Georesource Potential and Geohazard Status of the Bay of Bengal vis-à-vis Sustainable Development of 'Blue Economy'

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Abstract

Formation of the Bay of Bengal is linked to the opening of the Indian Ocean and covers an entire off-shore region of Bangladesh wherein the geological processes and tectonic activities in the Bengal Basin have greatly influenced in enriching the Bay of Bengal. Spreading and creation of new seafloor of the Bay of Bengal have continued with the Indian plate motion to the north and northeast. Hence, the Bay of Bengal has been enriched with georesources. 'Blue Economy' is a concept that can significantly contribute to the socio-economic development of the nations situated around the oceans and seas. However, the sustainability of 'Blue Economy' greatly depends on the proper assessment and utilisation of the marine georesources. It is equally important to evaluate the geological hazards of the seas and oceans around the coastal countries in order to better safeguard the development of 'Blue Economy'. Although Bangladesh is situated along the coast of northern Bay of Bengal having the largest continental shelf and the longest deep-sea fan within its legal exclusive economic zone (EEZ), it is the least studied and explored bay in the region that demands much greater attention. The present study is an effort to focus on to the possible geological resources like oil, gas and mineral potentials of the Bay of Bengal within EEZ of Bangladesh. Geological hazards like earthquake, tsunami and other ocean-related geological hazards have also been identified and their probable impact has been assessed for proper planning of development of a sustainable 'Blue Economy'.

Key Words: Georesources, Geohazards, Blue Economy, Bay of Bengal, Bangladesh.

Introduction

The Bay of Bengal, large but relatively shallow embayment of the north-eastern Indian Ocean, occupying an area of about 2,173,000 sq. km. It lies roughly between latitudes 5°N and 22°N and longitudes 80°E and 100°E (Fig. 1). It is bordered by Sri Lanka and India to the west, Bangladesh to the north, and Myanmar (Burma) and the northern part of the Malay Peninsula to the east. According to the definition of the International Hydrographic Bureau, the southern boundary extends from Dondra Head at the southern end of Sri Lanka in the west to the northern tip of the Indonesian island of Sumatra in the east. The bay is about 1,600 km

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wide, with an average depth of more than 2,600 metres. The maximum depth of water reaches to about 4,694 metres at the southern part of the bay (Morgen et al., 2009).

The Bay of Bengal is bordered to the north by a wide continental shelf having water depths ranging between 20m to 200m that narrows to the south and by slopes of varying gradient on the northwest, north, and northeast, all cut by canyons from the rivers. The deep floor of the bay is occupied by a vast abyssal (deep-sea) plain that slopes to the south. The offshore region of Bangladesh that occupy 63,000 sq. km area in waters shallower than 200 m is a southward extension of the Bengal Basin in the Bay of Bengal. The maritime boundary of Bangladesh covers mostly the central part of the northern Bay of Bengal up to approximately 18^{o}N latitude (Fig. 2; Burke, 2014).

The Bay of Bengal is a northern extended arm of the Indian ocean. Bengal Deep-Sea Fan, the largest deep-sea fan in the world and Swatch of No-ground, a deep-sea canyon (Fig. 3) located at the head of the Bay of Bengal are the two main geological features intrinsically related to the present context of the Bay of Bengal (Rogers et al., 2015). Bengal fan is attributed to the deposition of about 4 km thick sediments derived from the Himalaya Range and transported to the Bay of Bengal by the Ganges-Brahmaputra river system forming one of the largest deltas of prograding nature in the continental shelf of Bangladesh. The continental shelf of Bangladesh extends to about 200 km. Swatch of No Ground, on the other hand, is a tectonic element that marks the line of crustal break coinciding with 'down to the basin faults' in the region. Sediments derived from the Himalaya are continuously being supplied to the deep-sea fan through the Swatch of No Ground forming fan turbidites. The

Figure 1: Map illustrates the line depicting the outer limits of the continental shelf of Bangladesh overlying on a gridded bathymetric of the northern Bay of Bengal (Source: https://www.google.com).

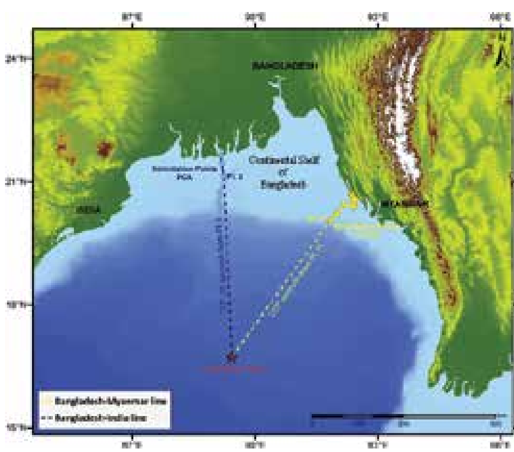

Figure 2: Maritime boundary of Bangladesh declared by UNCLOS covers a large area in the Bay of Bengal (Source: Redrawn from Burke, 2014).

Figure 3: MODIS image of the northern Bay of Bengal and bathymetry illustrating the proximity of the Swatch of No Ground canyon head to shore and to the subaqueous Ganges–Brahmaputra-Meghna delta. The clinoform topset–foreset rollover coincides with the seaward limit of the turbid water in the image (Source: Rogers et al., 2015).

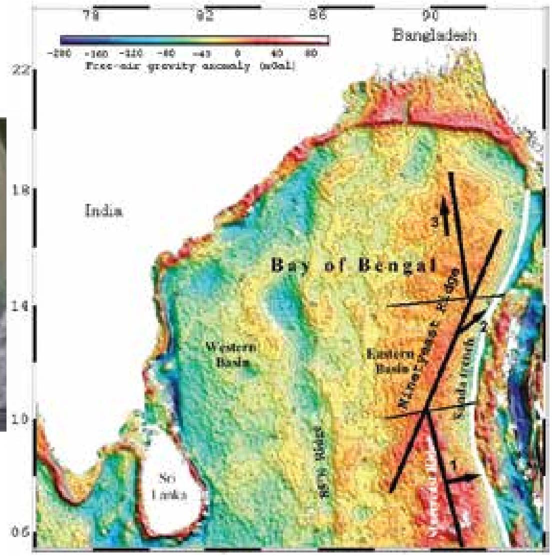

Figure 4: Free air gravity anomaly map of the Bay of Bengal. Two striking features are the gravity responses of the N-S trending buried 85°E and Ninety East Ridges. The buried 85°E Ridge has a negative gravity anomaly with a steep gradient at its eastern edge. The steep gradient is often characteristic of fracture zones. Arrows indicate motions and subduction directions of the crustal segments in the Bay of Bengal (Modified from Talwani et al., 2016).

"Swatch of No Ground" canyon in the Bay of Bengal is a shelf-incising submarine canyon that is actively aggrading in its upper reaches despite regular gravity-driven transport and mass wasting. Although the canyon lies 150 km down drift of its main sediment source, the Ganges–Brahmaputra–Meghna (GBM) river mouth, high sedimentation rates are sustained by both progradation of the subaqueous delta into the canyon head and the conveyance of shelf-generated hyperpycnal flows to the canyon floor (Rogers et al., 2015). Hyperpycnal flow is produced when the density of the river water entering the ocean basin is greater than the density of the standing water in the ocean basin.

Formation of the Bay of Bengal

Formation of the Bay of Bengal is intimately related to the early opening of the Eastern Indian Ocean. Norton and Sclater (1979) have first described the overall evolution of the Indian Ocean, but the evolutionary history of the Bay of Bengal has not yet been unravelled. Talwani et al (2016) have given an elaborate explanation on the opening / spreading of the crust of the Bay of Bengal based on the series of magnetic anomalies in the Western Basin of the Bay of Bengal (Fig. 4) which is correlated with conjugate magnetic anomaly in the western Enderby

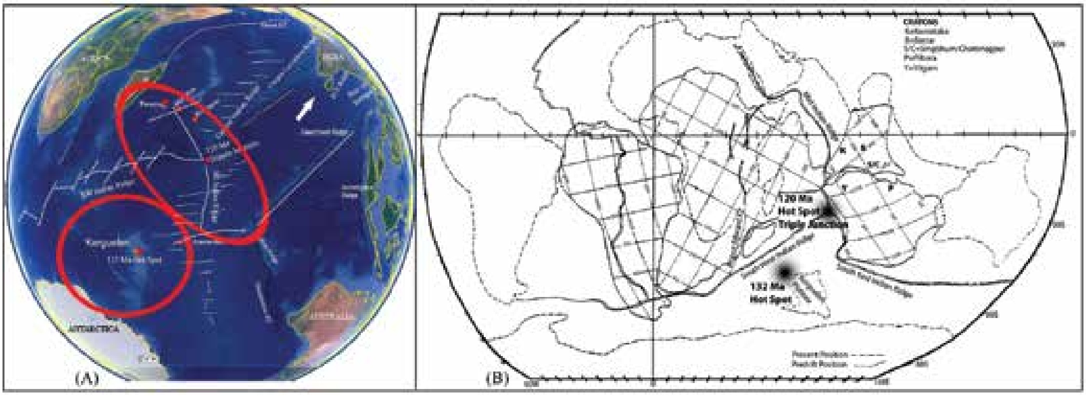

Figure 5: Reconstruction of Gondwanaland. (A) Mega hot spot (mantle plume) at the higher latitude (50^{o}S) of the Southern Ocean around Kerguelen Plateau have been evolved 132 million years ago that helped for the initial separation between Antarctica and India. Hot spot jump from 132 Ma to 120 Ma is evident. (B) Present position of the triple junction (a meeting point of Mid Indian Ridge, SW Indian Ridge and SE Indian Ridge) in the Indian Ocean exhibiting a shift of Kerguelen Hot Spot from an earlier position (132 Ma) to present position (120 Ma). Geological age of 120 million years and the affinity for magma from Kerguelen mantle plume source of both Sylhet and Rajmahal volcanics in the Bengal Basin suggest that these two volcanics were erupted when they were located with the Indian Plate at the position marked by "120 Ma Hot Spot Triple Junction". (after Khan, 1998).

Basin, located off of East Antarctica. This evidence strongly supports that the Western Basin of the Bay of Bengal and western Enderby Basin were together back in 132 million years ago wherein age has been determined from magnetic anomaly number. The present geographic positions of the Western Basin of the Bay of Bengal and the western Enderby Basin strongly support their association back in 132 (Ma) and thereby were separated and drifted from each other due to the seafloor spreading started first in the Indian Ocean.

Since, in general seafloor spreading starts from a triple junction due to the evolving of a hot spot (a mantle plume), it is confidently interpreted that a mega hot spot (mantle plume) in the higher latitudes around 50^{o}S of the Southern Ocean around Kerguelen Plateau must have been evolved 132 million years ago that helped for the initial separation between Antarctica and India (Fig. 5A). However, the present position of the triple junction (a meeting point of Mid Indian Ridge, SW Indian Ridge and SE Indian Ridge) in the Indian Ocean exhibits a definite shift from an earlier one suggesting a jump off the hot spot which is a part of the Kerguelen hot spot (Fig. 5B). Geological age of 120 million years and the affinity for magma from Kerguelen mantle plume source of both Sylhet and Rajmahal volcanics suggest that these two volcanics have erupted when they were located with the Indian Plate at the position marked by "120 Ma Hot Spot Triple Junction" (Khan, 1998; Fig. 5B). Hence an initial opening between 132 Ma and 120 Ma, Indian Ocean floor (oceanic crust) was spreading at a rate between 22 to 30 cm/yr which, in a geological sense, is "Hot Spot Jump". Since then Indian Plate has moved north until it is collided with Eurasia sometime around 55 million years back in the Eocene forming gigantic trans-Himalayan mountain belt. Hence, the Bay of

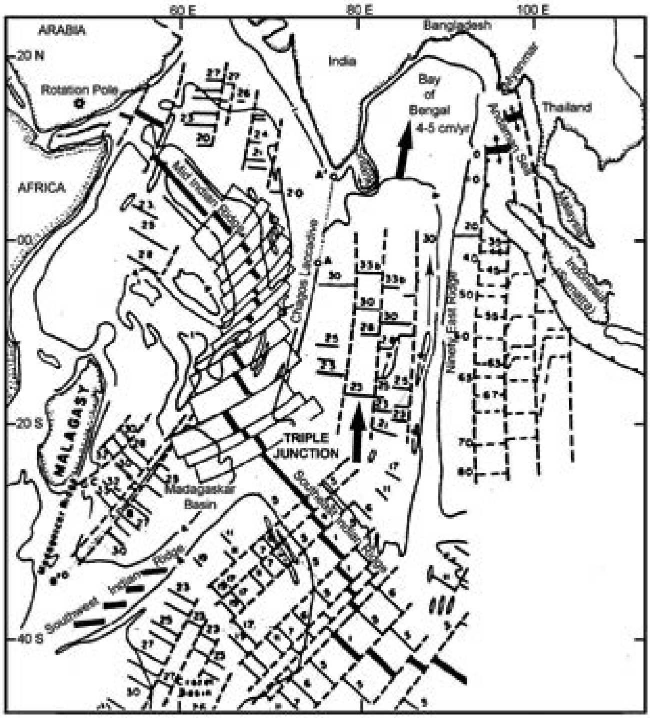

Figure 6: Magnetic anomaly pattern in the Indian Ocean showing direction of motion of the Indian Plate from triple junction. Dotted lines are the fracture zones with differential movements evident from the shift in the magnetic anomaly numbers. Present crustal motion in the Bay of Bengal is approximately 4-5 cm/yr. (Source: Schlich, 1975).

Bengal has opened-up and enlarged along with the northward motion of the Indian Plate between 120 Ma and 55 Ma at a rate of about 6 cm/yr. Present crustal motion due to the convergence of the oceanic crust in the Bay of Bengal with the Burma microplate is measured to be ~2 cm/yr based on satellite GPS (Steckler et al., 2008). It is inferred that the present crustal motion in the Bay of Bengal is being accommodated for isostatic balancing in the Himalayan orogenic belt and the Bengal Basin. Figure 6 demonstrates magnetic anomaly number in the Indian Ocean with increasing values to the north indicating progressively older crust in the Bay of Bengal to the north from the triple junction of the ridge-ridge-ridge setting of the Indian Ocean. Northward motion of the crust in the Bay of Bengal largely controlled by the Ninety East Ridge which is a mega transform fault, forming several longitudinal shear fractures those show a distinct shift in the magnetic anomaly numbers (Schlich, 1975).

Geological Features of the Bay of Bengal

The continental shelf of Bangladesh offshore is the extension of the Bengal Basin that has evolved largely over the remnant-ocean basin (Graham et al., 1975). The Bay of Bengal is characterised by the geological features those formed principally by the tectonic activities including volcanic and sedimentological processes. Tectonic activities for seafloor spreading started when Gondwanaland broke apart and the continental fragments started drifting. New ocean (mesoTethys) began to form with the emergence of the Indian Ocean about 200 Ma back in the Permo-Triassic period (Metcalfe, 2011). Upwelling of magma forming mantle plume around Kerguelen Plateau is the main source of all the tectonic activities in the region. The crust of the Gondwanaland eventually had undergone melting, doming, thinning, rifting and finally drifting that initiated seafloor spreading of the Indian Ocean. Seafloor spreading due to the drifting of the crust of the Gondwanaland progressed with the formation of Ninety East Ridge transform and 85oE Ridge transform, both acted as the principal driving lines for the Indian Plate motion (Fig. 4). Crustal segmentation occurred due to the differential motion of the Indian Plate and its variable collision mechanism with the Eurasian plate wherein the southern segment (marked 1 in figure 4) subducted more vertically below the Sunda Trench, central segment (marked 2 in figure 4) subducted obliquely below the Andaman Trench, and northern segment (marked 3 in figure 4)moved dominantly horizontal with major strike-slip component and insignificant thrust component. Hence, crustal segment 3 of the Bay of Bengal is in the state of pull-apart stress component that largely accommodates subsidence bounded by normal faults. Evidence of normal fault and strike-slip fault are derived from the fault plane/focal mechanism solutions and several surface features (Khan and Chouhan, 1996). The oblique convergence and the anti-clockwise rotation of the Indian plate with that of clockwise rotation of Burma plate have resulted in crustal segmentation of the converging plate having a right-slip component to compensate the plate rotation. Further, clockwise rotation and component of convergence of Burmese microplate with respect to Indian Plate can induce vertical derivative of the compressive force which helped in developing younger structures in the segment 3 of the Bay of Bengal. Crustal segmentation also developed several linear mega fractures longitudinally parallel to the Ninety East Ridge and 85^oE Ridge. These fractures are extended in the Bay of Bengal associated with the northward shift of the magnetic anomaly numbers (Fig. 6). On the other hand, 85^oE Ridge has separated Bay of Bengal into two distinct geologic domains viz., Western Basin and Eastern Basin (Talwani et al., 2016). Free-air gravity anomaly map of the Bay of Bengal (Fig. 4) characterises Western Basin with large negative gravity values suggesting subsided crustal blocks where sediments of greater thickness were deposited. While positive gravity values in the Eastern Basin are due to the high-density materials those must have erupted through the Ninety East Ridge resulting in the elevated crust and less sediments thickness associated with the Ninety East Ridge. The 85^oE Ridge is extended from Mahanadi Basin of the eastern margin of India up to the Afanasy Nikitin Seamount in the Central Indian Basin. The ridge is associated with two contrasting gravity anomalies: negative anomaly over the north part (up to 5^oN latitude), where the ridge structure is buried under thick Bengal Fan sediments and positive anomaly over the south part, where the structure is intermittently exposed above the seafloor. The ridge is buried by approximately 3 km thick Bengal Fan sediments on its crestal region and about 8 km thick pre- and post-collision sediments on the flanks (Sreejith et al., 2011).

Sedimentation in the Bay of Bengal

Himalaya orogenic belt is the main sediment source for the largest Bengal delta and Bengal deep-sea fan, while, the Ganges and Brahmaputra Rivers drain all the fore-slope and back-slope of the Himalayas. These rivers discharge about 1×10^9 t / yr of sediment with an appreciable bedload component for the Brahmaputra (Milliman and Syvitski, 1992). River deltas are the main gateway for terrigenous sediment flux to the oceans during transgression or highstands of the sea level when much river-borne material is trapped at the margin to form thick sediment sequences. The Ganges-Brahmaputra delta is situated in Bangladesh covering the majority of the Bengal Basin which lies in front of the Himalayan foredeep. Since at least the Miocene time (23 Ma), deltaic sediments have prograded from a northeast along undefined tectonic trend paralleling basin-margin fault line accumulating 4 km-thick deposits adjacent to the basin-margin fault zone and increasing to >10 km toward the modern shelf break (Lindsay et al., 1991). About 5×10^5 km^3 of sediment are contained within these deltaic deposits (Johnson, 1994). Beyond the shelf is the world's largest fan deposit, the Bengal Fan, covering 3×10^6 km^2 with a volume of ~1.25×10^7 km^3 (Curray, 1994). According to Goodbred (1999), 1500×10^9 m^3 of sediment fill has been sequestered within the flood plain and delta plain of Bangladesh. This value equates to 0.32×10^9 t/yr or about one-third of the estimated annual load. On the shelf, the subaqueous delta began to form approximately 7000 yr B.P., representing 0.42×10^9 t/yr of sediment storage. Together the flood-plain and subaqueous delta deposits account for ~75% of the estimated fluvial sediment discharge. About 25% of the load remains unaccounted for and apparently escapes the shelf through the Swatch of No Ground canyon. Allison (1998) quantified sediment aggradation between the shoreline and 50 m isobath (topset region) by using a geographic information system–based comparison of current and eighteenth-century British bathymetric charts and suggested that the recent load distribution is similar to the overall Holocene system (7000 Ma). Approximately 30% of the load is sequestered to the floodplains and ~40% is sequestered to the subaqueous delta. The remaining ~30% is presumed to reach the Swatch of No Ground (Kuehl et al., 1997) which is supported by rapid modern sediment accretion of greater than 50 cm/yr in the canyon head (Kudrass et al., 1998). The delta-front foresets are currently prograding seaward at a rate of 15 m/yr (Michels et al., 1998). The seaward progradation of delta front is also a measure of the emergence of new sandy beach in the coastal areas and evidence for relative sea level drop.

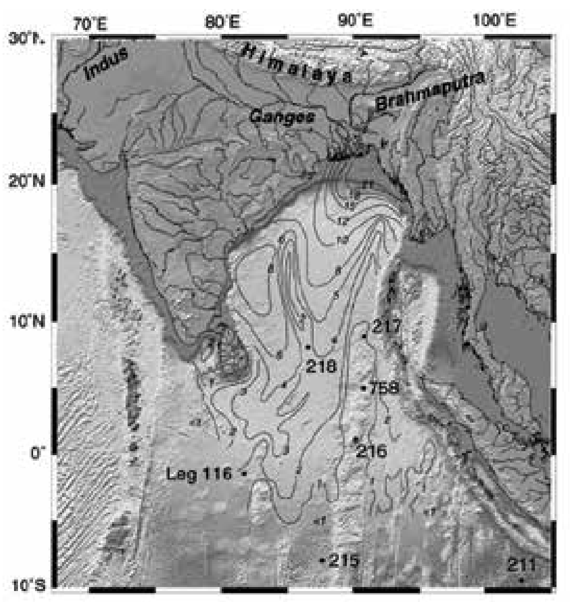

Figure 7: Map showing the position of the different DSDP and ODP Sites documenting the Bengal fan. They represent the total sedimentary and metasedimentary rocks above the oceanic crust, as interpreted from seismic reflection and refraction data. Isopach map of the sediments in the Bay of Bengal that shows maximum sedimentary fan thickness (~21 km) in the continental shelf of Bangladesh and minimum (~4 km) near DSDP 218 in the south. (Source: Curray, 1994).

The Bengal Fan covers the floor of all of the Bay of Bengal from the continental margin of Bangladesh along the west side of the Ninety East Ridge up to about 7˚S. The Bengal Fan was delineated and named by Curray and Moore (1971). Two reflecting seismic horizons pass into unconformities over the exposed and buried hills of folded sediments in the southern part of the fan and over the Ninety East Ridge. The ages of these unconformities were tentatively determined to be uppermost Miocene and upper Paleocene to middle Eocene by DSDP Leg 22 at Sites 218 and 217 respectively (Fig. 7).

Hence, the upper two sedimentary units of the Bengal Fan are associated with the upper Miocene unconformity. Based on the records of Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP), Curray (1994) has prepared an isopach map of the sediments in the Bay of Bengal (Fig. 7) that shows maximum sedimentary fan thickness (~21 km) in the continental shelf of Bangladesh and minimum (~4 km) near DSDP 218 in the south. Depositional processes in a sedimentary fan often reveal a high degree of complexity and lateral, vertical and temporal variability e.g. Amazon Fan (Flood et al., 1997), which limits the continuity of the sedimentary records and stratigraphic resolution. Sediment accumulation in the Bengal Fan is restricted to the currently active channel with a lateral extent of no more than 20-100 km. Maximum sedimentation rates are found on the flanks of the channel-levee system and on internal terraces. Piston coring to the base revealed an age of ~12,800 years and youngest sediment ages of 9700 years (Hübschera et al., 1997; Weber et al., 1997). This means that ~100 meters of sediment accumulated within ~3000 years, corresponding to average sedimentation rates of >30 m/ka in this locality. Figure 8 demonstrates (a) present topography and channel system of the Bengal Fan (redrawn after

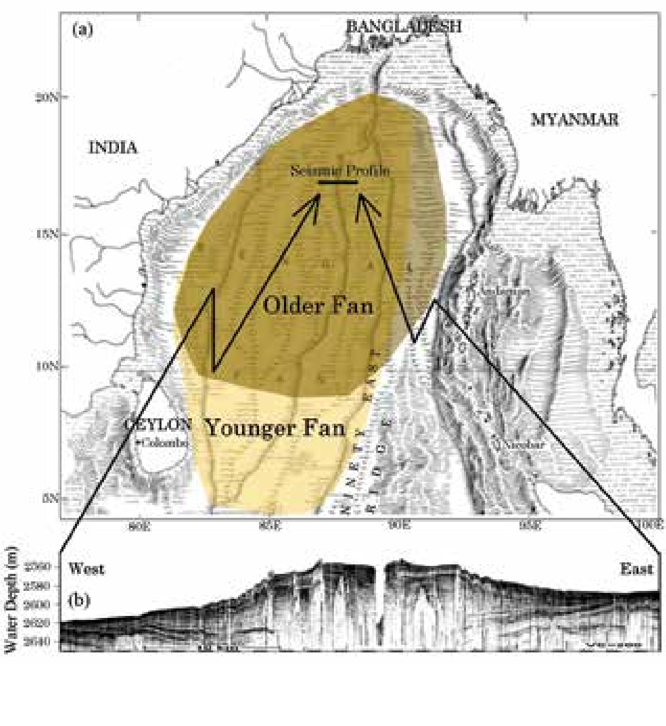

Figure 8: (a) Present topography and channel system of the Bengal Fan. Channel immediately west of Ninety East Ridge is being abandoned today. Extent of older and younger fan is envisaged (redrawn after Curray and Moore, 1974) and (b) segmented channel levee system from the Bengal Fan located at 16°50'N derived from high resolution multi-channel seismic survey (Source: Hübscher et al., 1997).

Curray and Moore, 1974) and (b) segmented channel-levee system from the Bengal Fan located at 16°50'N derived from high resolution multichannel seismic survey (Hübscher et al., 1997). Presumably, this material was deposited in a channel, which rapidly became buried when it was abandoned and a new main channel formed. Turbidites can be expected at the greater distance from the active channel due to the background sedimentation of eventual turbiditic activity. Dasgupta (2004) observed that the lower Bokabil Formation, an important hydrocarbon-bearing formation, exhibits complete Bouma sequence, en-echelon stacking of channels, frequent scouring, the dominance of positive megacycles and interchannel Tbcdturbidites often capped by muddy contourites, high sand-shale ratio and dominance of chaotic facies indicating deposition in a base-of slope to slope environment. The subsequent positions of the progressive sedimentation correlate well with the proto-Bengal fan (Alam, 1989) and the present day Bengal deep-sea fan (Curray and Moore, 1974; Graham et al., 1975).

The offshore stratigraphy is established based on the sedimentary sequence down to the depth of 4598m of BODC-1 well located 20.8^{o}N–91.9^{o}E, as upper and lower well-stratified successions of low energy environment having thickness 1500 m and 1200 m respectively, and about 1200 m thick intermediate sequence characterised by cross-bedding and channel sediments of high energy environment (Maroof Khan, 1980). The paleontologic evidence, primarily the pollen distribution, suggests that the boundary between upper and middle Miocene (base of Echtricolporitesspinosus) in Cox’s Bazar well occurs at around 3000m depth (Simpson, 1976). Correlation of seismic sections of Shahbazpur, Sangu, and Kutubdia well sites demonstrate that the sequence characterised by deep-sea channelling during lowstand condition thicken towards Sangu and the same is missing towards Shahbazpur to the north indicate that the region between Kutubdia and Shahbazpur was elevated prior to Mio-Pliocene deep-sea channelling.

Georesources of the Bay of Bengal

Recovery of minerals from the sea bed and our knowledge of new sources of marine minerals like polymetallic nodules, cobalt-rich crust, polymetallic massive sulphides, have developed rapidly during recent decades. Commercial exploitation of solid marine minerals has so far been limited to deposits originating from mechanical and chemical erosion of rocks on continents and transported to the ocean primarily by the rivers. These are found in relatively shallow offshore areas of the territorial sea and the 200-nautical-mile exclusive economic zone. Minerals derived by mechanical erosion from continental rocks are concentrated as placer deposits those are sorted by water motion according to the varying density of the constituent minerals. These minerals contain heavy metallic elements such as barium, chromium, gold, iron, rare earth elements, tin, thorium, tungsten, zirconium, and non-metals like a diamond, lime, siliceous sand, gravel. Sands and gravel are being mined from beaches and shallow offshore accumulations at many sites around the world for construction material and beach restoration. These are the marine materials with the highest annual production value. Of the non-solid minerals beneath the sea, fossil fuel, natural gas and petroleum are being exploited in shallow and deep water. Among the most promising of new fuel sources are methyl hydrates, a mixture of natural gas and water compressed into a solid by the cold and high pressures of the deep ocean floor in undersea basins of the continental margins. The continuous input of materials dissolved by chemical weathering from continental rocks and transported into the sea by rivers is considered adequate to meet future economic needs of several mineral types. One of these resources is phosphorite, which precipitates in the form of nodules and layers where seawater wells-up from the deep ocean at continental shelves within the belt of the trade winds between 30o latitudes in the north and south of the equator. Phosphorite is used as an agricultural fertiliser by adjacent coastal states. Land supply of phosphorite originally deposited beneath ancient seas fulfils present needs. Two metallic mineral resources of the deep seafloor incorporate dissolved metals from both continental and deep ocean sources. One of these consists of the golf-to-tennis ball-size polymetallic nodules of nickel, cobalt, iron and manganese in varying concentrations. These nodules precipitate from seawater over millions of years on sediment that forms the surface of the vast abyssal plains underlying the deep ocean of water depth 4 to 5 kilometres. Cobalt-rich ferromanganese crusts are the second of the two metallic mineral resources that incorporate metals from both land and sea sources. These precipitate from seawater as thin layers up to 25 centimetres thick on volcanic rocks of seamounts and submerged volcanic mountain ranges at water depths between 400 and 4,000 metres. The richest of these crusts lies within and beyond the exclusive economic zones of the island nations of the western Pacific. It is believed that one seabed mine site could provide up to 25% of the annual global market for cobalt used to make corrosion-resistant, light, strong metal alloys, and paints. In recent time, another important resource has been discovered from the ocean bottom, known as ‘oil shale’. Oil shale is a fine-grained sedimentary rock containing organic matter from which shale oil may be produced. The organic matter, derived mainly from aquatic organisms, is called kerogen. Oil shale and tar sands are strategically important domestic energy sources that should be developed to reduce the nation’s growing dependence on oil.

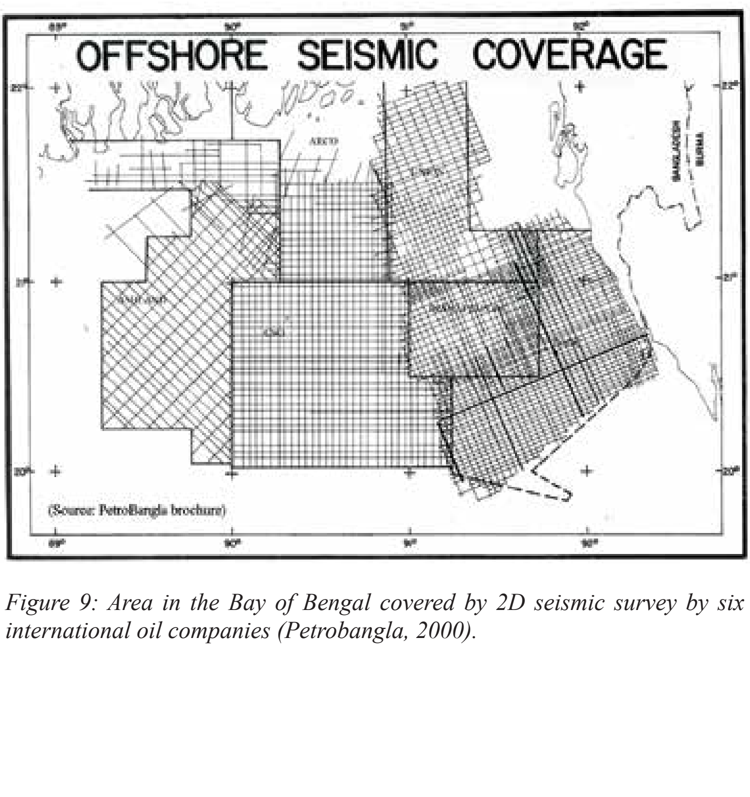

Figure 9: Area in the Bay of Bengal covered by 2D seismic survey by six international oil companies (Petrobangla, 2000).

Continental shelf of Bangladesh is the southward extension of the Bengal Basin which covers a large area of the exclusive economic zone in the Bay of Bengal (Fig. 2). Although the Bengal Basin has been proved to be a potential petroliferous basin, it is ironic that region within the maritime boundary of Bangladesh in the Bay of Bengal has remained as least studied and virgin area. Oil and gas exploration activities in the off-shore region of Bangladesh located between latitudes 20^{o}N–22^{o}N and longitudes 89^{o}E – 92.5^{o}E started in the year 1974 under Bangladesh Petroleum Act 1974 through the participation of six international oil companies such as Ashland, ARCO, CSO, Union, BODC and Ina Naftaplin (Fig. 9). Total coverage of multiple fold 2D seismic data was little over 31000 line-km along with approximately 18000 line-km gravity data (Petrobangla, 2000). Most of the 2D seismic data contain tremendous valuable geological information pertaining to the georesource potentials in the offshore area of Bangladesh. Hafiz (1997) made a geological study of the offshore area between latitudes 20^{o}N-21^{o}N and longitudes 90^{o}E-92^{o}E based on geophysical (seismic and gravity) data and found several prospective structures where hydrocarbon is likely to be trapped. Discovery of gas in Kutubdia and Sangu in the offshore strongly indicate the occurrence of hydrocarbon source rock and suitable structural traps in the continental shelf of Bay of Bengal. Trapping of hydrocarbon in the structures developed at 4-6 km depths is proposed. In addition, mud and sand-filled channels, incised valleys of intense channelling,

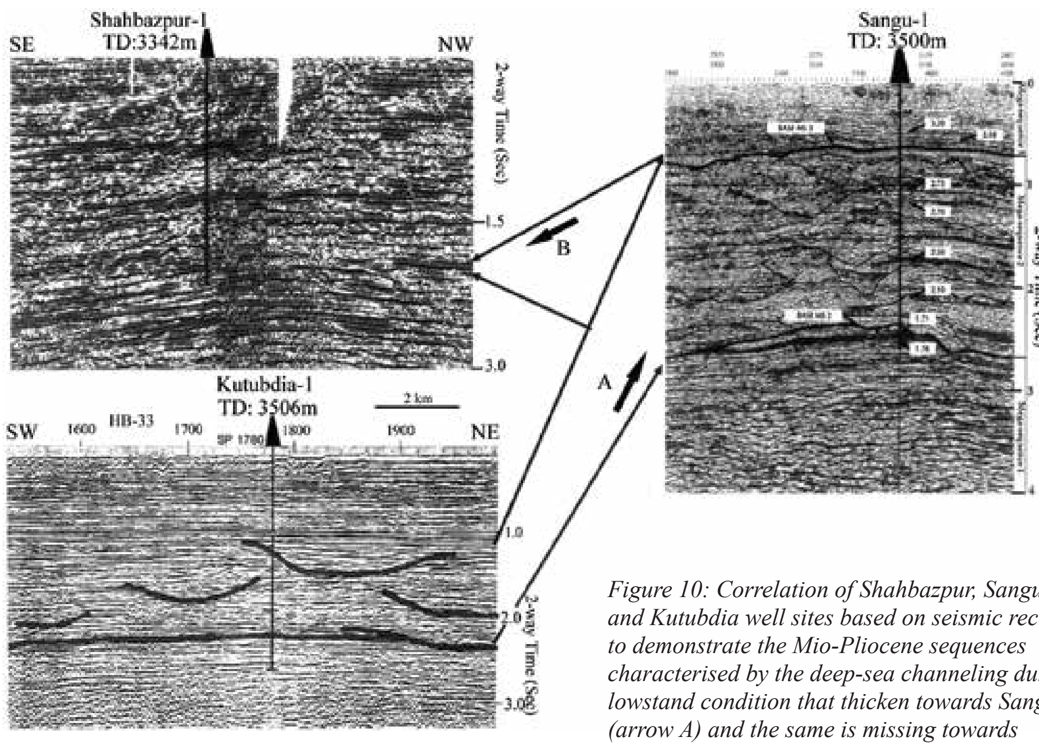

Figure 10: Correlation of Shahbazpur, Sangu, and Kutubdia well sites based on seismic records to demonstrate the Mio-Pliocene sequences characterised by the deep-sea channeling during lowstand condition that thicken towards Sangu (arrow A) and the same is missing towards Shahbazpur (arrow B) indicating that the region between Kutubdia and Shahbazpur was elevated prior to Mio-Pliocene deep-sea channeling.

and pro-delta clays pass up-dip to delta-front sand wedges are considered favourable for developing stratigraphic traps. Based on seismic and well data, the mid-Miocene gas-bearing horizon in Shahbazpur well is observed to occur at about 2600m depth while that in the Sangu well at around 3000m (Petrobangla, 2000).

Crustal segmentation and deformation have resulted in the development of folds and inversion with a variable pattern wherein the young structures are formed on to the older structures. The sediments represent an overall basin-ward progradation from deep marine to coastal marine depositional settings overlain by continental-fluvial type wherein the lower part represents a slope-apron within a migrating accretionary prism complex. Thick mud rock sequence at around 5-6 km depth is considered as upper source rock undergone a high degree of maturation within the oil window. Based on seismic and well data, the mid-Miocene gas-bearing horizon in Shahbazpur well is observed to occur at about 2600m depth while that in Sangu well at around 3000m. The paleontological evidence, primarily the pollen distribution, suggests that the boundary between upper and middle Miocene in Cox's Bazar well occurs at around 3000m depth. Seismic sections of Shahbazpur, Sangu, and Kutubdia well sites have been correlated to demonstrate the sequences characterised by the deep-sea channelling during lowstand condition that thickens towards Sangu and the same is missing towards Shahbazpur indicating that the region between Kutubdia and Shahbazpur was elevated prior to Mio-Pliocene deep-sea channelling (Fig.10). Favourable trapping of hydrocarbon in the structures developed at 4-6 km depths is proposed. In addition, mud and sand-filled channels, incised valleys of intense channelling, and pro-delta clays pass up-dip to delta-front sand wedges are considered as favourable stratigraphic traps. Discoveries include a series of gas fields in the deep-water of Krishna-Godavari Basin of India, new oil and gas fields in the deep-water Krishna-Godavari Basin of India, discovery of gas fields offshore of the Mahanadi Basin of India, and discovery of large deposit of Shwe gas in the Rakhine Basin of Myanmar, all exhibit strong evidence in favour of new future discoveries in the deep-water basins of Bangladesh.

Geohazard Vulnerability

This section deals with the natural hazards occur due to the geological processes. Natural hazards caused by the atmospheric processes are outside the scope of this study. Although Bangladesh coastal belt and the northern Bay of Bengal is highly vulnerable to frequent occurrences of atmospheric hazards like cyclone and storm surge, this study reveals that the vulnerability potentials of the geological hazards are low. Geohazard may be defined as a geological state of the art that may lead to widespread damage or risk. Geohazards are geological and environmental conditions and involve long-term or short-term geological processes. Important offshore geohazards include volcanic activities, mud diapirism and mud volcanism, slope instability, submarine landslide, turbidites, shallow gas, natural gas hydrates, shallow water flows, active fluid seepage, seafloor pockmark formation, seismicity and seismicity induced trans-oceanic tsunami, local tsunami and sea-level rise (Fig. 11). The Bay of Bengal, by and large, is potential for the above-mentioned geohazards. However, the vulnerability of these marine geohazards should properly be addressed and further research is warranted.

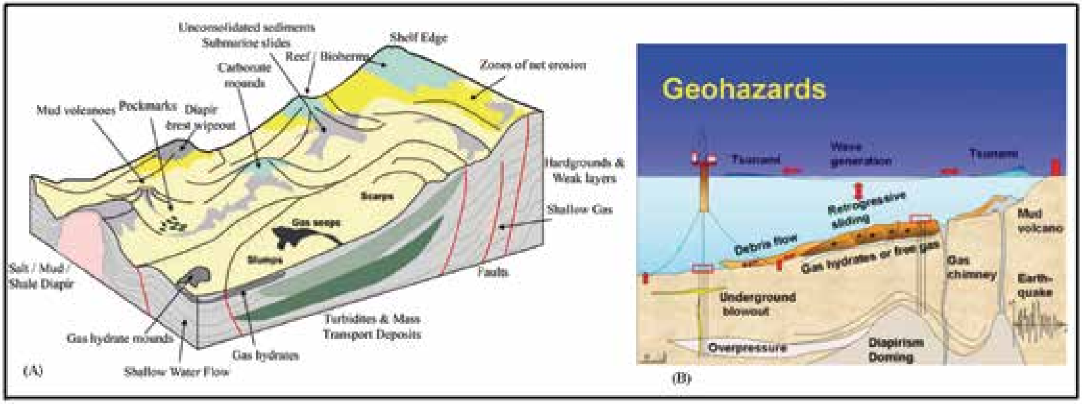

Figure 11: Cartoon of important offshore geohazards those include volcanic activities, mud diapirism and mud volcanism, slope instability, submarine landslide, turbidites, shallow gas, natural gas hydrates, seafloor pockmark formation, seismicity and seismicity induced trans-oceanic hazards.

Although earthquake record of the Bay of Bengal shows ‘no to weak’ seismicity associated with the region around the Ninety East Ridge and Eighty-Five East Ridge, it is customary to believe that the sources of earthquakes exist in the Bay of Bengal. Ongoing seismic activities is an indication of dynamic crust in the Bay of Bengal, especially in and around Andaman Trench and the Andaman Sea. Barren Island volcanic eruption of 18 April 2001 located south in the Andaman Sea. Eruptions of the Barren Volcano was recorded in 1787 and subsequent eruptions were recorded in 1789, 1795, 1803-04 and 1852 (Raghav, 2011). After nearly one and a half century of dormancy, the island had another eruption in 1991 that lasted six months and caused widespread damage. There were eruptions in 1994-1995 and 2005-07, the latter being considered to link to the 2004 Indian Ocean earthquake that generated a massive trans-oceanic tsunami. All these volcanic eruptions in the Andaman Sea are due to the subduction of the Indian plate in the Bay of Bengal beneath the Burmese plate. The most spectacular feature that has been formed due to the subduction along the Andaman Trench is the Andaman-Nicobar Volcanic Island Arc. Further, the eruptions of the subduction melts in the Andaman Sea can generate large earthquakes inducing back-arc extension in the Andaman Sea. According to Rao et al (2011) 30km thick double oceanic crustal column corresponding to a thickness of about 21km of Burmese crust including a 5km thick sedimentary column, underlain by a thinner Indian crust with an apparent thickness of about 9km modelling. This signifies for the crustal thickness in the Bay of Bengal is 9km. The 2009 August 10 Andaman Earthquake of moment magnitude (Mw) 7.5 and its aftershocks show vertical distribution of the hypocentral depths down to about 50km signify very close proximation of subduction. Rao et al (2011) further opined that there are two crustal groups in the Andaman region, i) normal faulting within 18 km depth, and ii) strike-slip faulting at greater depths down to 26km. This signifies that the Bay of Bengal around Andaman-Nicobar is characterised by extensional tectonics having both horizontal displacement and subsidence which can generate only local tsunami in the Andaman Sea.

In addition, the northern part of the Bay of Bengal especially the continental shelf shows induced seismicity effect from the continental source zone and tectonic trends. Seismicity induced hazards such as mud volcanism, slope instability, submarine landslides are likely to occur. Mud diaper, shallow gas, shallow water flows, high pressure and active fluid seepage are widespread and can pose threat. The Bay of Bengal, by and large, is free from occurrence of the tsunami because of the two fundamental reasons viz., shallow water depth and sea-bed rupture pattern. For tsunami wave, it is essential that due to an earthquake the sea bed rupture must be vertical to near vertical in order to displace vertically the entire water column. However, focal mechanism study revealed that the sea bed rupture pattern is dominantly horizontal i.e., strike-slip. Bangladesh coast is characterised by an added advantage of having wide, approximately 200 km long continental shelf that can act as the barrier as well as plays a key role in flattening the waveform of the tsunami through defocusing process. Any trans-oceanic tsunami like December 2004 Indian Ocean Tsunami due to Sumatra Earthquake, will have an abrupt fall of velocity along the continental shelf break. Decay factor of the tsunami height in dispersive mode resulted from bed configuration and free air anomaly calculated for 2004 Indian Ocean tsunami is equal to 0.324 m/km. This resulted in a total negative height drop of about 13m means a levelling with mean sea level at a distance about 43 km from the coast of Bangladesh. On reaching the coast, the estimated tsunami height would be -3m. Sea-level rise is the most legitimate concern that global warming is likely to induce. However, a recent publication by Khan (2018) revealed that global warming and polar ice-melt will not contribute to sea level rise. Hence, the Bay of Bengal also will not be affected by any so-called predicted sea level rise. Sea level in the Bay of Bengal will rise and fall only due to the subsidence and uplift of the crust. In the present context of prograding Ganges-Brahmaputra delta and deposition of about 40% yearly sediment influx on to the continental shelf of Bangladesh, relative sea-level is likely to drop. Hence, sea-level rise related hazards in the Bay of Bengal is unlikely to occur.

Development of 'Blue Economy'

'Blue Economy' is a term in economics relating to the exploitation and preservation of the marine environment. 'Blue Economy' refers to marine-based sustainable economic development which leads to improved human wellbeing and social equity through significantly reducing environmental risks and ecological scarcities. 'Blue Economy' aims for holistic and sustainable development along with enhancing human welfare. It is a broad concept as it is not only confined to minerals and marine products but also includes even maritime activities like shipping services, trade and business. This concept visualises oceans as the development spaces in which activities like conservation, sustainable energy production, mineral wealth extraction, bio-prospecting, marine transport etc. are integrated. The key elements thus can be summarised as a) optimum and efficient utilisation of resources, b) sustainable, inclusive, harmonious and environment friendly development, c) exploitation of opportunities in emerging marine industries, and, d) creating and streamlining legal and regulatory institutions which govern the access, use and protection of maritime resources.

'Blue Economy' concept is suitable for management and sustainable development of ocean resources. 'Blue Economy' also includes economic benefits that may not be marketed, such as carbon storage, coastal protection, cultural values and biodiversity by measuring variation at the genetic, species, and ecosystem level. A related term of the blue economy is ocean economy. However, these two terms represent different concepts. Ocean economy simply deals with the use of ocean resources and is strictly aimed at empowering the economic system of the ocean. 'Blue Economy' goes beyond viewing the ocean economy solely as a mechanism for economic growth. It focuses on the sustainability of the ocean for economic growth. Therefore, the blue economy encompasses ecological aspects of the ocean along with economic aspects. The World Bank (2017) specifies three challenges that limit the potential to develop a 'Blue Economy': a) current economic trends that have been rapidly degrading ocean resources, b) lack of investment in human capital for employment and development in innovative blue economy sectors, c) inadequate care for marine resources and ecosystem services of the oceans. The strategic and economic significance of the Indian Ocean and its implication for the Bay of Bengal is quite high (Khurshed Alam, 2018). Sustainable 'Blue Economy' Conference held in Nairobi, Kenya in November 2018 to advance a sustainable 'Blue Economy' includes marine protection, plastics and waste management, maritime safety and security, fisheries development, financing, infrastructure, biodiversity and climate change, technical assistance and capacity building, private sector support, and partnerships.

Conclusion

The Bay of Bengal is intimately related to the early opening of the Indian Ocean resulting in the creation of new seafloor overlain by the modern Bengal deep-sea fan at the top 4 km and 12 km thick older sediments at the bottom. The Bay of Bengal has opened-up and enlarged along with the northward motion of the Indian plate between 120 Ma and 55 Ma at a rate of about 6 cm/yr. The Bay of Bengal is characterised by the geological features those formed principally by the tectonic activities including volcanic and sedimentological processes. Evolution history of the Bay of Bengal suggests the occurrence and enrichment of georesource and marine minerals like polymetallic nodules, cobalt-rich crust, polymetallic massive sulphides etc. Oil shale and tar sands are strategically important domestic energy sources that should be developed to reduce the nation's growing dependence on oil. The occurrence of hydrocarbon, gas hydrates and gas shale has been established but a lack of detailed studies and exploration, its reserve estimation has not yet been possible. Favourable trapping of hydrocarbon in the structures developed at 4-6 km depths has been inferred. In addition, mud and sand-filled channels, incised valleys of intense channelling, and pro-delta clays pass up-dip to delta-front sand wedges are considered as favourable stratigraphic traps. Although, Bay of Bengal of Bangladesh is rich in georesources, yet it is quite vulnerable to atmospheric hazards like cyclone and storm surge but geohazards pertaining to earthquake and tsunami are not high except along the north-south trending narrow strip of Andaman-Nicobar Islands. Earthquake-related marine hazards may occur in some tectonically weak zones in the submarine environment. This study further warrants for detailed study and exploration in order to evaluate Bangladesh part of the Bay of Bengal that may ensure the development of the 'Blue Economy'.

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