Geo-resource exploration for sustainable development of energy in Bangladesh constraints of geological and geophysical studies of the continental shelf

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Abstract

Fundamental requirement of the sustainability of the energy development is an extensive exploration and production of the geo-resources like oil and gas. Continental shelf of the Bay of Bengal of Bangladesh maritime boundary is found to be the most resourceful offshore area where hydrocarbon especially natural gas potentially occurs. Geological and geophysical studies have revealed that down to the 4000m depth from sea floor the offshore basin beneath the continental shelf contains enormous natural gas. Very high formation pressure at depths around 3500m in the wells drilled and the occurrence of gas hydrates at around 400m depth in the continental slope further support the occurrence of natural gas in this offshore basin. The principal approach for the sustainable development of the energy resource needs extensive exploration activities in the continental shelf of the delta. Continental shelf which has developed due to enormous continuous sediments supply and deposition has emerged as the progading delta. The extraction and exploitation of non-living resources like oil, gas, gas hydrates and seabed minerals are the principal economic components for the sustainable energy development. Bangladesh has taken many folds development program in the continental shelf of ocean-based economy and planning the delta in favor of various maritime activities. This study is an effort to understand the continental shelf of the Bengal Delta in the perspective of its origin, formation, and potentiality of geological resources and its vulnerability of geological and atmospheric hazards. This study focuses mainly on to the geological resources like natural gas, gas hydrates and seabed minerals. Continental shelf-slope margin is also vulnerable to geohazards and atmospheric hazards those may hinder the sustainability of the development. This article also focuses on to the physical changes of the coastal belt since the mapping of Rennell in 1778 and the associated factors, vulnerability of geological hazards, review of the published works and revisiting the continental shelf-slope margin on the status of gas occurrence, gas hydrates and ocean related activities.

Key Words: Geology, Geophysics, Continental Shelf, Sustainable development, Energy Security

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1. Introduction

Bay of Bengal lies roughly between latitudes 5°N and 22°N and longitudes 80°E and 100°E, but the continental shelf is extended up to 20°N latitude from the coast. The continental shelf covers an area of about 190 km by 300 km with sediments thickness varying between 12 km in the deep-sea fan and 20 km in the northeastern portion of the shelf. The continental shelf is genetically characterized by the prominent delta lobes that have shifted from west to east about 300 kms at a rate of 45 to 50 m/yr. Since 1778 the present delta has moved 100 km southward at a rate of about 400 m/yr at an aspect ratio 1:8. Present delta is progressing through the Meghna estuary started at about 4 thousand years back pushing greatly coastline seaward. The initial delta build-up started around 6 to 7 thousand years back after the Holocene transgression in about 9000 years back. The bay is about 1,600 km wide, with an average depth of about 2,600 meters. The maximum depth of water reaches to about 4,694 meters at the southern part of the bay (Morgen et. al. 2009); (www.britannica.com).

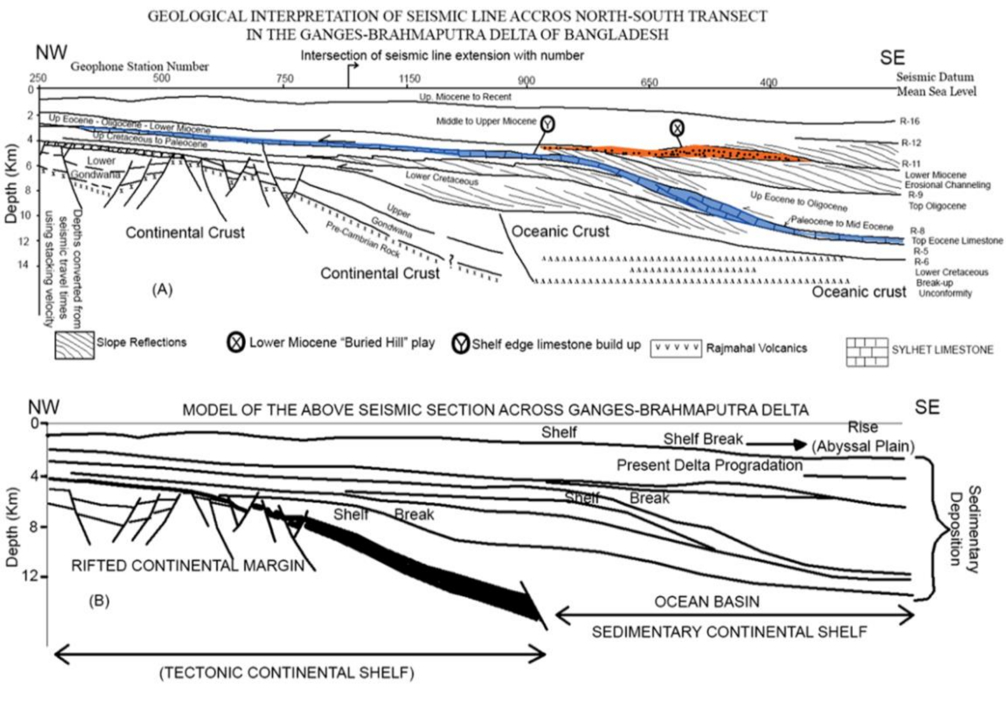

Figure 1: (A) Exhibits NW-SE trending seismic line where sedimentary clinoforms are shown. (B) Shows a model based on the above seismic coverage where advancement of shelf break is very clear with present delta progradation (Redrawn from Salt et al., 1986).

Water depths in the continental shelf vary between 20m to 200m. Continental shelf of the Bengal Delta, also known as Ganges-Brahmaputra Delta, is one the largest continental shelves that contains one of the thickest sediments deposits since about 118±5 Ma. Bengal Delta terminology is preferred because the delta has formed in the Bengal Basin due to the deposition of sediments carried by the rivers Ganges and Brahmaputra. Rajmahal volcanics of the Bengal Basin erupted during the Kerguelen Hot Spot activation located around 15^{o}N 85^{o}E. Rajmahal volcanics were deposited over the Gondwana sediments in the continental shelf. Continental shelf, in general, is of two types viz., the tectonics continental shelf and the sedimentary continental shelf.

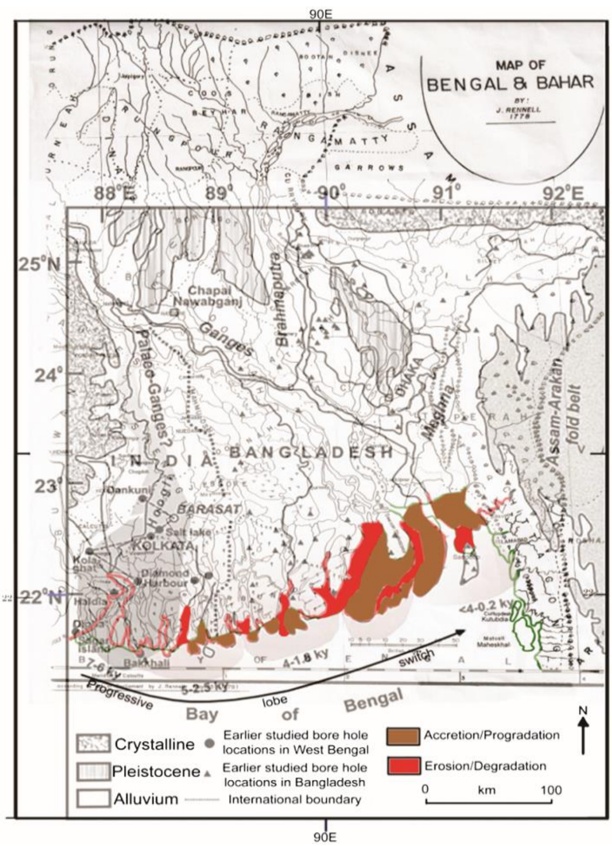

Figure 2: Regional map of Bengal Delta overlying the riverine map of Bengal & Bahar (Bihar) prepared by J. Rennell in 1778 exhibits distinct major accretion (brown color) and minor erosion (red color) of the coastal belt of Bangladesh since 1778. The overlying map taken from Sarkar et al (2009) also exhibits shifting of the initial Holocene delta that built down the Hoogli River (conduit of sediment supply subsequent to which shifting proceeded from west to east between 7000 and 200 years.

Tectonically induced continental shelves are those formed during the separation of the super-continent (example Gondwanaland break-up). However, the super-continental break left behind distinct structural pattern characterizing rifted dominated continental margin on to which the sedimentary deposition progressed (Fig. 1). Bengal Delta started to form after the Mid-Holocene marine transgression which occurred around 9000 to 10000 years back. But sediments filling in the Bengal Basin started at least from the Cretaceous period about 85 to 65 Ma ago. Intense monsoon and very high sediment discharge about 4 to 8 times greater than the modern time discharge caused a very rapid infilling in the Bengal Basin by the sediments during the entire Tertiary period. Occurrence of Late Quaternary marine clay and fluvial channel-overbank sediments below the Holocene deposits signify the initiation of the formation of Bengal Delta between 7 to 8 thousand years back (Sarkar et al., 2009). Mid Holocene marine transgression around 9 thousand years back is also evident from the occurrence of hypersaline calcium and magnesium rich aragonite mud and benthonic foraminifera 300 km inside the land at Chapai Nawabganj of Rajshahi (Khan et al., 2000). The Bengal Delta progradation occurred from west to east between 7000 to 200 years wherein the present delta is prograding through the Meghna estuary (Fig. 2).

2. Geological Conditions

2.1 Formation of the Continental Margin

After the break-up of supercontinent, the broken segments of the continents can drift away from each other to form new ocean basin due to the process of sea floor spreading. The sea floor of the newly formed ocean basin is characterized by the basic igneous rock known as basalt, while the continent is characterized by the acid igneous rock known as granite. In such geological environment both granite and basalt occur as the contact margin. Tectonically induced and initially built such margin is defined as the tectonic continental margin.

Sediments from the source region start depositing over the tectonic continental margin or shelf. As sedimentation progressed the tectonic continental margin got filled up to form a shelf like geomorphic feature of sediments known as sedimentary continental shelf. If such continental shelf becomes the floor of deposition of sediments carried by fluvial process can form delta. Such delta can prograd with the continuous supply of sediments in the sedimentary continental shelf. Formation of the sedimentary continental shelf depends on the sedimentary influx and the deposition of sediments over the tectonic continental shelf (Fig. 1). Tectonic continental shelf in the Bengal Basin formed due to the break of Gondwanaland around 132 Ma. India-Australia broke around 120 Ma (Fig. 3a). With the separation, India moved to the present position from the Kerguelen Hot Spot located at 48^{o}S latitude and 70^{o}E longitude. Combined India-

Australia moved to the position located at 30°S latitude and 88°E longitude from Kerguelen Hot Spot in 14 Ma time covering a distance of about 2500 km at a rate 18 cm/yr. Since 118±5 Ma from this point India Plate moved north and Australia moved east. Ninety East Ridge transform played main driving role for India to move to the north, and Broken Ridge and Diamantina fracture played main role for Australia drift (Fig. 3). Northward movement of India is further supported by the presence of distinct magnetic anomaly and the shift in the magnetic anomaly in the Bay of Bengal (Khan, 2019 and reference therein). Magnetic anomalies are characterized by the age of the magma injection in the floor of the Bay of Bengal. Progressive movement of India to the north and the collision of India with Eurasia around 66 Ma initiated the closure of palaeo-Tethys between India and Eurasia forming Himalayan orogenic belt. Himalayan

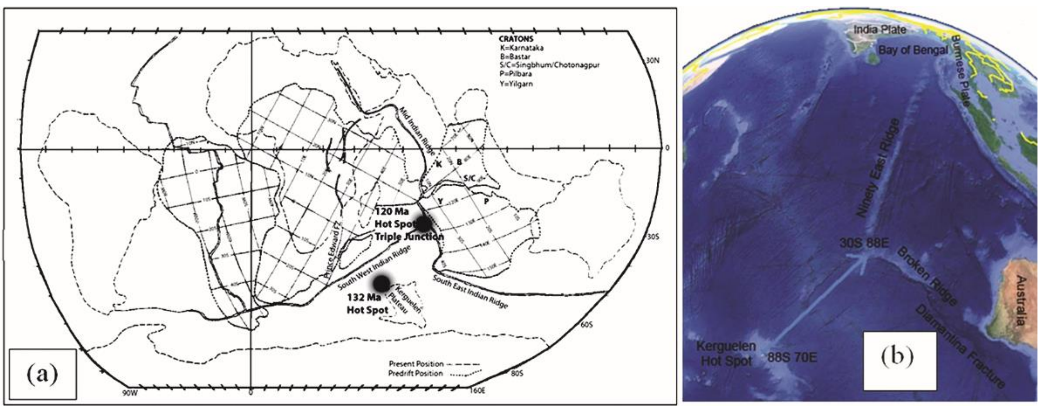

Figure 3: (a) India-Australia plate reconstruction of 132 Ma position and 120 Ma position wherein 120 Ma position is the point of Rajmahal volcanic eruption to result in the separation of India and Australia. (b) Major crustal features such as Kerguelen Hotspot, Ninety East Ridge and Broken Ridge in the Indian Ocean exhibit the role in the formation of Bay of Bengal.

Orogenic belt became the main source of sediments supply in the tectonic continental shelf and sedimentary continental shelf of the Bay of Bengal (Fig. 3b). As the entire Bengal Basin filled-up and the progressive sedimentation from Himalaya continued, the Bengal delta started to form with prograding in nature. The prograding nature of the delta formation progressed both longitudinally and latitudinally as it is seen in the Figure 2 wherein the Bengal Delta formed around 6 to 7 thousand years back in the southwestern region of Bangladesh and gradually shifted to the east at a rate of 45 to 50 m/yr laterally (latitudinal) and at a rate of 400 m/yr longitudinally. The initial delta build-up started around 6 to 7 thousand years back after the Holocene transgression in about 9000 years back. The sedimentary continental shelf is genetically related by the prominent delta lobes that have shifted from west to east laterally about 300 kms at a rate of 45 to 50 m/yr. Since 1778 the present delta has moved maximum upto 100 km southward at a rate of about 400 m/yr. Present delta is progressing through the Meghna estuary started at about 4 thousand years back pushing the coastal waterline further south seaward. This southward movement of coastal waterline of Bangladesh demands re-assessment of the maritime boundary of Bangladesh that will increase the area including EEZ.

2.2 Formation of the Bengal Delta

Geological record suggests that the Pleistocene deposits of the Bengal Basin such as Barind Tract in the NW Bangladesh, Modhupur Tract in the Mymensingh district and Lalmai Hills of Comilla district do not belong to the deposition of deltaic environment. Sediments deposited during the Pleistocene epoch signify mostly alluvial-fluvial deposits governed by the channel and flood plain environment. Borehole data indicate that the Late Quaternary deposits are due to the massive sediment discharge, tectonics, and eustasy. There was a major marine transgression around 10,000–11,000 cal yr BP along with rapid sediments influx that intersected a large portion of the low stand surface, marking the onset of delta growth. Rapid sediment influx poured into the subsided Holocene depression situated about 300 km land interior along the Ganges River where subsidence of about 50 ft (15.6 m) occurred (Fig. 4).

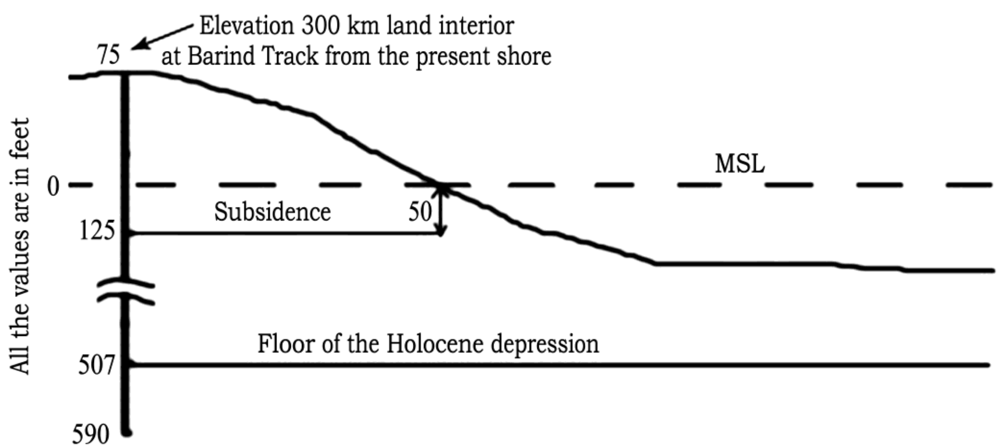

Figure 4: North-South cross section exhibits 50 ft (15.6m) subsidence of the continental crust 300 km land interior from the present coast during Holocene time depositing about 350 ft carbonate mud in a lagoon environment.

In addition, prominent depressions along Jamuna and Meghna rivers have also occurred. Khan et al (2000) suggested three well-defined Holocene depressions viz., Padma depression, Jamuna depression and Meghna depression wherein Padma depression acted as one of the main conduits for marine transgression where supra-tidal aragonite mud are deposited over the erosional surface of the Pleistocene deposits. However, sediment load was so enormous that despite the major subsidence of the tectonic continental margin in the Bengal Basin and marine transgression, the shoreline was stable means no-sea level change could occur due to huge sediments influx prograded seaward as prominent delta formation pushing sea more seaward which is also an active phenomenon in the recent times. Regional map of the Bengal Delta in the Figure 2 overlying on the riverine map of Bengal & Bahar (Bihar) prepared by J. Rennell in 1778 exhibits clearly the delta progradation. This coastal progradation and the fine-grained suspended sediments discharge bypassed the subaerial delta and formed a prograding deltaic clinoform on the shelf. Bengal Basin started to form during Jurassic around 135 Ma as the broken continental blocks drifted from Gondwanaland super-continent. Sediments in the newly formed ocean basin especially the Bengal Basin started contemporaneous to the rifting and drifting and occurred in all the three geotectonic elements such as peri-cratonic shelf, deeper basin zone, and in the transform trench of the converging plate margin to the east. The 9000 cal years BP transgression inundated the low stand surface resulting the coastline to enter ~300 km inland (Fig. 4) signifying subsidence of the continental crust or uplift of the oceanic crust (Fig. 5, Cases 2&3).

Mid-Holocene coastal region of the Bengal Delta was occurring at about 9000 cal years BP. The initial Bengal Delta front was located along the peri-cratonic rift margin, and the delta formation began from the points where rivers with high sediments influx enters and meets the sea. The alluvial fans were formed at the slope of the peri-cratonic margin. Similarly, very high sediment discharge (4–8 times higher than the modern) (Sarkar et al., 2009) caused a rapid aggradation of both floodplain and estuarine sediments at around 7000 cal years BP and the delta prograded up to the 7000 cal years BP coastline (Figure 6). Bengal Delta prograded uniformly southeastward since that time and maintained a regional slope 1:8 or ~5^{o} to the southwest pushing Bay of Bengal more and more oceanward. The 3000 cal years BP coastline strongly suggest that the progradation of the Bengal Delta continued maximum in the central and eastern part of the shelf (Fig. 6). DEM from Shuttle Radar Topographic Mission data 2000 of Bandyopadhyay (2007) clearly divides the coastal region into three different geomorphic zones. The pattern and tonal variations of each zone has distinct geomorphic characters. The zone between 9000 and 7000 cal years is characterized by enormous deeply cut streams and fluvial deposits.

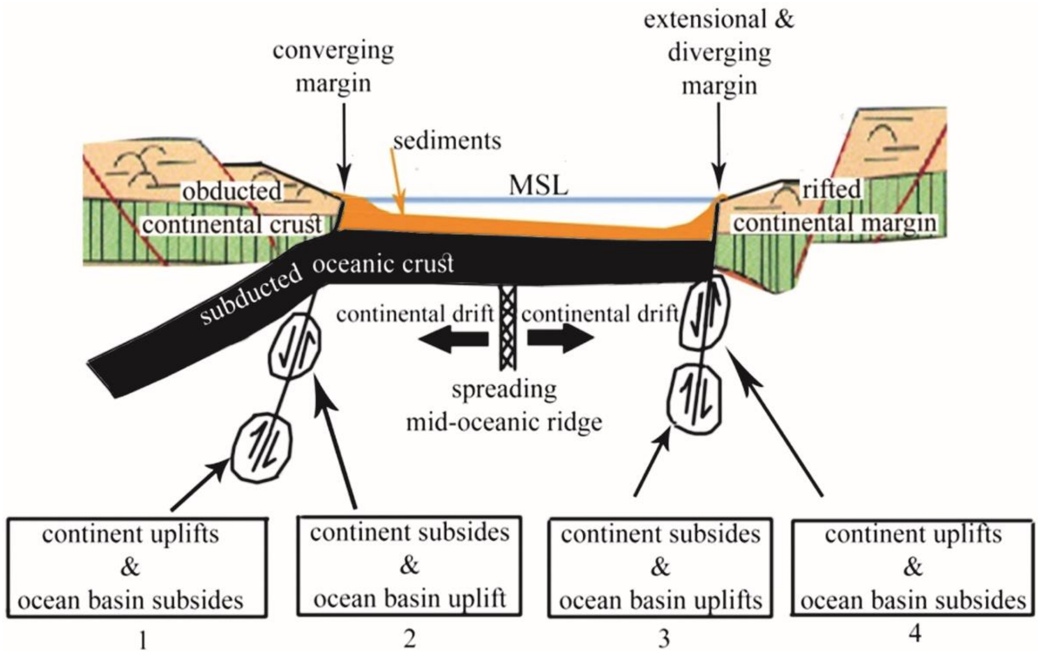

Figure 5: Model representing drifted continents, formation of an ocean by sea floor spreading from mid-oceanic ridge underlain by oceanic crust, and plate margins associated with various types of faults for crustal movement in order to signify apparent sea-level rise and fall. There are four different scenarios of fault movements two in the converging and two in the diverging plate margin those control the status of sea-level. Case 1 and 4 exhibit an uplift of the continent and subsidence of the ocean basin resulting in sea-level drop. Case 2 and 3 exhibit a subsidence of the continent and uplift of the ocean basin resulting in sea-level rise.

The zone between 7000 and 3000 cal years is characterized by incised swamps and lakes along with some existing similar geomorphic features. The zone between 3000 and the present coastline is characterized by simple progradational delta build-up resulting the emergence of good number of islands and sand bars. The present-day depositional continental shelf is genetically related to the prominent delta lobes that have been shifted from west to east laterally about 300 kms at a rate of 45 to 50 m/yr. Since Rennell's mapping of 1778 (Fig. 2) the present delta has moved maximum up to 100 km southward at a rate of about 400 m/yr. Hence, as opposed to the sea level rise concept, the Bengal Delta is largely a prograding delta which is conducive to the relative sea level drop and the emergence of new islands in the Bay of Bengal.

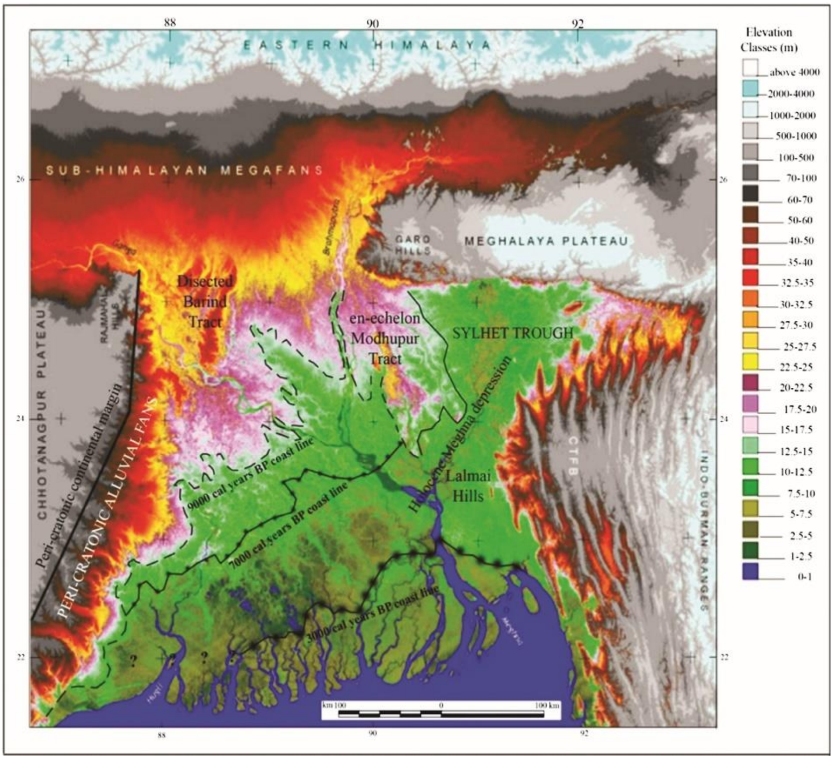

Figure 6: Map showing paleogeography of the Bengal Delta of the Bengal Basin. (Redrawn from Bandyopadhyay, 2007. DEM is prepared from Shuttle Radar Topographic Mission data of 2000).

2.3 Characterization of the Sedimentary Continental Shelf

Sedimentary continental shelf of the Bay of Bengal is characterized by the geological features those have formed principally by the tectonic, volcanic, and sedimentary processes. Continental shelf is characterized by the prominent geological features such as deep-sea canyon, popularly known as Swatch of No Ground (SoNG) in addition to one of the longest depositional continental shelves and the largest deep-sea fan beyond the shelf break. The SoNG acts as the main avenue for the sediment's transportation in the deep-sea region across the continental shelf to form deep sea fan. Sediments from the Himalayan orogenic belt are transported by the major rivers mainly Ganges, Brahmaputra, Padma, and Jamuna and to the lesser extent by the Meghna River to the Bay of Bengal measuring about 2 billion tons per year. Of which about 40 to 60 percent sediments both bed load and suspended sediments are transported to the deep-sea areas through the SoNG and 60 to 40 percent sediments are deposited in the continental shelf.

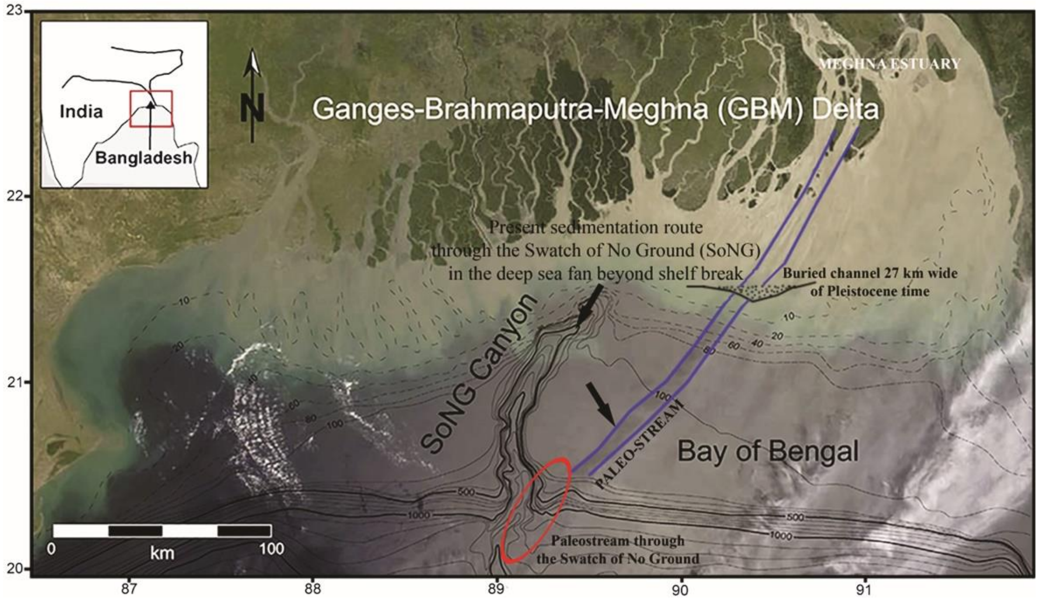

Figure 7: Important geological features of the continental shelf of the Bay of Bengal. Swatch of No Ground (SoNG), 27 km wide and 750m deep buried channel and its paleo-route of sediment transportation to the Bengal deep sea fan, and the shelf break are exhibited (Khan,1984).

In addition to the SoNG, the continental shelf of the Bay of Bengal was sub-aerially exposed to deglaciation during Pleistocene time about 2 Ma ago when sea was about 100m down the present sea level. This lowering of sea level was linked to the last and final Himalayan orogeny wherein peri-cratonic continental crust uplifted and BoB oceanic crust subsided resulting in the relative sea level drop. However, eustatic sea level maintained its hydrostatic equilibrium by redistributing the ocean water. At the end of the deglaciation, rejuvenation and erosion in the Himalaya, and accelerated sediments influx in the Bengal Delta, both the continental and oceanic crust in the Bengal Basin came under the process of isostatic rebalancing. The isostatic rebalancing caused differential crustal adjustment by relative subsidence and uplift. All the Holocene depressions in the Bengal Delta are the outcome of such differential crustal movement. Seismic and gravity data of the sedimentary continental shelf of the Bay of Bengal have revealed a major buried channel which formed during the Pleistocene glaciation (Fig. 7) (Khan, 1984). Buried channel is 27 km wide and could be traced for at least 200 km from the coast up to the SoNG which was a major route for the sediments supply of the continental shelf.

Peri-cratonic margin between continent and ocean in the Bengal Basin passes through the granitic and basaltic contact represented by the NE-SW tectonic trend TT3. It is interpreted as the deep-seated fracture that extends through the “Swatch of No-Ground” in the southwest direction (Khan and Chouhan, 1996). Further, SoNG is also interpreted as the interface between continental and oceanic crust in the region and genetically related to the formation of the Bay of Bengal. Swatch of No Ground, the deep-sea canyon lays 150 km downdrift from the main suspended sediment source in the Meghna estuary which acts as the main sediment dispersal route to the deep-sea fan in the Bay of Bengal. It discharges sediments at a rate of 5–50 cm/year in the deep-sea region.

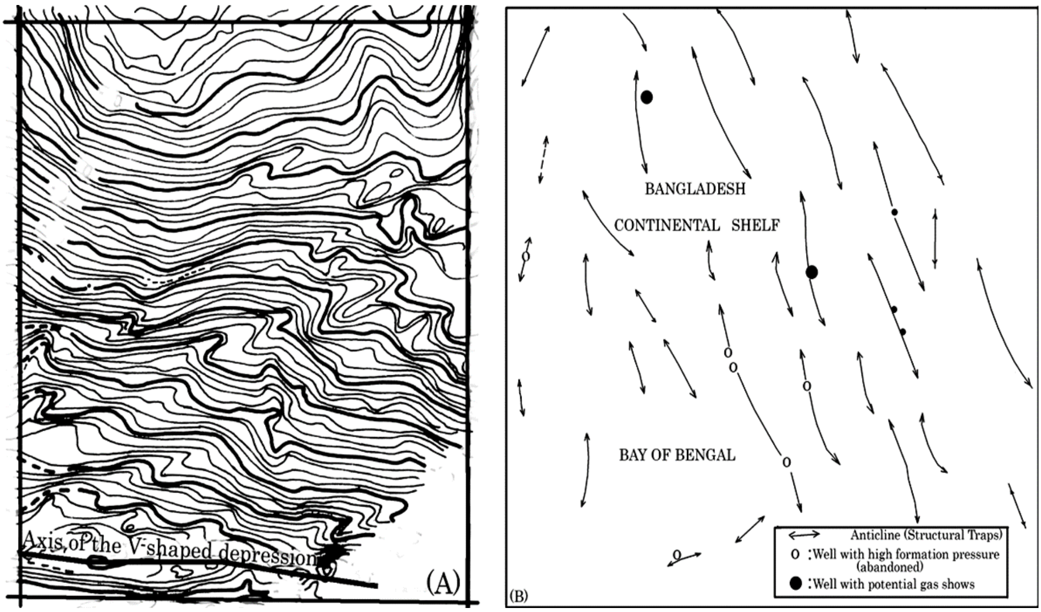

Figure 8: An anonymous area in the continental shelf of the Bay of Bengal showing (A) Gravity anomaly pattern depict hydrocarbon bearing subsurface structures, (B) number of anticlinal structures (hydrocarbon traps) and the wells drilled over the structures.

According to Rogers et al (2015) SoNG canyon deepens to >600 m within 60 km of the shore and intersects the regional trend of the shelf break around 170 km from shore which deepens up to 1200m deep with an average inclination of ~0.6°. Progradation nature of fan buildup in the deep-sea region through the SoNG formed subaqueous delta known as Bengal Deep Sea Fan. Sea floor spreading due to the drifting of the Indian Plate to converge with Eurasian plate progressed with the formation of Ninety East Ridge transform and 85^{o}E Ridge, both functioned as the principal driving lines for the Indian Plate motion.

Crust in the Bay of Bengal sustained pull-apart stress accommodating differential subsidence bounded by normal faults. Subsidence of the crust in the Bay of Bengal is evident from the crowding of east-west trending linear gravity anomaly pattern that coincides with the shelf break and slope zone (Fig. 8A). Crowding of the gravity contours in the southern side of the V-shaped depression is steeply inclined/dipping crust to the north while much sparse contour in the northern side of the fault line represents gently inclined/dipping crust to the south forming an asymmetrical V-shaped depression bounded by normal faults. Evidence of normal fault is derived from the fault plane / focal mechanism solutions and several surface features (Khan and Chouhan, 1996). The gravity anomaly pattern (Fig. 8A) further exhibits the potential hydrocarbon trapping zones (Fig. 8B) in the Bay of Bengal wherein a good number of anticlinal traps are found. The interpreted region of the potential hydrocarbon trapping needs much in depth study for the exploitation and development of hydrocarbon.

3. Geophysics of the Continental Margin

Geophysical data especially seismic revealed subsurface conditions in the shelf. The limitations of geophysical techniques in the maritime sector are constrained largely of seismic and, partly of gravity and magnetic. Continental shelf of the Bay of Bengal has already been covered by an extensive seismic survey of 31000-line kilometer (Petrobangla Brochure) and partly by gravity. However, these data are not available in the public domain. A good amount of seismic coverage has also been conducted by some international organization for the purpose of hydrocarbon exploration in the 1973 to 1977 period. Interpretation of published seismic records is carried out in view of gas hydrates occurrence and natural gas deposit which is the most essential ingredient to meet the energy demand of a nation. Subsurface imaging of the sedimentary continental shelf can be envisaged in the publication of Lietz and Kabir (1982) (Fig. 9). Seismic section (Fig. 9) depicts subsurface conditions across Hatia Trough in the continental shelf of the Bay of Bengal. The seismic image envisaged that sediments deposited at the top Miocene around five million years ago was the end of the paleo-delta formation when there was major erosion forming a distinct unconformity surface. Top Miocene also resembles clinoform of toplap sequence and shelf-slope margin. Pliocene onward since five million years the present delta started to form in prograding nature. The Plio-Pleistocene interface exhibits enormous channel cutting which is supported by the occurrence of 27 km wide and 750m deep buried channel shown in the Figure 7.

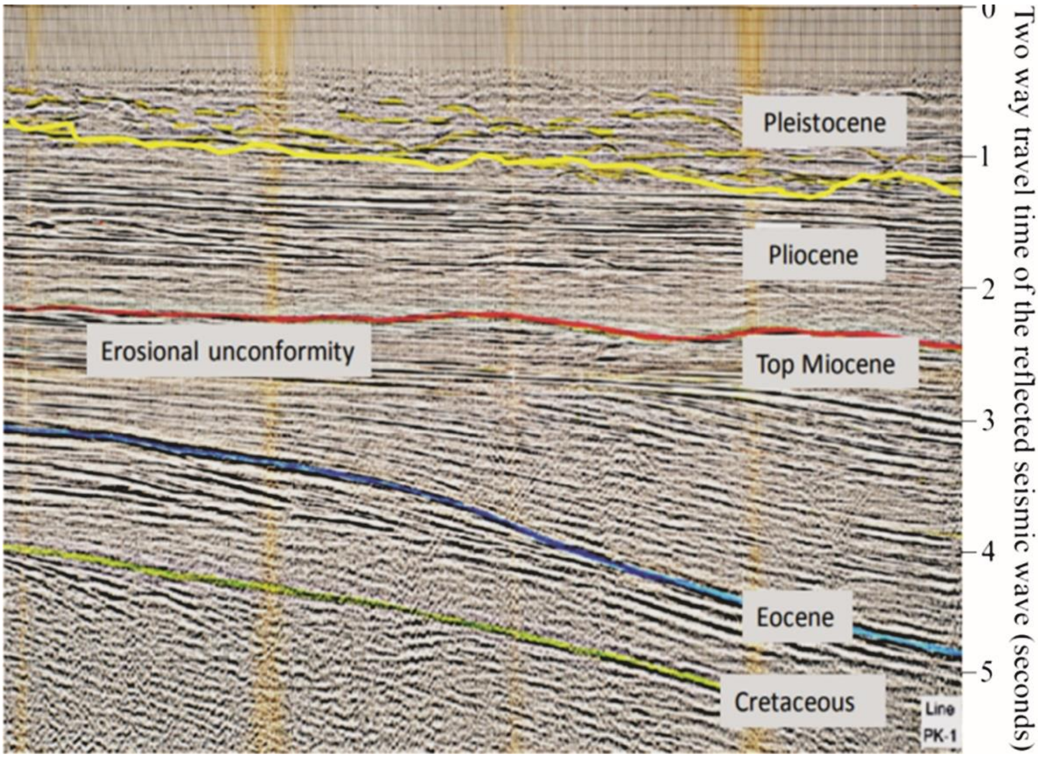

Figure 9: Paleogene prograding delta truncated by the Neogene sedimentation. Depositional truncation during delta formation has occurred during Miocene along the erosional unconformity surface showing depositional clinoform.

East-West seismic cross section of Nazman et al (2012) (Fig. 10) exhibits an extensive channeling of the mega-sequence MS2. In addition, the seismic section exhibits channeling pattern observed in the western side of the Sangu well is markedly different from that in the eastern side of the Sangu well indicating different tectonic environment both during syn-depositional and post-depositional period. Variable tectonic environment is responsible for the development of tight folding those are shown to occur in the eastern part, structural inversion in the middle part and open folding in the western part of the seismic section in the Figure 10. Geophysical seismic data display seismic attributes such as bottom simulating reflector (BSR) for identifying and mapping of gas hydrates occurrence. BSR is the seismic reflection signals formed due to the acoustic impedance contrast at the interface between two media. BSR is not a lithological boundary rather it is a physical interface between the gas hydrate-bearing sediments above and free-gas saturated or water-saturated sediments below (Ojha and Saini 2009).

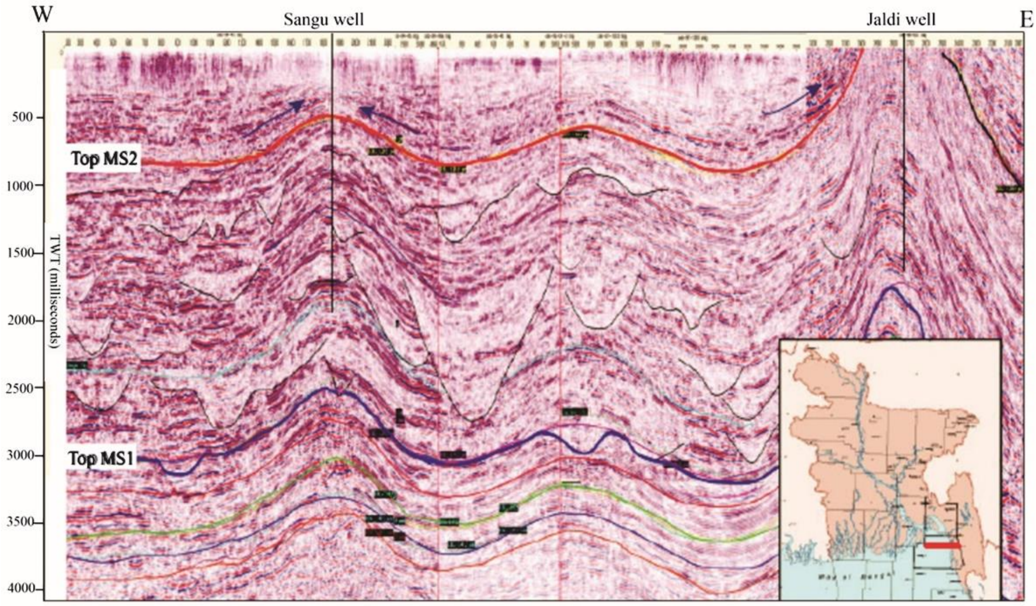

Figure 10: East-West seismic section passing through Sangu well in the Bay of Bengal upto Jaldi well located in the Chottogram coast. (Source: Nazman et al., 2012).

Gas hydrate occurs when water and natural gas are present at low temperature and high pressure. Seismic signals display strong acoustic impedance contrast between the overlying and underlying zones. It can be easily identifiable on the seismic section based on the seismic attributes such as occurrences of signals parallel to the seafloor, presence of strong amplitude, polarity reversal compared to the seafloor (Yuan et al. 2021). BSR is also interpreted as the base of the gas hydrate stability zone (GHSZ). According to (Gabitto and Tsouris, 2010) methane gas hydrates in sediments have been studied by several investigators as a possible future energy resource. Recent hydrate reserves have been estimated at approximately 10^{16} m^3 of methane gas worldwide at standard temperature and pressure conditions. Natural gas hydrate is dissociated to commercially exploitable form from the natural-gas hydrate-bearing sediment. Gas hydrates in sediments may alter physical properties of the sediments which are detected in well-logs. Interpretation of geophysical data requires the knowledge of physical properties of hydrate-bearing sediments derived in the field settings, borehole, and slope stability sampling; reservoir simulation; and production models. Presence of gas hydrates in the offshore continental margins has been inferred from seismic processing that visualizes the subsurface structure by means of reflected seismic signals. Sea floor is an interface of rock materials below and the sea water above. If the interface is marked by the prominent seismic signal, which is due to the acoustic impedance contrast of the two medium above and below, means the rock layer is harder than the water above. In acoustic terms, the acoustic impedance below the seafloor in the sediment is higher than the impedance of the water column. In contrast, the bottom-simulating reflector (BSR) is marked by the seismic signals that indicate high hydrate impedance above and gas-filled sediments below with low impedance. Gas hydrates are found in marine shelf sediments because in this setting the pressure-temperature conditions are within the hydrate stability field. Offshore hydrate-bearing sediments have generally been found in waters deeper than 300m. Enormous amounts of methane are believed to be trapped by hydrates, both in the hydrate crystal structure itself and also in sediments beneath hydrate deposits. Hydrates concentrate hydrocarbons to the tune of $1m^3$ of hydrates may contain as much as 180 SCM (standard cubic meters) of gas.

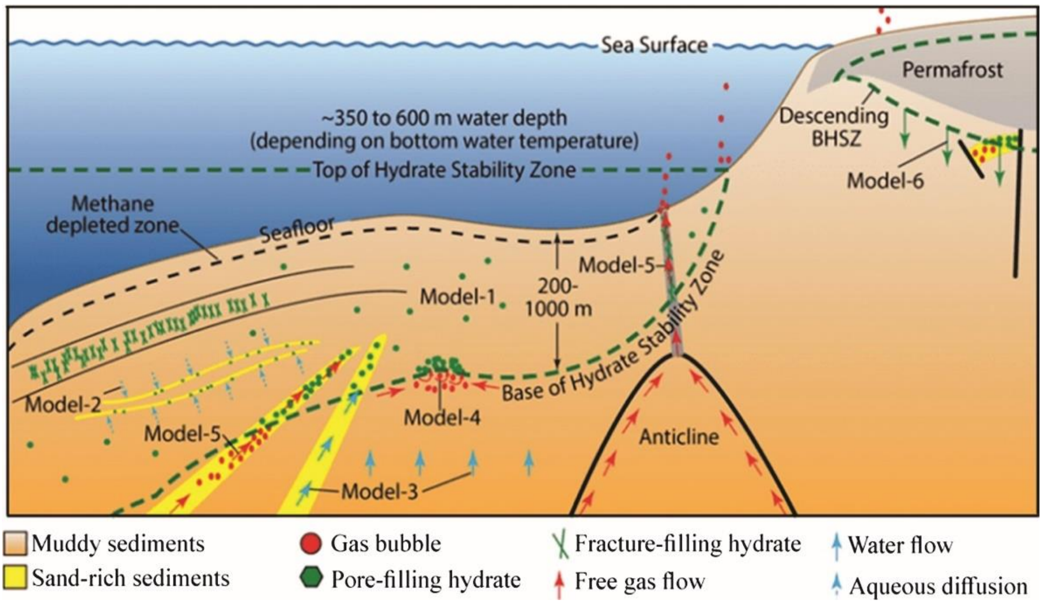

Figure 11: Six quantitative models of genetically related to different hydrate deposits observed. The models are grouped in i) local biogenesis (Model-1), ii) local diffusion (Model-2), iii) upward water flow and/or diffusion (Model-3), iv) methane recycling (Model-4), v) long-range free gas flow (Model-5), vi) solidification of a gas reservoir (Model-6). (Source: You et al., 2019; Figure 26).

Makogon (1965) indicated that large natural reserve of hydrocarbon exists in hydrated form, both in deep oceans and in the permafrost. Subsurface zones of gas hydrates occurrence are located using seismic where BSR is readily evident. BSR is a thermobaric surface rather than a structural or stratigraphic interface of hydrocarbon traps. BSR usually marks the base of a gas hydrate layer below which there is free gas. This free gas is interpreted to be derived from gas bearing subsurface zones. You et al

(2019) have proposed six different formation mechanisms of geological gas hydrate deposits. Figure 11 is a clear demonstration of the existing geological environment for the formation of gas hydrates. Hence, so-far geological studies conducted on the continental shelf of the Bay of Bengal suggest that it is characterized by all the geological environments conducive to the formation of gas hydrates. You et al (2019) further suggested that geological gas hydrates can be categorized into five major types and linked to the six different formation mechanisms. They further opined that free gas flow and capillary pressure play significant roles in forming many concentrated hydrate deposits and a better understanding of microbial methanogens will illuminate how methane hydrate deposits are formed in the geological systems. The methane in marine hydrates sampled by drilling is dominantly microbial in origin as determined from gas composition and carbon isotopic values (Kida et al., 2015; Lorenson and Collett, 2018; Pohlman et al., 2009). At low temperature less that $50^{o}C$ biodegraded organic matter can transform to microbial methane but the main methane generation process is the reduction of CO_2 by biologically produced hydrogen (Claypool and Kvenvolden, 1983). As organic matter is buried from the seafloor, it sequentially passes through several zones: an aerobic zone where organic matter is oxidized by dissolved oxygen, an anaerobic sulfate-reducing zone where organic matter is oxidized by the sulfate ion, and an anaerobic methane-producing zone (Claypool and Kaplan, 1974). Publications such as Collett et al (2019), Rangin and Jean-Claude (2017), Monteleone et al (2022), Ojha and Ghosh (2021), Saini et al (2012) have revealed discovery of huge gas hydrates deposit along the eastern continental margin of India. The NGHP-01 expedition established the presence of gas hydrates in the Krishnae-Godavari and Mahanadi Basins, and the Andaman Sea. The first Indian National Gas Hydrate Program Expedition 1 (NGHP-01) found gas hydrate as fracture-filled and pore-filled in fine-grained shallow sediments of Krishna-Godavari, Mahanadi, and Andaman offshore basins (Ojha and Ghosh, 2021). Gas of the discovered gas hydrates are derived both from microbial sources and migrated from deeper sources. Substantial reservoir heterogeneity and sufficient permeability throughout the reservoirs have been observed (Collett et al., 2019). The bathymetry, seafloor temperature, total organic carbon (TOC) content, sedimentary thickness, rate of sedimentation, geothermal gradient indicates good prospects of gas-hydrates along the Indian margin (Saini and Gupta, 2008). A limited extent of seismic interpretation by the present author has revealed the great potentiality of gas hydrates deposit alongwith natural gas in the shelf-slope margin of the continental shelf in the Bay of Bengal. The seismic method has been used to detect gas hydrate accumulation in the continental shelf of the Bay of Bengal. High-resolution 2D seismic data across the continental shelf and continental slope are used to identify the presence of gas hydrates.

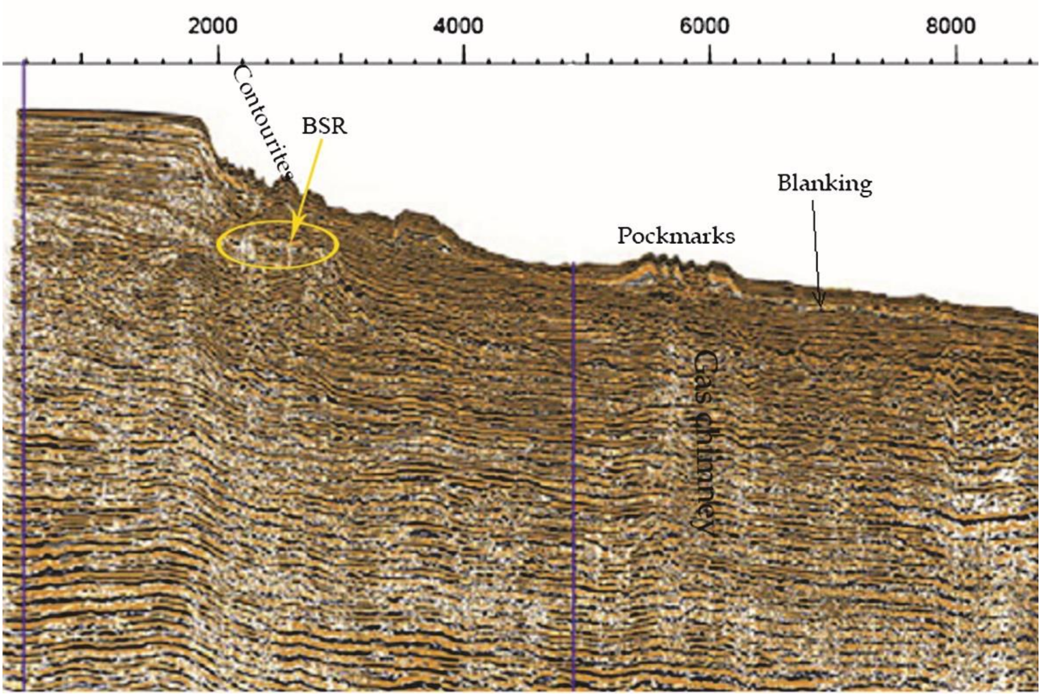

Figure 12: Reinterpreted seismic section published in the journal Marine and Petroleum Geology 2017 by Rangin and Sibuet (2017) showing features associated with gas hydrates such as contourites, pockmarks and BSR in a seismic record across shelf break and the abyssal plain in the Bay of Bengal. Seismic line B3-02 is from Maurin and Rangin (2009).

The presence of bottom simulating reflectors (BSR), blank zone and polarity reversal along with the sweetness attribute analysis signify the presence of gas hydrates. Presence of gas hydrate stability zone (GHSZ) in the multichannel seismic reflection profiles is the first evidence of the occurrence of natural gas hydrate in the offshore Bangladesh. According to Rangin and Sibuet (2017) a good amount of multichannel seismic data has been acquired from northern Bay of Bengal and they have interpreted those multichannel seismic data for determining structure of the Bay of Bengal crust. However, couple of seismic sections has been reinterpreted in the present study for the assessment of gas hydrates and it is found that many promising seismic features associated with gas hydrates such as BSR, gas chimney, pockmarks and contourites are present in the continental margin of the Bay of Bengal (Fig. 12). Study of Monteleone et al (2022) revealed that the high sedimentation rates, along with the high organic matter content has made the offshore Bangladesh including the Bengal deep sea fan area favorable for the formation of natural gas from both microbial and thermogenic sources.

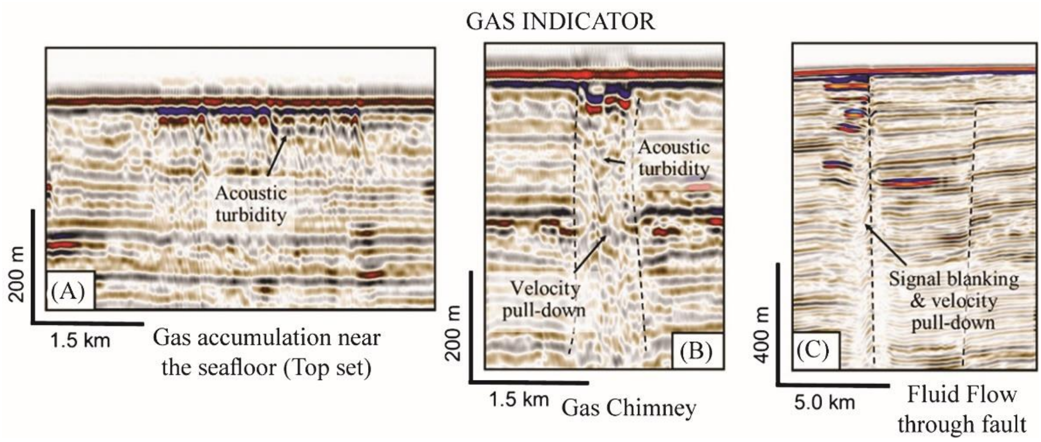

Figure 13: Seismic profiles illustrating seismic facies indicative of gas along the Bangladesh continental shelf (Source: Monteleone, 2022).

Seismic amplitude anomalies are widely distributed in the shelf deposits those are associated with localized free gas accumulations (Judd and Hovland, 1992; Liner and McGilvery, 2019) (Figs. 13A, 13B, 13C). High reflectivity suggests gas accumulation at the transition between high-permeability, high-amplitude, coarse-grained sediments, and low-permeability, low-amplitude finer-grained sediments (Figs. 13A, 13B, 13C). Both high- and low-amplitude anomaly commonly lie at or near the seafloor, and are associated with seismic signal blanking, chaotic facies, and/or velocity pull-down effects beneath them (Figs. 13A, 13B, 13C). Vertical or near-vertical zones with lower reflection strength than the surrounding sedimentary reflectors are interpreted as gas chimneys, and so pathways for the upward migration of fluids (Judd and Hovland, 1992) (Fig. 13B). Signal blanking and velocity pull-down effects along fault planes are interpreted as indication of fluids and thermogenic gas that migrates from deeper reservoirs to upper sedimentary layer through the faults (Fig. 13C).

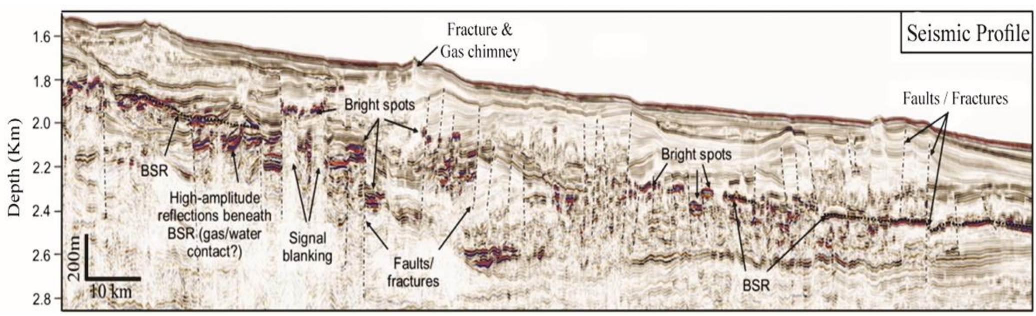

Figure 14: Seismic profile adopted from Monteleone et al (2022) and interpreted in relation to gas hydrates and related seismic attributes such bright spots and high amplitude reflectors.

There are other seismic profiles where seismic attribute anomalies are shown as small pockets of extraordinarily strong amplitude bright spots (Fig. 14).

4. Discussions

Natural gas and gas hydrates are the only natural ingredients those are potential for generating clean energy to meet the energy demand. Until now no alternate energy sources have been evolved to replace natural gas and gas hydrates. Hence, exploration and development of ocean basins for natural gas and gas hydrates are the most essential component to ensure energy security. The continental shelf-slope margin of the Bengal Delta is highly potential for the development of natural gas and gas hydrates. The thermogenic gas may migrate into the hydrates stabilized zone (HSZ) and contribute to gas hydrate formation. Temperature dependence microbial methanogenesis process has been adopted to evaluate in-place gas hydrate resources on the northern Gulf of Mexico continental slope (Frye, 2008). The amount of hydrate that can be formed in situ from the Microbial biodegradation can produce amount of hydrate due to lesser amounts of organic carbon in the typical continental margin sediments (Malinverno, 2010; Wallmann et al., 2012). Further, sediments cannot form thermogenic gas without being deeply buried or has not undergone elevated temperature stage to form thermogenic gas (Collett et al., 2009). Thus, to form high concentration of gas hydrate deposits, gas must migrate from other places to the gas hydrate occurrences. According to Collett et al (2009) gas hydrates migration mechanisms are of three types such as diffusion of dissolved gas in liquid water, advection of dissolved gas by pore water flow, and advection of free gas. In permeable or fractured fault systems or coarse-grained sediment layers free gas flows along permeable path due to diffusion of dissolved methane from high-porosity sediments of the hydrates stabilized zone (HSZ). It migrates toward topographic or structural highs by buoyancy in the crests of ridges or anticlines (Boswell et al., 2012). Pore-water flow also occurs toward permeable layer above and towards topographic highs. Such movement of gas hydrates through permeable layers is commonly observed in many gas hydrate accumulations. Gas hydrate can occur in both fine-grained sediments and also in coarse-grained sand-rich sediments. In fine-grain sediments gas hydrate saturation is low due to exceptionally low permeability. But in coarse-grained sediments with particularly good permeability may have high gas hydrate saturations filling the interconnected pores. Many studies of deep-marine coarse grain sediments have been done globally in view of gas hydrates potentiality and found that sedimentation of deep-marine environments is conducive to gas hydrates occurrence (Boswell et al., 2012). Occurrence of large continental shelf of delta sedimentation and the sand dominated deep marine fans sedimentation of about 4 km thick lend support for the occurrence gas hydrates in the Bay of Bengal. Occurrence of gas hydrates strongly supports the occurrence of natural gas in the deeper sedimentary layers in the continental shelf and in the deep-sea fan regions. Seismic signature of shale flowage and shale diapirs observed in the seismic sections also suggest that the geological formations with gas saturation have developed high formation pressure to help escape natural gas to move to the upper layers close to the seabed forming gas hydrates.

Gravity anomaly pattern revealed potential hydrocarbon structural traps in the Bay of Bengal. Presence of gas hydrates in the shelf-slope margin of the Bay of Bengal has been inferred from reflected seismic signals. The base of a gas hydrate layer marked by bottom-simulating reflector (BSR) below which free gas occurs which is derived from natural gas bearing subsurface zones. Discovery of oil, gas, and gas hydrates deposit along the eastern continental margin of India especially in the Godavari and Mahanadi offshore basins lend support for the occurrence of similar georesource in the continental shelf-slope margin of the continental shelf. Gas hydrate in the fracture-filled and pore-filled in fine-grained shallow sediments of Krishna-Godavari, Mahanadi and Andaman offshore basins is estimated to be about 1900 trillion cubic meters. Exploration and extraction of gas and gas hydrates definitely can meet the demand of energy of the country.

5. Conclusions and Recommendation

Non-living resources like natural gas and gas hydrates are the backbone of any sustainable development and socio-economic emancipation. However, these resources must be explored and exploited. Bengal Basin is a potential petroliferous basin which may be divided in two regions viz., on-shore and off-shore region. On-shore region especially the eastern part of Bangladesh is a proven gas prone region. The offshore region is not yet proven one but an occurrence of gas in the offshore basin is by and large established. However, the occurrence of natural gas could be determined by geophysical seismic exploration. The entire continental shelf of Bangladesh has already been surveyed of about 31000-line kilometer by 2D seismic conducted by PRAKLA-Seismos company Germany back in 1974 and 1975 cal year. These valuable data are lying with PetroBangla. These data need to be public for reinterpretation in view of the identification of hydrocarbon traps. Similarly, PetroBangla themselves should interpret these seismic data for finding oil and gas in the large (200 km x 300 km) continental shelf characterized by shallow water depths ranging between 5m and 60m.

Geological and geophysical studies of the continental shelf in the Bay of Bengal by various international agencies revealed very encouraging results about the occurrence of hydrocarbon especially natural gas. Occurrence of gas hydrates has also been identified in the shelf-slope break. Discoveries of gas in the Mahanadi Basin of India and the Shwe gas in the coast of Arakan of Mayanmar provided very strong evidence in favour of gas occurrence in the offshore basin of Bangladesh. Further, discovery of Sangu gas and Kutubdia gas located in the continental shelf provides evidence of gas occurrence in the offshore basin. Shew gas field is located within 100 km from the Nhila, and St. Martin structure located in the southern extreme of Bangladesh. In addition, 31000 line-km 2D seismic survey was done by the international oil companies in the early seventies. Seven wells have been drilled up to the depth of about 3000m to 4000m those encountered high formation pressure and all the wells were abandoned. The high formation pressure caused fishing, caving, and collapse of the drilling pipes. The high formation pressure is the direct evidence of fluid and gas saturation in the geologic formations. The occurrence of high formation pressure is further supported by the formation of shale flowage and shale diapirs found to occur in the exposed structures of the Chittagong Hill Tracts and in the several seismic sections. Extraction of gas hydrates will contribute to the energy sector, but extraction of gas hydrates is exceedingly difficult and hazardous venture that requires more extensive research for its development.

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