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Influence of Turbidity Sedimentary Environment on Gas Accumulation in the Deep-water Fan of the Bay of Bengal

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Abstract:

In order to further determine the influence of turbidite flow on gas accumulation in the Bay of Bengal, the paper applies 2D/3D seismic data and well data to study the Miocene-Pleistocene depositional architecture, evolution and reservoir quality of deep water fan in Bay of Bengal. Local sequence stratigraphic framework and sedimentary environment and accumulation model of deep-water fan are established in the Bay of Bengal. By using cyclical variation of fine and coarse granular sizes of deep-water sediments in study area, combined with cyclical variation of the amplitude in corresponding seismic profiles, five sequence interfaces of deep-water fan in Bay of Bengal on seismic profile can be identified. Results show that the TOC/TN ratios of continental and marine organic matter in the Bay of Bengal are 11.2 and 4, respectively, and the organic matter comes from mixed sources. Continental and marine facies account for 60% and 40% respectively. Six different types of deep-water architectural elements are recognized. Miocene channel complexes and Pliocene confined slope channel complexes and Pliocene channels and frontal splays in seismic facies show the best reservoir property. Key factors of hydrocarbon accumulation of the deep-water fan in the Bengal Basin include effective source rocks, deep-water fans at low water level and their overlying high-level-stage mudstones, which form favorable reservoir-cap combinations. Meanwhile faults, unconformities and wide-spreading sand bodies compose of favorable petroleum system. The amount of discovered natural gas in the Bay of Bengal is 101.52×108 ft3. The reservoir mainly located in the aggradation constrained channel complex in the middle-upper fan belts, as well natural levee sand bodies of tidal channel near "bottomless channel" in middle-lower fan belts. The formation mechanism of turbidity sedimentary indicates the direction of natural gas exploration and development in the same environment around the world.

***Keywords**: Bottomless Torrents; Cyclical Variation; Multi-stage; TOC/TN; Architectural element; Carrier system.*

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I. INTRODUCTION

Deep water fan transport systems in the Bay of Bengal include turbidities' flow, debris flow, contour current, slip flow, collapse flow and density flow, whereas sediment sources of large deep-water fans are generally supplied by river delta[1]. VALL has proposed a reasonable explanation about fan deposition in Bay of Bengal and understood deeply the cyclical variation law of global sea level[2]. The submarine fans are the main bodies of sequence LST (lowstand system tract) in the Bay of Bengal. When the sea level is low, transport systems can form a channel-levee system[3]. Due to their particularities in the sedimentation and genetic mechanism and hydrocarbon accumulation law, gas exploration in the fan of the Bay of Bengal is significantly different from that in the continent and other offshore areas[1], especially certain difficulties in identifying sequence units and interfaces of Bay of Bengal, and establishment of submarine fan sedimentary model[4-5]. Based on the sedimentary evolution of the deep-water fan in the Bay of Bengal, this paper proposes a sequence framework and sedimentary model for the fan in Bay of Bengal. Moreover, it analyzes gas accumulation conditions and takes the Rakhine Basin as an example.

II. BACKGROUND

Deep water fan in the Bay of Bengal, which is the largest submarine fan in the world, developed under the influence of the Indian passive continental margin and the Myanmar active continental margin. It turns to be underwater continuation of the Ganges Delta and the Krishna-Godavali River Delta, and distributes widely in the expansive deep waters in the north of Bangladesh Bay of Bengal basin, Mohannadi Bay of Bengal basin, Krishna-Godavali Bay of Bengal basin, Koffrey Bay of Bengal basin, Rakhine Bay of Bengal basin, and Ceylon Bay of Bengal plain. Underwater channel expands at least 2,800 km in length and more than 1,400 km in width. The apex of the Bangladesh Fan is located in the underwater "bottomless" canyon, with the most active channel on the fan. And the bottomless alluvial channel belongs to a levee-river system. The deep incised channels embed on a continental slope at a depth of 1,400 m and extend more than 2,300 km downwardly. Channels determine the shape of the canyon (Fig.1). Since the Early Eocene, the sea level in the Bay of Bengal has generally experienced a three-stage fall, the paleogeographic environment and provenance changes in this area show three different characteristics in the Early Eocene, the Middle Miocene and the Pliocene-Pleistocene correspondingly. It reveals that the paleogeographic conditions of intense thermal subsidence in this area are consistent with the three-stage global sea level variation [6-7].

However, Deep-water fan in the Bay of Bengal formed in the second half of the Pliocene-Pleistocene[8]. The Ganges River, Brahmaputra River, Krishna River, and Godavari River for fans in the Bay of Bengal. Under the background of a broad shelf, the abundant and stable sediments spread mainly on the continental slope and even the Bay of Bengal plain owing to turbidity activities. After a long geological history, a mud-rich fan of Bay of Bengal with thickness of more than 20km has formed. At the same time, the sediments with high supply rate are deeply incised into the submarine gorge of the Bangladeshi continental shelf near the "bottomless torrents", and deposited partially in it. The "bottomless torrents" have no obvious bifurcation over 2,500 km in length, and connect the modern continental shelf depocenter with the levee system[9-10]. Four major provenance systems in the Indian mainland,

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Himalayan, Rakhine, and Chan State control the sedimentation of the Bengal region; they play the important roles during the forming of hydrocarbon source, and longitudinal and planar distribution of favorable reservoir-caprock combinations, thereby determine hydrocarbon properties and distribution of oil and gas fields in the Bangladesh-Burma region. There are three major provenances and one small provenance.

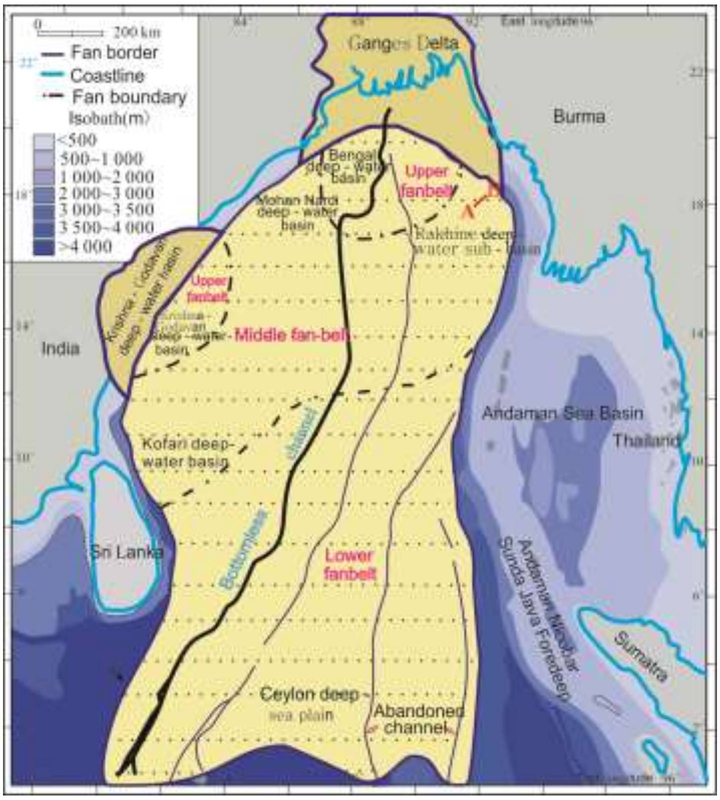

Fig. 1: Distribution schematic of the fan in Bay of Bengal (According to T. Schwenk, 2005[11]).

III. TURBIDITY SEDIMENTARY ENVIRONMENT

3.1 Sequence stratigraphic framework

According to sequence stratigraphy, the global eustasy is the key factor during the forming of sequences. When the sea level is relatively low, the sediments by river transporting fully unload in the Bay of Bengal canyon, then deposit and form sandy turbidities and slumps (massively transported complex). When the sea level is relatively high, coarse-grained sediments such as channel, turbidity lobes are significantly reduced, and are dominated by the depositional draped mud of the Bay of Bengal [11-12]. With the variation of sea level, deep water sediments form deposition cycles with alternate occurrence of fine and coarse sediments, and each set of sedimentation cycle is a third-level sequence l[9]. On the seismic profile of the middle sector in the Rakhine Sea in the northeastern fan in Bay of Bengal, the coarse-grained sediments of Bengal fan show stronger amplitudes. On the contrary, the fine-grained sediments such as Bay of Bengal draped mud show relatively weak amplitudes (Fig. 2a). After relationship

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is established between cyclical variation of fine and coarse granular sizes and the corresponding seismic amplitude in this area, five sequence interfaces of fan in the Bay of Bengal on seismic profile can be identified, and multi-channel complex sandstones [13], thereby corresponding sequence stratigraphic framework has been established[12] (Fig. 2b). Due to the variation of sea-level, deep-water sediments compose of alternate occurrence cycles of course and fine sediments. Each sediment cycle is a third-level sequence[1,7-9,11].It developed superimposed fan in different geological period in the Bay of Bengal, showed in sequence stratigraphic framework (Fig. 2b).

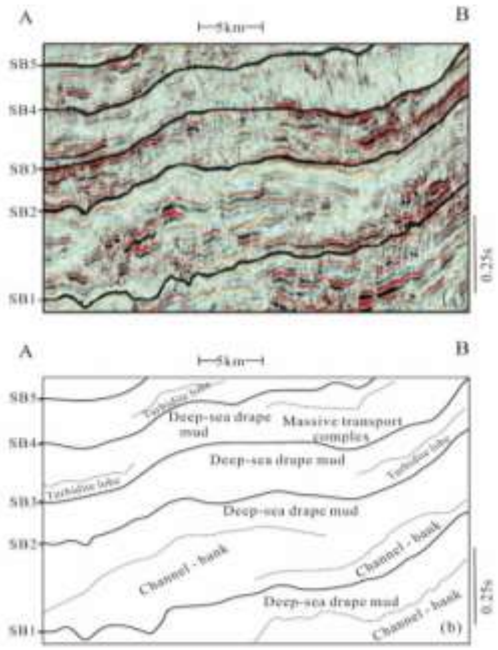

Fig 2: Seismic profile of typical sequence framework in the Rakhine Sub- basin, Section position from figure1[12]

(a) Seismic profile of typical sequence framework (b) Typical profile of the fan in Bay of Bengal

3.2 Sedimentary model

According to the classic model proposed by Walker, the deep-water fan in the Bay of Bengal can be divided into upper fan, middle fan and lower fan[14]. The upper fan connects the Ganges delta through the "Bottomless Canyon". Numerous braided channels widely distribute in the middle and lower fan belts, but they are abandoned since the Holocene except the one in the west central area. The granular size and quantity of sediments in the deep-water basin and the types of sedimentary facies correspond with the relative variation of sea level [3-4,6].

When the sea level is relatively low, the river fully unloads in the Bay of Bengal canyon, and a large number of sediments become unstable and collapse, so many channels are filled in by gravity flow. The banks and sandy lobes deposit and form, even massively transport complexes. When the sea level is relatively high, the Bay of Bengal canyon doesn't directly receive the sediments from the river. The frequency of event-based deposition greatly reduces, while the coarse-grained sediments such as channels and turbidities develop and drap muds in the Bay of Bengal mainly deposit (Fig. 2). Since the Miocene, the Bay of Bengal has been generally in regression, dominated by sedimentation in lowstand system tract. Submarine fans deposited in deep-water environment with the development of large-scale channel-fan system. When the sedimentation channels of submarine fan entered the slope and bottom of the basin through incised canyon, they diverted into many tributary channels. It is the typical representative of modern canyons and is invalid in the highstand of sea level. In the lowstand of sea level, the bottomless channel is a delta front gorge, which incises the flat continental shelf sediments, compared to underwater canyons. Reflection changes the dispersion system in the delta. The old sediment may be similar or smaller in volume because it is one of the largest delta front gorges. Therefore, the current Bangladesh submarine fan with huge scale has been forming. That is, it is the multi-stage superimposed composite sedimentation of submarine fan, in which the sedimentary architecture units mainly includes channel complex, sedimentary lobe, and thin-layered natural levee over bank deposits and comprise massive transportation system (including slump and debris flow deposition, etc.) (Fig.3). The maximum thickness of Bangladesh fan reaches 4 km. From the Eocene to Holocene, the volume of the Bangladesh Fan is 12.5×106km3, while the volume of bottomless channel is 2.95 ×103km3. Therefore, the Eocene and younger sedimentation of the Bangladesh Fan is equivalent to 4,200 times that of the bottomless channel. The similarities among the canyons filled by delta show that the old channels on the delta have roughly the same size.

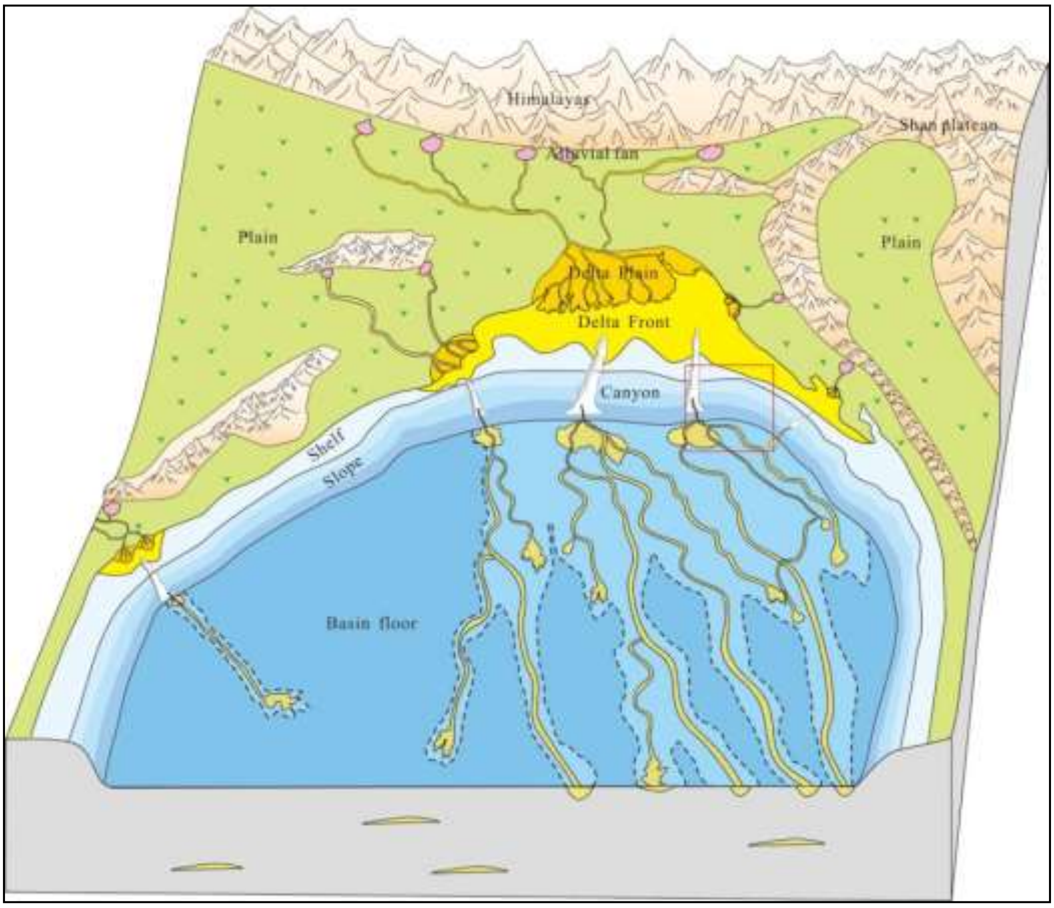

Fig 3: Sedimentary model of the fan in Bay of Bengal

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Shelf: sea floor with water depth less 200 m, the average slope 0.7°, width 10-70km; Slope: sea floor with water depth between 200m and 1000m, average slope 4-7°, average width is 20-100km; Canyon: Located in the estuary of Ganges River, it extends southward to Bottomless Canyon, 200km in length and 200m in max depth. Basin Floor: deep water area with depth more than 500m, mainly distribute near bottomless rapids; Delta front and delta plain: main supply area of sources, include Delta fronts and delta plains of the Ganges, Brahmaputra, Krishna and Godavari rivers. Plain: Indo-Gangetic Plain.

IV. TURBIDITY SEDIMENTARY ENVIRONMENT

4.1 Organic source

The TOC/TN ratio is widely applied to discriminate different sources of organic matter in the ocean. The annual input TOC flux in the Indus River is about 7.67×106t, the TOC/TN ratio of sediments at the estuary is about 11.6, and the annual input TOC flux in the Himalayan River (G-B) is about 16.6×106t, the floodplain in the Mena River. The TOC/TN ratio at the estuary is about 11[15]. The TOC/TN ratio of continental organic matter is about 11.2 according to the following mass balance formula (1):

$$TOC/TN = (F_i \times (TOC/TN)_i + F_h \times (TOC/TN)_h)/(F_i + F_h) \quad (1)$$

Where:

Fi, (TOC/TN) i represents the input TOC flux in the Indian River and the TOC/TN ratio at the estuary;

Fh, (TOC/TN) h represents the annual input TOC flux in the Himalayan River and the TOC/ TN ratio at the estuary respectively.

The fans in the Bay of Bengal have been receiving a large amount of nutrient from the land source. The N content in the Indian Ocean is higher than the global average. This results in the TOC/TN ratio of the marine organisms in the Indian Ocean being are lower than the global average. According to the following formula, TOC/TN ratio is 4 in the marine organic matter and it is appropriate (2) and (3):

$$TOC=TOC1+TOCw \quad (2)$$

$$TN=TN1+TNw \quad (3)$$

Where:

TOC and TN are measured values,

TOC1 and TOCw represent continental and marine organic carbon contents respectively,

TN1 and TNw represent continental and marine organic matter contents respectively.

Available (4) and (5):

$$TOC1=11.2(TOC-4TN)/7.2 \quad (4)$$

$$TOCw= (11.2TN-TOC)/1.8 \quad (5)$$

The relative contribution ratio of continental and marine organic matter is (6) and (7)

$$F1=TOC1/ (TOC1+TOCw) \tag{6}$$

$$Fw=TOC2/ (TOC1+TOCw) \tag{7}$$

In the formula, F1 and Fw are the relative contributions of continental and marine organic matter respectively. According to the formula the relative proportions of continental and marine organic matter in the surface sediment samples of the Bay of Bengal are calculated, the results show that the average relative contribution of continental and marine organic matter is respectively 60% and 40%, that is, the source of organic matter is a mixed source, mainly comes from land. The distribution of marine organic carbon is shown in Figure 4. The TOC/TN ratio of the sea with a large contribution is low, and there was a good correlation between the two indexes.

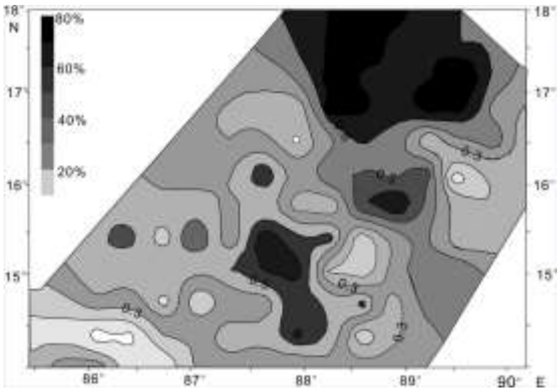

Fig 4: Distribution of the contribution proportions (%) of antigenic organic carbon from the oceanic sources

Average relative contribution of marine organic matter is about 40%. The largest hydrocarbon kitchen is located in the Ganges delta front and the upper fan-belt.

4.2 Reservoir characteristics

In the fan of Bay of Bengal, six different types of deep water architectural elements are recognized based on seismic facies, seismic attributes (Fig. 5) as following:

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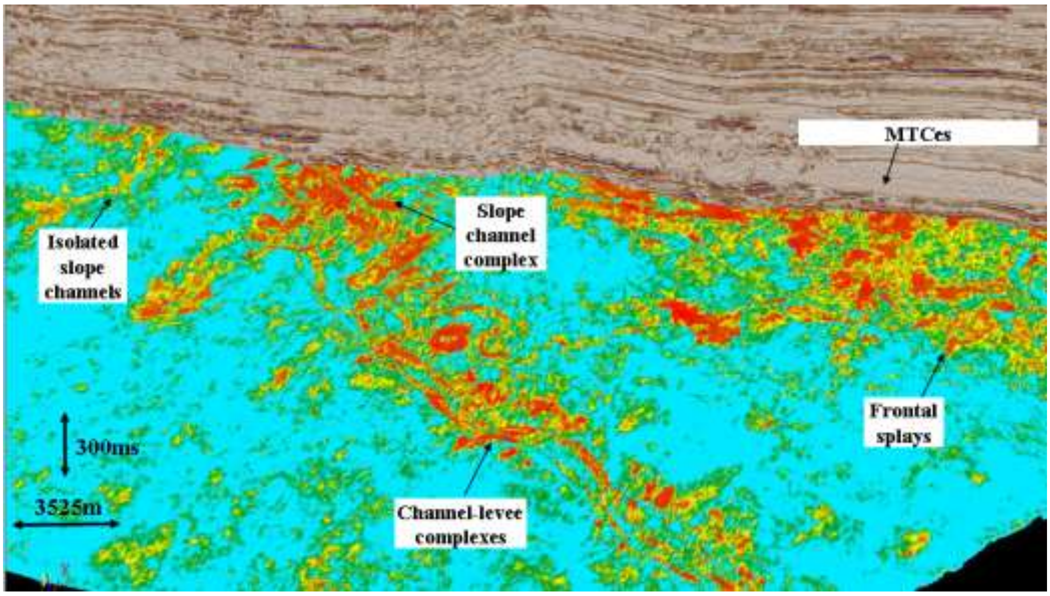

Fig 5: Reservoir distribution of the fan in Bay of Bengal

Red is the strong amplitude, which represents sandstone. Main sandstone bodies include Miocene slope channel complexes and Pliocene confined slope channel complexes and Pliocene channels and frontal splays and isolated slope channels. It is also the favorable development area of sand body. Blue shows weak amplitude and is dominated by mudstone.

Red is the strong amplitude, which represents sandstone. Main sandstone bodies include Miocene slope channel complexes and Pliocene confined slope channel complexes and Pliocene channels and frontal splays and isolated slope channels. It is also the favorable development area of sand body. Blue shows weak amplitude and is dominated by mudstone.

(1) Submarine canyons are characterized by large-scale erosion, with variable internal seismic geometries.

(2) Confined slope channel complexes are relatively thick (100-200 m), narrow, elongate, and coarse-grained with a high degree of internal complexity, which can be interpreted and classified as a hierarchical scheme framework based on Mail's(1985) ideas on sedimentary hierarchy schemes for fluvial systems[1].

(3) Aggradation channel–levee complexes are derived from the overbanking of finer-grained portions of sediment gravity flows as they travel down an aggradation channel and spread laterally beyond the channel margin[8,16].

(4) Frontal splays (depositional lobes) are defined as the depositional architectural elements that are deposited from decelerating flows at the terminus of channel.

(5) Isolated slope channels belong to the product of a single cycle of channel cutting and filling and avulsion or abandonment.

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(6) Mass-transport complexes(MTCs) re-sediment by subaqueous mass-wasting processes channel complexes and form due to the gravity flow either down the continental slope and submarine canyons or confined slope channel complexes.

Controlled by the depositional mechanism, Miocene channel complexes and Pliocene confined slope channel complexes and Pliocene channels and frontal splays (Proved by the wells in Shwe, Shwe Phyu and Mya fields) in seismic facies have the best reservoir property in the fan of Bay of Bengal (Table I).

TABLE I: Reservoir Characteristics of Architectural Element

Architectural element	Scale	Sediment fill	Reservoir potential
submarine canyons	multiphase stacked, width:3-12.8, thickess:200-850(TWT)	very clear multiphase fills with high amplitude discontinuous	multiple stratigraphic traps within submarine canyon fills
confined slope channel complexes	channel master erosional surface:5km wide on average; 400ms thick	Variable; High N: g (40-60%) bases; Inside levees 30-40% N: g;	cood reservoirs: Porosity=29.2-33.4%; Permeability=161-653 mD
aggradation channel – levee complexes	aggradation complex, gull-wing shape	High N: G in channel fills and crevasse splays, moderate N: G in proximal levees.	proximal levees porosity=23.7-30.2%; permeability=4.83-26mD
isolated slope channels	sinuous or linear channels have characteristic scroll	moderate N: G point bars, mud-filled channels	Sinuous channels can form discontinuous reservoir.
frontal splays	1km to 5km wide and 1km to 10 km long	thin-bedded sandstones or mostly massive sandy debris flows	some of the best reservoirs offshore porosity=24-27.3%; permeability=73.3-363mD
mass-transport complexes	variable, maximum width and thickness exceeds 22km	mainly mudstone and siltstone with large blocks of variable stratigraphy	poor reservoir

4.3 Carrier system

Gas migration from source rocks to reservoirs of the fan in the Bay of Bengal is relatively simple. Gas migration is dominated by secondary migration. Faults, unconformities, and sand bodies continuously constitute good petroleum systems. The key influencing factors are matched with each other, including gas charging and migration and suitable trap forming [2]

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4.4 Influence on gas accumulation

Deep water fan in Bay of Bengal has excellent petroleum geological conditions. The sand bodies of fans are vertically stacked on the source rocks, form plurality of overlapping combination lithologic traps, which have the potential to form large-scale stratigraphic traps[17-18]. The nature gas generated from Lower-Middle Miocene Bhuban Formation and Middle Oligocene kitchens in the fan of the Bay of Bengal, then migrated vertically along the vertical fault, unconformity, and connected sandbodies to the fans develop in lowstand period , accumulated under sealing of overlying marine mudstone in highstand period. The accumulation pattern includes the "lower-generating and upper-storage" stratigraphic reservoir or combination gas reservoir. The stratigraphic, lithological, and combination traps near the fault zone and source rock are the most advantageous exploration targets.

The deep-water fan system in Bay of Bengal has paleogeography conditions of intense thermal deposition since the Cretaceous. It developed a huge delta of the Bay of Bengal and a broad continental shelf background. Due to its rich and stable sediment source and the influence of various factors such as the three-stage relative falls of sea level, the Bay of Bengal received the huge thick sediment. It becomes favorable for basin formation, hydrocarbon generation and accumulation. The deep-water sedimentation system of the Bay of Bengal has many in common with that in the exploration hotspots on both sides of the Atlantic, such as the passive continental margin with long-term thermal and abundant sources deposition. With huge internal volume of deep-sea fan, three sets of hydrocarbon sources connect traps through vertical faults. Thus, deep-water fan system and shallow sea delta one together constitutes a favorable reservoir-cap combination in the deep-water of the Bay of Bengal. Therefore, high-quality source rocks, excellent carrier system, favorable reservoir-cap combination and organic matter constitute favorable factors for the deep fan in the Bay of Bengal. The stratigraphic traps in the fault zone and the lithological traps and rolling anticlines near source rocks should be the most favorable exploration targets, so the deep-fan of the Bay of Bengal has the geological foundation for the large oil and gas discoveries.

Therefore, the key factors of hydrocarbon accumulation in the deep-water fan involve in effective source rocks, deep water fans at low water level and their overlying high-level-stage mudstones, which form favorable reservoir-cap combinations. Meanwhile faults and unconformities and well-distributed sand bodies compose of excellent hydrocarbon carrier system. Gas from Middle Military Bhuban Formation and the Mesozoic Jenam Formation migrates to the reservoir along the faults, unconformity and the connected vertically sand bodies. It aggregates under the capping of the overlying marine mudstone. That is the hydrocarbon accumulation model of so-called "gas pool overlying kitchen", which belongs to stratigraphic or lenticular lithological reservoirs (Fig. 6).

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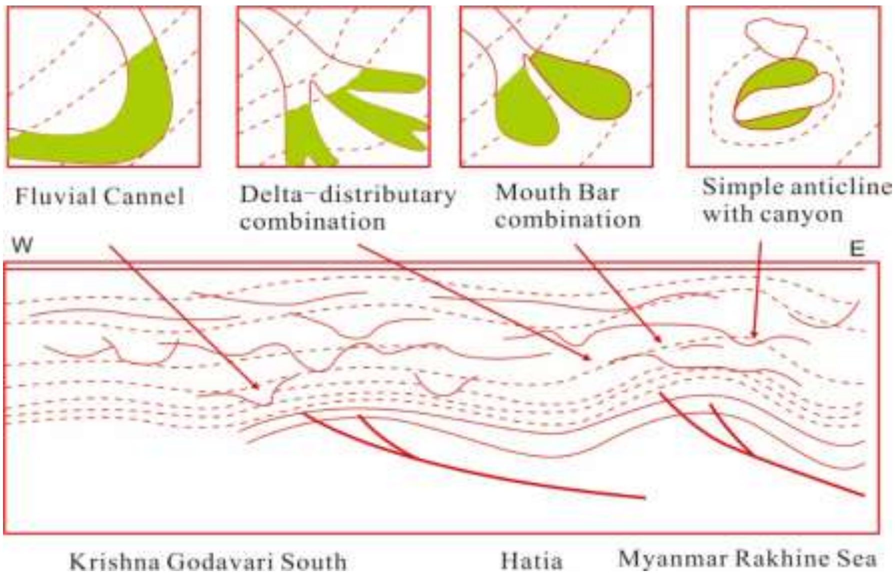

Fig 6: Trap diagram of the deep-water fan t in the Bay of Bengal

4.5 Case study

The SHWE gas field is located in the A1 Block of the deep-water sub-basin in the northeastern fan in the Bay of Bengal. The gas source comes from the Oligocene/Miocene marine mudstones, and the reservoir composes of the G sandstone in the Pliocene submarine fan (Fig. 7). The sand bodies are thick-layered and widespread in the NS-SE direction. They are typical accumulative constrained channel complexes with various coarse-grained sedimentary inside it[19-20]. In seismic profile, the channel sand bodies have continuous high amplitude, while sand bodies of the outer bank show medium amplitude. Their porosity is 22~28% and permeability 190~2000×10-3 μm2, and the thickness of the sand layer 15 to 30 m. The caprocks are the marine mudstones, they deposited in each high sea level period. The structural high spots are favorable areas for gas accumulation. The gas reservoirs mainly exist in the parts, in which lobe, channel, and over bank sedimentations are well configured with structures. The fault activity frequency is low in this block that there is no uniform gas-water interface in the area (Fig. 7). Types of the pools belong to up-dipping sandstone traps and lithological-fault traps; their maximum gas product goes as high as 260 million cubic feet with dry gas and high quality. Due to the large thickness and good vertical connectivity and physical properties of the constrained channel complexes, the gas pools have high ultimate recovery efficiency [21].

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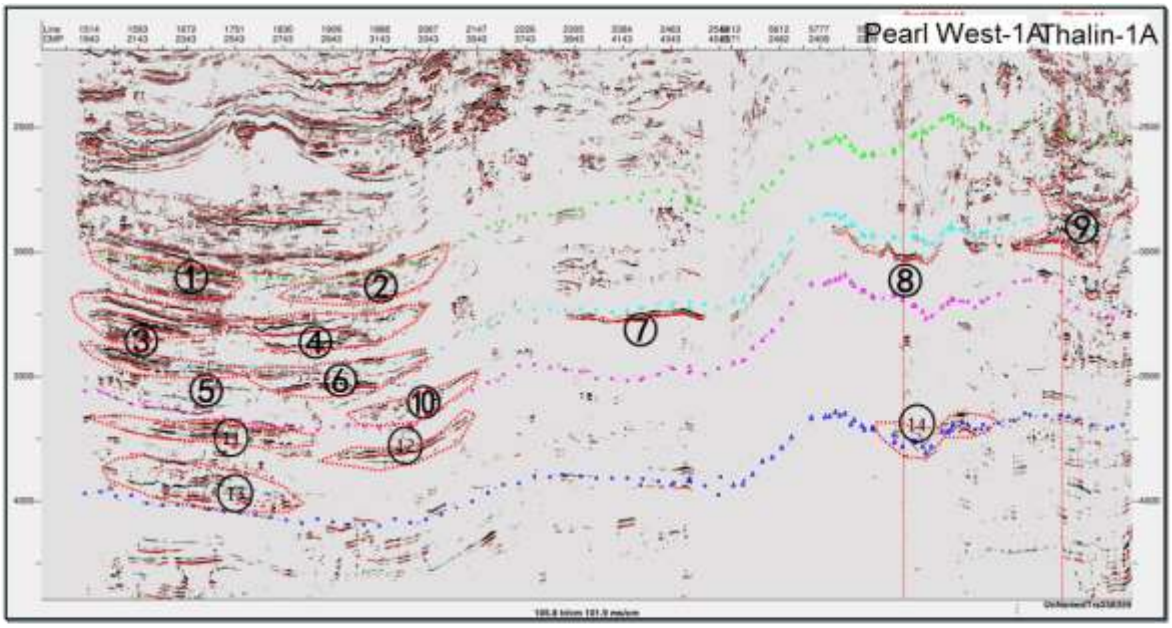

Fig 7: Seismic facies and reservoir profiles of the G Sandbody of submarine fan in the Rakhine Sub-basin.

Legend ①②③④⑤⑥⑩channel sandstones are chartered by dome reflection disorderly or discontinuously with Large amplitude variation;

⑨Outer fans mainly compose of sheet-shaped sand bodies and their amplitudes diminish or disappear.

⑦⑧ Eroded channels cut through shale and are chartered by incised filling or mouse-shaped, and their two wings show asymmetrical or symmetrical inverted bell, U-shaped and V-shaped, which are obviously out of harmony.

V. DISSCUSSION

According to relationship between cyclical variation of granular sizes and the corresponding seismic amplitude in this area, six different types of seismic facies can be identified. There are submarine canyons, confined slope channel complexes, aggradation channel –levee complexes, frontal splays (depositional lobes), isolated slope channels, and mass-transport complexes (MTCs).

The TOC/TN ratio indicates that the TOC/TN ratios of continental and marine organic matter in the fan of the Bay of Bengal are 11.2 and 4, respectively, and the organic matter sources are mixed sources. The contribution ratios of continental and marine organic matter are about 60% and 40%, respectively. The key factors of hydrocarbon accumulation of the deep-water fan include active source rocks, deep-water fans at low water level and their overlying high-level-stage mudstones, they form favorable reservoir-cap combinations. Meanwhile faults and unconformities and well-distributed sand bodies compose of excellent hydrocarbon carrier system.

Gas migration from source rocks to reservoirs of the fan is relatively simple. Gas migration is dominated by secondary migration. Faults, unconformities, and sand bodies continuously constitute good transport system[7]. The key influencing factors are matched with each other, including gas charging and migration and suitable trap forming.

The latest resources evaluation indicates that the undiscovered oil and gas resources in the deep waters of the Bay of Bengal mainly distributes in the Eocene, Oligocene-Miocene accumulation combination and Pliocene one. Undiscovered gas resources are 101.52 trillion Cubic Feet. The largest exploration potential comes from the Oligocene-Miocene accumulation combination.

VI. CONCLUSIONS

Based on the above analysis results, the favorable exploration areas of the fan in Bay of Bengal are as follows:

(1) In the Ganges River Bay of Bengal basin, the Rakhine Bay of Bengal basin, the middle and upper fan belt of the Mohannai Bay of Bengal basin, the major target layer is the Pliocene reservoir. There are two different types of reservoirs in the area; one is the submarine fan with a submarine channel system, the strike-slip fault and the channel filled by shale. And the other is the slope fan, in which the sand body shows laminated distribution. And the channel and lobe are the most favorable reservoir types. Two large gas fields have been currently found in this area;

(2) In the middle and upper fan belts in the Krishna and Godavari Bay of Bengal basins in the eastern waters of Indian, the targets are the upper Tertiary turbidity sandstone channel and lobe reservoirs, with depth of 2000-3000 m. Gas source comes from the Paleogene- Oligocene Bay of Bengal shale. Currently, two fields have been discovered in the deep waters, their recoverable reserves exceed 100 million barrels, rest five reservoirs more than 1 billion cubic feet.

(3) In the Tertiary tidal channel natural alluvial levee sandstone near the “bottomless channel” in the middle and lower fan belts, there has been no oil and gas discoveries.

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