Seismic Facies Analysis and Structural Interpretation of the Sandakan Sub-basin, Sulu Sea, Philippines*

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Abstract

Synthesis of seismic facies analysis, sequence stratigraphy and structural interpretation can help reconstruct basin paleogeography and provide useful insights to a basin's petroleum system. This article presents a gross seismic facies mapping analysis and structural interpretation of the Sandakan sub-basin, located between the islands of Borneo (Malaysia) and Sulu (Philippines). This sub-basin, an element of the Sulu Sea Basin, has been the interest of several exploration efforts in Malaysia and Philippines, but there is still no production activity in the area. Data incorporated in this analysis includes 2D seismic, gamma-ray logs, biostratigraphy and cuttings description from four wells (Figure 1).

Methodology

Seismic Sequence Analysis

The underlying concept of seismic sequence analysis is that the seismic section is divided into packages of relatively conformable or concordant seismic reflections, bound by unconformities. The unconformities are identified in the section by reflection terminations against them or by discordant surfaces. Seismic sequences are assumed to be deposited in temporally confined episodes in a usually wide geographic distribution, thus creating a laterally extensive identifiable surface and a chronologic framework for correlation between sequences in a region (Cross and Lessenger, 1988). Seismic sequence analysis was carried out on the seismic data by picking major unconformities identified from reflector terminations, change in seismic facies character, or choosing significant boundaries from well data.

Seismic Facies Analysis

The objective of this step is to be able to correlate reflection attributes to the stratigraphic characteristics of identified sequences and provide a correlating framework between seismic and well data. These reflection characteristics are thought to correspond to unique geological and depositional history of the sequence (Mitchum et al., 1977). Several previous studies worldwide have shown a direct correlation between seismic facies type and lithology (Table 1). Nevertheless, calibration between the two is still basin-specific; hence, an independent analysis must be carried out in every basin of interest.

In this study, we employed four reflection attributes to discriminate between different seismic facies: 1) external geometry, 2) internal reflector configuration, 3) reflector continuity, and 4) amplitude. Each seismic facies identified was assigned a unique two-way time which was mapped in the seismic grid to create the distribution framework of the seismic facies and to generate facies maps. Amplitude correction and balancing was not carried out because of time constraints. Hence, amplitude values are estimated at every line.

Seismic Facies and Lithofacies Calibration

Each seismic facies type identified was correlated with well data (gamma ray/GR log curves and lithofacies from cuttings description) from four wells to establish a relationship between the seismic facies and lithofacies. Correlation panels were generated to illustrate the lithofacies that correspond with each seismic facies. A gross lithologic map was generated for each interval after establishing the relationship between the facies.

Paleogeographic Reconstruction

Paleogeographic maps were produced with the aid of biostratigraphic data and depositional environment interpretation from well completion reports.

Results

Structural Interpretation

Both normal and reverse faults are present with a NW-SE trend (Figure 2) and mostly extends deep into the subsurface (>5 s TWT) where they terminate against a possible detachment layer. Several planar faults develop into growth faults. These seismic scale extensional faults have strike lengths which extend tens of kilometers and have moderate to steep dips pointing basinwards (NE). Active normal faults have produced fault scarps that significantly affect the seafloor topography in the area.

Evidence of synkinematic deposition is observed on thickening packages on the hanging wall of the growth faults. Post-kinematic deposits are inferred from the uniformity in thickness of the packages across the faults and also in the change in the dominant seismic facies type.

At the toe end of the shelf are thrust faults dipping to the west. These toe-thrusts have produced associated fault-propagation folds. The faults are of seismic scale and have moderate dips pointing landward (SW). These faults appear to be active as observed from the irregular seabed topography. Other associated features include ponded synclines where synkinematic deposits develop more thickness on one limb of the fold. Sediment packages continuously thin and taper as more toe thrusts develop deeper in the basin. It is notable that extensional processes dominate in the proximal part of the study area with a distinct change to compressional processes in the distal portions.

Seismic Sequence Analysis

Twelve horizons were picked from the seismic data (Figure 2). The seabed was interpreted first to gain a sense of the topography in the study area. The deepest horizon interpreted was the detachment layer where most faults seem to terminate. The next horizon is the Deep Regional Unconformity (DRU) (Horizon 1-cyan) which was also interpreted as a sequence boundary from the well data. This horizon was identified by erosional truncations and several downlaps. The Shallow Regional Unconformity (SRU) horizon (Horizon 6 - light orange), which represents the top of the Sebahat Formation, was identified as a surface downlapped by reflections in the overlying prograding seismic packages, especially in the central part of the study area. The Pliocene Unconformity (Horizon 10 - pink) was characterized by erosional truncations and is downlapped by low amplitude reflections. The packages bound by these horizons were further subdivided based on seismic reflector terminations, changes in seismic facies character, or from picking important surfaces identified from wells. Horizons 2, 3, 4 and 5 were all interpreted as sequence boundaries in the wells, while Horizons 7 and 8 were interpreted as flooding surfaces.

Seismic Facies Analysis

After establishing the key horizons, seismic facies in the units between horizons were identified. Six seismic facies were recognized in the study area (Table 2). The distribution of seismic facies types (Figure 3) usually trend parallel to the present shelf location (NW-SE), although patchy distributions are also common. There is also an apparent transition in the dominant seismic facies type from the Middle Miocene (Units 1 to 3), through the Late Miocene (Units 4 to 7) to the Pliocene (Units 8 to 10).

Facies Calibration

Correlation panels were created for wells that intersected each seismic facies to associate seismic facies with lithofacies. This correlation has placed the seismic intervals interpreted in the context of the regional stratigraphy of the study area (Figure 4).

Well data reveal that the basin is dominated by fine-grained sediments (claystone) interbedded with other clastics (sandstone, siltstone, shale) throughout the investigated time interval. Carbonate development appears to be significant during the later stages of basin evolution. There is correlation between seismic facies type, well log response and lithofacies observed in the data set. However, lithofacies tend to change with regards to position in the basin (inboard vs outboard) which is sometimes not directly manifested in the seismic facies (Table 3).

Discussion

The transition of the dominant facies type from seismic facies C-D-B-A, through time appears to correspond to a switch from a paralic to a marine depositional environment as indicated by biostratigraphic data (Figure 5). The paleogeography of the Sandakan Basin has evolved from a fluvio-deltaic setting during the Late-Middle Miocene to a shelfal environment during the Pliocene.

Several important assertions can be made from the paleogeographic reconstruction of the Sandakan Basin:

a) The structural regime of the study area is typical of a deepwater fold-thrust belt (DWFTB) system.

Two unique structural provinces are observed in the study area: extension in the landward portion and compression in the basinward portions, typical of DWFTB (King et al., 2009). Gravity-driven collapse of the shelf leads to extension on the delta top, which in turn generates downslope compression resulting in a DWFTB or delta toe (Dailly, 1976; Mandl and Crans, 1981; Morley, 2003; Rowan et al. 2004; Bilotti and Shaw, 2006).

The Baram Delta System, found NW of Sabah, is a classic example of a DWFTB (King et al., 2009, Tingay et al., 2005) and is known for its prolific hydrocarbon resources. This delta system exhibits typical prograding delta tectonic systems and is similar to the tectonic province of the Sandakan Delta System.

b) The Late-Middle Miocene was a time of active progradation.

Several pieces of evidence assert this statement: (1) dominance of interbedded clastics, with little or no marine (carbonate) influence, (2) mostly blocky or coarsening-up GR log responses typical of progradation or aggradation, (3) presence of common wedge to lens-shaped seismic packages, containing oblique internal reflectors (clinoforms), and downlapping into the underlying surface – typical of progradational packages, and (4) the presence of numerous and diverse terrigenous palynological data with rare marine indicators.

Active building out of the Sandakan Delta System into the sea is documented in several papers and is deemed to be caused by several events (CCOP, 2006; Hall and Nichols, 2002;Walker, 1993; Nichols et al., 1990): (1) the creation of accommodation space due to an inversion event in the Middle Miocene, which led to post-rift deposition and several events of compression in the Late Miocene, (2) the high sediment influx from active erosion of previously deposited and uplifted Rajangand Kinabatangan Groups, (3) the active distributary function of the Kinabatangan Riverinto the sea, and (4) the eustatic sea level fall during the Tortonian.

This progradation (Figure 6) has produced associated slumping and slope fan processes in the basin shelf-edge, which in turn has generated possible turbidite deposits and created sand fairways such as channel-levee systems and slope fans. Consequently, it has also shifted the NW-SE shoreline towards the NE as discussed by previous workers (CCOP 2006; Pablico 2000). This can be observed from the shifting of prograding clinoforms.

c) Carbonate development was the dominant depositional process in the Pliocene-Pleistocene.

A change in the dominant seismic facies from chaotic, mounded, oblique facies (B, C, D) to more parallel to sub-parallel, highlycontinuous, seismic facies (A) seem to imply a drastic change in the depositional process in the basin. A regional transgressive event which brought the basin into a truly marine environment caused abandonment of previous distributary channels, reef development and the deposition of deepwater sediments on top of shallow-water deposits. Nichols et al. (1990) and Walker (1993) postulated that a decrease in the supply of clastic detritus from arc and continental sources and a change in the level of the carbonate compensation depth during this period resulted in a shift from siliciclastic to pelagic carbonate deposition throughout this period.

d) The source of sediment is mainland Borneo.

The direction of the paleoshelf migration and shifting clinoforms supports this claim (Pablico, 2000). Provenance studies also show that majority of the sediments in the basin were derived initially from erosion of onshore Sabah Paleogene sediments and later from cannibalization of older Neogene sediments during inversion of the prograding delta (van de Weerd and Armin, 1992; Sandal, 1996; Moss and Chambers, 1999).

e) The delta system is predominantly mud-dominated.

Drilling results of the four wells have revealed the predominance of fine-grained sediments (claystone) over the entire basin and patchy, lateral distribution of sand bodies. Mud-dominated systems tend to form well-developed channel levee systems. Although seismic data seem to indicate presence of these bodies, it is still uncertain and needs to be further investigated.

Implications for Petroleum System

Reservoir

The main reservoir units in the basin, the Sebahat and Ganduman formations, were deposited during the active deltaic progradation process, implying that reservoir quality will decrease with depth and basinward. Lateral connectivity of the reservoir units is also not expected (unless channel systems coalesce) because of the distributary mouth bar system inherent in deltaic systems. Passive margins (strandline and coastline systems), on the other hand, can form laterally extensive sand sheets. Potential reservoir units can also be found in depositional wedges, channels and slopes (turbidites) especially during lowstand periods and carbonate build-ups during the Pliocene to Pleistocene.

Seal and Trap

The transgressive event in the Pliocene generated a potential regional seal by shifting deepwater, fine clastics deposition to a more inboard position. Intraformational seals are also present and prove to be important especially in the formation of stacked reservoirs, which is actually a more common scenario in a fluvio-deltaic system. Possible seals were also developed with the post-kinematic deposits as more fine-grained deposits exist during this quiescence.

Fault seals are also involved in the interplay of petroleum elements in the basin. The development of growth faults is highly controlled by shale gouge ratio and impacts sealing capacity. Seal development might be a problem in proximal locations of the delta because of the predominace of coarse grains. However, in the more distal locations, seal breaching will be a major problem because of low compaction rates and has associated implications to drilling such as shallow hazards and overpressured zones.

The DWFTB setting of the sub-basin developed associated structural traps such as fault blocks (proximal portions) and fault-propagation folds (distal portions). The fault blocks may be associated with the rifting almost throughout the Middle-Late Miocene while the folds may be related to several events of compression in the Late Miocene. The active delta progradation also has produced several stratigraphic traps which include pinch-outs and wedges. This progradation also furthered the development of growth faults that thickened the sedimentary fill in the basin and led to the deposition of mostly clastic (quartzose) sandstones. Complex structures in the area are a major problem, as they might cause breaching of previously trapped accumulations especially if they post-date migration and accumulation.

Source, Maturity, Timing and Generation

Hydrocarbon and maturity indices in the basin are low to moderate, with fair potential to generate hydrocarbons (DOE, 2001; DOE, 1986). Source rocks tend to be intraformational (Ganduman and Sebahat formations) or located more inboard (onshore Borneo). Probable lack of migration pathways, high sealing capacity of faults (which can serve as migration conduits), or trap breaching and fault reactivation can be postulated to be causes of insufficient charge in most wells drilled in the basin. However, some of these large-scale faults were active most of the time (reaches the seabed) and must have served as migration pathways to charge shallower structures.

Conclusions and Recommendations

Seismic facies mapping in the Sandakan Sub-basin revealed that seismic facies have correlation with lithofacies and depositonal environment. Analysis of the data shows that the basin has evolved from an actively prograding fluvio-deltaic system, mainly fed by the Kinabatangan River in Borneo, into a shelfal marine environment. The mapping procedure has enabled generation of the paleogeography of the basin and provided insights into further understanding the basin's prospectivity. Furthermore, the result of the structural interpretation of the seismic data provides insights into the timing of deformation in the Sandakan Sub-basin and the presence of related structural traps. To improve the findings of this study, more well calibration and defining smaller seismic intervals are recommended.

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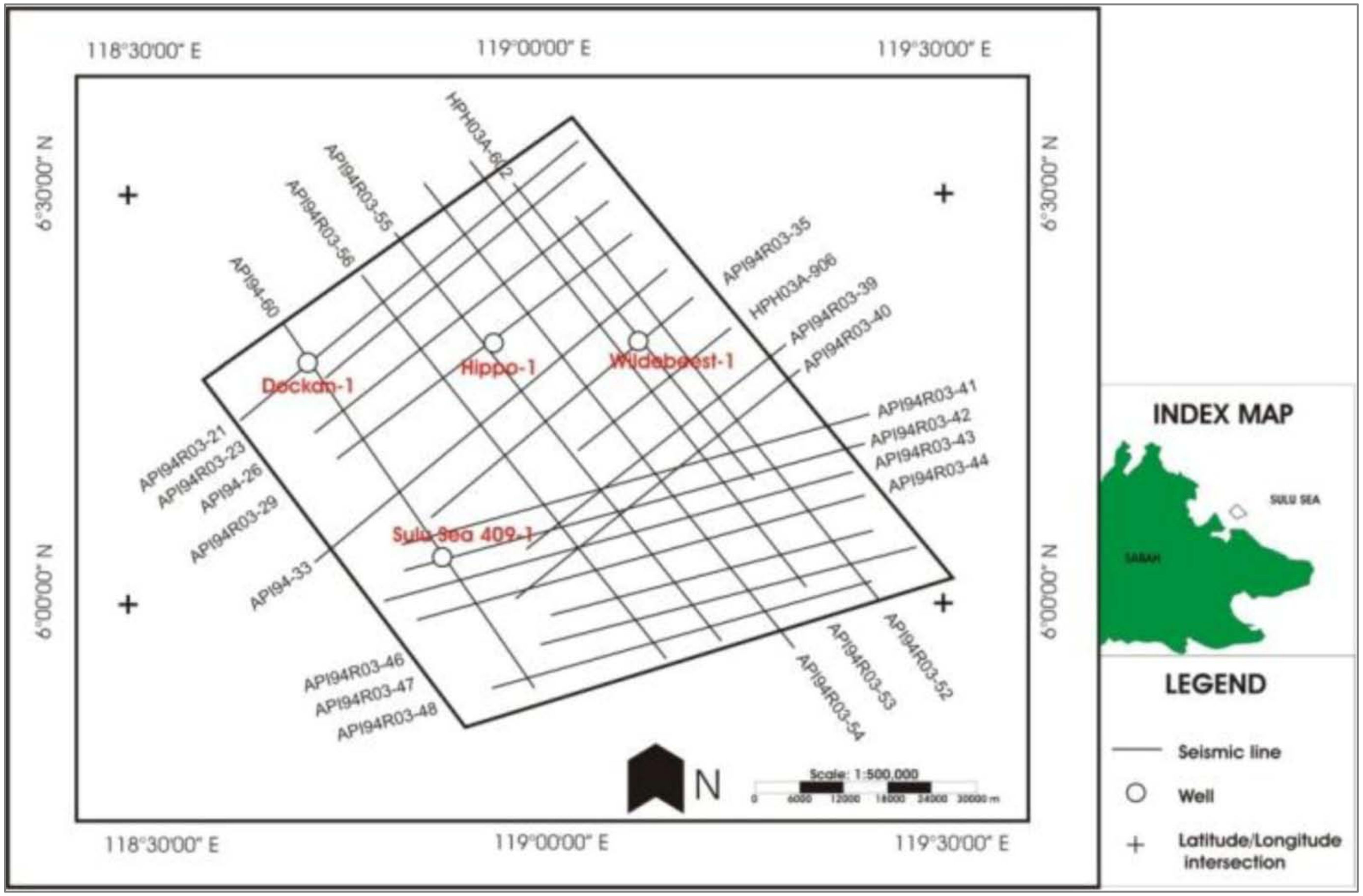


Figure 1. Study area seismic lines. The area of interest is enclosed within the polygon. Dip lines are trending NW-SE while strike lines trend NE-SW.

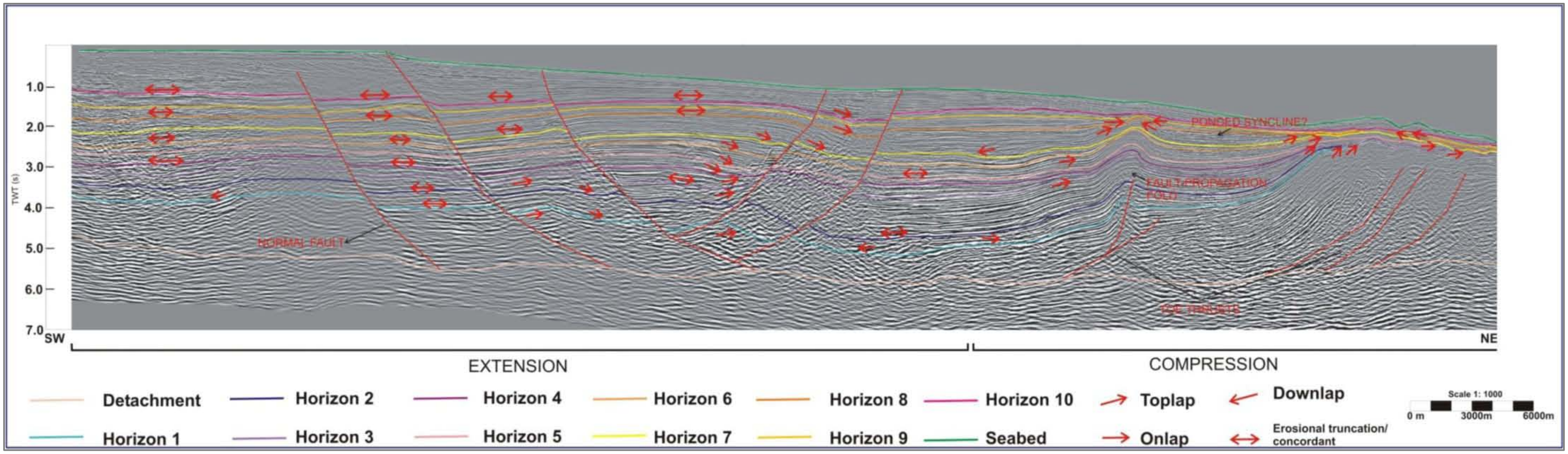


Figure 2. Representative seismic section for the study area showing the structural interpretation and seismic sequence analysis.

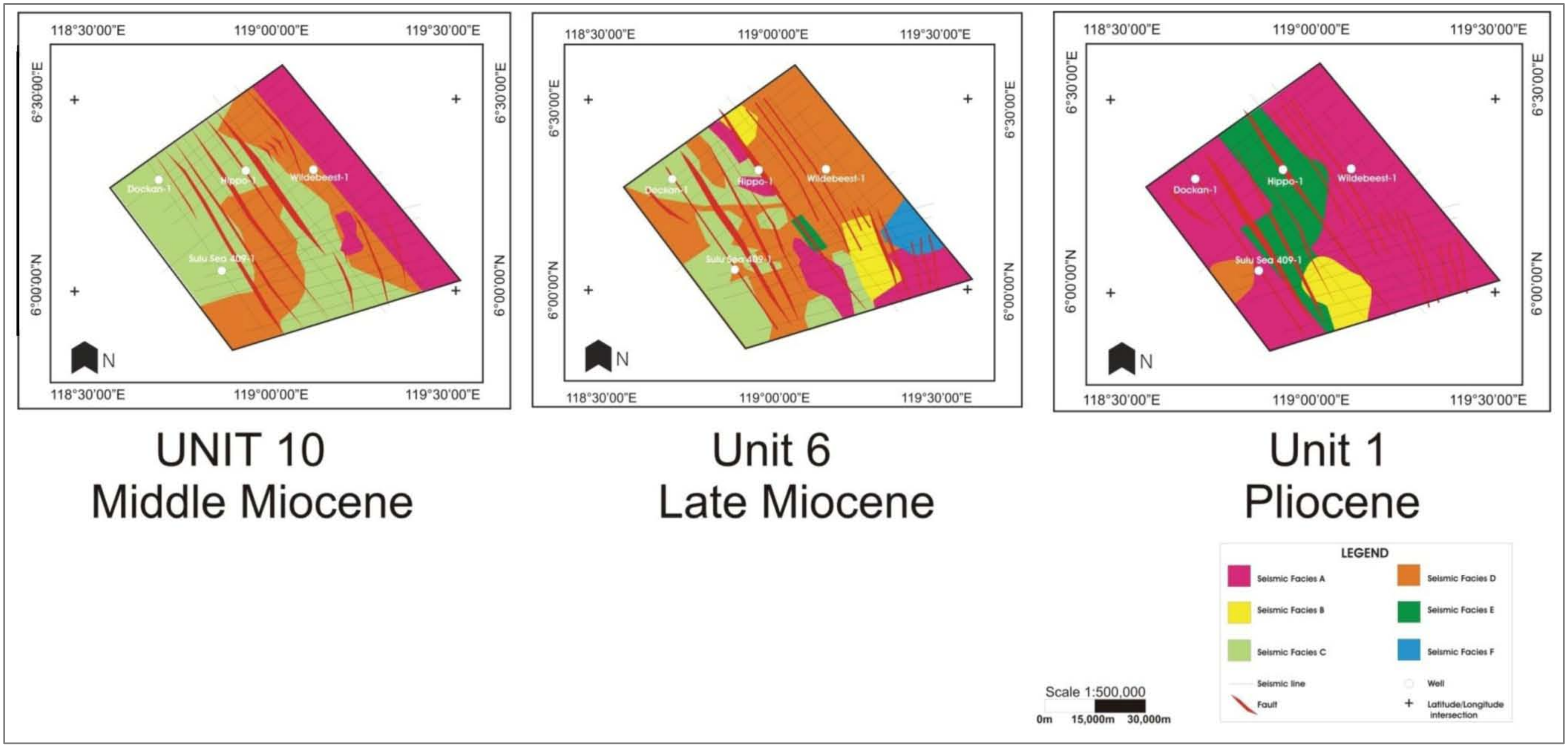


Figure 3. Representative seismic facies map of Middle Miocene to Pliocene. During the Middle Miocene (Unit 10), the entire study area is populated mostly by seismic facies C, which was replaced by seismic facies D (inboard portion) and seismic facies B (outboard portion) in the early-middle stages of the Late Miocene (Unit 6). The Pliocene (Unit 1) was dominated by seismic facies A.

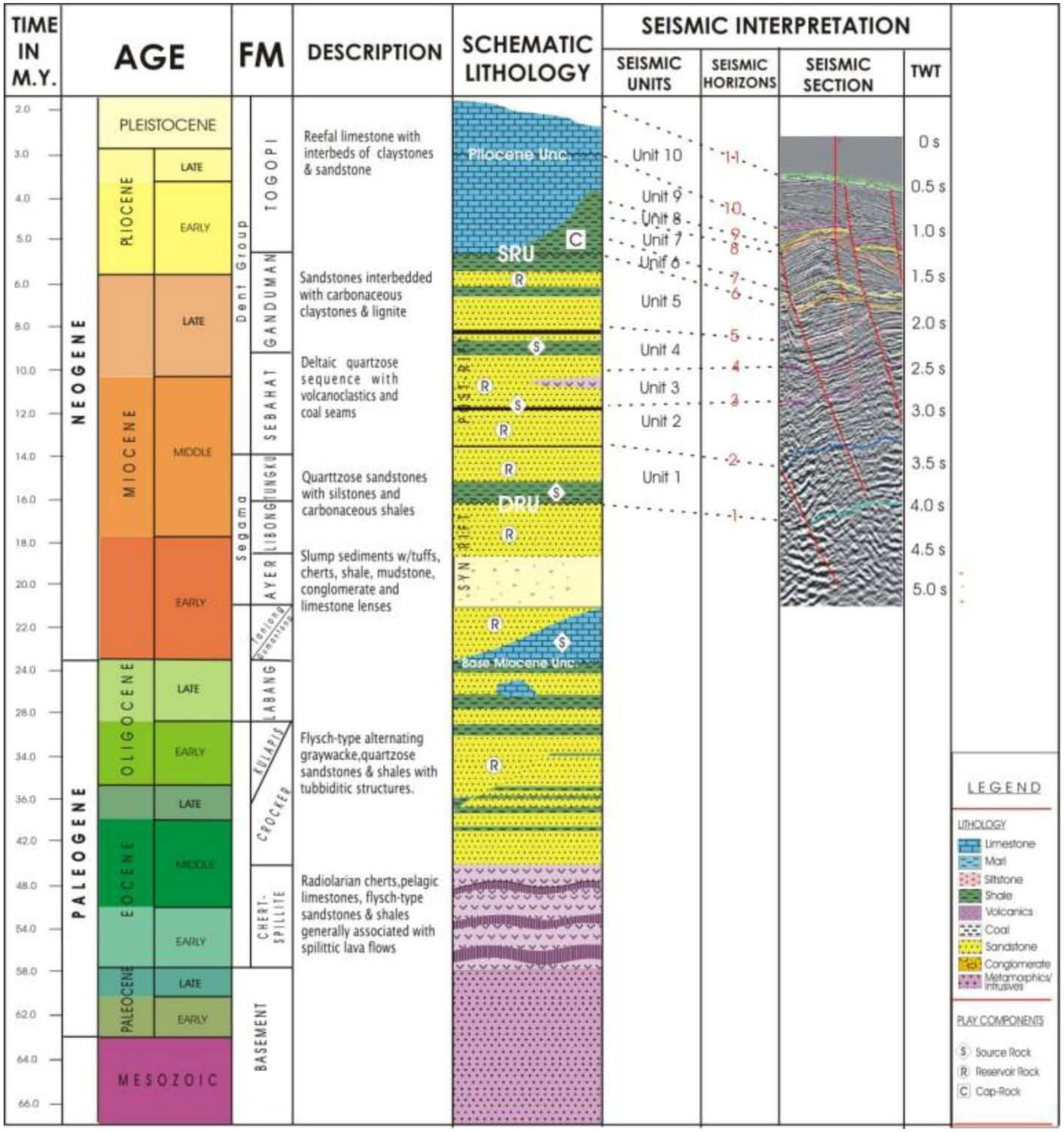


Figure 4. Regional stratigraphy of Sabah (modified from DOE, 2001) incorporating the seismic horizons and seismic units interpreted in the study area.

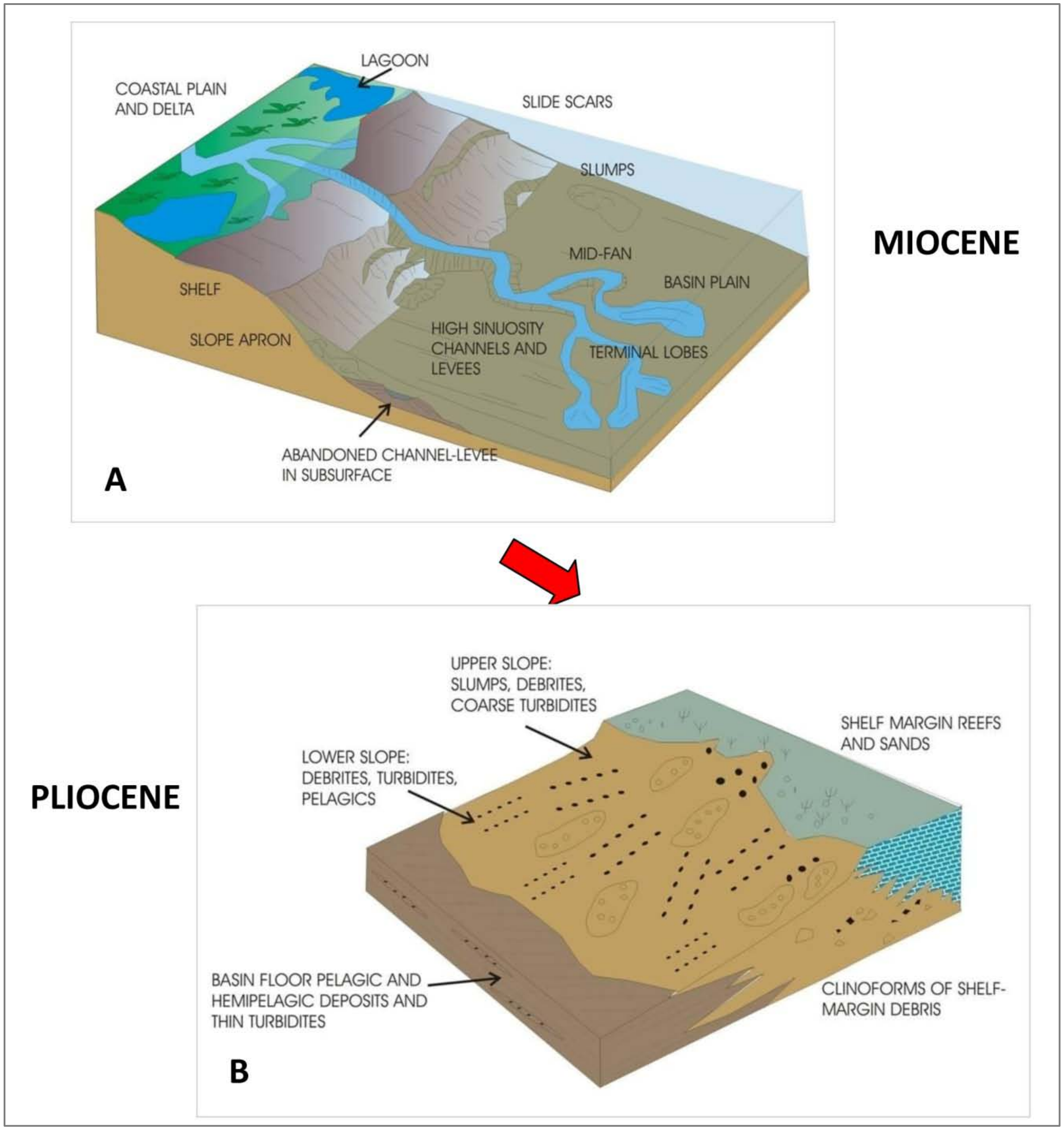


Figure 5. Idealized paralic (A) paleoenvironment (modified from Emery and Myer, 1996) in the Sandakan Sub-basin during the Late to Middle Miocene. This period is dominated by active fluvio-deltaic deposition of the Sandakan Delta into the Sulu Sea. It shifted to a shelfal (B) paleoenvironment (modified from Tucker, 1990) during the Pliocene. Regional transgression during the Early Pliocene has caused a major transition in the depositional environment in the Sandakan Sub-basin from an active delta to shelf environment.

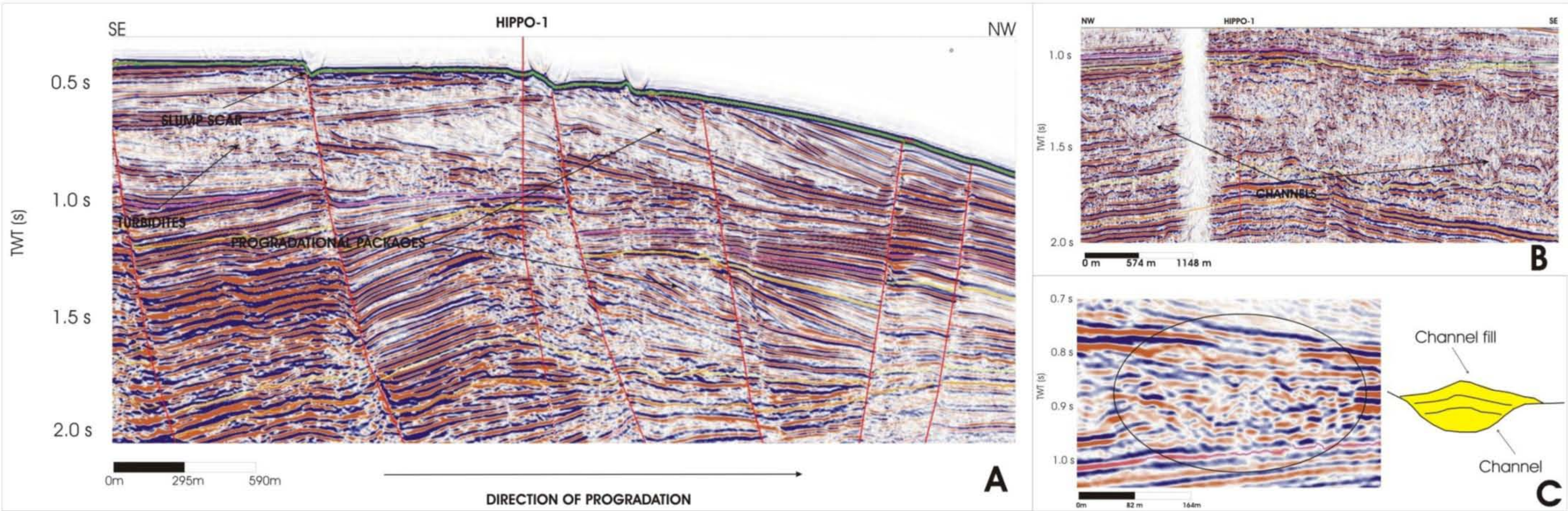


Figure 6. Depositional features common in active progradational systems (A). Direction of progradation is to the NW. Growth faulting is commonly associated with progradation and produces associated slump scars in slope areas. Rapid slope processes and high sedimentation rates also cause siliciclastic deposition in deeper waters such as turbidites, channels (B) and associated channel-levee systems (C).

Seismic Facies	**Lithofacies**	**Gamma Ray Response**
A	***Inboard:*** limestone with interbedded clastics ***Outboard:*** claystone with minor limestone interbeds	***Inboard:*** funnel-shaped ***Outboard:*** ratty to crescent-shaped
B	***Inboard:*** sandstone interbedded with silststone, claystone (with trace coal and limestone stringers around Dockan-1 area)	ratty – bell- shaped - blocky

Table 1. General correlation observed between seismic facies and lithofacies from several studies worldwide (Emery and Myers, 1996).

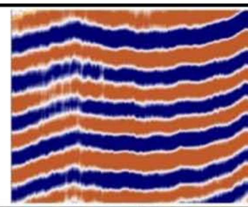
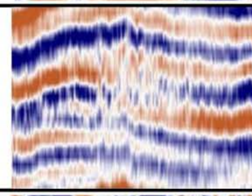
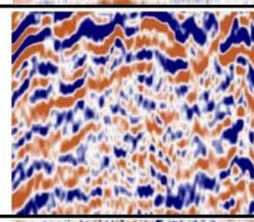
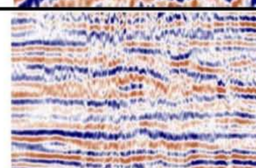
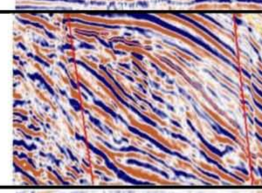
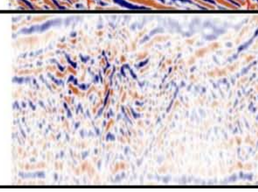
Seismic Facies		**Reflection Attributes** *(a – external geometry, b – internal configuration, c – continuity, d) amplitude strength)*
A		a) sheet to wedge b) parallel to wavy c) high continuity d) moderate to high
B		a) sheet to wedge b) parallel to wavy c) semi-continuous to high continuity d) low to moderate
C		a) sheet to mound b) wavy to hummocky c) disrupted to discontinuous d) moderate to high
D		a) sheet to wedge b) parallel to subparallel c) semi-continuous to disrupted d) low to moderate
E		a) lens to wedge b) subparallel to convergent to oblique c) semi-continuous to high continuity d) low to moderate
F		a) lens to channel-shaped b) wavy to chaotic c) discontinuous d) low to moderate

Table 2. The six different seismic facies identified in the study area. Four seismic reflection attributes were used to classify the facies types: external geometry, internal configuration, amplitude and continuity. External geometry is observed from a 3D view of the package (i.e. combination of dip and strike lines) and hence, not exemplified in the figures above.

	Outboard: claystone interbedded with sandstone, siltstone, limestone	
C	***Inboard:*** sandstone with siltstone interbeds (with trace coal and limestone stringers around Dockan-1 area) ***Outboard:*** claystone with minor siltstone and sandstone interbeds	***Inboard:*** blocky to funnel/bell-shaped ***Outboard:*** ratty
D	***Inboard:*** interbedded sandstone, siltstone, claystone (with limestone and shale in Sulu Sea 409-1) ***Outboard:*** claystone interbedded with siltstone, sandstone, limestone	***Inboard:*** funnel-shaped - blocky ***Outboard:*** ratty –funnel-shaped - blocky
E	***Inboard:*** no well calibration ***Outboard:*** claystone with argillaceous limestone, siltstone	***Inboard:*** no well ***Outboard:*** ratty – bow-trend
F	No well calibration	No well calibration

Table 3. Results of the seismic facies-litholfacies calibration in the study area.