# Deposition of the Tembungo deep-water sands

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**Abstract:** One of the main elements of the sequence stratigraphy model concerns the development of deep-marine systems (Posamentier and Vail, 1988). Deep-marine systems can be classified into basinfloor (lowstand) fans and slope fans where each, according to sequence stratigraphic concepts, is assumed to be primarily controlled by the rate of eustatic changes.

This seismic-based classification of deep-water systems is based on modifications of Mitchum's (1985) model. In contrast, many of the previous submarine fan models were based on smaller-scale observations from shallow seismic data integrated with shallow cores on modern submarine fans, and on detailed outcrop-based facies studies often with limited outcrop exposures (see review by Mutti and Normark, 1987). A notable exception is the submarine fan model proposed by Mutti (1985) which attempted to reconcile outcrop-based studies to variations in sediment influx and relative sea-level changes.

The different scales of observation of deep-marine systems have resulted in many, often conflicting, submarine fan models, each applicable to a particular setting. In addition, studies relating sedimentary facies to large-scale sequence stratigraphic models are lacking. The main aim of this paper is to use core and seismic reflection data to investigate the evolution of a Middle Miocene turbidite sequence offshore NW Borneo called the Tembungo deep-water sands. The origin of these turbidites is closely related to a prominent regional unconformity called the Shallow Regional Unconformity (SRU). The depositional model derived from this study is compared with the submarine fan models of Mutti (1985) and models arising from sequence stratigraphic concepts.

The approach is based on integrating information from high quality multichannel seismic data with wireline logs calibrated with sedimentary facies studies of cores. Seismic stratigraphy provides the large-scale framework useful for relating turbidite system deposition to temporal and spatial boundaries of depositional sequences. This, when combined with identification of the different seismic facies, and relating them to cores and wireline logs, can result in the recognition of the different phases of growth of the turbidite system.

## INTRODUCTION

### Geologic Setting and Previous Interpretations

The Tembungo structure is a northeastsouthwest trending anticline about 17 km long and 8 km wide. It is located about 25 km west of a prominent shore-parallel structural high, named the Bunbury-St Joseph Ridge (Fig. 1). Exploration wells drilled on the Tembungo structure encountered packages of thin to thick-bedded deepmarine sands near the base of Upper Miocene. This sequence marks rapid build-up of the basin margin characterised by well-developed clinoforms, which clearly delineate the rapidly changing boundaries between the shelf, slope and basin. Whittle and Short (1978), using seismic and palaeontological data, interpreted these sands to be deposited in a lobate fan complex at the break of the continental slope. They inferred that sediment supply emanated from a point source on the continental slope, and that inner-littoral clastics underlay the deep-marine sediment. In general,

<sup>\*</sup> Footnote: Noor A'zim Ibrahim obtained his PhD degree from the University of Cambridge in January 1994, under the supervision of Dr. N. J. White and Prof. I.N. McCave. As fate would have it, on April 25th of the same year, he tragically drowned at Kuala Koh in Gua Musang, Kelantan while on a work-related field trip. His loss was twofold; not just to his family but also to the geoscience community, in which he was well-liked and respected. As an effort to share part of A'zim's PhD work, I decided to publish the chapter on deepwater sand deposition, recognizing the current interest in deepwater exploration. This paper, however, would not have seen the light of day had it not been for the persistent encouragement and assistance of Peter Abolins; to him, my sincere thanks.



Figure 1. a) Location map of the Tembungo structure. The anticline is separated from the Bunbury-St. Joseph Ridge by the Pritchard syncline. b) Structural map showing locations of exploration and production wells (modified from Whittle and Short, 1978).

they have identified three types of deep-water sands: a) shaly sand deposited at the base of the sand complex, b) lenticular and thick sand bodies in the middle part interpreted as channel sands, and c) thin and discontinuous sands at the top interpreted as overbank and crevasse splays. Deposition of these sands was attributed to eustatic fall at the end of Middle Miocene.

### STRATIGRAPHIC SUBDIVISION

Detailed well-to-well correlation based on gamma-ray logs of six exploration wells is difficult due to the absence of key beds and inconsistent sand development patterns. Nevertheless. correlation of broad stratigraphic units between these exploration wells is still reliable (Fig. 2). The identification and correlation of several seismic markers assists stratigraphic subdivision. Four reflectors, including the Shallow Regional Unconformity, have been identified and mapped across Tembungo and adjacent areas. In ascending order, these reflectors are named as Blue, Green and Red, all lying above the Shallow Regional Unconformity. These markers divide the slope and base of slope sediments into 5 seismic units, i.e.

Unit 1 to Unit 5. Most of the cores were taken from Unit 2 and Unit 3 which, together, represent the main body of the Tembungo deep marine sands (Fig. 2). The seismic facies and wireline log descriptions of the five units are given below.

#### Unit 1

Unit 1 underlies the Shallow Regional Unconformity, a prominent angular unconformity near the basin margin. Internally, it consists of variable to high-amplitude, alternating discontinuous and continuous, reflectors in the Tembungo area (Fig. 3). Proximal to the base of slope, mound and chaotic reflection patterns are much more prevalent and, in places, are associated with 1 to 2 km long shallow slump channels (Figs. 3 and 4). On wireline logs, this unit is dominated by mudstones with isolated thin sandstone and siltstone interbeds (< 1 m) occurring as spikes on the gamma-ray logs (Fig. 2).

Whittle and Short (1978) interpreted this unit to be deposited in an inner littoral setting, but the presence of numerous deep-water benthic foraminifera and its occurrence near the base of large-scale clinoforms suggests deposition in a lower bathyal setting (pers. comm. Basiron Jalil, 1991;



Figure 2. Correlation of 6 exploration wells approximately parallel to strike illustrating the 4 seismic markers which separate the deep-water sediments into 5 seismic units. Note the variability of the gamma-ray log characters within units 2, 3 and 4. Also shown are the core locations.

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**Figure 3.** Uninterpreted and interpreted seismic profile 1 parallel to depositional dip showing various seismic units which are bounded by seismic markers; Horizon 4 (H4), Blue (B), Green (G) and Red (R). The Tembungo structure is towards the northwest. The upper part of Unit 1 is commonly incised by spoon-shaped slump channels. A slump channel also truuncates the upper part of Unit 2. Also, note that deposition of Unit 3 is accompanied by basinward growth of the shelf edge.



**Figure 4.** Uninterpreted and interpreted seismic profile 2 parallel to depositional dip showing various seismic units which are bounded by seismic markers; Horizon 4 (H4), Blue (B), and Green (G). Seismic facies of Units 1, 2 and 3 are characterized by discontinuous and irregular reflections accompanied by shallow slump channel.

pers. comm. Karim, 1994). Palaeobathymetric estimation based on seismic foresets suggests deposition in water depths of at least 500 m. This estimate does not consider the effect of compaction.

#### Unit 2

This unit is bounded at the top by the Blue reflector and below by the Shallow Regional Unconformity (Fig. 2). At many places in the upper and lower parts of the slope, the Shallow Regional Unconformity occupies the base of slump-scars a few km in length (Fig. 5). Consequently, parts of Unit 2 near the base of the slope consist of slump channel-fills. The upper surface of Unit 2 is often mounded and, in places, contorted near the base of slope, becoming subparallel to the bottom boundary basinward. On a larger perspective, this unit has a wedge-like dip profile that pinches gradually against the Shallow Regional Unconformity westward. It is thicker near the base of slope and, in most cases, passes into a zone dominated by numerous overlapping cut and fill features ranging from 0.5 to 2.0 km long. On average, these channels are smaller than those associated with the Shallow Regional Unconformity. Along depositional strike. the unit is lens-shaped and can be traced for a distance of at least 30 km along slope (Fig. 6).

Internally, the reflection amplitude is low, characterised by short, discontinuous and dipping reflections, mostly downlapping against the Shallow Regional Unconformity (Figs. 3, 5 and 6). The upper and middle parts of the slope are heavily scalloped with shallow slump channels about 100 to 150 m deep and between 0.2 to 3 km wide (Fig. 4). Bi-directional downlapping is also present in places. Away from the base of slope, Unit 2 is characterised by high-amplitude continuous reflectors that blanket structurally low areas and pinch against structural highs.

On wireline logs, this unit is characterised by well-developed sandstone packages with an aggregate thickness varying from 40 m in the Tembungo 2 well to 150 m in the other wells (Fig. 2). It is thinner at Tembungo 2 since it is located near the crest of the Tembungo anticline, which was a palaeostructural high during the deposition of these sands. This feature is further illustrated in along depositional dip well to well correlation panels (Figs. 7 and 8). The sandstone development pattern, based on wireline log characters, varies from one well to another along depositional strike (Fig. 2). However, along depositional dip, individual sandstone units can be easily correlated (Fig. 8). Generally, the lower part is strongly progradational comprising coarsening- and thickening-upward units 5 to 10 m thick which, closer to base of slope,

is succeeded by an association of 'funnel' and 'blocky'shaped sandstone units varying from 5 to 30 m thick. Away from the basin margin to the west, it is dominated almost entirely by smaller 'funnel'shaped sandstone units (Figs. 7 and 8). The intervening mudstones are represented by serrated gamma-ray profiles commonly 5 to 10 m thick.

#### Unit 3

This unit is bounded at the top and bottom by the Green and Blue seismic markers, respectively. It is thicker in the southwestern part of Tembungo, where it is about 140 m thick, and pinches towards the Tembungo 3 and 6 wells, where the Green reflector downlaps onto Unit 2 (Fig. 9). In contrast to Unit 2, growth of Unit 3 is accompanied by rapid progradation of the shelf-edge to a position 4 to 8 km basinward from that of the Unit 2 position (Figs. 3, 5 and 9). The upper surface is typically mounded near the base of the slope and becomes smoother towards the deeper parts of the basin (Figs. 3, 5 and 9).

Internally, the unit comprises generally lowamplitude, overlapping slump channel-fill on the slope that alternates occasionally with highamplitude, well-defined clinoforms (Figs. 3, 5 and 9). The clinoform reflections eventually merge together forming a high-amplitude reflection further to the west.

The maximum thickness of the unit encountered in the Tembungo wells is about 120 m but with a lower sandstone to shale ratio than Unit 2. Like the underlying unit, the pattern of sandstone package development along strike varies from well to well and can be easily correlated along certain dip transects (Figs. 7 and 8). The lower part is typically dominated by mudstones 10 to 50 m thick becoming sandier towards the top. There are also suggestions that sandstones in the upper part of the unit gradually downlap onto Unit 2 further to the west (Fig. 8). Small-scale (a few metres thick) 'funnel'-shaped sandstone units are prevalent in the westernmost wells while closer to the base of slope, they are thicker, generally 'blocky' and 'bell'shaped (Figs. 7 and 8). Here, thinner 'funnel'shaped units commonly constitute the base of the thicker sandstone units.

Figure 10 shows the variability of sandstone package development within the central area of the Tembungo field. The laterally variable 'blocky' log character labelled 'A' is interpreted as a channelfill unit, and assuming limited lateral migration, it represents a channel of at least 250 m wide. Correspondingly, the thinner sandstone units below the channel-fill may be interpreted as aggrading proximal overbank deposits.



**Figure 5.** Uninterpreted and interpreted seismic profile 3 parallel to depositional dip showing various seismic units which are bounded by seismic markers; Horizon 4 (H4), Blue (B), and Green (G) and Red (R). It illustrates the presence of a km-scale slump channel at Horizon 4 filled with low-amplitude reflection pattern. Deposition of Unit 3 is accompanied by basinward growth of the shelf. Bidirectional onlapping pattern is visible in Unit 4.



**Figure 6.** Uninterpreted and interpreted seismic profile 4 parallel to depositional strike taken near the axis of the Pritchard Syncline. It shows various seismic units which are bounded by seismic markers; Horizon 4(H4), Blue (B), and Green (G) and Red (R). Note the lateral change in the geometry of the different units.



**Figure 7.** Well correlation panel 2 along a dip transect, suggesting that deposition of Unit 2 is structurally controlled. The lowest turbidite packages in Unit 2 in Tembungo T4 well onlap towards the crest of the structure while deposition of Unit 3 is less constrained by the structure.



**Figure 8.** Well correlation panel 3, along a dip transect showing the difference in gamma-ray log characters between Unit 2 and Unit 3. Sand packages in unit 3 are shown as progressively downlapping onto Unit 2 basinward.

## Unit 4

Unit 4 is bounded on top by the Red marker and below by the Green marker (Fig. 2). This unit is usually characterised by low reflection amplitude and irregular seismic reflection of the upper surface, which is often difficult to correlate (Figs. 3, 5 and 9). In the northeastern part, this unit appears to onlap against the underlying Unit 3 in the slope area (Fig. 5), while in other places, it constitutes a part of the outbuilding shelf. Internally, this unit consists of low-amplitude, irregular reflections which, in a few cases, are interbedded with welldefined clinoforms. Near the base of the slope, overlapping low-amplitude bi-directional downlaps, varying from 2 to 4 km long, are common. These are interpreted as small channel-levee complexes (Figs. 5 and 11). Basinward of the Tembungo area, the unit gradually pinches out against the underlying unit. On wireline logs, this unit varies from 90 to 150 m thick and correlates with a dominantly shaly interval. Sandstones occur sporadically as 5 to 10 m thick 'funnel' and 'bell'shaped units and as thin lenses less than 2 m (Fig. 2).

### Unit 5

On seismic sections, Unit 5 corresponds to the lower to the upper parts of the slope in the Tembungo area. It is separated from the underlying Unit 4 by the Red seismic marker and at the top by seismic foresets (Fig. 11). Internally, the seismic facies is similar to that of Unit 4 consisting of lowamplitude, irregular reflections with occasional high-amplitude clinoforms. Near the base of the slope are several overlapping mounded structures with bi-directional dipping reflections (Fig. 11). Unit 5 progressively pinches basinward of the Tembungo area.

On wireline log, the relatively thick mudstone is characterised by a monotonous high gamma-ray profile (Fig. 2), which progressively shows an increase in sand content towards the top. Near the base of the unit, sandstone intervals are rare; where present, they consist of thin packages less than 2 m thick. Benthic foraminifera obtained from ditchcuttings consists of species indicative of a bathyal setting (pers. comm. Karim, 1994).

## **FACIES ASSOCIATION**

This section describes the major facies associations based not only on facies studies of cores from three Tembungo wells, but also include aspects such as gamma-ray pattern (i.e. generalised coarsening and fining upward trends), thickness, lateral continuity and seismic facies (Table 1). Where appropriate, the more generalised facies schemes adopted here are compared to the widely used turbidite facies scheme of Mutti and Ricci Lucchi (1972, 1975) summarised in Table 2, and to Bouma's (1962) turbidite divisions.

Distinction between channelised and nonchannelised deposits requires knowledge on the lateral extent of a particular deposit. This information can only be inferred by well-to-well correlation using wireline log data. Another important criteria is the overall thickening (and coarsening) and thinning (and fining)-upward facies sequences. In an uncored interval, this is again reliant on log data. These vertical trends have long been associated with lobe and aggrading levee, and channel-fill deposits, respectively (Mutti and Ricci Lucchi, 1972; Mutti and Ghibaudo, 1972; Stow, 1986). Some of these vertical trends have been confirmed in the DSDP Leg 96 well drilled into the Mississippi fan (Pickering et al., 1989). However, Walker (1980) and Hiscott (1980) suggested a more cautious approach when applying these concepts to deep-marine systems.

### **Basin Plain**

The basin plain facies association comprises a monotonous sequence of laminated and massive mudstones of facies MI and Mm, respectively. Where sandstones occur, it is generally very finegrained and restricted to a few isolated thin beds bearing current-ripples (Figs. 12, 13, 15 and 16). The mudstones are occasionally heavily bioturbated and contain layers rich in comminuted organic matter. This sediment corresponds broadly to the facies G and D of Mutti and Ricci Lucchi (1972). This facies association is characterised by a serrated high gamma-ray log pattern and is distinguished from proximal overbank facies association by being thicker and more widespread in its distribution. In places, it can be mistakenly identified as the slope mudstone. However, the slope mudstone is commonly recognised by its occurrence within seismic foresets, while the basin plain mudstone is usually associated with parallel to subparallel seismic facies. The mudstones contain several species of exclusively arenaceous benthic for a such as Bathysiphon sp, Cyclammina amplectens, Cribrostomoides deformis, Cyclammina Glomispira amplectens. charoides and Trochammina renzi. This foraminiferal association is indicative of a bathyal setting.

### **Prograding Lobe**

The prograding lobe facies association generally shows a coarsening upward sequence. In cases where the upward coarsening profile is poorly developed, it is distinguished from a channel-fill by the lateral continuity of the association. A typical



**Figure 9.** Uninterpreted and interpreted seismic profile 5 taken along the north-eastern part of the Tembungo area parallel to depositional dip. It shows the various seismic units which are bounded by seismic markers; Horizon 4 (H4), Blue (B), and Green (G) and Red (R). Note that Unit 3 downlaps onto the blue marker; as a result, it is absent or occurs as a thin unit basinward of the slope.



Figure 10. This figure illustrates the variability of the sand-development pattern. Note the lateral distribution of the 'A' sand interpreted as channel-fill deposits. Well locations are shown in Figure 4.1.

association consists of a lower laminated mudstone interval of facies MI with sandstone laminae and thin rippled sandstone beds (0.5 to 3 cm thick). The frequency of these intercalated sandstones increases towards the top of the association. The sandstones in the upper part are generally medium-bedded varying between 15 to 25 cm thick, very fine to finegrained and normal graded.

Individual sandstone beds typically comprise a lower massive sandstone of facies Sm grading upward to parallel-laminated and/or crosslaminated sandstone of facies Sl and Sc, respectively (Figs. 13 and 20A). Evidence for scouring at the base of sandstone beds is absent. They can be described as the Bouma turbidite divisions with missing Td and Te units. Rip-up mud clasts and transported shallow water shell fragments are occasionally found in the lower massive units, while plant matter accumulates near the tops of the beds.

Samples taken from the mudstone interval contain the following foraminifera species: Cribrostomoides deformis, Cribrostomoides sp, Haplophragmoides sp and Trochammina renzi. This assemblage of arenaceous benthic foraminifera is indicative of a bathyal setting.

#### **Channel-Fill**

Distinguishing channel-fill association from that of a prograding lobe based on core data can be difficult. This difficulty is further compounded by the absence of significant influx of coarse material into the area resulting in poorly developed finingupward trends, typical of channel-fills. The channelfill facies association comprises intercepted fine- to medium-grained sandstones. The sandstones vary from medium to thickly bedded and generally show normal grading (Fig. 20B and E). A typical unit contains a massive sandstone bed of facies Sm at the base often accompanied by a scour surface and rip-up mud clasts, grading upward to thinly-bedded and laminated sandstone of facies Sb and Sl, respectively (Figs. 14, 17 and 18). In other cases, the sandstones are structureless except for occasional organic matter linings in the upper parts (Fig. 20C and D). Some of the sandstones have a current rippled top. The assemblages of primary sedimentary structures suggest that several varieties of stripped Bouma turbidite units, such as Ta-Tb-Tc and Tb-Tc units, are present and correspond to facies C of Mutti and Ricci Lucchi



**Figure 11.** Uninterpreted and interpreted seismic profile 6 parallel to depositional dip showing the various seismic units which are bounded by seismic markers; Horizon 4 (H4), Blue (B), and Green (G) and Red (R). Seismic facies of Units 5 and 4 consist of mound and bidirectional downlapping reflections.

Deposition Environment	Basin Plain	Prograding Lobe	Submarine Channel	Proximal Overbank	Slope
Facies Association	MI, Mm	Sm, Sl, Sc	Sm, Sc, SI, Sa	MI, Hb	MI, Hc
Gamma-Ray Pattern		7	5	-TH-	
Thickness and Lateral Continuity	> 10 m thick, laterally continuous	2–5 m thick, relatively widespread	2–25 m thick, discontinuous	Thin and laterally variable	Very thick, > 200 m and laterally widespread
Seismic Facies	Parallel, variable amplitude reflection pattern	Subparallel to mounding, high-amplitude reflection pattern	Subparallel to mounding, high-amplitude reflection pattern	Usually not resolvable but when associated with mud-rich channel-levee complexes tends to be of low-amplitude, parallel to subparallel reflection pattern	Well-developed large-scale clinoforms with overlapping slump channels

Table 1. Seimentary and seismic facies, and wireline log pattern of the different deep-water deposits.

Table 2. Mutti and Ricci Lucchi (1972, 1975) turbidite facies scheme.

FACIES A	Very thick and very coarse-grained, absence of tractive structure				
	Subfacies	A1:	"Organised" conglomerate, pebbly sandstone, sandstone		
		A2:	"Disorganised" conglomerate, pebbly mudstone, "slurried beds"		
FACIES B	Thick, medium- to coarse-grained				
	Subfacies	B1:	Relatively continuous beds, 30-200 cm thick.		
		<i>B2</i> :	Lenticular, wedging, top molded by dunes and ripples, 20-50 cm thick		
FACIES C	Complete graded Bouma sequence beds				
	Subfacies	C1:	Coarse to fine-grained sand, Coarse-tail grading, Tace and Tac		
		C2:	Medium- to fine-grained sand, distribution grading, Tabcde, Tabce,		
			Tabde		
FACIES D	Base-missing graded Bouma sequence beds				
	Subfacies	D1:	Tb-e, Tc-e, Tde, ss:sh >1, 3–40 cm thick		
		D2:	Tb-e, Tc-e, Tdc, ss:sh <1, 30–150 cm thick		
		D3:	Te mudstone only, 3-200 cm thick		
FACIES E	Thin bedded, medium- to coarse-grained sandstone with discontinuous shale partings, high ss:sh ratio, irregular geometry, ungraded, high-angle cross-bedding, sharp tops, 3–20 cm thick				
FACIES F	Chaotic deposits except debris flows (A2) from gravity sliding and slumping				
FACIES G	Pelites from hemipelagic deposition and 'rainfall'				



Figure 12. Sedimentary facies and depositional interpretation of Core 1.



Figure 13. Sedimentary facies and depositional interpretation of Core 2.



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Figure 15. Sedimentary facies and depositional interpretation of Core 4.



Figure 16. Sedimentary facies and depositional interpretation of Core 5.



Figure 17. Sedimentary facies and depositional interpretation of Core 6.



Figure 18. Sedimentary facies and depositional interpretation of Core 7.



Figure 19. Sedimentary facies and depositional interpretation of Core 8.

(1972, 1975). Transported shallow-water shells and foraminifera occur in a few intervals. Coaly laminae are common features of the sandstones, usually arranged parallel to beddings although, in parts, haphazardly.

The channel-fill association is usually characterised by a blocky-shaped log pattern. This feature usually occurs in groups at the top of stratigraphic Units 2 and 3. Intervals containing multiple units of channel-fills and prograding submarine lobes generally correspond to prominent



**Figure 20.** Core photographs showing examples of deepwater sandstones and mudstones. (A) normal graded massive sandstones (unchannelled deposit) with possible ripples based on alignments of organic lineations, (B) normal graded part of a channel-fill. Note the overlying heterolithic unit (possibly overbank or fine-grained channel-fill), (C) massive normal graded sandstone of a channel-fill, note the chaotic pattern of the organic linings at the top, (D) massive sandstone with hints of plane bedding at the top, (E) amalgamated normal graded sandstone with erosive contact of a channel-fill, and (F) heterolithic unit (overbank deposit) with resins and carbonaceous matter.

and mounded high-amplitude reflection patterns. These reflection attributes commonly occur at the base of seismic clinoforms. They can be broadly used to separate the basin plain from areas of active deep-water sand deposition.

#### **Proximal Overbank**

The proximal overbank facies association usually occurs as thin serrated high gamma-ray units between 'funnel' and 'blocky'-shaped gammaray profiles (Fig. 18). The major components of this association comprise alternating units of very finegrained sandstones and mudstones of facies Hb, and laminated mudstone of facies MI (Figs. 14, 18 and 20B). These sediments correspond to the facies D of Mutti and Ricci Lucchi (1972, 1975).

Plant fragments are common; occurring as thin coal laminae in places (Fig. 20F). There are also occasional thin to medium sandstone layers comprising a basal plane bedded unit and an upper cross-laminated unit of facies Sc. These units resemble the Bouma Tb and Tc divisions and, together, they form the facies D of Mutti and Ricci Lucchi (1972, 1975). The amount of benthic foraminifera obtained from the mudstones is comparatively low compared to those of the basin plain and slope facies associations. The dominant species are Ammodicus sp, Bathysiphon sp, Cibicides pseudoungerianus, Haplophragmoides sp, Karreriella sp and Sigmoilopsis schlumbergeri, which are indicative of a bathyal setting.

The close association of the proximal overbank deposits with channel-fills, suggests that some parts of the association are likely to constitute parts of the channel-fill units. Muddy channel-fills have been cored on modern submarine fans such as the Mississippi fan (Pickering, *et al.*, 1986). However, this fine-grained channel-fill is difficult to recognise in cores, and is therefore tentatively included as part of the proximal overbank deposit.

#### Slope

Sediments belonging to the slope facies association are only encountered in core 8 of Tembungo l well (Unit 5). The cored interval is located within the large-scale seismic foresets which correlates to an interval characterised by consistently high gamma-ray values (Fig. 19). Since the facies association is similar to that of the basin plain, the main criteria differentiating the slope from the basin-plain sediments is the presence of seismic foresets.

The dominant sedimentary facies consists of olive-grey laminated and bioturbated mudstones of facies MI (Fig. 19), containing cm long horizontal sand-filled burrows. Organic matter occurs as plant remains, resins and coaly bands as thick as 1 cm. There are occasional fine to very fine-grained rippled thin sandstone beds and laminae corresponding to the Bouma Tc and Td divisions. Sandstone is restricted only to a 45 cm thick, parallel-laminated, fine-grained sandstone layer of facies Sl (Fig. 19). The slope mudstone contains for a minifera endemic to bathyal setting.

## DEVELOPMENT PATTERN OF TEMBUNGO SANDS

The Tembungo deep-water sands consist of three main sandy units (2, 3 and 4) encased by slope and basinal mudstones of units 4 and 1, respectively. These units, which are assumed to be chronostratigraphic units, exhibit characteristic seismic and sedimentary facies, and lateral continuity which are interpreted to represent the different phases of the Tembungo deep-water sands development. Accumulation of these deep-water sands is not simply by stacking of offlapping shelf, slope and basinal units as proposed by Field and Gardner (1990) for the Rio Ebro margin. In the Tembungo case, it is controlled by the volume of sediment gravity flow that is strongly governed by tectonic and eustatic changes. This will be discussed in the following section.

A model depicting the different stages of growth of the Tembungo deep-water sands is shown in Figure 21. Deposition of the Unit 2 sediments during the initial phase of the deep-water accumulation is attributed to the lowering of relative sea level. This is mainly attributed to structural uplift onshore, especially along the Bunbury-St Joseph trend (Fig. 21A). This event is manifested to the east and southeast areas of the Sabah basin by a prominent angular unconformity. Active slumping accompanied by sustained turbidity flows along the tilted shelf-edge resulted in deposition of a laterally continuous sheet-like deposit of Unit 2. It can be traced for a distance of at least 30 km parallel to the slope and 25 km from the base of the slope. Progressive pinching-out of the unit towards the crest of the Tembungo structure indicates that its deposition was structurally controlled. It is thickest in the Pritchard synclinal axis, where it attains a maximum thickness of 200 m. In a few places along the slope, the unit pinches and onlaps



**Figure 21.** Depositional model of the Tembungo deep-water deposits. (A) Deposition of Unit 2 submarine fan, triggered by an episode of uplift at the basin flank. (B) Deposition of Unit 3 submarine fan contemporaneous with basinward growth of the shelf. (C) Accumulation of Unit 4 fine-grained channel-levee system as sediment supply wanes.

against the Shallow Regional Unconformity, and together with erosional truncation of the shelf, suggest that there is no coeval shelf unit. The shelf, and at least part of the slope, acts as a sediment-bypass zone funnelling sediments through numerous slump channels and gullies to the deeper parts of the basin.

The growth of Unit 2 was by the progradation of turbidite lobes as indicated by a series of basinward offlapping and downlapping internal reflections, manifested in wells as a series 5 m thick coarsening-upward units. The stacking of these units may represent gradual shifting of local depocentres in response to excessive vertical aggradation resembling the 'compensation cycle' of Mutti and Sonnino (1981). Continued growth of Unit 2 is represented by the juxtaposition of channel sands near the top of the unit as suggested by the common occurrence of 'blocky' and fining/thinning upward gamma-ray profiles. The sediments may be derived from several multiple point sources in the slope as implied by the along strike variability of the sand distribution pattern. Similar association of a basal coarsening-upward and upper finingupward profiles, interpreted as sheet and channel sands, respectively, have been shown in the Frigg and Balder fields submarine fans (McGoveney and Radovich, 1985; Sarg and Skiold, 1982).

The following phase of basin-infilling is marked by a thick and strongly prograding shelf and slope system of Unit 3 (Fig. 21B). This event coincided with the relative rise in sea level indicated by the thickness of the onlapping shelf unit. Towards the northeast, Unit 3 downlaps onto Unit 2 as illustrated by the pinching of the unit in Tembungo 3 and 6 wells (Fig. 2). In contrast, in the southwestern part of the basin. Unit 3 is represented by a thicker turbidite unit, which in the other four wells, comprises a sequence of upward-coarsening and fining sand packages. Facies studies on cores suggest that they principally represent channelfills and overbank deposits. The absence of Unit 3 towards the north is interpreted to be a consequence of diminishing volume of mass-flow in the area. Continuing structural movements, accompanied by a narrower and steeper shelf in the south, which is about 4 km in width as opposed to around 8 km towards the north, could have provided ample sediments for the Unit 3 deep-water sands in this area.

Continuing rise in the relative sea level, trapping most of the coarser fraction nearshore, is manifested by the deposition of the generally lowamplitude mounded reflections of Unit 3. In a few places, it is in the form of overlapping channellevee complexes. It has the lowest sand to shale ratio when compared with Unit 2 and Unit 3. Sandstone intervals are likely to be associated with channel and proximal levee deposits.

## DISCUSSION

#### Submarine Fan versus Apron

As increasing varieties of turbidite systems and submarine slides have been described, the term submarine fan and apron have often been misused. The following definitions of submarine fan and apron are based on the study of Nelson *et al.* (1991). A submarine slope apron consists of sediment derived from multiple sediment failures in the source area, characterised by proximal wedges of sand and mud which are occasionally chaotic in character. Away from the slope, the sediment comprises sheets of thin-bedded turbidite lacking in channel-fill deposits. In contrast, a submarine fan is characterised by a point source leading to a proximal channelised facies which grade basinward into unchanneled depositional lobe deposits.

The presence of numerous slump channels along the length of the slope suggests that the earlier phase of turbidite deposition was possibly in the form of a coalescing base of slope apron system. The occasional occurrence of chaotic and irregular seismic reflections may represent contorted proximal debris flows. However, such chaotic and irregular reflections have not been drilled. The association of the more laterally extensive basal sandy unit capped by channel-fill sands, and canyons along the slope, suggest deposition in a multiple-sourced submarine fan setting. Similar associations of fan and apron deposits have been noted in many studies of modern deep-marine environments (Droz and Bellaiche, 1985; Manley and Flood, 1988; Nelson and Maldonado, 1988; Weimer, 1990).

## CONTROLS ON THE GROWTH OF THE TEMBUNGO SUBMARINE FAN

Several models relating evolution of turbidite systems to relative changes in sea level have been proposed. These models are briefly summarised below. Mutti (1985) differentiated turbidite systems into three end members based on years of study of the Eocene Hecho Group (Fig. 22), which are primarily based on inferred location relative to source, near which the bulk of the sandstone facies occurs. Type I represents the 'highly efficient' turbidites of Mutti (1979) dominantly composed of unchannelled sandstone lobes. These lenticular bodies of sand are physically detached from the channels and slump scars from which the bulk of



Figure 22. Mutti (1985) turbidite system classification showing the composition and stacking pattern of type I, II and III submarine fans.

the sand for the lobes is derived. Type II deposits are finer grained and generally smaller than the Type I. They comprise varieties of channel-fill types that pass basinward into sandstone lobes. The sediment dispersal pattern falls in the 'poorly efficient' type of Mutti (1979). Type III deposits consist of fine-grained and thin-bedded sediments that are commonly interpreted as channel-levee complexes and as various types of slope drape. Sandstone bodies are restricted to channel-fill and proximal overbank deposits.

During the same time, Mitchum (1985) published a submarine fan model based only on multichannel seismic reflection data. His model is based on a single canyon fan system partly derived from modern and ancient examples, consisting of a lower and an upper fan units. This seismic-based submarine-fan model was subsequently incorporated in the lowstand systems tract of the sequence stratigraphic scheme by Posamentier and Vail (1988). The lowstand systems tract occurs



Figure 23. Exxon basin-floor and slope fan models.

during the time of relative sea-level fall and subsequent slow rise. It comprises basin-floor fan and slope fan (Fig. 23).

Morphologically, the basin-floor fan resembles the Type I fan of Mutti, i.e., physically detached from the canyon and older than the slope fan. Similarly, the slope fan resembles the Types II and III fans of Mutti's (Figs. 22 and 23). These models are similar in many aspects by relating the formation of the different types of turbidite systems to the volume of the sediments transported by gravity flow. Stacking patterns consisting of a basin-floor fan overlain by slope-fan, or Type I followed by Types II and III have been interpreted to reflect progressive rise in the relative sea level from a lowstand position. In the absence of sufficient supporting data from core analysis and field studies, Posamentier *et al.* (1991) correlated the basin-floor fan to the types I and II fans, and the slope fan as Types II and III fans of Mutti (1985).

Deposition of the Unit 2 submarine fan in the Tembungo and adjacent areas is attributed to a lowering in the relative sea level which triggered active truncation of the shelf and formation of numerous gullies and canyons on the continental slope. In a few locations, the submarine fan is physically detached from base of slope slump channels and characterised by prograding lobes capped by submarine channel-fills and proximal overbank deposits.

Therefore, compositionally and morphologically, the Unit 2 submarine fan resembles Mutti Type II system and the Posamentier and Vail (1988) basinfloor fan. Deposition of the Unit 3 submarine fan in the subsequent phase was, however, different. It was not as widespread and, more significantly, was accompanied by rapid progradation and aggradation of the shelf as a result of a relative rise in sea level. The locus of turbidite deposition also shifted towards the southern parts of the basin where structural deformation was still continuing. In spite of these differences, its sedimentary facies is similar to that of Unit 2, consisting of progradation of channel and overbank deposits over prograding lobe sediments. Again, it would be classified as the Type II turbidite of Mutti's (1985) and the basinfloor fan of Posamentier and Vail (1988), based on sedimentary facies characteristics. It, however, differs from the Mutti (1985) and the Posamentier and Vail (1988) models with regards to the timing of shelf margin outbuilding. In both these models, the deposition of Type II and basin-floor fan is not synchronous (pre-date) with progradation of the shelf margin as shown in Figures 22 and 23. The boundary between these fans and the overlying shelf and slope prograding complex is shown as a downlap surface, whereas in the Tembungo sands, deposition of the Unit 3 fan is closely linked to outbuilding of the shelf (Fig. 21). This discrepancy highlights the limitation of these models, especially in areas where structural deformation plays an important role. It creates instability along the slope for the creation of canyons, and provides ample sediment for continuing growth of deep-water systems even during the time of a general rise in relative sea level.

As their names imply, identification of basin floor and slope fans in the Posamentier and Vail (1988) model is related to where they are deposited. Consequently, the sedimentary facies of these fans will vary from one system to another, depending on the type of sediment and the frequency of mass flows. As an example, the basin-floor fan of the Mississippi River, deposited during time of maximum sea-level lowstand, consists of mud-rich channel-levee complexes (Weimer, 1990), and thus will be classified as Mutti's Type III fan. It is also likely that the identification of basin-floor fan, in many cases, is limited by the vertical resolution of the seismic data.

Seismic evidence indicates that the deposition of the Tembungo submarine fan complexes is related to the relative fall in sea level. Discriminating between the tectonic and eustatic components of the fall is, however, difficult and can only be surmised. The age of the Shallow Regional Unconformity, which is at the base of the submarine fans, has been estimated to be near the boundary of the nannofossil NN9 and NN10 biozones at around 9 Ma; while the closest eustatic fall from the Exxon onlap chart is at 8.2 Ma, which is at the boundary of NN10 and NN11 biozones. Furthermore, the rate and amount of the eustatic fall, which is less than 50 m, are comparatively smaller than the others on the Exxon curve.

There are also much thicker and laterally widespread units of turbidite deposited in the preceding Sequence 2 and Sequence 3, which do not tie with a lowstand in the Exxon eustatic onlap curve. These turbidites, resembling the basin-floor fan of Posamentier *et al.* (1991) on seismic sections, were derived from large-scale slumping of the mechanically active margin described by Levell and Kasumajaya (1985), and therefore, cannot be used as evidence of eustatic changes.

Onshore structural deformation preceding the deposition of the submarine fans was intense, especially in the southeastern parts of the basin. There are two main effects of the structural movements: large volume of sediment source and steepening of the depositional slope. Closer to the shelf edge, repeated uplifts of the Bunbury-St Joseph Ridge provided large amounts of shallow marine clastics, which were reworked and bypassed the narrow shelf into the basin. These sediments were funnelled into the basin plain through a series of canyons along the base of the slope. Numerous occurrences of reworked foraminifera, supported by seismic data, indicate that the residence times of the sediment deposited before being subsequently eroded, in many cases, are less than 1 Ma.

#### CONCLUSIONS

- 1. Deposition of the Tembungo deep-water sands is interpreted to occur in three different stages as opposed to an earlier interpretation by Whittle and Short (1978) of a single, prograding submarine fan consisting of vertically stacked basin plain, outer fan and inner fan deposits.
- 2. The first stage consists of deposition of the Unit 2 submarine fan, which is laterally widespread, accompanied by extensive truncation of the shelf and slumping processes along the continental slope. Deposition of the Unit 3 submarine fan and contemporaneous build-up of the continental shelf represent the second stage. The third stage comprises deposition of Units 4 and 5 which thin-bedded turbidites associated with small-scale mud-rich channel-levee complexes.
- 3. Sequential development of the three stages is interpreted as being controlled by the volume of sediment gravity flow, which relates to structural deformation and relative sea-level changes. Unit 1 coincides with relative sealevel lowstand, while Units 2, 3, 4 and 5 occur during the following rise.
- Several aspects of the Tembungo deep-water 4. sands resemble the Mutti (1985) and Exxon (1988) Models. The main difference is in the deposition of the sand-rich Unit 3 submarine fan, which was accompanied by rapid build-up of the continental shelf. In their models, the deposition of sand-rich turbidite system (i.e. basin floor-fan and Type I and II fans) predates the growth of the shelf. This association is rather strange because one would expect rapid shelf build-up to be accompanied by trapping of sands in shelf depositional systems. Therefore, there must have been a substantial increase in the rate of supply of sandy material (due to source area uplift) in order to satisfy the demands of both shelf and fan. An efficient conduit for sands through points on the shelf must also have existed.

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