Geological Evolution and the Hydrocarbon Potentiality of the Bay of Bengal

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Abstract

Geological history reveals that the sea-floor spreading process back in 118±5 Ma has formed the ocean-basin of the Bay of Bengal with the initial sedimentation began at least 65 to 85 Ma back. Two characteristics properties prevail in the geological records of the Bay of Bengal are the occurrence of oceanic crust (basaltic) in the offshore basin and the marine environment of sedimentation for the entire period of its occurrence. Petroleum source rock generation and maturation requires marine sedimentation for organic matter enrichment and TTP for proper cooking respectively. Geochemical analyses of sediments and discoveries of gas in the Mahanadi Basin of India to the west and the Rakhain Basin of Mayanmar to the east strongly suggest hydrocarbon generation, expulsion and trapping in the offshore Bengal Basin of the Bay of Bengal. Hydrocarbon after migration from source rock finds either a suitable structural trap or a stratigraphic trap. Offshore Bengal basin is dominantly characterized by stratigraphic trap mostly channel sands for hydrocarbon accumulation. On the otherhand, the development of structural traps are limited upto the deformation front in the eastern part of the basin where deformation front has obstructed for the limited development of structural traps in the deep offshore basin region. Crustal segmentation and deformation has developed complex folding and inversion wherein young structures have been superimposed on to the older structural trends. The sediments represent an overall basinwardprogradation of sedimentation from deep marine to coastal marine setting is overlain by continental-fluvial deposition. The lower part of the sequence represents a slope sedimentation within a westward migrating structural development of accretionary prism complex. Thick mud rock sequence of accretionary complex at around 5-6 km depth is considered as upper source rock undergone high degree of maturation with a possible oil window phase. Two major zones have been identified where the development of hydrocarbon traps occurred viz., a) the zone of intense channeling in the upper part of the accretionary prism, and b) the limited development of structural highs between the paleodeformation and neodeformation fronts. Favorable traps of hydrocarbon likely to occur at 4-6 km depths zone. Further, mud and sand-filled channels, incised valleys of intense channeling, and pro-delta clays frequently pass up-dip to delta-front sand wedges as favorable stratigraphic trap.

Key words: Geology; Hydrocarbon potentiality; Trapping, Offshore basin; Bay of Bengal

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Introduction

The onshore Bengal Basin is a proven hydrocarbon basin of category-I having commercial production. However, the offshore one is still is in the status of category-II & III as because no significant commercial production has yet been discovered from known occurrence but geological status suggests a prospective one. Geology of the offshore Bengal basin is characterized by the formation of basaltic depositional floor that has undergone the influence of regional tectonic activities and dominantly by the deposition of marine sediments ranging in age of Cretaceous and Tertiary. Cretaceous sedimentation in the offshore basin in the Bay of Bengal was derived from Sibumasu terrane (Fig. 1 inset).

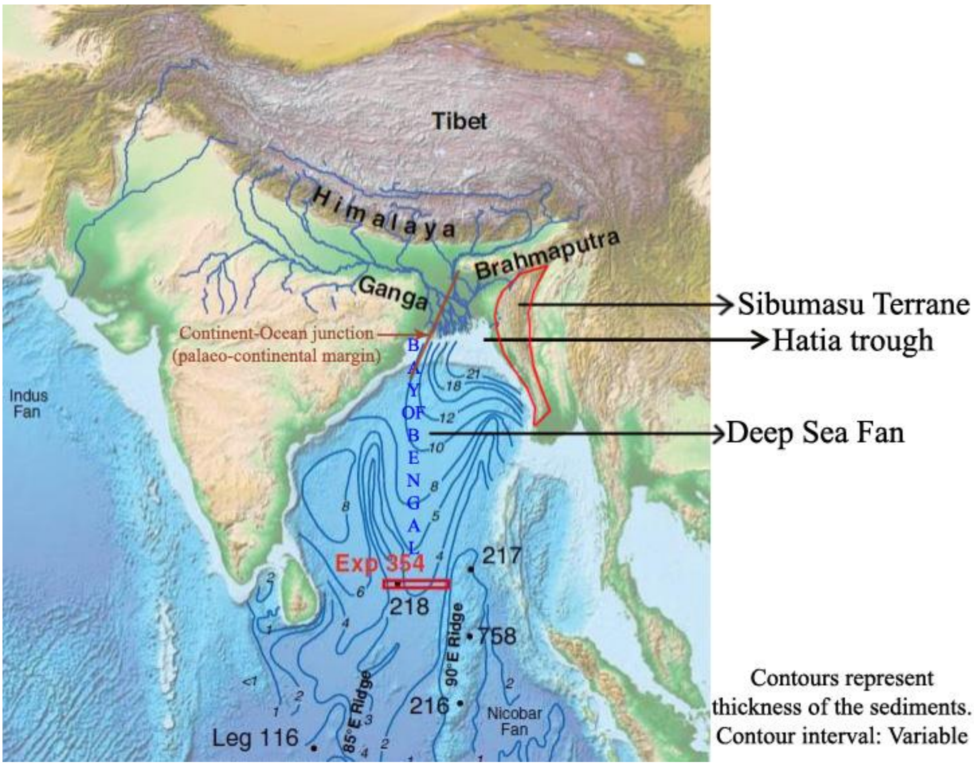

Figure 1: Position of the different DSDP and ODP Sites for documenting the Bengal deep sea fan that represents sedimentary and metasedimentary rocks above the oceanic crust, as interpreted from seismic reflection and refraction data. Isopach map of the sediments in the Bay of Bengal that shows maximum sedimentary thickness (~21 km) in the Hatia trough and minimum (~4 km) near DSDP 218 in the south. ***(Source of the figure is Curray, 1994). Inset (present study):*** *Sibumasu terrane (coined by Metcalfe 2011) marked by red line signifies pre-Tertiary-Mesozoic sedimentation source for Hatia trough and surrounding basin.*

Sibumasu terrane was drifted from East Gondwanaland in the Triassic (Metcalfe, 2011). As the collision of India with Eurasia began in Palaeo-Eocene and with the exhumation of Himalayan orogenic belt, great rivers like Ganges and Brahamaputra drains entire sediments in the Bay of Bengal through Bangladesh to build one of the largest deltas out into the Bay of Bengal. The offshore region of Bangladesh is the southward extension of the Bengal Basin comprising of a large continental shelf that covers an area between 20^{o}N and 22^{o}N latitudes and 89^{o}E and 92.5^{o}E longitudes. The offshore Bengal Basin comprises of 63,000 sq. km offshore area in waters shallower than 200 m. The continental shelf of Bangladesh has long been affected by the prograding delta buildup, the world's largest delta. Most of the detritus sediment passes through the delta to form present day the Bengal deep sea fan of 3000 km long and 1000 km wide (Curray and Moore, 1971) in the Bay of Bengal.

The isopach (Fig. 1) equal thickness map of sediments in the Bay of Bengal suggests that the basin floor is inclined to the north having its deepest part located along the plate converging margin in the Bay of Bengal. The northward inclination of the depositional floor caused relatively thinner sedimentary thickness in the deeper part of the Bay of Bengal where the Bengal deep sea fan is situated. The thinner and relatively younger sediments in the southern Bay of Bengal signify poor hydrocarbon potentiality but the northern region of the Bay of Bengal signifies very good potentiality due to the older and greater thickness of marine sediments. Geophysical data of the modern Bengal deep-sea fan suggest 4 km thickness of the upper most sedimentary column. Approximately 12 km thick sediments are expected under the fan. Deposition of the modern fan are structurally complex, particularly in the proximal part, where overlapping of natural levees and channel deposits occur. An extension of the Miocene deep-sea fan has been proposed approximately upto 15^{o}N latitude (Akhter et al., 1998).

Hydrocarbon potentiality in the onshore region of Bangladesh has been proved through the discovery of twenty-two gas fields and one oil field situated in the eastern folded belt of the onshore Bengal Basin. However, the status of hydrocarbon prospects in the offshore basin in the Bay of Bengal has remained a conjecture due to lack of scientific research and data acquisition. Oil and gas exploration activities in the offshore region in the Bay of Bengal between latitudes 20^{o}N–22^{o}N and longitudes 89^{o}E–92.5^{o}E started in the year 1974 under the Bangladesh Petroleum Act 1974 and six international oil companies participated in the exploration activities. Total coverage of multiple fold seismic data was little over 31000 line-kms alongwith approximately 18000 line-km gravity data (Petrobangla, 2000). Number of prospective structures were drilled and most of the wells encountered very high formation pressure although all the wells were abandoned. However, large discoveries of gas in the Mahanadi Basin of India to the west and in the Rakhain Basin of Mayanmar to the east suggest that the northern Bay of Bengal has a good hydrocarbon potentiality. Gas shows in Kutubdia well, Magnama well and Cox's Bazar well and discovery of Sangu gas field demand a fresh hydrocarbon exploration activities in the offshore region of Bangladesh. Recently, the presence of gas hydrates in the Bay of Bengal further enhanced the potentiality of gas occurrence. Present study is an attempt to evaluate hydrocarbon potentiality in the offshore region of the Bengal Basin based on the interpretation of litholog data, offshore seismic and gravity data and other published and unpublished data.

Geology of the Offshore Bengal Basin

Basement character, basin configuration, sediment-crust thickness and Moho topography are the fundamental attributes in evaluating an ocean basin. Ismaiel et al (2019) revealed that the Bay of Bengal has evolved by the process of rifting based on the study of multichannel seismic reflection data, together with 3D gravity inversion and 2D gravity forward modelling. They have further opined that the interface of continent-ocean crust occurs in the Bay of Bengal. Talwani et al (2016) interpreted that the Bay of Bengal has evolved by seafloor-spreading process evident from magnetic anomaly ranging in age from 132 Ma (M12n) to 120 Ma (M0). They have also determined a new spreading axis that joins the line between Rajmahal volcanics and Sylhet volcanics. Khan (1991) suggested a tectonic model on the evolution of the Bengal Basin showing NE-SW trending parallel lines of magmatic intrusions and a prominent Moho upwarping signifying the evolution of crust in the Bay of Bengal by the rifting process prior to the drifting of the Indian plate. This geological condition justifies the opening of the Bay of Bengal by the process of sea floor spreading that started back in 132 Ma. Opening of the Bay of Bengal lead to the formation of ocean basin that synchronizes with the northward drift of Sibumasu terrane during Triassic-Jurassic time now occurs as the West Burma block to the east (Fig. 1, inset) and the northward drift of India during Cretaceous-early Tertiary time. Above mentioned geological condition strongly suggest that the crust of the deeper basin of the Bengal Basin, Hatia trough, and of the Bay of Bengal are characterized by the oceanic (basaltic) crust. It is further inferred that the interface of oceanic crust-continental crust passes through the onshore Bengal Basin with a NE-SW trend that can meet Dauki fault of Shillong plateau in the northeast and Swatch of No Ground (SoNG), a deep sea canyon to the southwest in the Bay of Bengal. The rifted continental margin of the Eastern Ghat India is also characterized by the extensional passive margin setting supported by the occurrence of Mahanadi graben and Krishna-Godabari graben. Rangin and Sibuet (2017) constructed east-west cross section based on multi-channel seismic data that demonstrates several tectonic features associated with the crustal structure, sediment-crust thickness and the type of the crust in the Bay of Bengal. They have opined that the prominent features are the mantle upwarp affecting the crust of the offshore basin floored by a thinned (15 km thick) continental crust, injected by Mesozoic volcanism (Fig. 2).

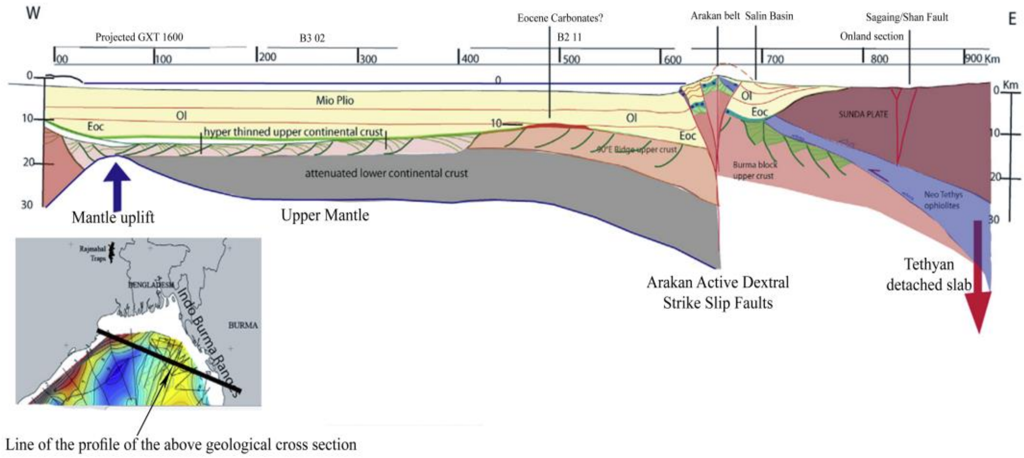

Figure 2: NW-SE trending synthetic cross-section of the northern Bay of Bengal. This section was drawn perpendicularly to the NE-SW extension direction of the rifted basin. To the west, the synthetic section of the Mahanadi basin was built. The onshore Myanmar cross-section is seen to the east of the profile. Location of cross-section is shown in the inset map below right. Dominant tectonic pattern is marked by NE-SW trending tilted blocks filled by syn-rift sediments clearly identified on seismic profiles. The uppermost part of this continental crust (3-4 km thick) shows a complex assemblage of dipping reflectors and west-facing tilted blocks injected by volcanic build-ups. The lower crustal sequence (11-12 km thick) does not reveal significant reflectors ***(Source: Rangin and Sibuet, 2017)***.

According to Rangin and Sibuet (2017), crustal fabric of the Bay of Bengal is characterized by overlying disconformable thin reflector attributed to the Late Cretaceous-Paleocene pelagic sequence deposited during drifting of Indian plate and spreading of Bay of Bengal. Talwani et al (2016) in their study revealed that sea floor spreading is the main geological process that has helped the formation of the Bay of Bengal. New spreading axis opened close to the line joining the Rajmahal and Sylhet volcanics at about 118 Ma defining the interface of granite and oceanic crust. Newly generated oceanic crust underlies Bangladesh and Bay of Bengal is younger than 118 Ma. The present study reveals that the geological condition of the Bay of Bengal supports Talwani et al (2016) but disagree with Rangin and Sibuet (2017). In the present study a gravity modelling was performed for 700 km long north-south transect from Shillong plateau to the Bay of Bengal across the continental block of the Bengal Basin. From the model it was found that the eastern segment of the Bengal Basin across Hatia trough down to the Bay of Bengal is underlain by the oceanic (basaltic) crust and not by attenuated continental crust (Fig. 3). However, the northern region of the profile exhibit a "Remnant Granitic Crust" occurs below Sylhet trough which is believed to be the down-faulted block of the Shillong Plateau.

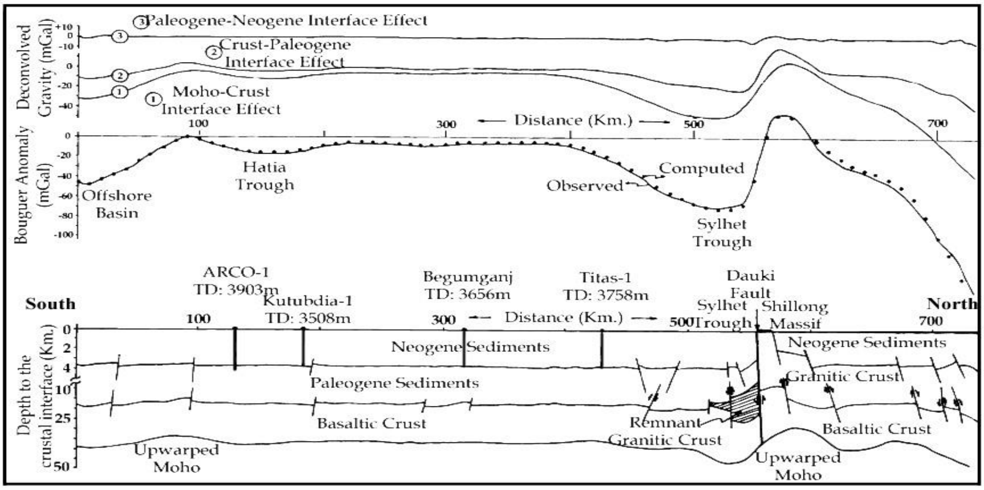

Figure 3: North-South 700 km long geological cross section based on gravity modelling exhibits nature of the crust and sediment thickness in the Bay of Bengal. ARCO-1 and Kutubdia-1 well are located in the Bay of Bengal ***(Source: present study)****.*

Occurrence of Moho upwarped zones in the Figure 3 coincide with the mantle uplift in the Figure 2 proposed by Rangin and Sibuet (2017). Gravity modelling suggests crustal thickness of around 20 km in the Bay of Bengal and sediments thickness 19 km deposited over the oceanic (basaltic) crust which is formed during Gondwanaland break-up and Indian plate drift from Gondwana super-continent. Syn-rift fabric of the Bay of Bengal crust is attributed to the Mesozoic to the Early Cretaceous period. This crustal fabric is overlain disconformably by a thin reflector attributed to the Late Cretaceous-Palaeocene pelagic sequence deposited during India/Bay of Bengal drifting before the CenozoicIndia-Asia collision marked by thick clastic sediments associated with delta progradation. According to Graham et al. (1975) the Indian plate motion and the major flysh route is related to the formation of Himalayan orogenic belt emerged from closing of the sea of Tethys.

The offshore basin was filled mainly by orogenic sediments derived from the eastern Himalayas to the north which is underlain by the sediments derived from Sibumasu terrane in the east during the Mesozoic. The offshore basin in the eastern collision margin of the Indian plate has experienced inbred tectonic instability. The downward continuation of gravity field revealed a gradual change of the structures upto 10 km depth with a distinct flattening of the amplitude of the structures and a prominent tongue shape depression below at least 10 km depth in the eastern region of the Hatia trough (Fig. 4) (Khan et al., 2002). The tongue shape depression is interpreted as the sedimentation route of the older sediments derived principally from the Sibumasu terrane. Presence of very high pressure of the formation below 4 km depth encountered in all the wells drilled so far in the offshore basin of the Bay of Bengal signify the occurrence of organic rich thick mud rock sequence possibly act as the zone of high formation pressure (Fig. 5a). Occurrence of extensive shale diapirs (shale flowage) (Fig. 5b) and mud volcanoes in the Chittagong Hill Tracts support the inferences. Further, it is inferred the occurrences of more east-west trending tongue shape depressions in the basin floor those served as the sedimentation routes for the deeper sediments from Sibumasu terrane in the east. This kind of structural features often can serve as the sub-marine channels conducive for the formation of channel sands and turbidite sequence. Presence of turbidites and channel sands in the Chittagong Hill Tracts are the examples of the presence of such sub-marine channels and shelf-slope break zones.

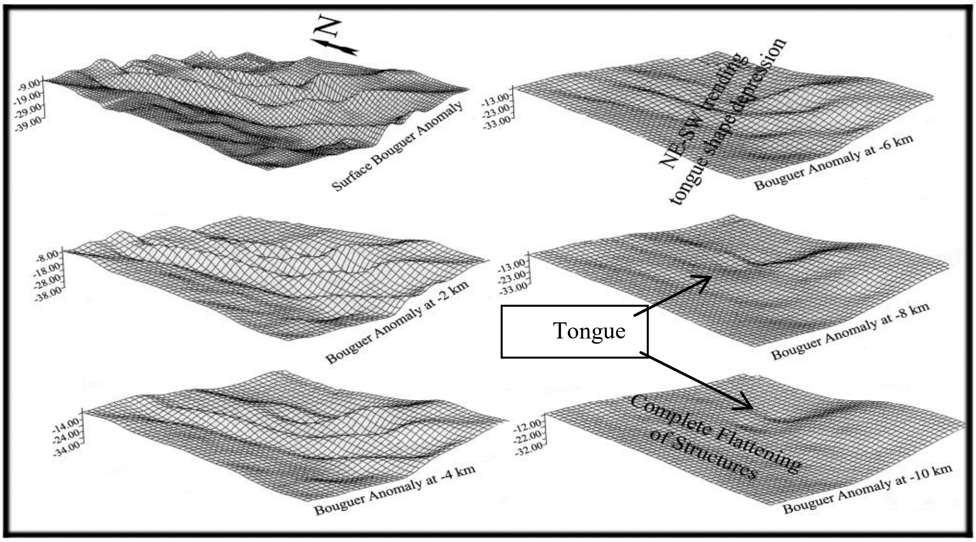

*Figure 4: Continuation of gravity field in the Chittagong Hill Tracts region showing flattening of structures and the occurrence of NE-SW to E-W trending tongue shape depressions for sedimentation route from Sibumasu terrane on to the offshore basin **(Source: Khan et al., 2002)**.*

Figure 5(a): Channel sand and carboneceous mud ***(Source: present study).***

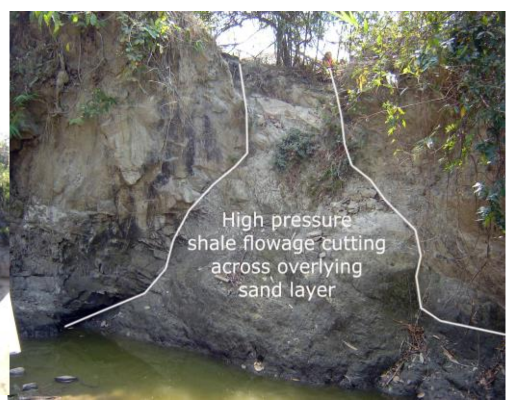

Figure 5(b): High pressure shale flowage. ***(Source: present study).***

Sedimentation along the active eastern collision margin of the Bengal Basin is associated with the plate interaction since at least Jurassic-Cretaceous to Plio-Pleistocene time. With the uplift of the Arakan subduction complexes, the entire accretionary prism of the Bengal Basin has suffered two distinct domains of sedimentation, viz., the northern domain where a basinward migrating sedimentation occurred and the southern domain where a trench-slope migrating sedimentation occurred (Khan et al., 2002). The major deep-sea fan propagation and migration occurred along the northern bathymetric domain while locally developed fans are distributed along the southern bathymetric domain. The occurrence of deep-sea clastic in the Assam-Arakan region (Dasgupta et al., 1991) lend support to the sedimentation and the migration of the major deep-sea fan through the northern bathymetric domain. While the trench-slope deep sea clastics locally developed are recorded in the southern bathymetric domain where deep-sea fans associated with the transverse slope channels or gullies are preserved. Chittagong Hill Tracts having westward extension of the Arakan subduction complex exhibits occurrence of submarine channel, deep-sea fan turbidites with partial Bouma sequence and debris flow (Fig. 6).

Figure 6: Clockwise from top left. Submarine channel with slope failure deposits. Debris flow at the base of the turbidites. Fossil assemblages in the deep marine shale. Mid-fan turbidites (partial Bouma sequence). ***(Source: present study).***

According to Dasgupta (2004) the lower Bokabil (?) Formation is characterized by complete Bouma sequence, enechelon pattern of channel deposits with frequent scouring, inter-channel Tbcd turbidites overlain by muddy contourites, high sand-shale ratio and dominance of chaotic facies indicating deposition in a base-of slope that signify submarine channels. According to Gani and Alam (1999) the entire sedimentary succession (3000+ m thick) in the Chittagong Hill Tracts, are grouped from oldest to youngest into three composite sequences as deep-water base-of-slope clastics overlain by thick slope mud that passes upward into shallow marine and nearshore clastics. The offshore stratigraphy of the Bay of Bengal exhibits upper and lower well stratified successions of low energy environment based on sedimentary sequence down to depth of 4598m from BODC-1 well (Khan, 2019). The paleontological evidence, primarily the pollen distribution, suggests that the boundary between upper and middle Miocene (base of Echtricolporites spinosus) in Cox's Bazar well occurs at around 3000m depth (Simpson, 1976).

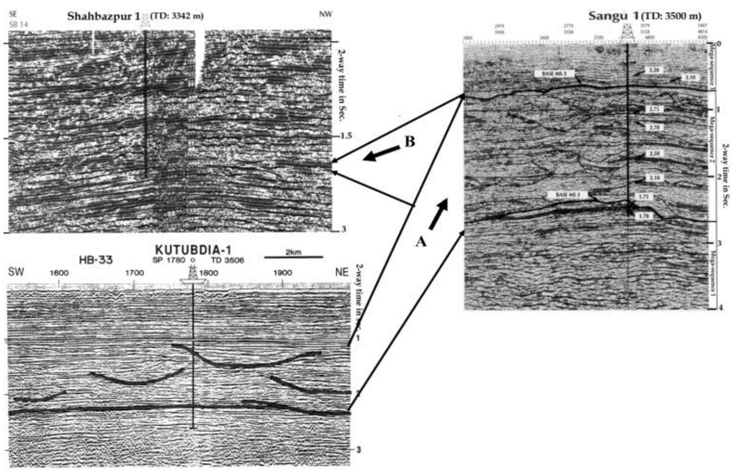

Figure 7: Seismic correlation between Shahbazpur, Sangu, and Kutubdia clearly demonstrate that the thickness of Mio-Pliocene deep-sea channeling increases towards Sangu (arrow ***A****) in the northeast with respect to that of Kutubdia located southwest of Sangu. The same is missing towards Shahbazpur (arrow* ***B****) located west of northwest of Sangu and northwest of Kutubdia. This supports that Shahbazpur was much elevated structure than that of Sangu and Kutubdia prior to Mio-Pliocene deep-sea channeling.* ***(Source: present study)****.*

The mid-Miocene gas-bearing horizon is identified from seismic and well data that occurs in Shahbazpur well at around 2600m depth but the same gas bearing horizon occurs at around 3000m depth in Sangu well (Petrobangla, 2000). Correlation of seismic sections of Shahbazpur, Sangu, and Kutubdia demonstrate that the sequence characterized by the deep-sea channeling during lowstand condition that thicken towards Sangu and the same is missing towards Shahbazpur. Missing of horizon characterized by deep sea channel deposits around Shahbazpur indicates that the region between Kutubdia and Shahbazpur was uplifted before Mio-Pliocene deep-sea channeling at Sangu (Fig. 7). Correlation of the wells MND-1 and MND-2 located in the offshore Mahanadi basin of India suggests a southeastward thickening of the sediments wherein mid-Miocene sediments occur between 1000m and 2500m depths. Based on the information derived from all the wells drilled both onshore and offshore, a mid-Miocene basin configuration of the Bengal Basin and its extension in the Bay of Bengal is prepared. A crescent shaped (shaded) structurally elevated zone thus is identified in the offshore part of the basin (Fig. 8) where the mid-Miocene sediments likely to occur at less than 3000m depth.

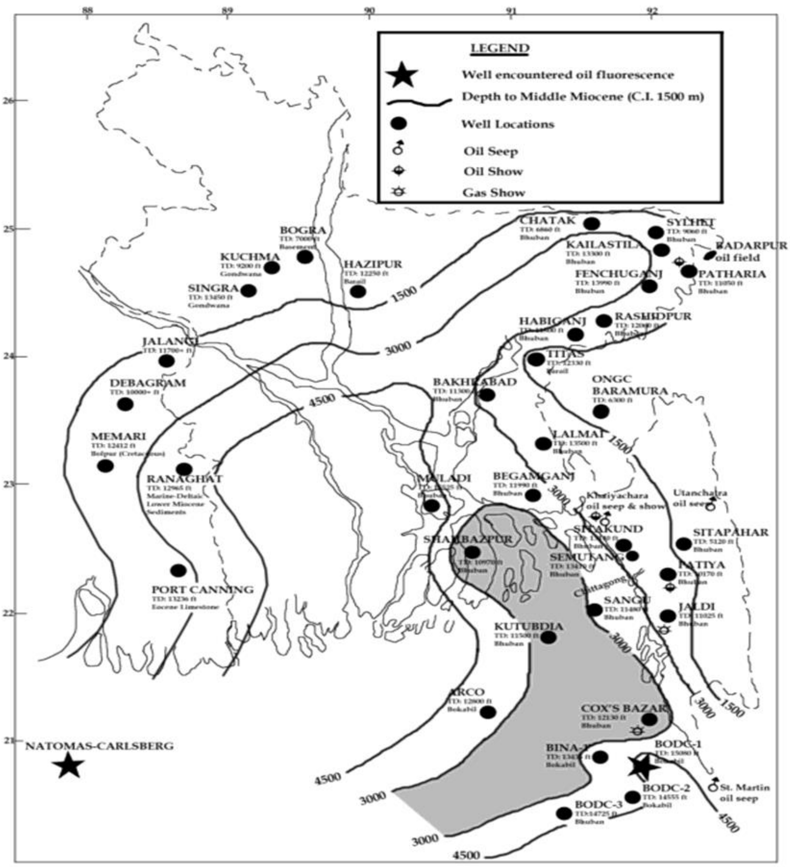

Figure 8: Contour of depths for mid-Miocence sediments act as the hydrocarbon reservoir showing basin configuration of Hatia trough and the offshore region. ***(Source: present study).***

Petroleum Systems

Bengal Basin is a proven gas province that produces a small amount of liquid hydrocarbon, mostly condensates and light oil. Largely, it is accepted that the source rock belongs to Oligo-Miocene sediments while the reservoir rock belongs to Mio-Pliocene sediments in all over the Bengal basin. Several authors have tried to evaluate source rock status in the Bengal basin but most of the works are limited within the middle Miocene sediments encountered in the drilling depths in excess of 4+ kms. Dasgupta (2004) opined that in Assam-Arakan orogen the Surma Group unconformably overlie the Paleogene turbidites and Paleogene submarine fan complex appear to have continued into the overlying deep-water and associated clastics while such deep-marine facies associations of prolific hydrocarbon reserves have been least attended. Shamsuddin and Coleman (2004) suggested the Bhuban Formation a possible source for the Hatia Petroleum System of the offshore Bengal Basin. According to Shahjahan et al. (2002) the oil/condensate beyond Surma basin to the south and southeast are isotopically heavier (-24.5 to -26.6%) with negative canonical variables and are indicative of marine or marine influenced source rocks possibly generated from type-II or type-II/III kerogen. Ismail and Shamsuddin (1991) opined that the influence of time on organic matter maturity plays an important role wherein the low vitrinite reflectance values of the sediments indicate a rapid burial and the oil generation window is extended between 5400m and 10000m depths. Carbon isotope values of methane in Mio-Pliocene reservoirs suggest a high degree of maturation of source rock (Hiller and Elahi, 1984). Imam and Hussain (2002) suggested that where shale buried deeply in adjacent “hydrocarbon generative depressions” has undergone maturation very much within the oil window. A source rock potential evaluation of selected cores from the Muladi-1 well, Bangladesh, (Robertson Research International Limited, Memorandum No. 2718, Project No. S / I / 767 / 34 – IID), reveals that extractable organic material related to carbon content increases with depth in the shale samples indicating increasing maturity and source oil. Oil show in Patharia well, and oil seeps at Hararganj, Sitakund, and Utan Chatra (Fig. 8) suggest generation of liquid hydrocarbon from mature source rocks within the oil generation window (Shahjahan et al., 2002). Except for the lower Miocene gas prone source rocks; Oligocene, upper Eocene and Paleocene show fair to good oil source potential having oil window maturity zone between 5000m - 8000m in the deeper basin (Petrobangla, 2000). The geochemical and source rock palynological data from West Bengal, India suggest that mature source rocks are present near the Eocene slope break, in the Paleogene-Early Neogene sequence (Roybarman, 1983). The studies on samples from well MND-2 located in the offshore Mahanadi basin indicate that mature oil-prone source rocks occur below a depth of 2500m (basal Miocene) and samples below 3300m have a tendency towards wet gas occurrence (Jagannathan et al., 1983). Since Jenum Formation of Oligocene Barail Group is considered the major source rock in Assam and in Surma basin, with progressive deformation and prograding delta build-up, the Bhuban and the older formation is strongly believed to be the source rock in the offshore Bengal Basin.

Offshore Bengal Basin is envisaged as the geological domain where sediments characterizes all the characters of source rock, reservoir rock and cap rock. The occurrences of such sediments likely to have generated an ideal condition for trapping of hydrocarbons. The offshore basin region is characterized by crustal segmentations where variable pattern of folding and inversion have formed. There are zones characterized by structural “Highs”. Younger folding and inversion are mostly of low amplitude and simple within the zone between paleodeformation and neodeformation fronts. Small scale buried folds are likely to develop in the zones of inversion. Basement controlled fault-bound structural closures are likely to occur. Since the migration of hydrocarbon is generally vertical along fractures and laterally up-dip along the paleoslope (Wandrey et al., 2000), it is opined that a favorable trapping of hydrocarbon within 4-6 km depths occurs in the offshore Bengal Basin. In addition to structural trapping of hydrocarbon, mud and sand-filled channels, channel sands and incised valleys where intense channeling has occurred and pro-delta clays pass up-dip to delta-front sand wedges act as the favorable stratigraphic traps.

Conclusions

Offshore Bengal Basin has long been ignored and least attended in evaluating its hydrocarbon potentiality. It was previously thought that the Bengal Basin and its extension in the offshore Bay of Bengal is a newly formed Tertiary basin where sedimentation progressed only after the formation of the Himalayan orogenic belt in the north and Arakan orogenic belt in the east. Present study revealed that offshore basin of the Bay of Bengal is much older and started to form due to the sea floor spreading of the Indian Ocean at least 118±5 Ma and linked to the evolution of Rajmahal and Sylhet volcanics. Sedimentation in the offshore basin progressed in two phases, first, when Sibumasu terrane drifted from Gondwanaland and occurred as West Burma block in Triassic, and second, when India collided with Eurasia forming Himalaya during early Tertiary. Sediments derived from Sibumasu terrane mostly filled Hatia trough and its extension to the south down to the Rakhain Basin of Myanmar overlain by sediments derived from Himalayan orogenic belt. Dominant sedimentation progressed under the marine environment of deposition in the 'Arc-Trench-Ocean' bathymetry. The entire sediments in the offshore basin represent an overall basinward progradation of deep marine to coastal marine depositional settings wherein the lower part represents a slope-apron within the westward migrating accretionary prism complex. The hydrocarbon source rocks are characterized by marine environment of deposition having high maturity level within oil generation window for deeper sediments. Sedimentation has also been controlled by the converging crustal configuration, trench migration and syn-depositional structural development. In addition to the structural trapping, zones of mud, sand-filled channels and incised valleys where intense channeling has occurred and pro-delta clays pass up-dip to delta-front sand wedges, also recognized favorable sites for hydrocarbon trapping. Geochemical analyses of sediments and discoveries of gas in the Mahanadi Basin of India to the west and the Rakhain Basin of Mayanmar to the east strongly suggest hydrocarbon generation, expulsion and trapping in the offshore Bengal Basin of the Bay of Bengal.

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