Formation in the Chittagong Hills (e.g., surface exposures near the Semutang well, see Akhter et al., 1998; Gani and Alam, 1999). Notably, there is no indication in the isopach data of barriers to sedimentation in the present-day region of the western foothills of the Indo–Burman ranges. This region in the Miocene was near the zone of plate convergence between India and Burma, with Bengal basin strata overlying the subducting oceanic crust of Indian plate. Thus, much of the Bhuban Formation in this region may have been deposited on an outer trench slope as Burma approached from the east, and so is likely to comprise

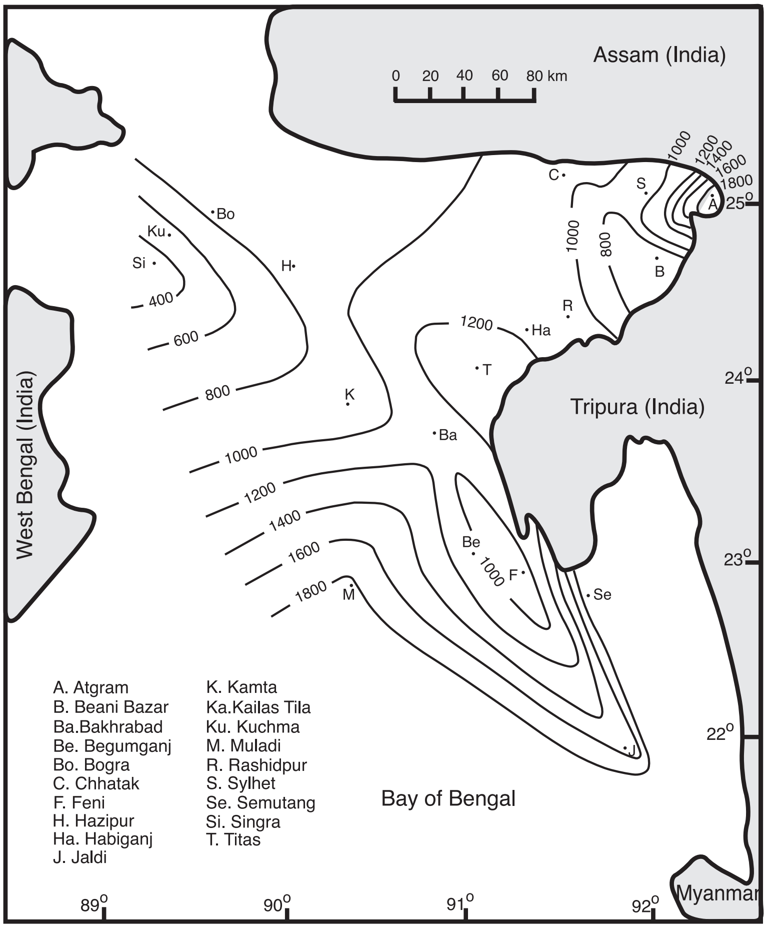

Fig. 4. Isopach map (in meters) of the lower to Middle Miocene Bhuban Formation. Well data from the southwest part of the basin not available. Index provides key to well names referred in text. The outline indicated by the shaded areas in Figs. 4, 5 and 6 correspond to the political boundary of Bangladesh.

deep-marine deposits. The one obvious anomaly to this regular pattern is the zone of thin strata extending from the Bakhrabad (Ba) well to the Jaldi (J) well. This area of anomalously thin Bhuban strata is enigmatic; perhaps it overlies a pre-existing bathymetric high, or for some reason relatively thin strata were deposited, or at least preserved here. The map pattern of isopachs in this region has been compressed by strong east–west shortening during the Late Neogene. The original depositional pattern would therefore have been considerably smoother, with thicknesses increasing more gradually to the east. Elsewhere, most Bhuban strata that have been analyzed are interpreted to be shallow-marine to subaerial deposits. We have no well data in the southwestern part of the basin; we presume that thickness variations here likely continue as shown, roughly parallel to the (SW-trending) continent–ocean boundary and Hinge zone.

An isopach map of the Boka Bil Formation (midd to upper Miocene; Fig. 5) shows one major depocenter in the central part of the basin, with stratal thickness ranges mimicking those of the Bhuban strata. The thickest deposition of Boka Bil strata is found at the Muladi (well M) area with strata gradually thinning toward the northwest, north and to a lesser degree to the east. Anomalously thick strata, however, are found in the area of Rashidpur (well R). Significantly, there is no extensive area of thick Boka Bil strata in southeast

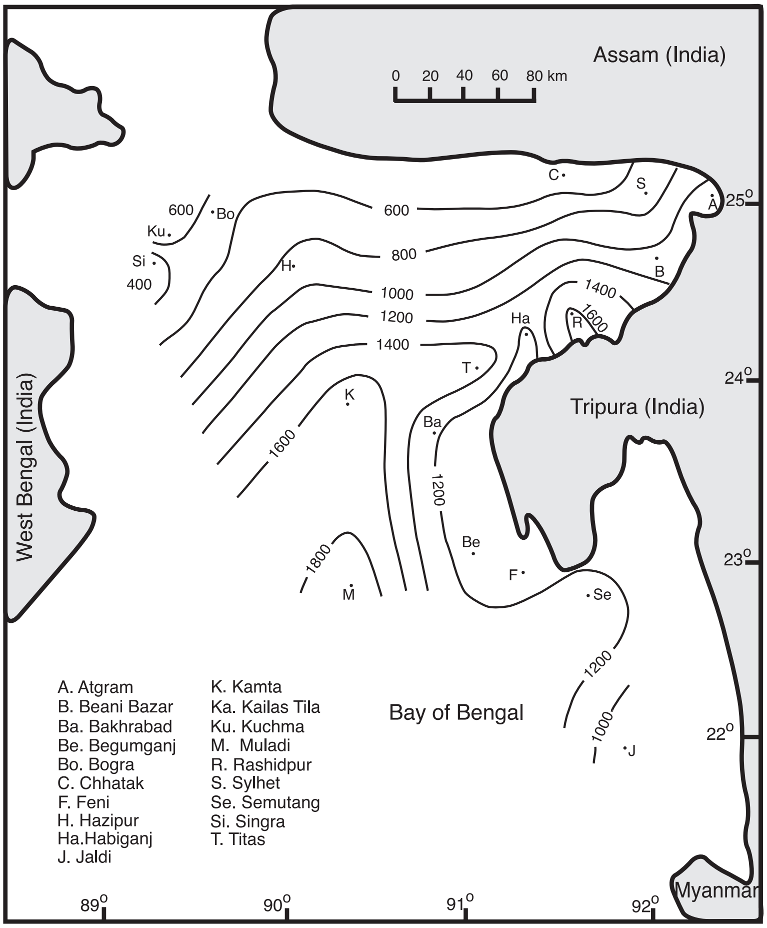

Fig. 5. Isopach map (in meters) of the Middle to Upper Miocene Boka Bil Formation of the Surma Group. Index provides key to well names referred to in the text.

Bangladesh, and no turbidites have been reported from these units. Continuing E–W plate convergence has closed the topographic embayment associated with the trench by this time, resulting in deposition of relatively uniform thickness of mostly shallow-marine Boka Bil strata in southeast Bangladesh. As was true for the Bhuban Formation, complex thickness variations along the eastern basin margin suggest that the Indo–Burman ranges were continuing to encroach on the Bengal basin throughout the Miocene, particularly in the area of the Chittagong Hills (far eastern portion of central and southern Bangladesh).

The thinnest section of both formations is located at the Singra well, which is closer to the exposed Indian craton to the west than are any other wells in this study. This area apparently experienced less subsidence than most of the rest of the basin through the Miocene.

4.1. Basin tectonics

The Bouguer anomaly map (Fig. 6) of Bangladesh helps recognize four key features that are important to discuss the tectonics of the Bengal basin:

(a) A linear gravity anomaly parallels the Hinge zone (slightly offset to northwest), marking rapid sediment thickening to the southeast, toward oceanic crust.

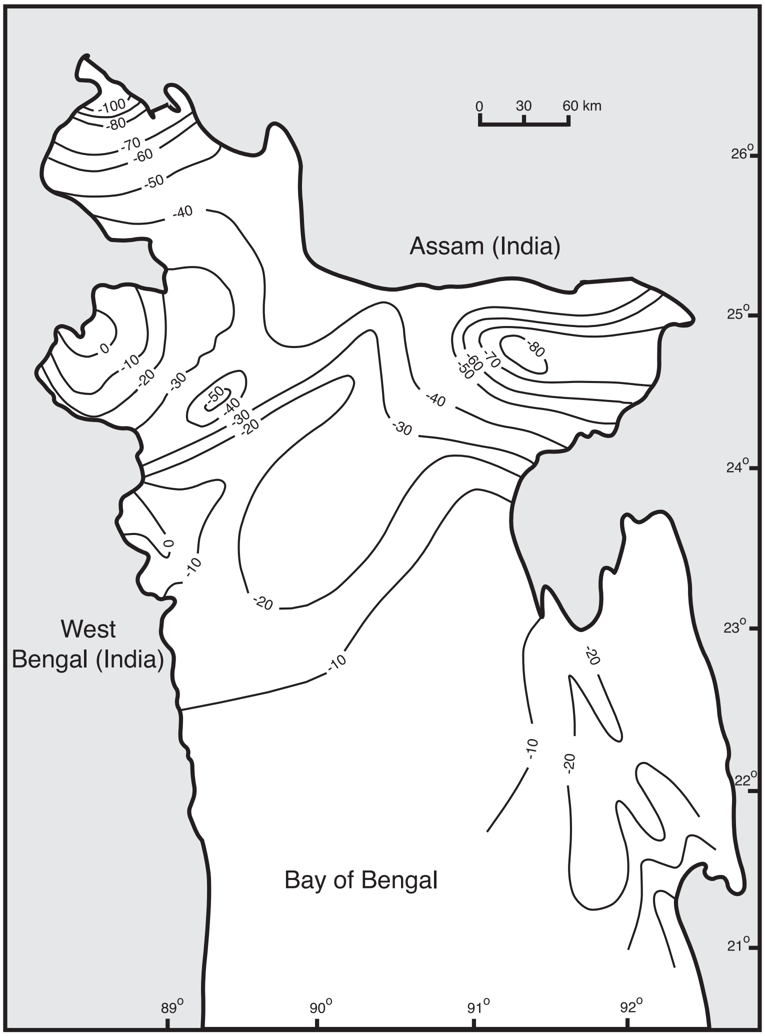

Fig. 6. Simplified Bouguer anomaly map of Bangladesh (from many different sources, including Brunnschweiler 1980; Rahman et al. 1990; Khan and Agarwal 1993). Bouguer data are in milligals.

(b) A high negative gravity anomaly in the extreme northwest of Bangladesh suggests marked thickening of basinal strata northward into the Siwalik foreland basin of the eastern Himalayas.

(c) A strong negative gravity anomaly over the Sylhet trough reflects thick basin strata, but the consistency of thickness of Miocene strata demonstrates that this is a Pliocene (and younger?) feature, indicating that the Shillong Plateau was uplifted after the Miocene.

(d) Linear north–south gravity anomalies in the Chittagong Hill region reflect the folded nature of the western basin margin, and the amplitudes of the gravity anomalies indicate that basement is involved in the folding. The eastward trend to greater negative gravity values reflects the deepening Moho, presumably due to lithospheric flexure caused by loading of the Indo–Burman ranges. This is much less pronounced than the dramatic gravity signature of the Himalayan foreland in northwestern Bangladesh.

The Bengal basin was essentially a southeast facing passive margin prior to involvement in the

Tertiary collision (Johnson and Nur Alam, 1991). Orogenic uplifts in the Indo–Burman ranges, the Naga Hills and the Himalayas in Assam began by the Late Eocene and Oligocene (Brunnschweiler, 1966; Rangarao, 1983; Uddin et al., 1999). There are several kilometers of thickness of Eo–Oligocene orogenic strata preserved in Assam (Rangarao, 1983), potentially far removed from the Bengal basin at the time (Uddin et al., 1999). Peripheral effects of crustal loading must have been observed in the Sylhet trough, which contains about 1.5 km of Oligocene Barail sediments. Barail sandstones in Bangladesh are shallow marine (Rangarao, 1983; Alam, 1991) and are extremely quartz-rich, suggesting a derivation probably from the Indian craton to the west and northwest (Uddin and Lundberg, 1998a).

Orogenic sedimentation had clearly been initiated by the deposition of the thick Surma Group of sediments. Encroachment of the Indo–Burman ranges from the east and the Himalayas from the north caused accelerated subsidence of the Sylhet trough and the Bengal basin where voluminous sediments were deposited in a prograding delta (Figs. 4 and 5). Sedimentation in the Bengal basin during Miocene time must have kept pace with subsidence of the basin (Hoque, 1974), except in southern and southeast Bangladesh, where turbidite deposits indicate excess accommodation space. These isopach maps do not obviously show a "closed contour" pattern of the Surma Group of sediments during Miocene time. The gravity map of Bangladesh suggests a Bouguer minimum (-80 mgl) for the Sylhet trough (Fig. 6). Comparison of this gravity anomaly does not match the Miocene stratigraphic thicknesses in the Sylhet trough. It can thus be inferred that maximum subsidence of the Sylhet trough did not take place during Miocene time (Uddin, 1990; Johnson and Nur Alam, 1991). Pliocene uplift of the Shillong Plateau (Johnson and Nur Alam, 1991) and the gradual encroachment of the Indo–Burman ranges toward the Bengal basin in the west suggest that the major subsidence of the Sylhet trough took place during Pliocene time.

An interesting question revolves around whether there was actual basin thickening due to tectonic loading in the Bengal basin during the Miocene. In the case of the Himalayan orogen, the mountain front was too far north of this region in the Miocene to have produced significant loading, or likely even a peripheral forebulge. On the other hand, the Indo–Burman ranges to the east were likely close enough to have driven basin flexure, resulting in additional accommodation space along the eastern margin of the basin. This eastern basin margin was a very complicated region during the Miocene, with deep-water turbidites reported by many workers who have studied the Bhuban unit. Thus, the Chittagong Hills area is the one part of the Bengal basin known to have been substantially deeper than shallow marine conditions during at least part of the Miocene. This area was the site of the northern extension of the Andaman–Nicobar trench, experiencing active east–west convergence. No turbidites have been reported in the younger Boka Bil Formation in this area (or elsewhere), and so apparently the combination of tectonic convergence and deposition of approximately 2 km of strata raised and/or filled this deep-water part of the basin by the Late Miocene. Across the remainder of the Bengal basin, deposition of the Bhuban Formation in the early to middle Miocene was dominated by deltaic processes (Alam, 1989). Very thick deposits at the Atgram well (Table 1, Figs. 4 and 5) are anomalous relative to nearby wells in Bangladesh. This likewise may be due to structural thickening related to east–west shortening of the Indo–Burman ranges, either by directly thickening this section by thrust faults or by tectonic loading relatively near the axis of Indo–Burman orogenic activity. The overall picture of deltaic sedimentation prograding southward in the Bhuban continued in the late Miocene, with similar thickness variations in the Boka Bil Formation, and without the complication of thick deep-water deposits in the region that is now southeastern Bangladesh.

4.2. Regional implications

The Eocene to Oligocene precollisional to syncollisional sediments in the Bangladesh portion of the Bengal basin are overwhelmingly quartzose and contain only small amounts of heavy minerals (mainly ultra-stable species of zircon, tourmaline, and rutile) of which about 60% are opaque varieties (Uddin and Lundberg, 1998a,b). The compositions and textures of Eocene and Oligocene sandstones in the Bengal basin do not obviously 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 (Uddin and Lundberg, 1998a).

Increased thicknesses of Miocene strata and the composition of Miocene sandstones of the Surma Group in the eastern Bangladesh yield a clear record of orogenic unroofing (Uddin and Lundberg, 1998a). The source rocks from which these sands were derived were dominated by supracrustal rocks, producing detritus rich in monocrystalline quartz, sedimentary to low-grade metamorphic lithic fragments, and a host of various heavy minerals, including a substantial input of garnet, but also epidote, chlorites, tremolite, actinolite, staurolite, and kyanite (Uddin and Lundberg, 1998a,b). Preliminary isotopic studies of the Miocene sediments from the Bengal basin revealed relatively uniform $^{87}Sr/^{86}Sr$ isotope ratios (about 0.72–0.73), which suggests that the most likely source rocks in the Himalayas were relatively unchanged throughout the unroofing process during Miocene time (Uddin et al., 2000). Similar inferences have also been drawn from the sediments of the Bengal fan (France-Lanord et al., 1993). Sedimentation rates in the Bengal fan increased during this time, perhaps due to increased rate of erosion (Cochran, 1990). This represents a dramatic southward advance of the deformation front of the eastern Himalayas, whereas the deformation front of the Indo–Burman ranges has likely advanced more gradually westward, progressively encroaching on the Bengal basin.

Trends from the subsurface lithofacies maps of the Miocene sediments from Bangladesh suggest that deltaic deposits entered the Bengal basin from the northeast, and that the source terranes of this sediment included the eastern Himalayas and the north-trending Indo–Burman ranges immediately adjacent to the east. This is consistent with preservation of thick orogenic sequences immediately northeast in Assam (northeast India, Sinha and Sastri, 1973; Uddin et al., 2002). A consistent increase in sand percentages from the Bhuban to Boka Bil Formations in most of the eastern wells of Bangladesh suggests progradation of the delta, perhaps along with westward migration of the Indo–Burman ranges as a proximal source (Uddin and Lundberg, 1999).

Increases in sand percentages from the Bhuban to the Boka Bil Formations in northeastern Bangladesh may reflect westward advance of the Indo–Burman orogenic front toward the Sylhet trough and the Chittagong Hill tracts (Fig. 1; Uddin and Lundberg, 1998a). Consistent increase in the thickness of the Miocene sediments in the eastern Bengal basin suggests the presence of major river systems (i.e., paleo-Brahmaputra, paleo-Meghna, paleo-Karnafuli) delivering detritus from the Indo–Burman ranges and the eastern Himalayas straight to the Bengal fan through the Sylhet trough and the northern Chittagong Hill tracts forming a major delta complex at the northeastern part of Bangladesh. Some of these paleo-drainage systems may have been submarine, because marine sequences have been identified in the coeval rocks of the Chittagong Hill tracts (Akhter et al., 1998; Gani and Alam, 1999; Alam et al., 2003). These Miocene channels were likely distributaries of a major drainage system that transported orogenic sediment into the early Bengal fan. These Miocene deltas in Bangladesh migrated from east to west and from north to south, toward the Bay of Bengal, as underthrusting of India beneath southeast Asia along the present-day Java trench and its northern extension continued. Subsidence due to deltaic loading has been active since at least the Miocene, with subsidence near the mountain belts accelerated by loading of the advancing orogens. The lithofacies trends also indicate that the Shillong Plateau, an uplifted massif of Precambrian basement rocks standing adjacent on the north of the Bengal basin, was not a source of sediments during the Miocene time (Fig. 1; Johnson and Nur Alam, 1991; Uddin and Lundberg, 1999).

The isopach data also show evidence of thickening of basin fill toward the south, opposite of the normal foreland basin, presumably because of the transition to oceanic crust—like the Mississippi Delta, with downfaulting toward the basin (e.g., Worrall and Snelson, 1989). From west to east across the basin, in contrast, the overall shape is typical for a foreland basin, apparently because the continent-to-ocean transition has the "normal" polarity, with oceanic crust having subducted first, followed by transitional and then continental crust.

5. Conclusions

Miocene deposits of the Bengal basin of Bangladesh clearly record orogenic activity in the eastern Himalayas and the Indo–Burman ranges as a result of continent–continent collision. Isopach maps constructed from electric logs obtained from oil and gas exploration in the region, coupled with gravity data, document Miocene sedimentation and subsidence patterns in the Bangladesh part of the Bengal basin. These new data on sediment thickness and previously reported seismic data indicate that sedimentary lithofacies in the fill of this asymmetric basin were controlled mainly by subsidence due to deltaic progradation over the continent/ocean boundary, overprinted by tectonic loading and oblique convergence along its eastern boundary. Deltaic progradation through most of Bangladesh in the Miocene followed earlier deltaic accumulations closer to the Himalayas in the Eo–Oligocene (+6 km of largely pre-Miocene deltaic strata in Assam). Since the Miocene, the deltaic depocenter has continued to prograde southward toward the southern Bangladesh offshore and the Bengal deep-sea fan.

Isopach data of the Bhuban and Boka Bil formations across much of Bangladesh indicate that the considerable subsidence of the Sylhet trough in the northeast, which has the lowest gravity value of the region, did not take place in or by the Miocene. Because there are no depocenters represented in the Miocene isopachs of the Sylhet trough, subsidence must have taken place since Miocene time, consistent with results of recent research on sediment composition.

Isopach data show that there is considerable vertical relief along the base of the Miocene stratigraphic sequence. The southeast part of the basin overlies oceanic crust, and had considerable accommodation space, relative to the remainder of the basin, which is floored by (attenuated?) continental crust. Indeed, turbidites have been reported from the Bhuban Formation in the southeast Bengal basin. In part due to the transition from continental to oceanic crust, the Bengal basin as a whole thickens away from the Himalayas in a N–S profile. This is opposite to the pattern normally seen in foreland basins, due to the continent–ocean boundary, presumably exacerbated by sedimentary loading and basinward downfaulting analogous to that seen along the northern Gulf of Mexico. In an E–W profile, the basin shape is more typical of a foreland basin, with sediment thickening eastward toward the Indo–Burman ranges. This dramatic lowering of the base of the Miocene is apparently due to flexure associated with subduction beneath Southeast Asia and tectonic loading of the Indo–Burman ranges. Toward the north, regional lowering northward into the Sylhet trough is seen above the Miocene strata, and is attributed to flexure caused by southward thrusting of the Shillong Plateau along the Dauki fault.

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