Unveiling the petroleum potential of one of the world's last frontier petroleum provinces: the Bengal Fan, offshore Bangladesh

Elisabeth Gillbard[1]*, presents high-resolution seismic imaging illustrating the extensive petroleum potential of the Bengal Fan, from shelf and slope to the deep water domain.

Abstract

The Bay of Bengal contains the world's largest deep marine fan and yet remains almost entirely unexplored for petroleum. Evaluation of more than 12,600 line km of 2D seismic, gravity and magnetics data acquired by TGS and their partners SLB in 2023 (Figure 1), alongside historic well data, has provided a regional framework for understanding the evolution of the whole geological history of the basin and insight into the extensive petroleum potential of this highly frontier region. In this paper, we will present high-resolution seismic imaging, characterising the facies and reservoir architecture within the fan and illustrating the extensive petroleum potential of the Bengal Fan, from shelf and slope to the deep water domain.

Introduction

The discovery of several large gas fields within the Bengal Fan between 2004 and 2016 (e.g., Shwe, Shwe-Phyu, Mya, Thalin gas fields) has proven the vast potential within this highly active petroleum system. In March 2024 the Government of the People's Republic of Bangladesh and The Bangladesh Oil, Gas and Mineral Corporation (Petrobangla) announced an offshore bidding round for oil and gas exploration, the first since 2012. This highly anticipated licensing round offers 24 blocks extending from the shelf and slope to the deep water, a significant area of which is covered by 2D seismic data, which is the subject of this paper (*Figure 1*).

The 2D seismic data spanning the shelf, slope and deep water offshore Bangladesh were acquired with long offsets (10 km) and have been processed with modern preprocessing workflows (including deghosting, surface-related multiple-elimination (SRME), shallow-water demultiple) with particular emphasis on the shallow-water area on the platform. For the velocity model building, an integrated tomography and full-waveform inversion (FWI) workflow was implemented alongside geological interpretation to refine and improve the imaging of discrete features such as channel bodies and gas pockets and to constrain anisotropy.

Geological setting

The Bay of Bengal is a rifted passive margin initially established during the disintegration of Gondwana (e.g., Curray, 1982; Powell, 1988; Curray, 1994). Rifting was initiated during the early Jurassic (~180 Ma) period, with the first oceanic crust forming in the Lower Cretaceous (120-130 Ma) as a result of the separation of the Indian and Antarctica plates (e.g., Gopala Rao et al., 1997). As India drifted northwards, it started its collision with Asia around 59 Ma, initiating the Himalayan uplift. However, the full hard continent-continent collision did not begin until around 15 Ma, resulting in the main Himalayan Orogeny and the major increase in sedimentation, which resulted in the deposition of

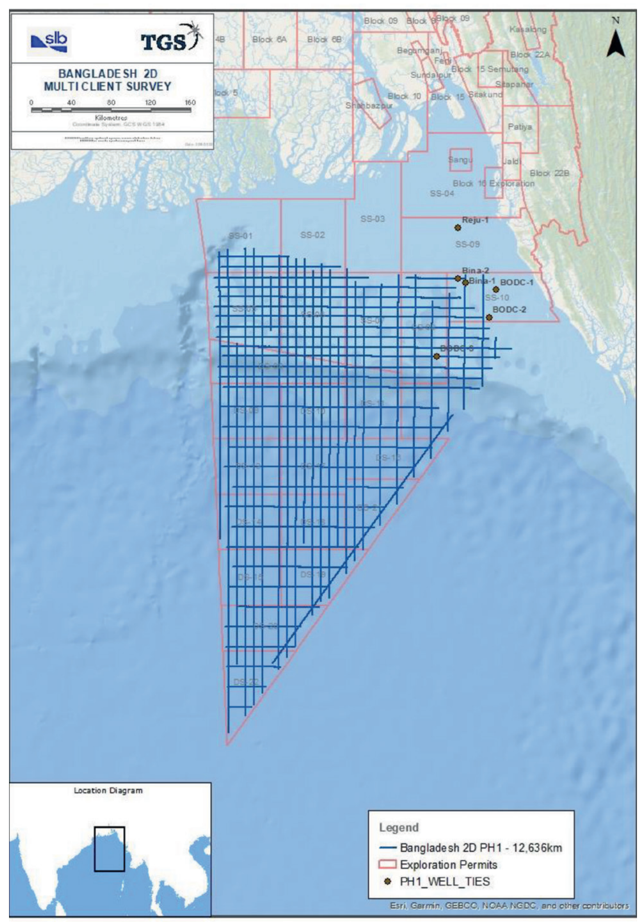

Figure 1 Location map of the 2D seismic data used in this study

[1] TGS
* Corresponding author, E-mail: elisabeth.gillbard@tgs.com
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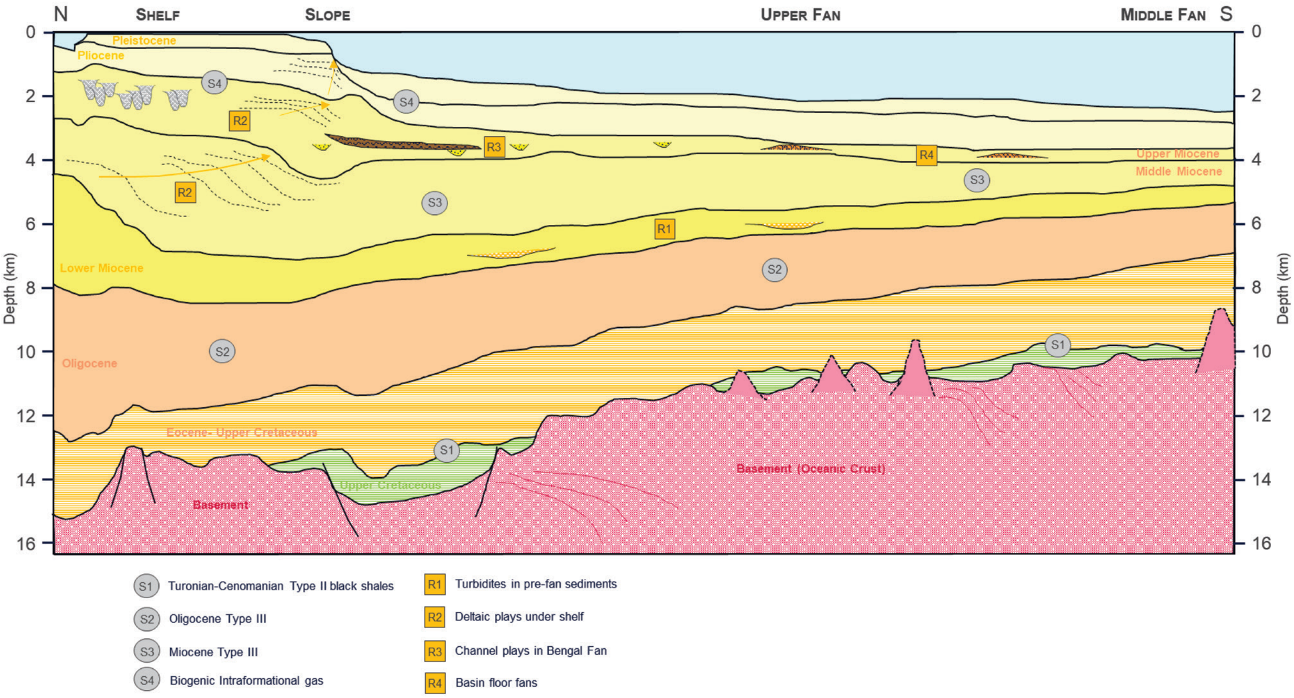

Figure 2 Schematic geo-seismic dip section across the Bengal Fan, showing the regional sequences and key hydrocarbon plays discussed in this study.

the Bengal Fan. The Sunda Subduction Zone and Indo-Burman accretionary prism mark the eastern extent of the Bay of Bengal, active since approximately 20 Ma. Compression from this margin is evident in the east part of the area of interest (AOI), with structural deformation decreasing westwards.

The Bengal Fan is the largest submarine fan in the world, with a length of up to 3000 km, a width of 1200 km, and up to 16 km of sediment thickness (Curray et al., 2003). The primary sedimentary source is the Ganges-Brahmaputra and equivalent historic river systems, which are relatively sandy compared to major modern rivers (Coleman, 1969). The uplift of the Indo-Burman Ranges provided an additional secondary sediment input to the Bay of Bengal, increasing in influence during the Pliocene (Alam et al., 2001). Both erode from a mainly volcanic provenance, resulting in the deposition of clean and well-sorted sediments.

Initial fan sedimentation was likely started as early as the lower Eocene (Curray, 1994). However, the majority of the sediment has been deposited since the Lower Miocene period, with the development of prograding deltaic deposits on the shelf and linked deep-water sequences. The present-day sediment input to the fan is confined to a large submarine channel known as the 'Swatch of no Ground' (SoNG). Equivalent ancient feeder systems have migrated significantly over the geological past, with rapid migration of depositional centres from the east to the present position in the west. Although many studies have documented sedimentary processes relating to the SoNG (e.g., Curray et al., 2003; Schwenk et al., 2005) and around petroleum discoveries on the northeastern flank of the fan (e.g., Ma et al., 2020; Shoup et al., 2017), very little has been published on the rest of the fan.

Nearly 200 m of well-sorted Pliocene-aged silts and sands were encountered within pelagic sediments in Deep Sea Drilling Program (DSDP) Site 211, over 2800 km from the present-day shoreline (Curray et al., 2003). Site 218 cored 125 m of silty sand in water depths of 3759 m over the 90-degree E ridge. Deep-sea sands have also been encountered in several wells offshore Myanmar (e.g., Shwe Field), with porosities up to 33%, maximum permeability of 653 mD and net to gross of 83% (Zhou et al., 2020). The presence of high-quality sand material within the deep-water distal fan, alongside a comparison with other large fan systems (e.g., Niger Delta, Mississippi Fan), offers high confidence in the transportation of coarse material considerable distances from the sediment source.

Bengal fan play concepts

Several play concepts are recognised within the Bengal Fan, offshore Bangladesh (Figure 2). Biogenic, and both proven and untested thermogenic, source rocks have been identified in the regional data (S1-S4). Predicted reservoirs can be divided into early fan, shelf, slope and deep-water facies (R1-R4). Intraformational sequences, channel muds and lateral pinch-outs provide seal and stratigraphic traps. Structural traps within low-wavelength anticlines and faulted structures have also been identified within the AOI. These plays will be discussed in the subsequent sections and leads at multiple stratigraphic levels have been identified.

Source Rocks and Petroleum Systems

All the recent discoveries within the Bengal Fan have been sourced from intraformational biogenic gas contemporaneous with the reservoirs (Shoup et al., 2017). However, there is also considerable evidence for several thermogenic systems. The gas source for the nearshore Sangu Field has been typed to Miocene interbedded shales, and equivalent sequences were drilled in the BODC and Bina wells further offshore, where they were found to be oil-prone Type III shales (Baric et al., 1977). Pre-fan, Late Eocene to Early Oligocene source rocks actively produce oil and gas in adjacent

Myanmar. Meanwhile, analogue basins offshore East India yield oil-prone source rocks of Upper Cretaceous age. Gas hydrates and direct hydrocarbon indicators (DHIs) are very common within the seismic data, proving an active gas system (*Figure 3*).

While the intraformational Miocene and Pliocene source rocks have been well documented, the presence of a Cretaceous source rock has not been proven within the Bay of Bengal. Cenomanian-Turonian syn-rift source rocks are producing gas from oil-prone source rocks offshore East India (Qin et al., 2017). The Turonian/Cenomanian Oceanic Anoxic Event (OAE II) resulted in global occurrences of black shales. Correlation of proven Cretaceous units from the east Indian basins shows the presence of a thin syn-rift unit overlying basement structures across the AOI. This unit is characteristically low amplitude and transparent

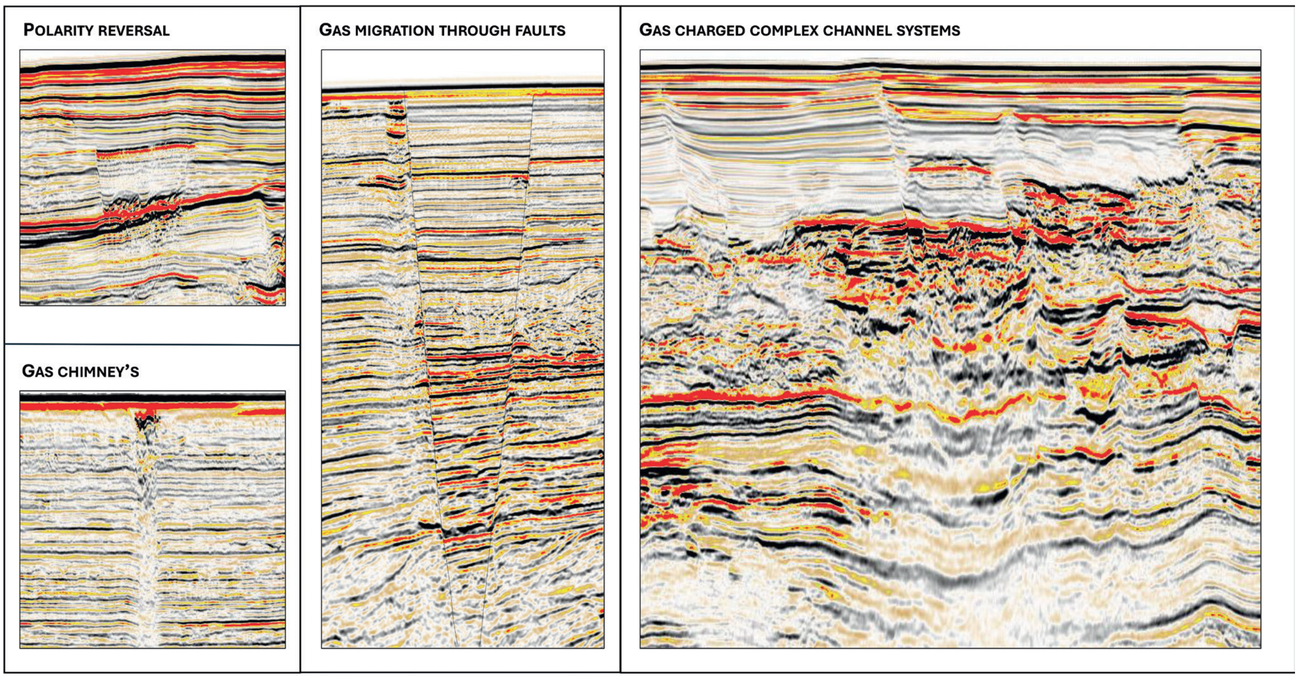

Figure 3 Pre-stack time migrated (PSTM) seismic images showing direct hydrocarbon indicators (DHIs) in the form of gas anomalies throughout the data.

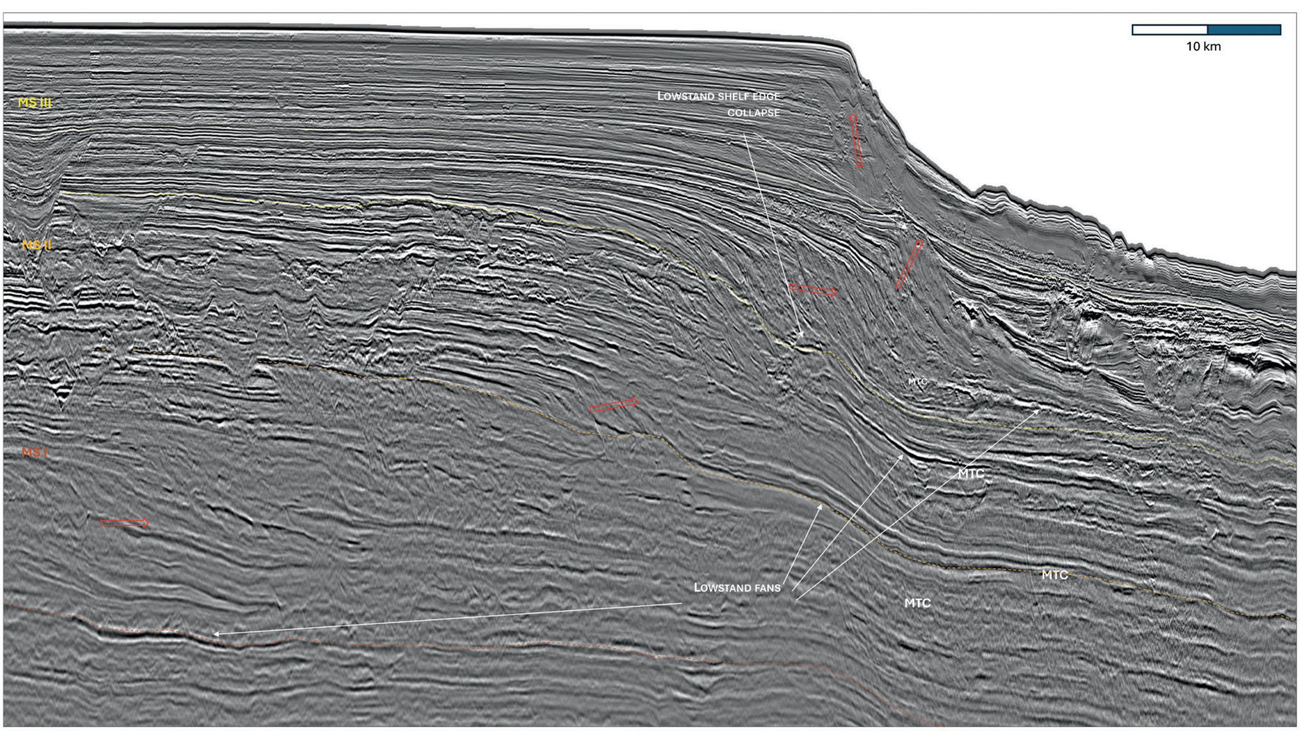

Figure 4 PSTM seismic dip line through from shelf to slope showing the three identified megasequences (MS I, MS II and MS III) and associated MRS. Associated low-stand features have been highlighted, such as the large-scale truncation relating to shelf collapse and downslope occurrence of basin floor fans and mass transport deposits within predictable sequences. Red arrows denote the direction of shelf break, showing progradation in MSI and MSII, downlapping progradation to aggradation in MSIII then retrogradation since the Pleistocene.

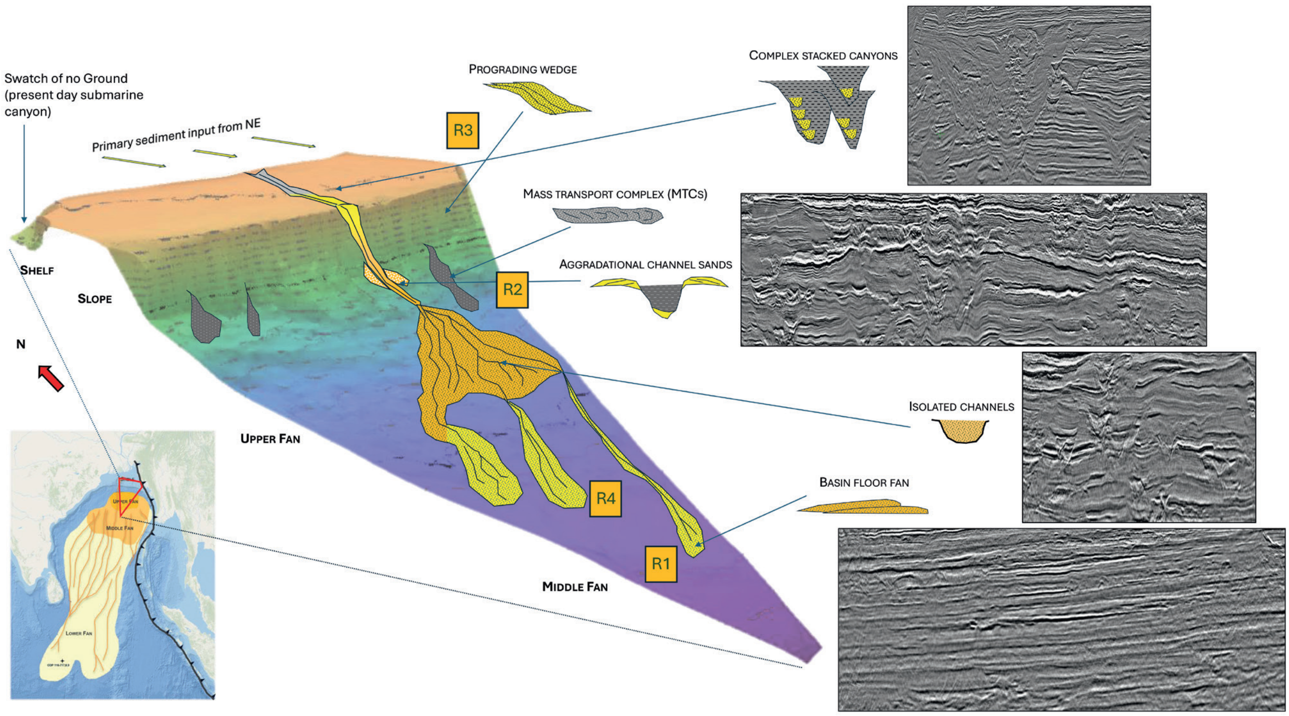

Figure 5 Schematic showing the basin play model for a single submarine fan system, from shelf to basin floor. Reservoir potential facies are predicted within the prograding shelf sands on the platform, within complex channel systems and levees on the slope and in isolated channels and basin floor fans in the deep water.

and shows thinning onto structural and volcanic highs, with local restriction. Tectonic reconstruction of the mid-Cretaceous shows that although the Bay of Bengal sat in the open ocean, there was localised restriction due to the emplacement of the Kerguelen Hot Spot around 120 Ma, forming the 85-degree E and 90-degree E ridges (Scotese and Zumberge, 2007). These restrictions could have enabled the formation of high-class OAE source rocks within syn-rift basins overlying the basement.

Although no direct geothermal gradient data is available, imaging of the whole sedimentary unit to basement provides confidence that petroleum systems modelling would be relatively easy to constrain in the Bay of Bengal. Further work needs to be done to confirm regional modelling of potential and known source rock units.

Reservoir architecture and seismic facies

In order to develop a predictive reservoir model for the Bengal Fan, it is essential to understand how the system evolved within the AOI, from early fan deposition through to present-day bypass. By looking at the whole fan system, we are better able to see the changing character and architecture of the potential reservoir facies moving from shelf to basin floor.

Within the shelf area of the AOI, the fan can broadly be divided into three mega sequences (MS) (*Figure 4*): Lower Miocene (MS I), Middle Miocene to Pliocene (MS II) and Pliocene to Recent (MS III). These mega-sequences can be readily identified in the seismic data and represent the progressive facies changes within the prograding system, divided by regional maximum regression surfaces (MRS) relating to lowstand events. MS I is characterised by broadly prograding sequences with limited channelisation and numerous high amplitude features, particularly down-dip from the ancient shelf break. MS II is dominated by complex, erosive, stacked canyons with a downstepping prograding shelf break. MS III is characterised by laterally continuous facies cut by rare, deeply erosive canyon features. The sequences show a transition from progradation to aggradation and then retrogradation since the Pleistocene.

The overall progradation of the fan since inception has resulted in the stacking of deep marine distal facies under slope and shelf facies within the present-day shelf. The identification of lowstand events within the ancient system can help to predict aggradational reservoir facies on the slope and sand-rich turbidites on the basin floor.

Figure 5 shows the characteristic features of a schematic single lobe of the Bengal Fan and the associated predicted seismic facies. Within the AOI, all the fan system elements are evident in predictable locations.

Giant fan systems are primarily fed by a single canyon system at a time, with avulsion processes resulting in the lateral and vertical growth of the system and progradation leading to down-dip migration (Schwenk et al., 2005). Unlike other modern fan systems, the Bengal Fan has been fed by different distinct submarine canyons in the past relating to changes in river location, sediment supply and sea level (Curray et al., 2003). These canyon systems were particularly active during MS II, where the whole shelf is cut by complex aggrading and meandering systems (*Figure 4*). The canyon complexes are generally mud-rich, but stacked internal sand-rich channels are common, often characterised by lenticular high amplitudes (*Figure 5*). The canyons often cut through high amplitude prograding facies, providing lateral seal and trap geometries.

As the slope increases, the characteristic complex stacked channels become more confined and develop into aggrading channel systems. These channels are wedge-shaped, the core often infilled with chaotic and high amplitude seismic facies (*Figure 5*). Levee and overbank deposits can also be identified as dipping reflectors on the flanks of the channel and crevasse splays as bright amplitude laminar events on the flanks. 3D mapping of these channels shows them to be generally meandering with common abandonment (e.g., Schwenk et al., 2003; Thomas et al., 2012), resulting in sediment traps. The steepened slope also results in the common occurrence of mass transport complexes (MTCs) which can act as seals and intraformational source rocks as well as sediment and petroleum conduits (Lu et al., 2023).

All these shelf and slope canyon and channel feeder systems ultimately provide thick sand accumulation in unconfined basin floor settings (*Figure 5*). These basin floor fans commonly contain the cleanest sandstones and largest reservoirs. They are often characterised by gigantic, thin, high-amplitude and lobe-shaped bodies with updip channel feeder systems. Basin floor fans have been identified at two stratigraphic levels within the AOI; Lower Miocene under the present-day shelf and within the Upper Miocene to Pliocene lowstand sequences off the shelf break. The optimal reservoir facies is usually found in the amalgamated sheets closest to the feeder system (Yang and Kim, 2013).

Identified Leads

Using the predictive seismic facies and seismic stratigraphy, numerous examples of the key play types can be identified within the 2D data. Some features are of such a scale they can be traced across multiple strike and dip lines. On the shelf, low amplitude anticlines and deep-rooted faulting create structural traps within shelfal reservoir sands, with additional stratigraphic upsides in levee sands with lateral pinch-outs (*Figure 6a*).

Within the slope, the primary leads comprise complex stacked canyons and aggradational channels with associated mass

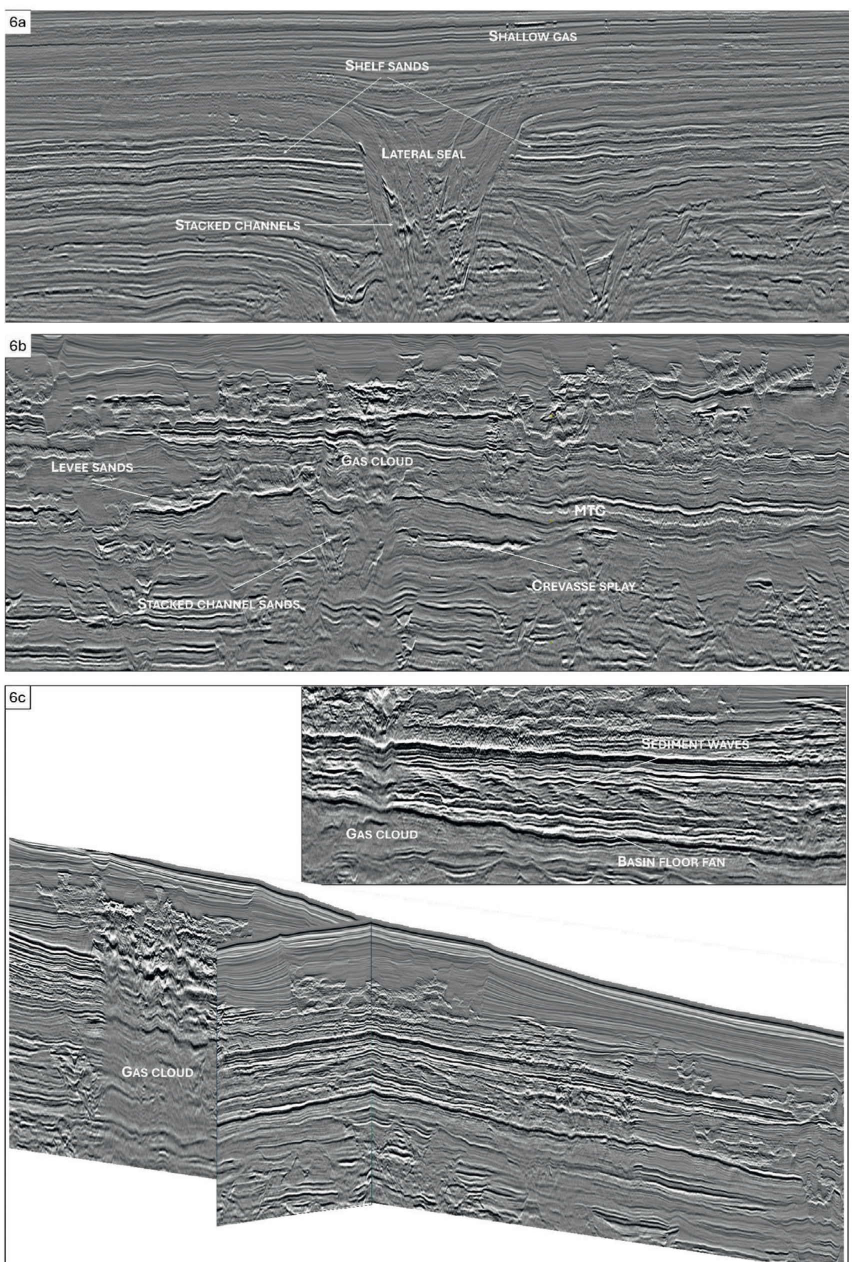

Figure 6 PSTM seismic images showing identified leads within the AOI, progressively from shelf to basin floor. 6a: high amplitude shelf sands laterally sealed by a large erosive mud-dominated complex channel system, containing stacked sand-filled channels. Trapped within a low amplitude anticline. 6b: Aggradational channel complex overlying high amplitude fan bodies and stacked channel sands. Detail within the channel complex shows high amplitude stacked channel sands within the core and elongate splays and overbank deposits. A chaotic MTC overlays the system providing lateral and top seal to some of the sand units. 6c: Large-scale basin floor fan with associated sediment waves indicative of lowstand deposition with high potential for coarser grained facies. The fan system can be seen in both strike and dip lines as a high amplitude soft-topped feature.

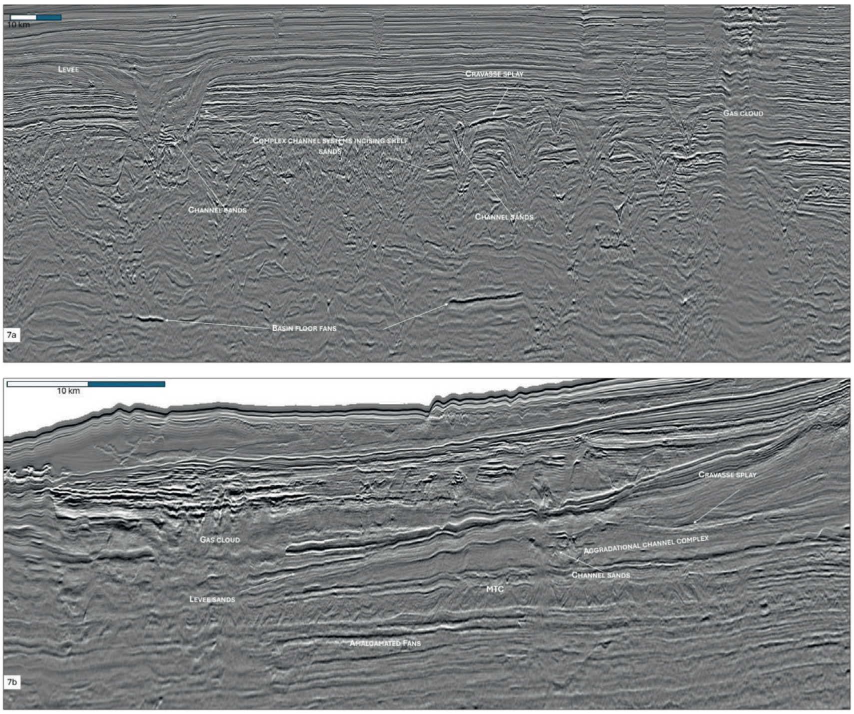

Figure 7 PSTM seismic images showing stacked leads on the shelf and slope within the AOI. 7b: PSTM seismic image showing an example of a Lower Miocene basin floor fan. Complex channel systems overlay the fan proving additional targets at shallower levels. 7a: PSTM seismic image showing an example of stacked leads on the present-day slope.

transport complex facies acting as lateral and top seals, often with a pinch-out component (*Figure 6b*).

There are frequent examples of giant fan systems on the basin floor, with lateral and updip pinch-outs (*Figure 6c*). These systems are large enough to be mapped across several strike and dip lines, and their associated canyon feeder systems are often evident. The association of these fans with lowstand depositional features such as sediment waves and collapse structures provides additional support to the potential for sand-rich systems.

Giant basin floor fans have also been identified at Lower Miocene level under the present-day shelf break (*Figure 7a*). Some of these high-amplitude soft-topped bodies are up to 20 km across and extend 40 km downslope. They are often intrinsically connected to overlying and lateral MTCs.

Stacked plays are common, particularly under the present-day shelf and slope, where the progression and aggradation of the historic shelf break enables the stacking of multiple leads from early basin floor fans through to aggradational channel systems and canyon leads (*Figure 7b*).

Conclusions

The Bengal Fan has huge untapped potential for petroleum exploration, and the recent announcement of a licence round offshore in Bangladesh has ignited significant interest. Regional studies will be vital in understanding the source, timing and optimal reservoir presence for successful petroleum exploration.

High-resolution regional 2D seismic data evaluation has offered insight into evolving reservoir architecture and seismic character, enabling potential reservoir prediction. There is extensive evidence of a working petroleum system at multiple levels, and further work to constrain this can be performed. Identification several leads at multiple stratigraphic levels, including stacked plays on the shelf and slope and gigantic basin floor fans in the deep water, demonstrates the considerable potential of the Bengal Fan for future giant petroleum discoveries.

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