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Tarakan Basin, NE Kalimantan, Indonesia: a century of exploration and future potential

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Abstract: Nearly a century of exploration in the Tarakan Basin of NE Kalimantan, Indonesia, has yielded four major oilfields, with a total cumulative production to end-1986 of 312 MMBO (million barrels of oil), plus one large gas field and five minor oil accumulations. Reserves reside mainly in stacked, predominantly fluviatile, thick sandstone reservoirs of Pliocene and Pleistocene ages. Multiple reservoirs (up to 90 zones) also occur within shallow marine sandstones of Upper Miocene to Pliocene age Traps are primarily downthrown, independently-closed, roughly north-trending anticlines, ranging between 960 and 2600 acres. Most major accumulations are located on Tarakan and Bunyu islands, with only one on the mainland but as yet none offshore.

Over 86% of produced reserves had been discovered prior to 1923 (Pamusian, 1901; Bunyu, 1923). Both structures were easily identified by their surface expressions and oil seeps. Recent exploration (post 1970), with over 30 exploration wells drilled onshore and 16 offshore, added the medium-sized Sembakung oil field and the large Bunyu Tapa gasfield. The lack of success offshore is largely attributable to the rarity of sufficiently large, independently-closed structures at shallow depths, within the Plio-Pleistocene sand-prone levels so productive in the largest onshore fields.

Migration timing is partly constrained, at least on Bunyu Island, by the presence of Pleistocene reservoirs, indicating extremely late migration, into structures which are either early Pleistocene or possibly re-activated Pliocene or earlier features. Bunyu and Tarakan Islands were depocenters during the late Miocene and Pliocene and were only inverted in late Pleistocene times. Precise dating of tectonic phases is rendered difficult by a lack of age-diagnostic fossils and by laterally discontinuous seismic events which do not correlate laterally with wells nor onshore outcrops.

Technical problems have been partially solved by high-quality seismic data, new wells and isotope age dating. Untested plays include closures at older stratigraphic horizons, growth-fault plays in the deep-water area and stratigraphic traps. This review presents a summary of the Tarakan Basin stratigraphy and structure in relation to the exploration history and an assessment of the currently perceived hydrocarbon potential. The combination of high technology and understanding of basin dynamics will hopefully be the key to success, before the close of a century of exploration.

INTRODUCTION

The area discussed surrounds Sceptre Resources' Offshore Bunyu PSC (Fig. 1). The PSC (Production Sharing Contract) is surrounded by the Northeast Kalimantan basinal area (Fig. 2) which is a collection of four Tertiary depocentres which include the Tarakan basin. Although the latter is sometimes referred to as a sub-basin or as the 'Bulungan' sub-basin, since it covers an area of 7,000 km^2 and contains over 5,000 metres of mainly Plio-Pleistocene sediments, it is here regarded in informal oil company terms as a basin in its own right.

Nearly a century of geological and hydrocarbon exploration has been conducted in the basin, yielding four major oilfields, with a total cumulative production of over 320 MMBO (million barrels of oil) to the present. Also, one large gas field and five minor oil accumulations have been produced. Reserves reside mainly in thick, stacked, fluviatile, Pliocene sandstone reservoirs, although significant production is also obtained from thinner, marine sandstones (up to 90 zones in some cases) of late Miocene to Pliocene age and a few zones in the Pleistocene on Bunyu.

The two largest accumulations are trapped in downthrown, independently-closed, roughly north trending anticlines, ranging in size from 960 to 2,600 acres (3.9 to 10.6 km^2 respectively), located on Tarakan and Bunyu islands (Fig. 3). Apart from the island fields, there is only one field which has produced commercially on the mainland. As yet, no commercial discoveries have been made offshore, although several wells had sub-commercial flows. The lack of commercial finds offshore is largely attributable to the rarity of sufficiently large, independently-closed structures at shallow depths,

Figure 1. Indonesia location map. The Offshore Bunyu Production Sharing Contract area, operated by Sceptre Resources Bunyu, is located in the extreme north-east of Kalimantan, Indonesia.

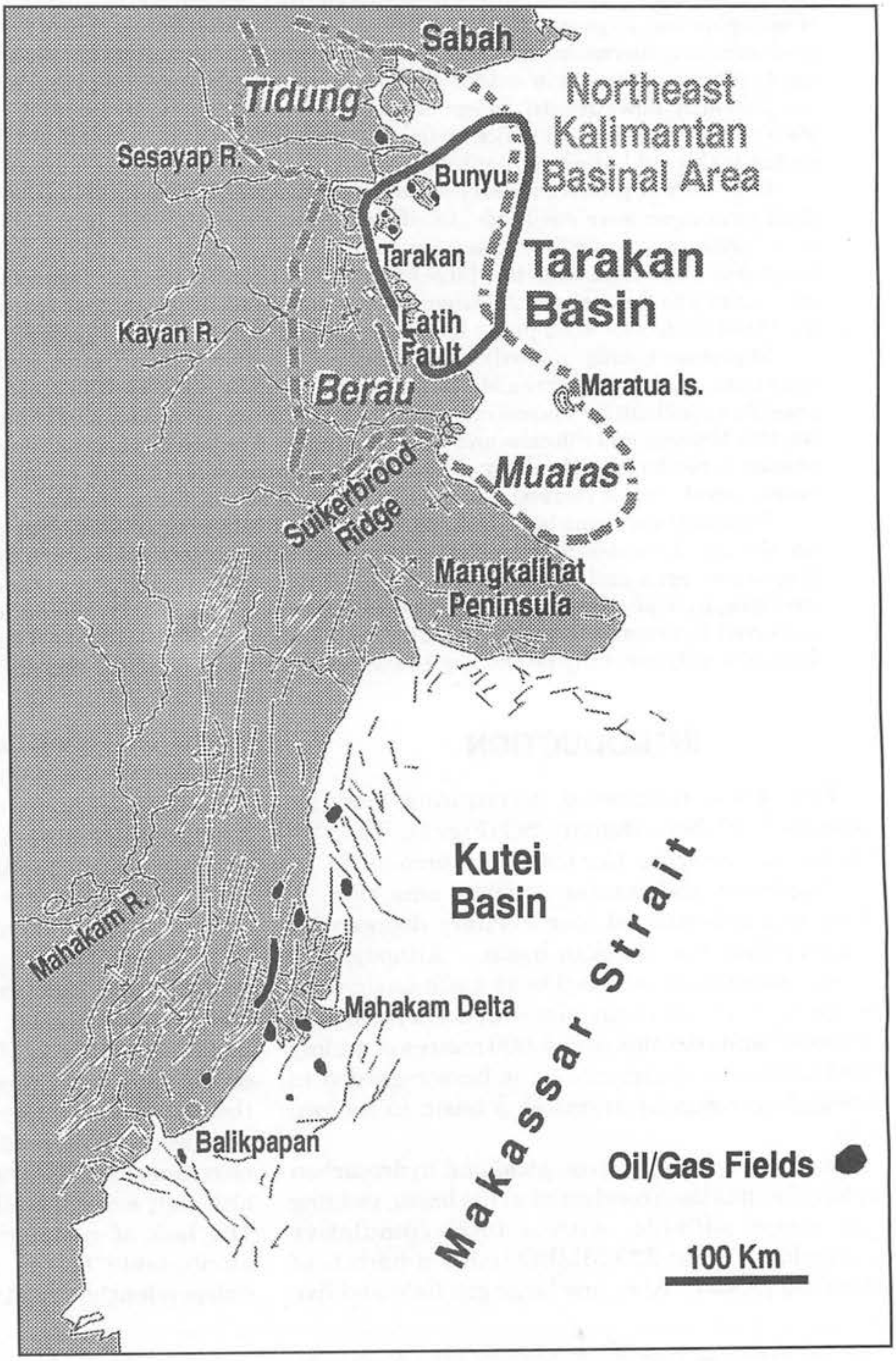

Figure 2. East Kalimantan basins. The Tarakan Basin, as informally defined by oil-industry operators, is outlined. It lies within the greater Northeast Kalimantan Basin area, which comprises two offshore basins (Tarakan and Muaras) and two onshore ones (Tidung and Berau). Although these have been regarded as sub-basins, all are considered to be of sufficient size to rank as full basins elsewhere. They are paired, such that the onshore basins are merely the uplifted and eroded Paleogene to early Neogene sequences, the equivalents of which lie below the late offshore Neogene ones (Pertamina/Beicip, 1985).

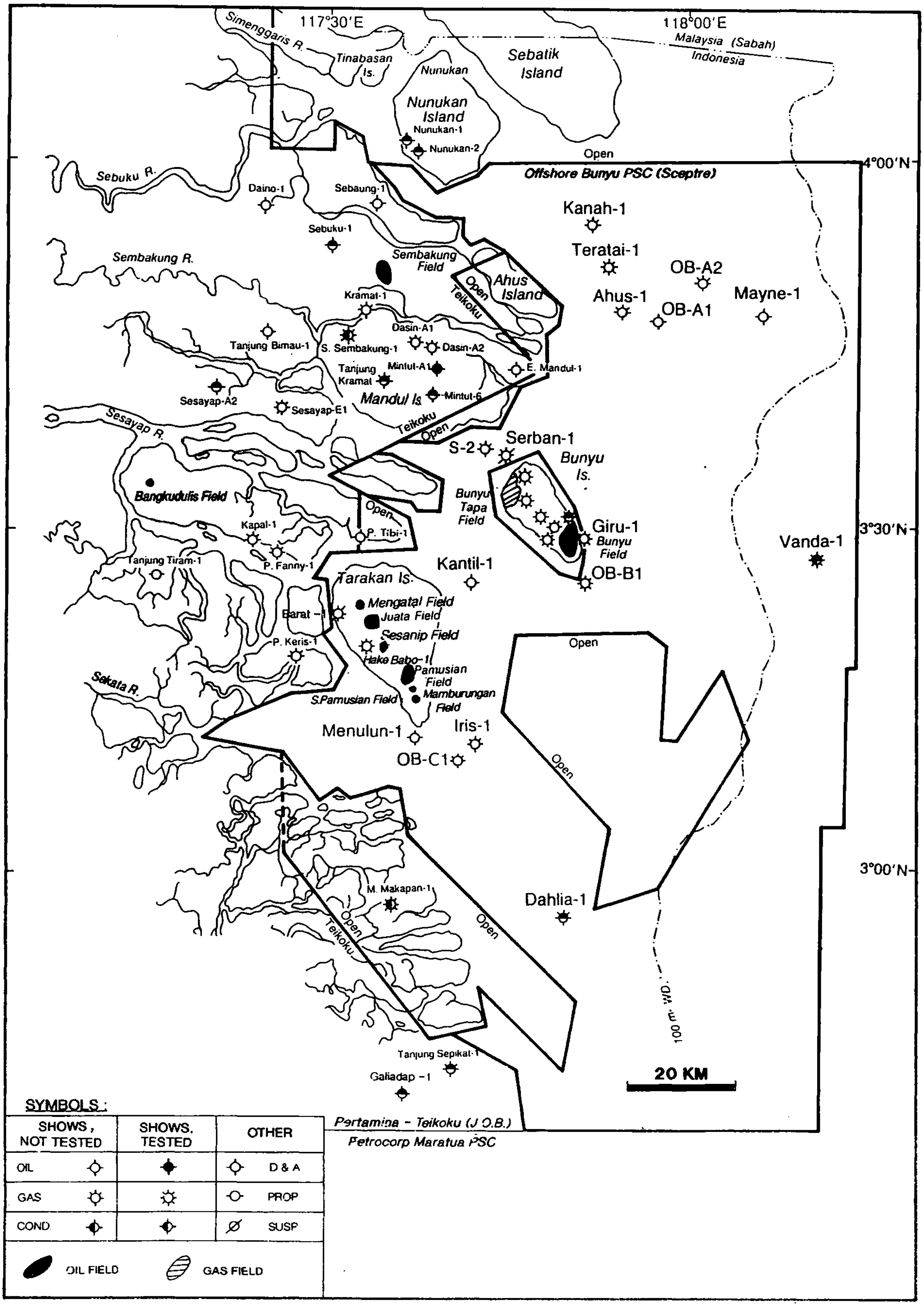

Figure 3. Tarakan Basin — wells and fields. Ten of the twelve commercially produced fields are shown, with the largest five (Pamusian, Bunyu, Sembakung, Juata and Bunyu Tapa) highlighted. The concentration of commercial fields on Tarakan and Bunyu islands is partly due to abundance of accessible structures and prolific, stacked, shallow Plio-Pleistocene sandstone reservoirs. The onshore area is less accessible, less heavily explored and has Miocene reservoirs of lower quality. The sixteen offshore wells, drilled by Japex, Total, Amoseas and finally Sceptre, boast several sub-commercial finds: a suspended gas well (Serban-1), three wells with tested or log-calculated gas zones (Teratai-1, OB-B1 and Giru-1) and a tested gas condensate discovery with oil from RFT (Vanda-1).

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Over 90% of produced reserves had been discovered prior to 1923 (Pamusian, 1901; Juata, 1918 and Bunyu, 1923). These structures were easily identified by their surface expressions and oil seeps. Recent exploration (post 1970), with over 30 exploration wells drilled onshore and 16 offshore, added the medium-sized Sembakung oil field and the large Bunyu Tapa gas field.

Precise dating of tectonic phases is rendered difficult by a lack of age-diagnostic fossils and by laterally discontinuous seismic events which do not correlate laterally with wells nor onshore outcrops. Migration timing is partly constrained, at least on Bunyu Island, by the presence of Pleistocene reservoirs, indicating extremely late migration into what appear to be early Pleistocene structures but may also be re-activated Pliocene or Miocene features. Bunyu and Tarakan Islands were depocenters during either late Miocene, Pliocene or early Pleistocene times and were only inverted during late Pleistocene times.

Geophysical and geological problems, some technical and others due to the monotonous stratigraphy, have been partially solved by high-quality seismic data, new wells and strontium isotope age dating. This review presents a summary of the Tarakan basin exploration history in relation to tectono-stratigraphy and concludes with an assessment of the remaining hydrocarbon potential. Untested plays include closures at older stratigraphic horizons, growth-fault plays in the deep-water area and stratigraphic traps. The combination of high technology and a modern approach to basin dynamics will hopefully be the key to success, before the close of a century of exploration.

EXPLORATION AND PRODUCTION HISTORY

Hydrocarbon exploration began in NE Kalimantan just before the turn of the nineteenth century. Several years of geological field surveys, at first in search of coal and other economic minerals, eventually resulted in the identification of oil and gas seeps on Tarakan and Bunyu islands. Drilling began on Tarakan island as early as 1897 and in 1901 the largest field to date in the Tarakan basin, Pamusian, was discovered and put on production in 1906 (Fig. 3). It has produced with various interruptions until the present day with a cumulative production of 193 MMBO, representing 60% of the basin production to date (Figs. 4 and 5).

Exploration continued on Tarakan, Bunyu and Mandul islands, with the discovery of gas seeps at Bunyu field in 1901, although the true size of the accumulation, not realized until deeper wells were drilled, was not put into full production until 1929. It is the second largest field in the Tarakan basin with cumulative production of 83 MMBO representing 26% of the basin total (Figs. 4 and 5). Juata field, with 17 MMBO representing 5% of the total cumulative production (Figs. 4 and 5) was found in 1918. Thus by the early 1920's the three fields containing over 90% of the presently produced reserves had been identified and partly developed.

The structural style of Pamusian and Bunyu fields (Figs. 6 and 7) is that of independent closures on the downthrown sides of north to northeast oriented normal faults. The Juata field differs in being an upthrown fault-dependent feature, (Fig. 8) as is the small Sesanip field, unusual in being trapped by a small reverse fault. During the next 50 years since the mid 1920's, despite extensive onshore geological mapping, gravity surveying and drilling, only 28 MMBO (8%) were discovered (Fig. 4). The bulk of these (23.2 MMBO) were from the third largest field, Sembakung, discovered in 1976, onshore north of Mandul island, (where minor production, established briefly in 1913 at Mintut, had indicated onshore potential). The Sembakung field (Fig. 9) produces from marine, deltaic, Upper Miocene sandstones, contrasting with the Tarakan fields which produce from the Pliocene only. Structurally, it is a rollover bounded by late, northwest oriented faults, but its closure is independent of the major down-to-basin, northeast oriented, normal fault which lies to the northwest. It is possible that the rollover was generated by growth-faulting.

Apart from the major discoveries, many smaller oil fields have been produced, such as the fault blocks on the northwest side of Bunyu field, i.e. B. Nibung and B. Nibung Barat and the Mengatal, S.Pamusian and Mamburungan fields on Tarakan island. Other accumulations, not included as commercial producers in the basin are the Bangkudulis field which produced for a short time from 1973 and the Mintut wells on Mandul Island. Only two gas accumulations, Bunyu Tapa and Selatan, have been commercial so far although gas and condensate have been tested from many wells on Tarakan and Bunyu islands as well as offshore. It is hoped that increased gas demand and recently improved pricing will promote further developments in this sphere.

In summary, of the 14 accumulations which have produced commercially, ten oil fields and one gas are still productive (Table 1). Three sub-

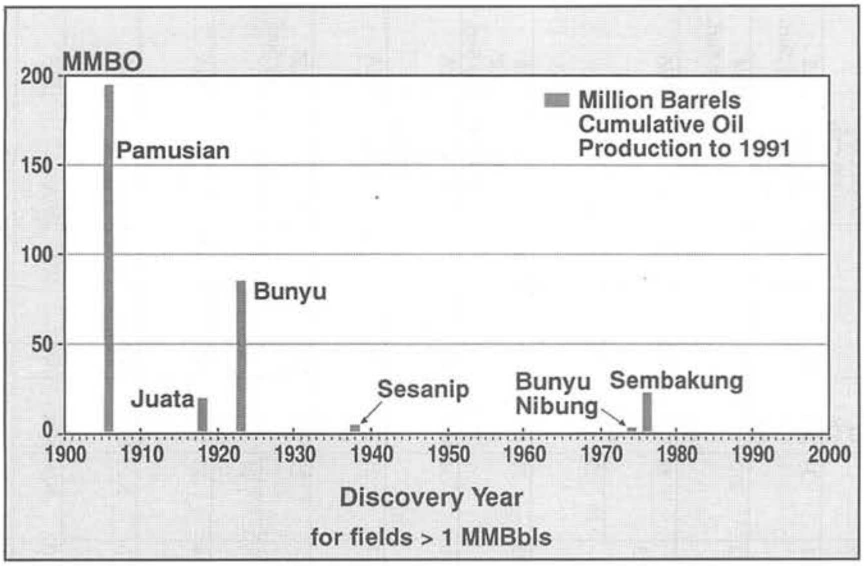

Figure 4. Tarakan Basin production. Cumulative production to 1991 was 320 MMBO (million barrels of oil), with three of the largest fields discovered between 1901 and 1924. No major reserves have been added since the 1970's (MMBls = million barrels).

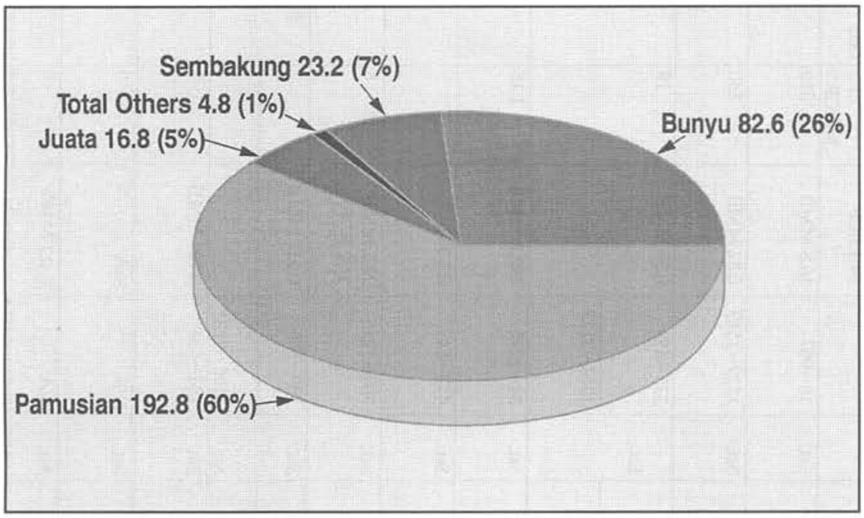

Figure 5. Cumulative oil production by field. Pamusian, with 192 MMBO (million barrels of oil) cumulative production, is the largest field in the basin. Together with the other Tarakan island fields, this represents 66% of the total. The second largest field is Bunyu, with 82.6 MMBO or 26%, followed by Sembakung with 23.2 MMBO, or 7% (MMBls = million barrels).

commercial gas or gas condensate finds have been made offshore and eight gas finds on Bunyu island. The total cumulative oil production to date is 320 MMBO in a basin of 7,000 km^2 with only eighteen offshore and approximately twenty-three onshore exploration wells. To the outside observer, the basin thus seems to be under explored and also to have the potential to contain significantly larger reserves, as will be discussed below.

STRUCTURE

Depocentres

The informal oil company term 'Tarakan basin' as used here encompasses the offshore and island areas centred around Tarakan and Bunyu island. Its boundaries with the neighbouring Tidung, Berau and Muaras sub-basins (Achmad and Samuel, 1984) can be more rigorously defined in terms of stratigraphy and structure, as being that collection of contiguous Plio-Pleistocene depocentres underlain by Miocene depocentres which have not been uplifted to outcrop, such as is the case in the onshore sub-basins (Fig. 2). Using this definition, the northwestern and western basin boundaries follow regional-scale, northeast and north-northwest oriented fault trends, respectively. The northeast trend, perpendicular to the the Ahus arch has, on its upthrown, northwest side near the Kanah-1 well, a shallow, uplifted, Miocene limestone shelf edge overlain by relatively thin Plio-Pleistocene sediments. Nunukan and Sebatik islands and onshore Simengaris, to the northwest of the boundary, are part of a Miocene depocentre, the Tidung sub-basin, the distal deltaic part of which continues below the main Tarakan basin. Southeast of the boundary fault, the Pliocene

Table 1: Tarakan Basin — Oil and gas fields data. From IPA Oil and Gas Fields Atlas, Kalimantan, 1991.

NO.	FIELD NAME	1992 Operator (Old OP.)	Status	YEAR DISC.	AREA (Prod.)	FORM./AGE	LITH.	PAY DEPTH (m ss.)	CUM. PROD. (1991)	CURR. PROD. BOPD	CURR. PROD. WELLS	AVE. POR. (%)	PERM. (mD.)	VERT. CLOS. (m.)	H/C COL. (m.)	OIL GRAV. (^{0}API) GAS COMP.	Rw Ohmm/m^2
1	BUNYU	Pert. IV	Oil Prod.	1923	1483 ac 6 km^2	Bunyu, Tarakan Tabul Pleist. – U. Mio.	Sst.	300–1818	82.6 MMB 2.42 BCF	3330 –	Oil 45 Gas 6	21	N/A	N/A	1518	33.24 2% CO_2 89% CH_4	0.40 @ Surf.
2	BUNYU NIBUNG	Pert. IV	Oil, Gas Prod.	1974	914 ac 37 km^2	Bunyu, Tarakan Tabul Pleist.–U. Mio.	Sst.	917–3165	1.1 MMB 14.5 BCF	54 –	Oil 2 Gas 2	20	409	N/A	2248	39.2 7% CO_2 88.6% CH_4	N/A
3	BUNYU NIBUNG BARAT	Pert. IV	Oil, Gas Prod.	1979	1038 ac 4.2 km^2 ?	Tarakan, Tabul Plio.–U. Mio.	Sst.	950–3200	0.3 MMB 0.43 BCF	–	N/A N/A	25	612	80	2250	N/A 2% CO_2	0.21 @ 135 °C
4	BUNYU TAPA	Pert. IV	Gas, Oil Prod.	1975	2619 ac 10.6 km^2	Bunyu, Tarakan Tabul Pleist.–U. Mio.	Sst.	220–3105	0.5 MMB 39.3 BCF	346 23.1 MMCF	Oil 2 Gas 9	26	56 to 576	75	2885	49.59 2.5% CO_2 86.9% CH_4	N/A
5	JUATA	Exspan (Tesoro)	Oil Prod.	1918	(544 ac) (2.2 km^2)	Tarakan Plio.	Sst.	18–967	16.8 MMB	310	21	34	300 to 800	50	949	18.9 – 20.5 3.7% CO_2 95% CH_4	1.2 @ Surf.
6	MAMBURUNGAN	Exspan (Tesoro)	Oil Prod.	1985	346 ac 1.4 km^2	Tarakan Plio.	Sst.	1529–1563	0.32 MMB	540	2	25.5	450 to 850	18	34	32.1	0.4 @ Surf.
7	MENGATAL + GUNUNG CANGKOL	Exspan (Tesoro)	Oil	1936	(198 ac) (0.8 km^2)	Tarakan Plio.	Sst.	335–673	0.39 MMB	19	3	32	250 to 450	125	48	19.6	N/A
					(49 ac) (0.2 km^2)	Sesanip U. Mio.		1263–2129				27		50	10	41	
8	PAMUSIAN	Exspan (Tesoro)	Oil Prod.	1901	(961 ac) (3.89 km^2)	Tarakan Plio.	Sst.	54–1272	192.8 MMB	1.18	93	37	500 to 1700	40	1121	18 – 26.7 5% CO_2 94.7% CH_4	1.8 4.05 @ Surf.
9	SELATAN	Exspan (Tesoro)	Gas Aband.	1976	247 ac 1 km^2	Tarakan Plio.	Sst.	477–843	0.2 BCF		0	31	N/A	66	57	17.9 5% CO_2 96.5% CH_4	N/A
10	SEMBAKUNG	Pert. IV (Arco)	Oil, Gas Prod.	1976	2224 ac 9 km^2	Tabul U. Mio.	Sst.	500–1235	23.2 MMB 24.2 BCF	2831.8	17	21	33 to 892	50	366	38	N/A
11	S. PAMUSIAN	Exspan (Tesoro)	Oil Prod.	1973	74 ac 0.3 km^2	Tarakan Plio.	Sst.	589–846	0.035 MMB		N/A	27	N/A	360	7	20.6	0.35 @ Surf.
						Sesanip U. Mio.	Sst.	2195–2231				24			4		
12	SESANIP	Exspan (Tesoro)	Oil	1938	(309 ac) (1.25 km^2)	Sesanip U. Mio.	Sst.	188–634	2.126 MMB	98	4	35	250 to 350	42	446	N/A 88% CH_4	N/A
13	BANGKUDULIS	Pert. IV (Arco)	Oil Temp. Abd.	?1976	N/A	?U. Mio.	Sst.	N/A	N/A	0	0	N/A	N/A	N/A	N/A	N/A	N/A
14	MINTUT	(BPM)	Oil Abd.	?1975	N/A	?U. Mio.	Sst.	N/A	± 0.3 MMB	0	0	N/A	N/A	N/A	N/A	N/A	N/A

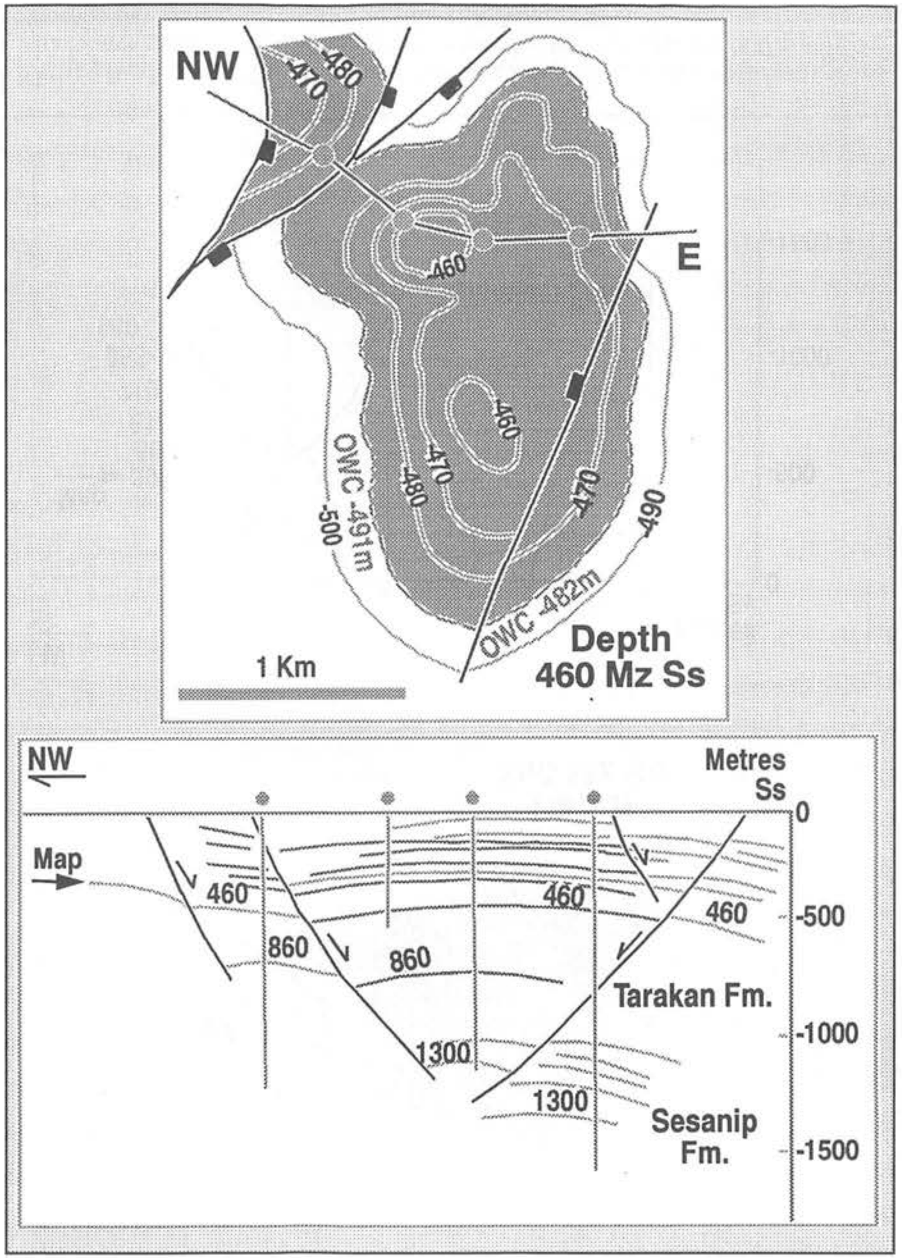

Figure 6. Pamusian. A structure map and cross-section (simplified from the Pertamina-IPA Atlas, 1991) show the downthrown, rollover style and multiple, Plicoene, stacked pay zones, at subsea depths mainly above 460 m (heavy oil) and 860 m (lighter oil). The structure is oriented north-south and may result partially from local growth-faulting.

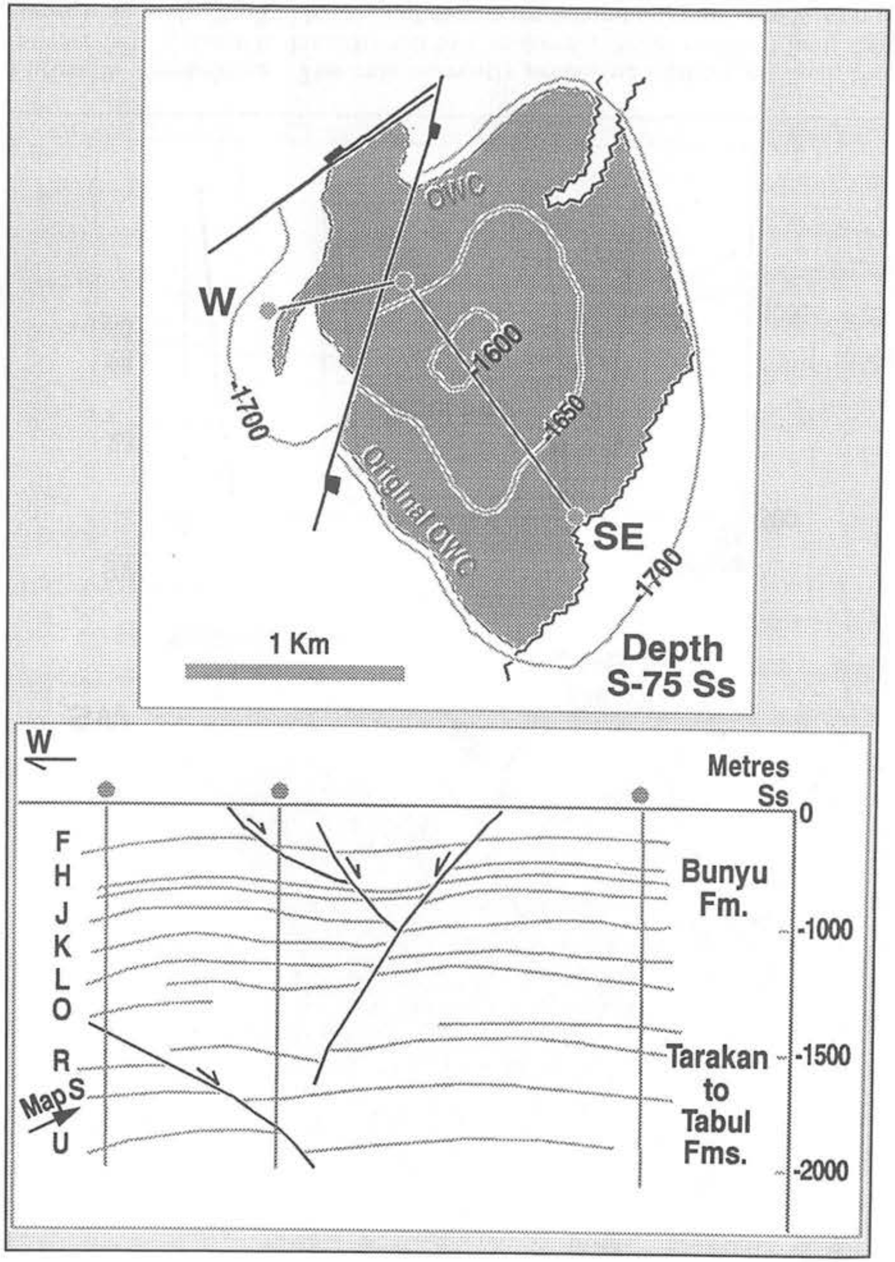

Figure 7. Bunyu. A structure map and cross-section (Pertamina-IPA Atlas, 1991) show the north-south oriented, downthrown rollover and multiple, stacked pays ranging down to around 2,000 m subsea in the Pleistocene, Pliocene and Miocene. Note the similar orientation and possible growth origin to Pamusian.

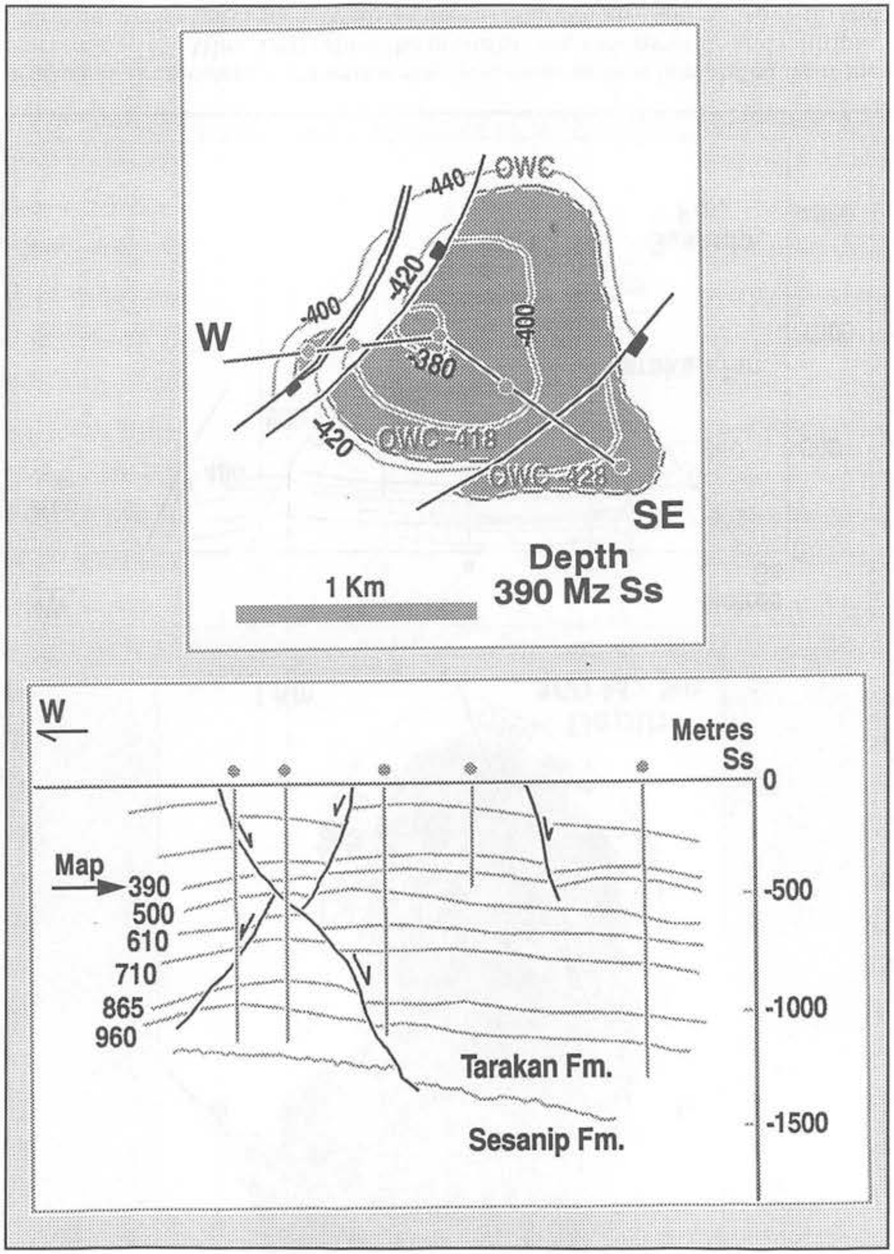

Figure 8. Juanta. This field and Sesanip are the only two upthrown traps which have produced in the basin. Juata has shallow, (less than 1,000 m subsea) Pliocene pay zones. (From Pertamina-IPA Atlas, 1991).

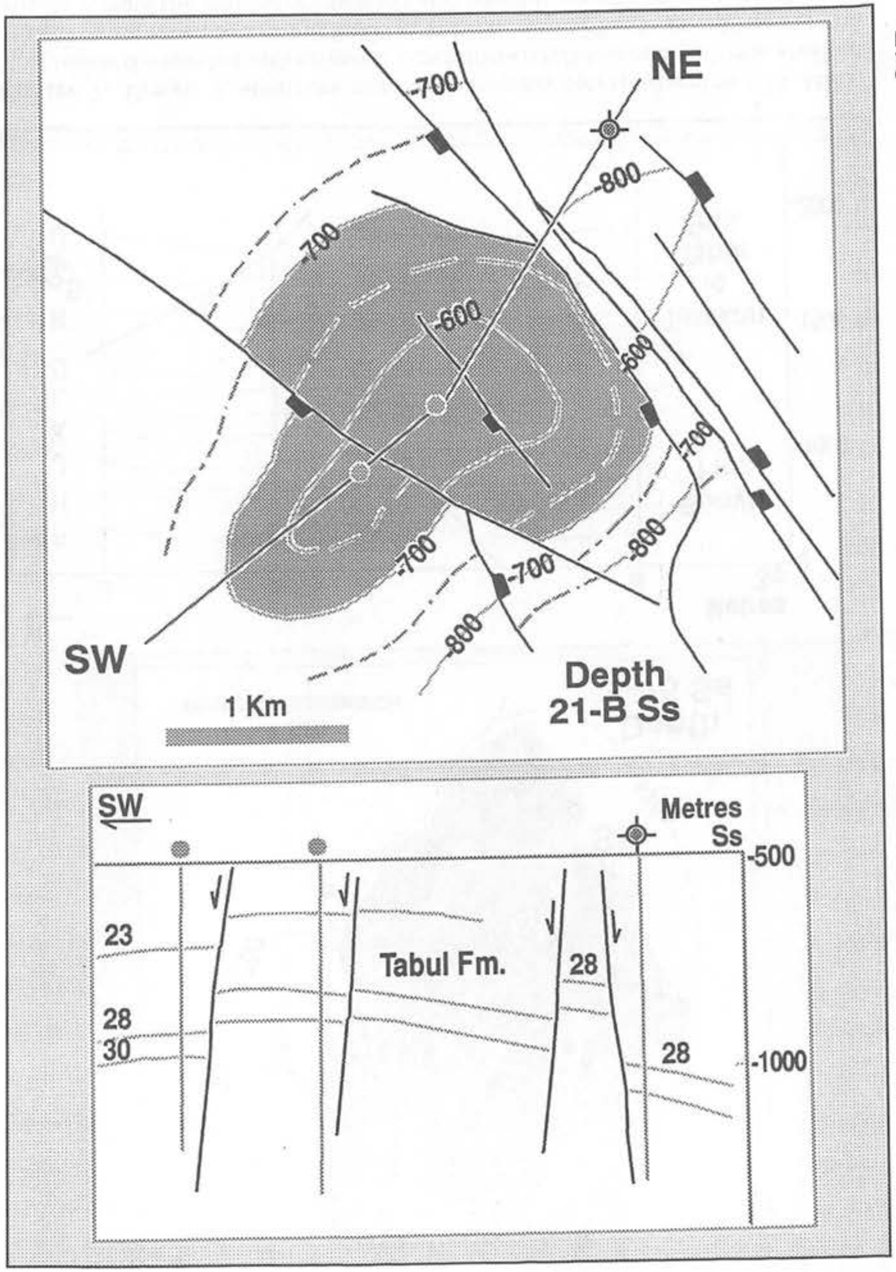

Figure 9. Sembakung. The only currently producing onshore oil field, this independent rollover is downthrown to a major northeast oriented fault (not shown). It is also faulted by a set of northwest-trending faults. Production is from Upper Miocene deltaic sandstones from between 300 and 1,800 m subsea.

thickens abruptly, consisting of several thousand metres of massive fluviatile sandstones overlying overpressured marine shales; the base of the Pliocene reaches nearly 4,000 m (Fig. 10).

The western basin boundary (Fig. 2) follows the northeast fault trend southwards towards Bunyu island, opposite which, in Mandul island to the northwest, the Miocene has been uplifted several thousand metres to outcrop in a complexly faulted, mud diapiric dome. In the channel between Mandul and Bunyu islands, a series of listric, down-to-basin, normal faults terminate at the northern end of the Bunyu arch. In the Sesayap river mouth, the basin boundary turns through 120°, from a northeasterly direction to the north/north-northwest fault trend passing through Tarakan island (Fig. 11). As in the north, the Plio-Pleistocene cover west of the basin-bounding fault is less than 1,500 m, but offshore to the east, there is an abrupt thickening to over 3,000 m.

Towards the southern end of the basin, the boundary passes through the root of the Bulungan delta and into the major Latih fault (Fig. 2), west of which the Plio-Pleistocene is absent, probably due to non-deposition following the late Miocene uplift. Immediately east of the fault, the Plio-Pleistocene unconformably onlaps folded Miocene, thickening significantly farther eastwards across a series of probable growth faults, into the shelf margin area. The southern basin boundary is taken as the point where the Pliocene clastics give way to limestones, near Bunyut-1 well.

Seismic definition of the eastern basin boundary is arbitrarily taken as the shelf break at the 200 m isobath, beyond which little data exist. It is also poorly defined due to sea-bottom multiples obscuring the thinned Neogene sequence, which contains slump structures and possible mud diapirs.

Internally, the Tarakan basin comprises both Pliocene and Pleistocene depocentres (Fig. 10). The Pliocene ones are inverted, as for example below Tarakan and Bunyu islands, while the Pleistocene ones, the Kantil and Mandul troughs, continued to subside. The easternmost depocentre, east of the Mayne Fault, contains active growth-faulting of both Pliocene and Pleistocene ages.

Depocentre outlines and their sedimentary environments appear to have been controlled by several factors: (a) Subsidence and loading in deltaic areas supplied by large rivers such as the Kayan river (Bulungan delta) in the south, the Sesayap river (Pliocene delta) in the central area and the Simengaris river (Miocene and Pliocene deltas) in the north, (b) Switching of river channels diverted by islands formed by the uplift of inverted depocentres (c) Growth faulting along the entire eastern margin. The most pronounced of these depocentres, the Kantil trough (Fig. 10), contains vast thicknesses of sandstone; for example 768 m in Kantil-1 (Table 2) and has a total Pleistocene thickness in its eastern portion in excess of 4500 m. The other significant Pleistocene thickening (up to 3,000 m) occurs in some areas immediately east of the Mayne fault system, where Pleistocene growth-faults with throws exceeding one second seismic TWT occur in the north (line A, Fig. 12).

Pliocene depocentres do not generally correspond with the Pleistocene ones, owing to differential growth along the Mayne fault and also of the asynchronous formation of the arches, which appear from seismic stratigraphy to young from south to north. Thick Pliocene underlies the eastern part of Tarakan island (where it also outcrops), below Bunyu island and at the eastern end of the Ahus arch. East of the Mayne growth fault system, near Vanda-1 well, the Pliocene is greatly expanded (to around 2,500 m thinning eastward to less than 1,000 m over the East Vanda high. This feature is an elongate, north-south rollover anticline, involving Pliocene beds and generated by the Mayne growth-faults, which sole-out around 5.5 sec seismic TWT. Its origin, however, may be older, since the (?Miocene) dips steeply westwards and is discordant with the east-dipping younger section, suggesting the presence of a Mio-Pliocene unconformity, suspected to be widespread in the basin. This boundary may also be a décollement surface.

Anticlines

The largest anticlines in the basin are the elongate Tarakan (± 100 km) and Bunyu (± 40 km) arches, the shorter (± 30 km) Ahus arch to the north, the Mandul dome, the Sembakung high, the series of north-south oriented growth-anticlines on the downthrown side of the Mayne fault and the East-Vanda high (Fig. 11). The Tarakan and Bunyu arches (Line B, Fig. 13) host 92% of all commercial hydrocarbon accumulations in the basin, and their plunging noses or flanks have been the scene of most of the offshore exploration effort.

The Tarakan arch, the longest of the three, runs down the spine of the island and plunges south-southeastwards past the Dahlia-1 well. The arch is obliquely transected by a series of left-stepping, north-northwest to north oriented faults with a subsidiary set of north-east normal (? growth) faults. Several small fields occur along this complex, discontinuous series of faults and show considerable variety in trap style, such as the small Sesanip field mentioned above, the Mengatal field, with a complex (?flower) structure and Juata field, unusual for the basin in being an upthrown closure on the eastern side of a northeast oriented normal fault (Fig. 8). The downthrown rollover at Pamusian

Table 2: Tarakan Basin — Cumulative net sandstone.

WELL NAME	KB (m.)	Water Depth/ Ground Level (m.)	T.D. (m.)	PLEIST. + QUATERNARY			TARAKAN (Pliocene)			SANTUL (Pliocene)			TOTAL PLIO. THICK
				Thickness (m)	Cum. Ss. (m)	% Ss.	Thickness (m)	Cum. Ss. (m)	% Ss.	Thickness (m)	Cum. Ss. (m)	% Ss.	
OB-A1 *	17.9	13.0	3,004.5	711.0	193.1	37.0	899.5	611.8	68.0	1,381.0	260.3	18.8	2,280.5
OB-A2 *	16.9	13.0	3,224.0	864.0	180.5	26.4	868.0	493.0	57.0	1,479.0	315.0	21.0	2,347.0
AHUS-1	12.5	3.0	2,795.0	480.5	123.0	27.8	972.0	672.0	69.1	1,327.0	321.0	24.2	2,299.0
OB-B1 *	17.8	18.0	3,034.0	1,365.0	297.0	25.1	422.0	116.0	27.5	1,229.0	177.5	14.4	1,651.0
BN-3	65.6	+ 60.5	3,296.0	542.6	130.9	24.6	830.4	332.0	40.0	1,917.9	573.0	29.9	2,748.3
BT-2	10.7	+ 4.8	3,659.0	719.0	285.4	39.9	1,007.0	433.3	43.0	1,927.0	768.7	39.9	2,934.0
OB-C1	17.5	8.5	3,296.9	803.5	45.0	7.2	1,248.0	414.0	33.2	1,236.9	240.0	19.4	2,484.9
DAHLIA-1	25.2	8.3	3,060.0	1,422.5	211.5	15.5	1,604.0	422.0	26.3	–	–	–	1,604.0
GIRU-1	11.3	3.3	2,755.1	956.5	150.9	19.9	403.5	171.0	42.4	1,380.5	430.6	31.2	1,784.0
IRIS-1	25.2	10.0	2,732.0	765.8	170.0	23.8	1,263.0	353.0	28.0	668.0	185.0	27.7	1,931.0
KANAH-1	25.0	9.0	2,515.0	496.0	203.5	44.6	643.0	452.6	70.4	320.0	12.7	4.0	963.0
KANTIL-1	25.6	11.8	3,100.0	1,136.6	514.5	47.3	1,316.0	858.0	65.2	610.0	253.0	41.5	1,926.0
MAYNE-1	19.2	55.5	3,326.0	1,131.8	46.5	3.8	144.5	180.0	12.5	675.0	63.9	9.5	2,119.5
M. MAKAPAN-1	16.7	1.7	3,300.0	1,161.6	368.0	33.2	823.5	134.0	16.3	536.0	50.5	0.4	1,359.5
MAMB. -IX	52.1	+ 46.6	3,055.6	96.6	26.8	27.9	1,399.9	908.3	65.0	1,553.6	325.5	21.0	2,953.5
E. MANDUL-1	8.5	+ 1.7	2,876.7	454.7	204.8	485.0	744.0	216.4	29.1	1,024.5	229.8	22.4	1,768.5
TERATAI-1	25.7	9.6	2,730.0	420.7	150.0	42.0	1,002.0	793.0	79.0	672.0	177.0	26.3	1,674.0
SERBAN-1	13.3	4.3	2,552.0	571.5	188.5	34.8	968.0	355.0	36.7	1,024.0	232.5	22.7	1,963.0
VANDA-1	15.0	348.0	3,720.0	2,092.0	216.2	10.3	1265.0 +	33.6	2.6	–	–	–	1,265.0 +
		NB. : * Logs measured from msl, all other values are from KB.								Irwan Zuhri, Robbie Lesmana & A. Wight, Feb. 1992			

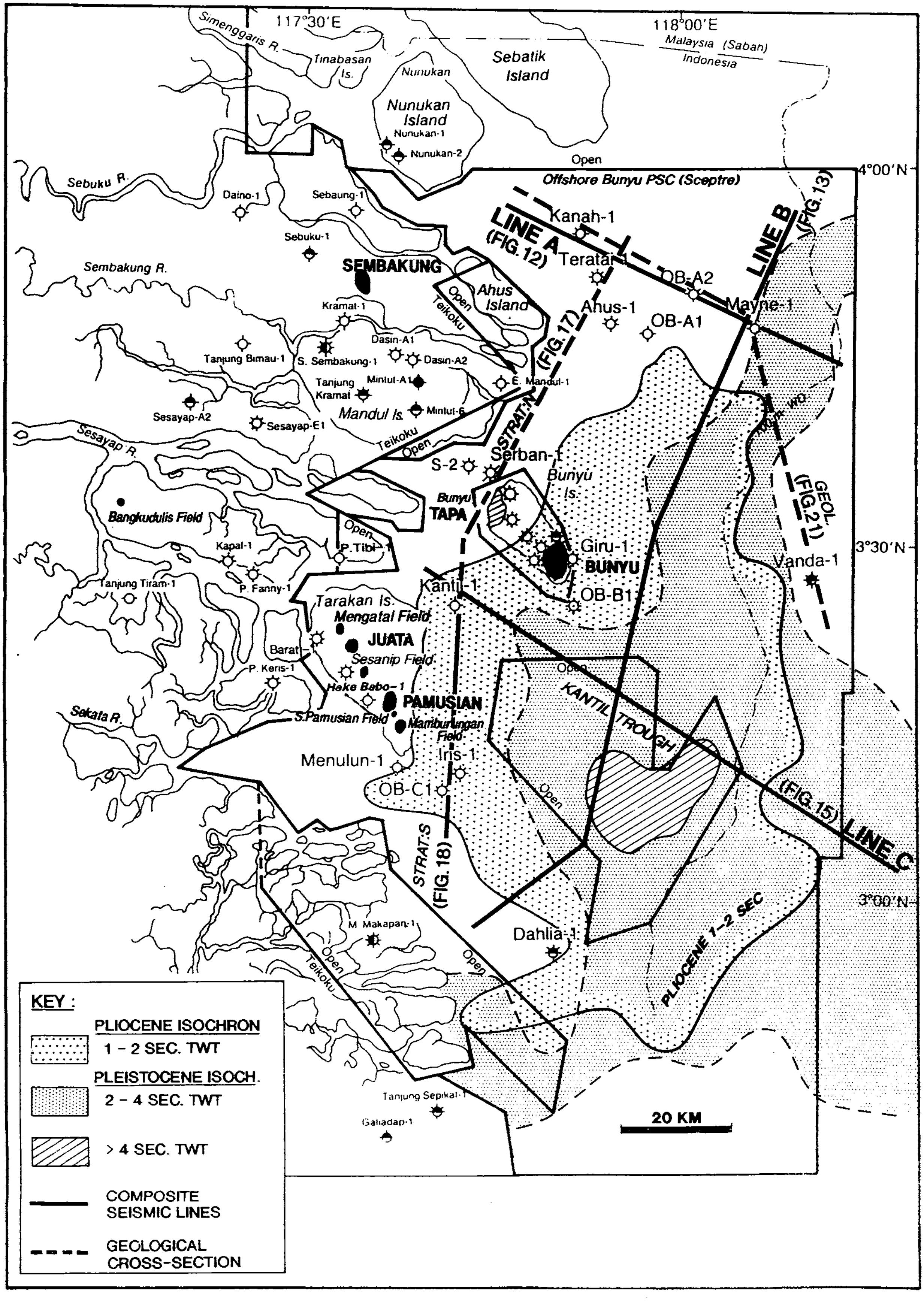

Figure 10. Offshore depocentres. The Pliocene is thickest below Tarakan and Bunyu islands and east of parts of the Mayne fault. The deepest Pleistocene depocentre (Kantil trough) attains a thickness of up to 4,500 m; the others lie east of the Mayne fault; none correspond exactly with the Pliocene ones. This map also shows locations of seismic lines and cross-sections, (Figs. 13, 14, 15, 16, 19, 20 and 22) as well as the Holocene shelf edge (200 m isobath).

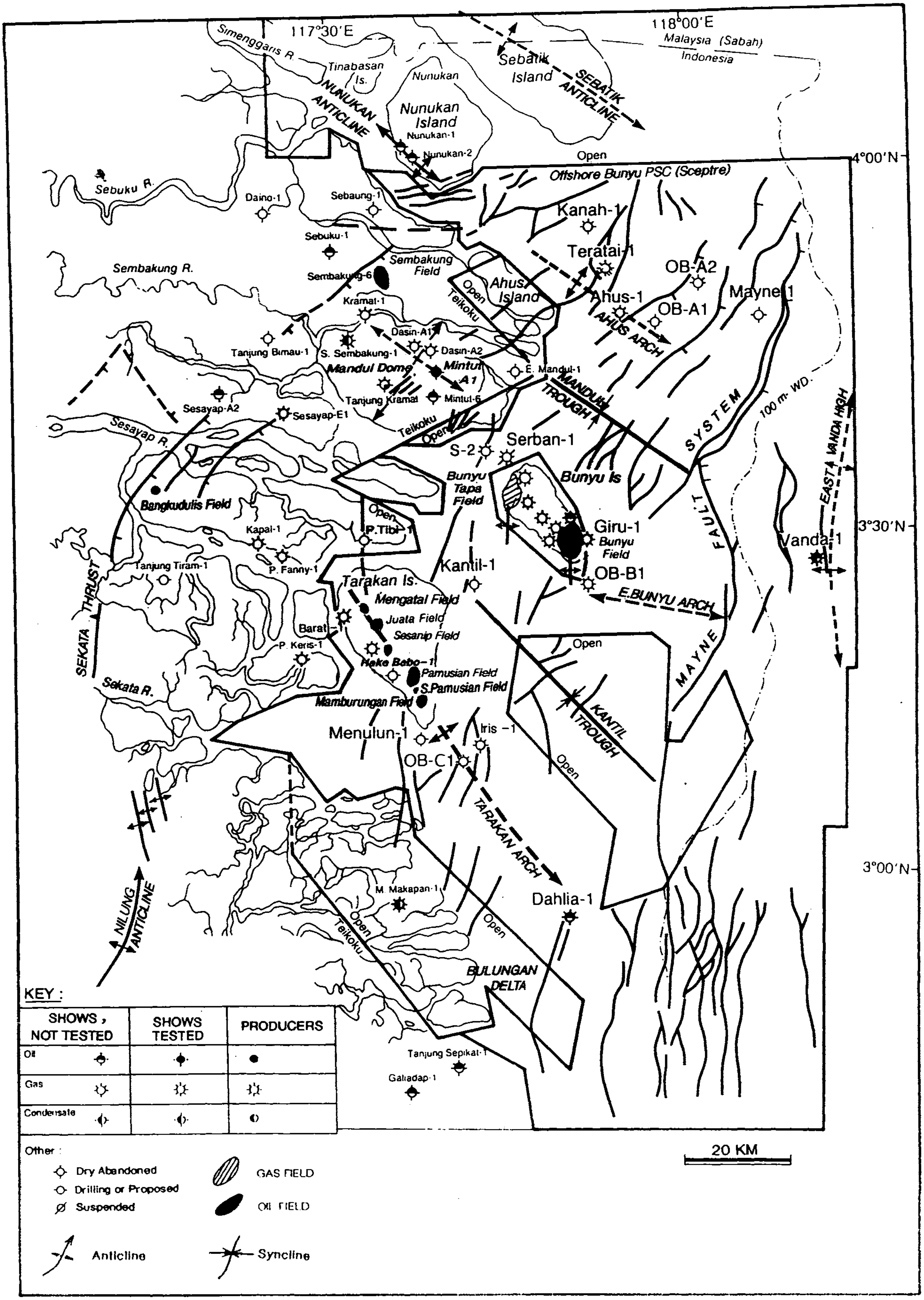

Figure 11. Tarakan Basin structure. The three major arches, Tarakan, Bunyu and Ahus and their corresponding troughs, Kantil and Mandul, all trend north-northwest or northwest. Other major highs are the E Vanda high to the east and the Mandul dome onshore. The north and northeast fault trends are normal, tensional faults which meet at 120° to each other north of Tarakan Island. The Mayne fault system is an almost continous chain of growth-faults controlling the eastern margin of the basin. One thrust (on the Sekatak River) and the reverse fault at Sesanip (Tarakan Island) are the only other evident compressional features, although it is speculated that the arches are isoclinal folds produced by thrusts too deep to be seen on current seismic. Minor strike-slip faulting probably also occurs, helping lateral sealing of the high sand: shale ratio sequences.

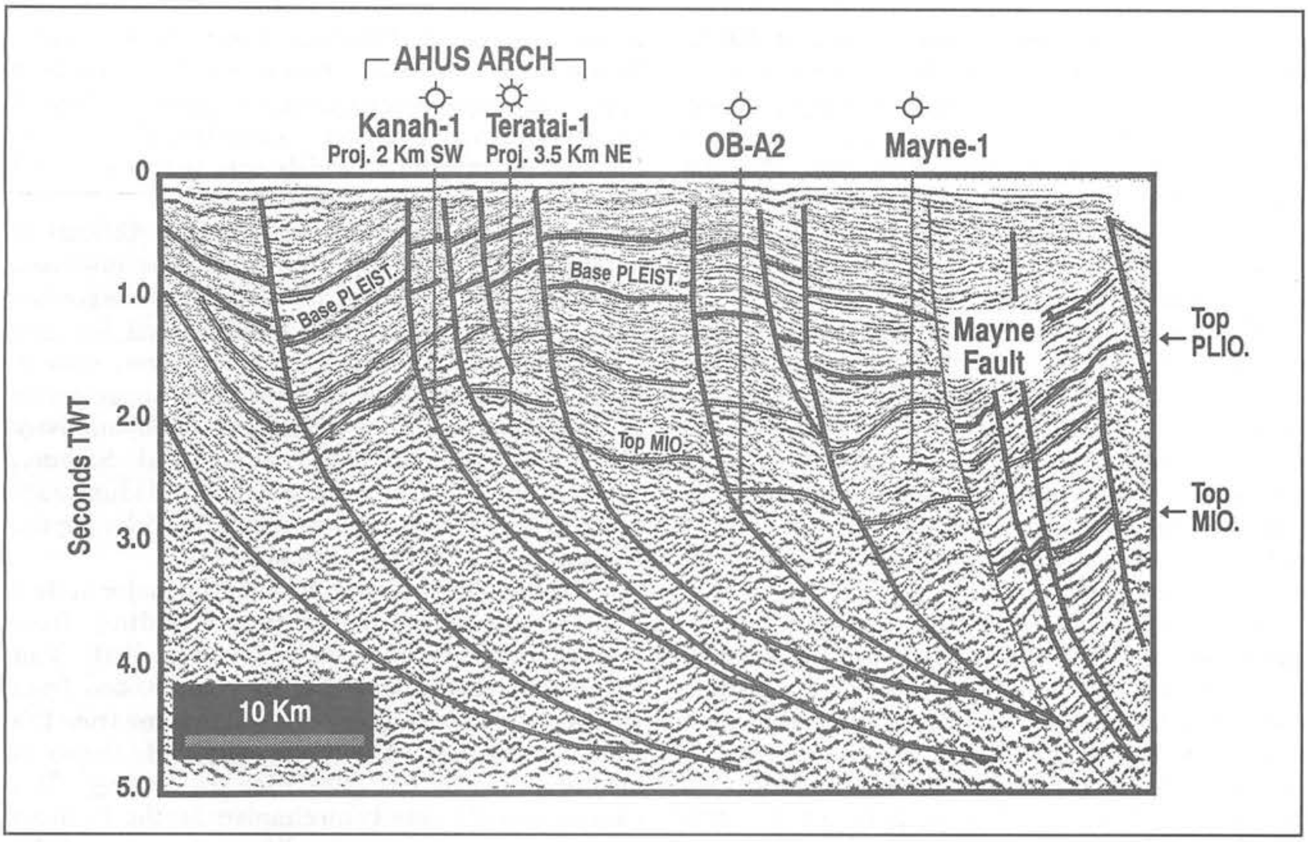

Figure 12. Composite Line A. A specially processed, composite seismic line along the axis of the Ahus Arch shows: (a) a western trough with an angular unconformity between the Pliocene and the Pleistocene, (b) the shallow, uplifted Miocene shelf edge (carbonates), (c) easterly thickening of the Pliocene, (d) Pliocene growth-faulting east of OB-A2, (e) a footwall anticline on the Mayne fault (Mayne-1), (f) Thick Pleistocene growth east of the Mayne fault.

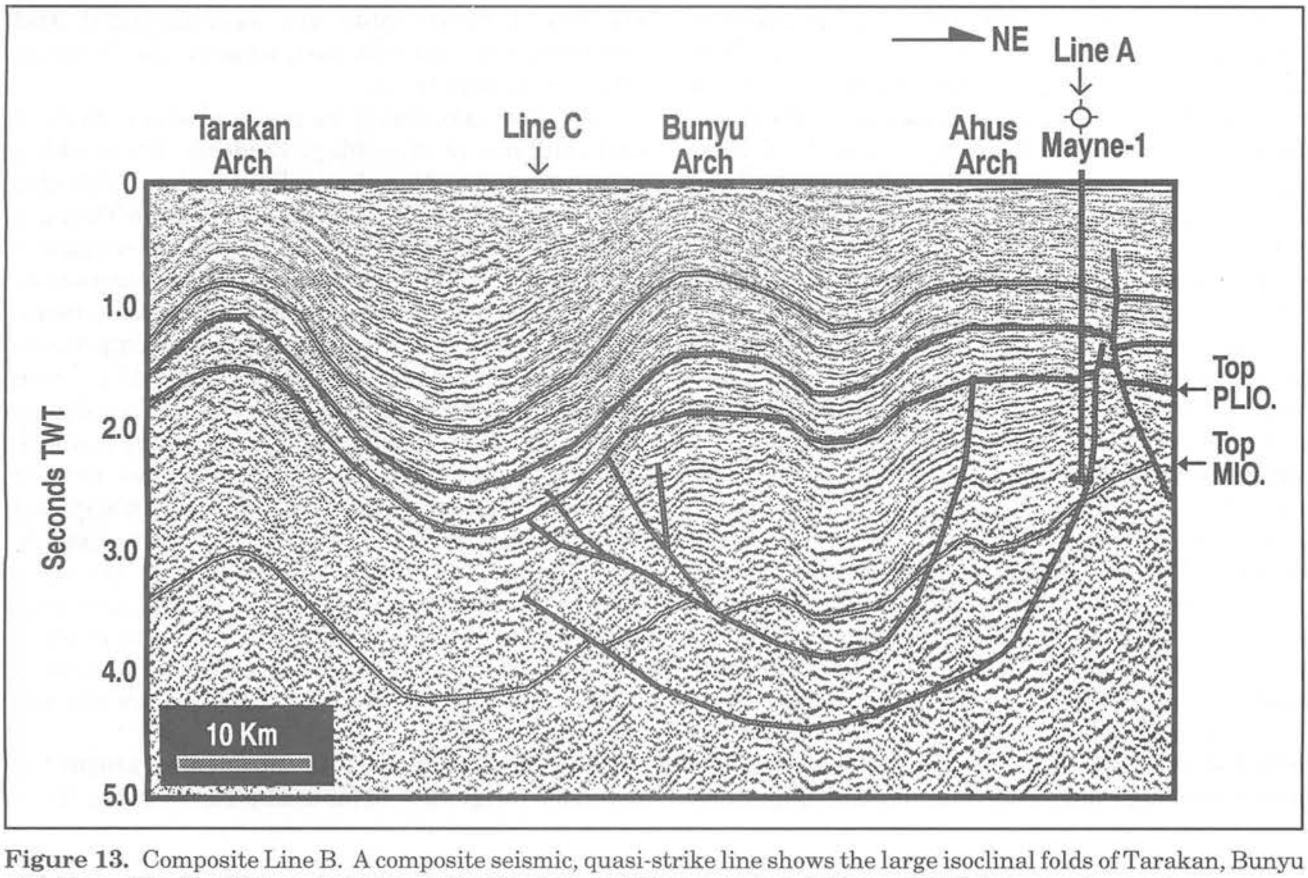

Figure 13. Composite Line B. A composite seismic, quasi-strike line shows the large isoclinal folds of Tarakan, Bunyu and Ahus. The Kantil trough, between the Tarakan and Bunyu arches, is the major Pleistocene depocentre.

(Fig. 6) has characteristics resembling a growth-fault anticline, first documented by Nordeck (1974), although this interpretation relies on correlation of featureless, massive sandstone sequences across faults with considerable throw and is difficult to corroborate due to poor seismic definition, Pliocene growth-faults are well documented in other areas, however, so growth could explain both the rapid thickening and structural similarity with Gulf of Mexico examples.

This great variety of fault styles within a small area, including reverse faults and discontinuous step faults, suggests a possible strike-slip component. Wrenching cannot be proven from seismic however, as the quality of reflections is poor and confirmation of basement-involvement is precluded both by the excessive depth of basement and the absence of a basement reflector over most of the offshore area.

The Bunyu arch is much shorter and plunges southeast, ie. at an azimuth close but not parallel to, the Tarakan arch axis. There is also a suggestion, at depth, of an underlying, discontinuous east-west high below the surface Bunyu arch, but which can only be traced as far east as the Mayne fault. On Bunyu island itself, a set of north oriented, down-to-basin normal faults anastomose and curve northeastwards, towards the Ahus arch. The axis of the large Bunyu field is also roughly north oriented and its downthrown closure is independent of a north-south fault. Some horizons appear to be fault-sealed however, as the small B. Nibung and B. Nibung Barat accumulations lie in adjacent, parallel fault slices to the west of the main field. Off the northern end of the island, a series of shallow, listric, northeast-trending, curvilinear faults have rotated sufficiently to trap the Serban-1 gas accumulation and ultimately also the large Bunyu Tapa gas field. The Bunyu Tapa and Bunyu field structures have also recently been described as likely growth-fault rollovers (Purnomo and Kadir, 1992).

The Ahus arch (Fig. 12) is oriented nearly northwest but due to heavy cross-faulting it is less continuous than the other two. It is an extension of the Nunukan anticline, although the two are separated by a small, intervening Pleistocene trough underlain by Pliocene below an angular unconformity, attesting to a major post-Pliocene orogeny. The arch terminates to the southeast at the uplifted Miocene carbonate shelf edge (near Kanah-1). Four wells were drilled on shallow, faulted culminations of the arch, with Pliocene sandstone or Miocene carbonate objectives.

A regional strike line (Fig. 13) crossing all three arches shows beds up to early Pleistocene age are involved in late Pleistocene folding. The uppermost Pleistocene lies in small troughs and onlaps the highest, eroded, Pliocene fault-block crests. Thickening into the arches, not immediately apparent on unrestored lines, can be demonstrated by flattening (Fig. 14), showing the latest Pleistocene inversion, which was responsible for forming Bunyu and Tarakan islands.

The relative ages of the arches are difficult to determine exactly due to the short time involved, sparse off-arch well control, lack of age-diagnostic fossils and facies changes making well log and seismic correlations equivocal. However, seismic data and regional tectonics tentatively suggest that the folds young to the northeast. Fold intensity also increases northwards, (Achmad and Samuel, 1984) as shown in the tight folds in the Tidung sub-basin, for example the Simengaris, Silimpopon, Nunukan and Sebatik anticlines.

Theories for the generation of the major arches include eastward gravitational sliding, first suggested by van Bemmelen (1949 p. 354). Van Bemmelen also proposed early compression from the east which was later reversed to come from the west. In the Kutei basin a gravity-glide theory is also proposed by Ott (1987) for the folding. The expressions of a gravity mechanism for the Tarakan basin folding appear to be different to that of the Kutei basin: firstly the fold axes are oblique to the present-day low, (whereas in the Kutei basin, folds are roughly north-south, perpendicular to both the depocentres and to the eastward-directed compression). Secondly, fold styles are different; the Kutei basin folds are asymmetrical and overturned towards the east, whereas the Tarakan folds are symmetrical.

Another possibility is regional-scale rotation and uplift due to wrenching. Evidence of wrenching is interpreted at Nunukan island and possibly also present in some of the small structures on Tarakan island. A preliminary solution which reconciles both small scale wrench effects and tensional features alike is suggested by D.T. Moffat (pers. comm.). His solution, involving varying components of kinematic regional convergence and divergence on bounding strike-slip fault systems, is consistent with a broadly tensional regime subsiding towards the southeast and east and yet allows for the presence, on a local scale, of minor strike-slip and listric faults, which appear to be spoon-shaped. This theory has the advantage that it does not require invoking compressional and tensional compartments separated by the Mayne fault but a series of relatively localized transfer tear faults in a dynamic system with broadly southward net regional extension.

The presently most favoured mechanism for inversion (originally advanced by T.P. Harding Esso/

BP/Sceptre internal unpublished study 1990), is deep thrusting from the west. Only two thrusts have so far been identified in Tertiary rocks onshore, one in the Sekatak river area, near Tarakan Island and one far to the south, a sector of the Latih fault, in Berau. Although none have yet been identified offshore, probably due to their great depths in the thicker offshore sections (below the existing seismic at 5 seconds TWT), the large isoclinal folds offshore NW Sabah interpreted as formed by deep thrusting (Hinz *et al.*, 1989 their Figures 6-9 A, B) are so similar in style to the Tarakan and Bunyu arches, that their thrust origin is considered to be a good analogue for the Tarakan folds.

Thus the tectonic history since the late Miocene was of original extension, with growth across north-south faults, forming rollover anticlines. These were inverted during the Pleistocene (possibly still continuing) to form the isoclinal arches. The effects of this thrusting from the west die out down-plunge to the south-southeast, where extension continues across a younger set of north-south faults. The arches themselves are gravitationally sliding eastwards, with minor strike-slip faults parallel to the coasts of Tarakan and Bunyu islands and listric faults at their northern ends. The keys to the two largest hydrocarbon accumulations at Pamusian and Bunyu therefore seem to be: (a) early rollover into growth-faults, (b) their present-day crestal position, such that the south-southeasterly thrust-induced fold plunges have not tilted out their critical early-formed counter-basinal closures.

FAULT SYSTEMS

The two predominant fault sets in the Tarakan basin are north to north-northwest and northeast oriented (Fig. 11) with a trend change shown by the prominent swing in coastline orientation at the Sesayap river mouth, from north-northwest below Tarakan to northeast above Bunyu. The set of north oriented faults are most continuous, longest and have the largest displacements in the east, at the Mayne fault system, which extends over 150 km from the Bulungan delta to north of the Mayne-1 well. This represents the extensional edge of the Holocene basin. A regional seismic dip line down the Kantil trough (Fig. 15), shows the typical expression of the extensional zone and north-south Mayne fault system in relation to the folded area to the west, where the fold axes are generally north-northwest to northwest oriented.

The Mayne system consists of normal, down-to-basin growth faults with throws exceeding one second TWT (equivalent to 2,000 m+). Growth occurs variously in Pliocene and Pleistocene sequences at different locations along the trend, giving rise to several large, elongate, fault-dependent closures, best developed west of the Vanda-1 well. This type of structure, so far undrilled, probably represents the best potential in the basin, due to size, proven source rocks (shown by Vanda-1 well tests) and multiple structures. Other shorter, but important, north-south faults are those which control the major accumulations of Pamusian and Bunyu fields.

The northeast trending fault set, ubiquitous in the northwest part of the basin is rare south of Tarakan and also consists of normal, down-to-basin tensional faults with associated upthrown and downthrown closures. Most are areally small and downthrown closures often lack independent closure, accounting for at least eight dry holes. Occasionally, small traps have been filled, such as on Tarakan Island, but these would not be commercial offshore. The large Sembakung field is also associated with a major northeast-oriented fault which can be traced from the southeast corner of Nunukan island past Sembakung, thence via the small Bangkudulis oil field and even farther southwestwards, perhaps continuing into a pronounced lineament controlling the Kayan river.

The Mayne fault system soles out around 5.5 sec TWT, below the East Vanda high. It appears to separate a subsiding, tensional, passive margin to the east, from the triangular tract which contains compressive folds to the west. The folding was contemporaneous (in places) with, but decoupled from, this tensional regime. The juxtaposition of these two regimes can be explained by the relaxation in stress away from the thrust-front which plunges and decreases in intensity to the southeast, where extension is occurring into the accomodation space created by subsidence into the Celebes Sea.

STRATIGRAPHY

The stratigraphic sequence in the Northeast Kalimantan basinal area has been divided into five cycles (Achmad and Samuel, 1984). Each cycle, beginning with the oldest (Paleogene to Late Eocene) sedimentary rocks exposed in the Berau sub-basin, was terminated by volcanism, uplift and unconformity. Cycle boundaries were considered to be generally correlable with Haq *et al.*'s (1987) global coastal onlap curves, such as those at 16.5 (Mid-Miocene), 6.6 (Late Miocene) and 2.8 Ma (Mid-Pliocene). For the purpose of this paper, the first two cycles will not be discussed, as much of the Tarakan basin (*sensu stricto*) sequence (Fig. 16), in terms of drilling targets, effectively begins in most areas during the mid to late Miocene.

Miocene

Although paleontologic dates are equivocal,

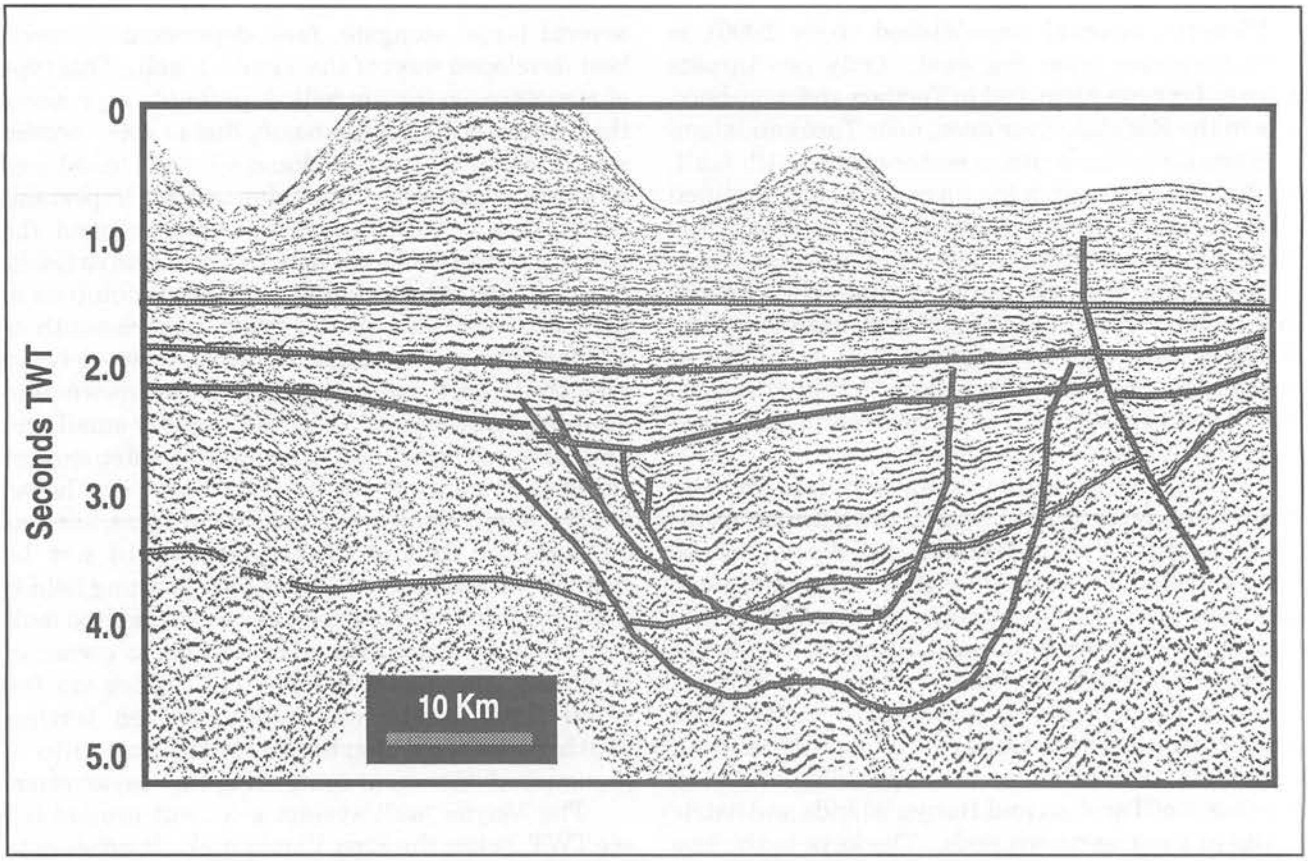

Figure 14. Flattened Line B. Line B, flattened on an intra-Pleistocene horizon, shows thickening into the Tarakan arch, demonstrating inversion of a Pliocene depocentre.

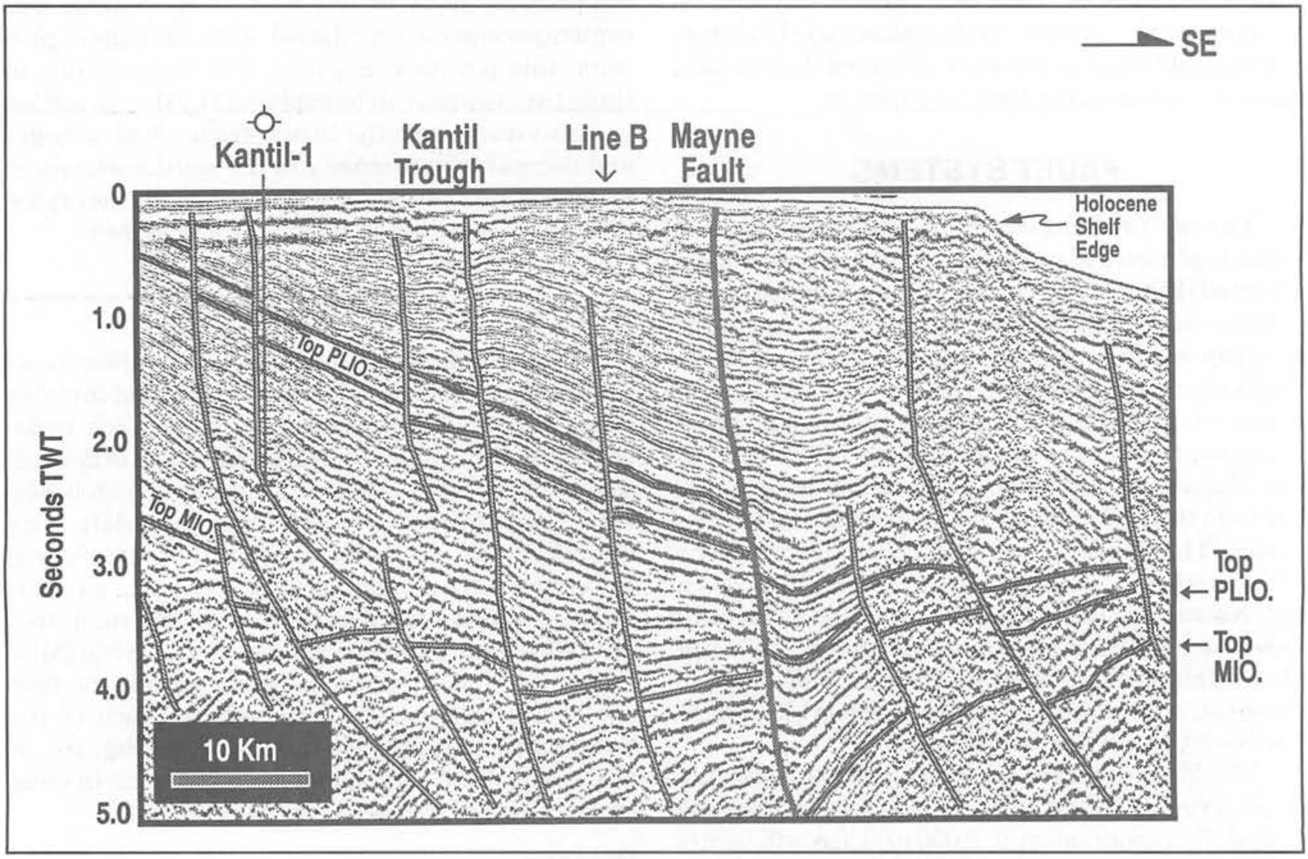

Figure 15. Composite Line C. A dip line down the axis of the Kantil trough, this shows the extreme Pleistocene thickening, towards the Mayne growth fault system, beyond which westerly dips show the discordant relationship between the Miocene and younger sequences, demonstrating an unconformity caused by a possible end-Miocene tectonic phase. These westerly dips persist right across the basin, where thickening into the Tarakan Island inverted depocentre can be clearly seen.

there are three offshore wells in which probable late Miocene sediments have been encountered: Vanda-1 in the east and Kanah-1 and Teratai-1 in the north. Onshore, outcrops and well penetrations in the neighbouring Tidung basin are largely Miocene in age. The total offshore Miocene thickness is unknown, as only up to a few hundred metres have so far been drilled, although from Miocene outcrops onshore to the west, thicknesses of up to five thousand metres were estimated by Arco field mapping. Late Miocene facies encountered vary from proximal deltaics in the Sembakung well, prograding eastwards to Nunukan island, with shallow to deep marine delta front/ facies encountered in the Kanah-1 and Teratai-1 wells. Surprisingly, however, shallow marine and even continental facies are present far to the east, at Vanda-1, suggesting that the eastern basin margin was emergent during at least part of the Miocene. These clastic sequences were all succeeded by shallow marine limestones deposited variously in delta-front or platform environments.

Elsewhere offshore, the top of the Miocene is too deep to have been penetrated in wells as an objective, although it is thought from poorly age-diagnostic paleo-faunas to be present in wells on Bunyu island (Akuanbatin *et al.*, 1984). The productive sequence on Bunyu island comprises mainly Tabul, Santul and Tarakan formation sandstones of Miocene to Pliocene age but a few reservoirs (Bunyu Formation) are Pleistocene. The Mio-Pliocene formations consist of delta-front facies of a late Miocene to Pliocene delta interpreted at Bunyu to have prograded locally from the southwest (Akuanbatin *et al.*, 1984). Similarly, on Tarakan island, although the thick sequences at Pamusian and Mamburungan fields in the southeast are all interpreted to be Pliocene to below 3,000 m, wells in fields to the northwest (for example Selatan, Mengatal, Juata and Sesanip), reach the Miocene Sesanip Beds at around 1,500 m. These beds are marine shales and marls with sporadic thin, tight

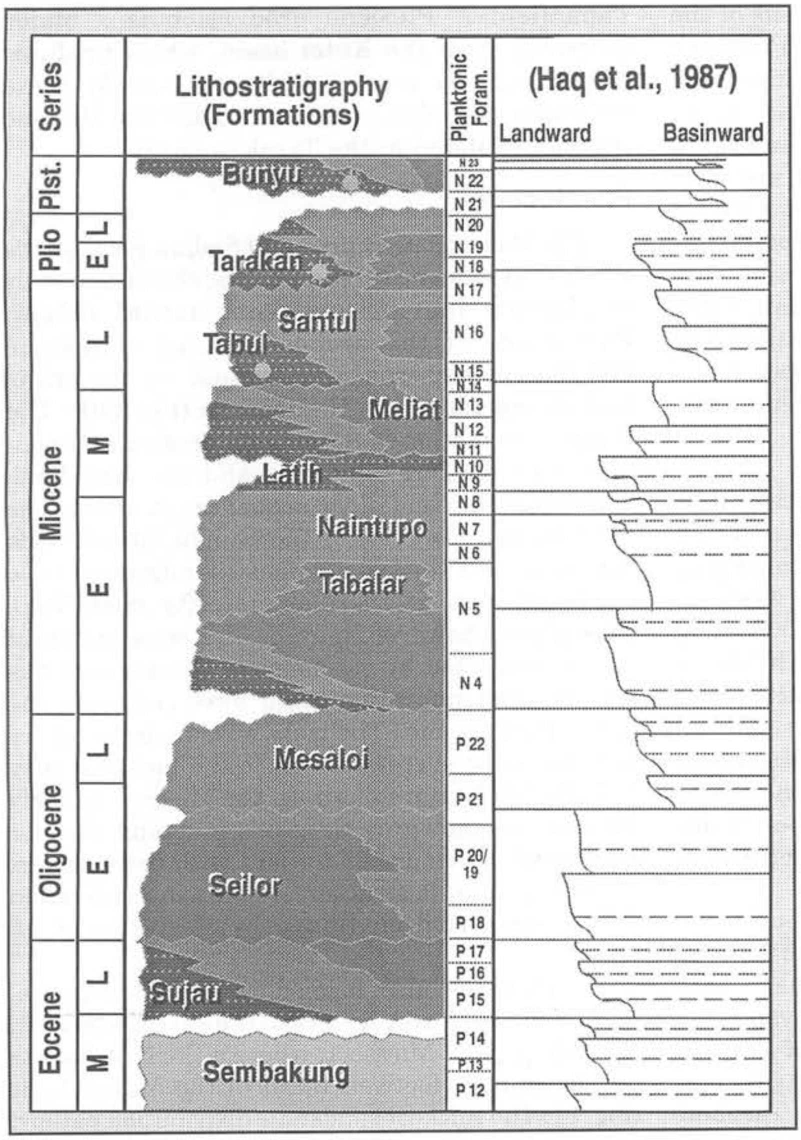

Figure 16. Tarakan Basin stratigraphy. The reservoir targets drilled offshore in Pleistocene to Miocene clastic formations show a generally regressive sequence through time. Away from the deltas, carbonates developed as platforms, pinnacles and delta-front reefs. The Miocene sequence, exposed onshore, contains clastics in the Tidung sub-basin to the northwest but predominantly carbonates to the south in the Muaras sub-basin. The Eocene Sembakung Formation forms economic basement and is underlain by metamorphosed, Cretaceous, island-arc spilites of the Danau Formation.

limestones which underlie the Pliocene Tarakan Formation with angular discordance.

Sceptre's Iris-1, Dahlia-1 and Kantil-1 wells have palynological determinations also suggesting an unconformity between the early Pliocene and Middle Miocene. This dating, however, depends largely on a lack of age diagnostic flora above the Middle Miocene, casting doubt on the possible absence of the late Miocene. Also semi-regional seismic correlations tied from three wells to Vanda-1 suggest that the Pliocene boundary is deeper, including sediments formerly thought from Paleocene to be Miocene. The Middle Miocene flora are reworked in several wells, suggesting that the unconformity could be intra-Pliocene in age.

In order to solve the age problem, an attempt was made to date these questionable sequences (in deeper water facies) with nannoplankton. Also strontium isotope (Sr^{87}/Sr^{86}) dating was attempted in order to gain more precision and to use a method independent of conventional paleontology. However, results gave out-of-sequence ages or ones with large margins of error (due to the flattening out of the Sr^{87}/Sr^{86} age curve for the late Miocene to Pliocene).

Another problem is the general lack of good seismic reflectors due to the monotonous stratigraphy. The presence of ubiquitous multiples precludes the use of seismic stratigraphy, except in the uppermost Pleistocene, which is not a target horizon. Furthermore, the base of the Pliocene has poor acoustic impedance and is deep, being only rarely visible east of the Miocene carbonate shelf-edge. Pliocene depocentres (Fig. 10) can therefore only be poorly defined. They lie below Tarakan and Bunyu islands and the area east of the Ahus arch.

Pliocene

The facies of the Pliocene began either with deep or shallow marine shales, siltstones and thin interbedded sandstones unconformably overlying Miocene platform carbonates. In the west, on Tarakan and Bunyu islands, up to 3,000 m of Pliocene sandstones and shales, exhibiting coarsening-upwards, deltaic marine characteristics (the 'Santul'-type facies, dated tentatively as Miocene on Bunyu island but elsewhere possibly at least partly Pliocene), was succeeded by continental sandstones, coals and progressively thinner shales of the Tarakan Formation which outcrops on Tarakan island.

The mega-sequence therefore shows evidence for a major regression and corresponds to the overall global rise in sea-level of the Pliocene. This highstand system caused the paleo-Sesayap river to back up and deposit vast volumes of braided stream sandstones. The thickest massive Pliocene sandstones (over 1,200 m cumulative) on Tarakan island and nearly 1,000 m in wells to the north on the Ahus arch (Table 2) are shown in the stratigraphic cross-sections (Figs. 17 and 18).

The stratigraphic section also shows there is little joy for the would-be seismic stratigrapher: neither can geological sequence boundaries be identified on logs in these massive sandstone sequences, nor does the seismic show continuous reflectors representing easily-traceable sequence boundaries with well-defined onlaps, offlaps and other distinguishing features. Although thin carbonates are occasionally present, the Pliocene is predominantly clastic-dominated. Pliocene sandstones (Fig. 19) were derived from two different sources — the paleo-Sesayap river to the west and rivers in the Simengaris area to the northwest, as interpreted from overall sandstone counts, although local variations attributed to channel-switching and intervening islands are evident.

The massive Pliocene sandstones of the Tarakan Formation are the prolific producers in the Pamusian, Juata and much of the Bunyu and B. Tapa fields. Pliocene production is a major difference from the Kutei basin, which produces predominantly from Middle to late Miocene sandstones, emphasizing the fact that the Miocene is under-explored in the Tarakan basin.

Pleistocene

The Pleistocene Bunyu and Sadjau Formations comprise a sequence of sandstones, shales and coals of shallow marine and continental origin. Emergence of the arches affected sandstone distribution patterns, with bypass on the crests and concentrations in the troughs (Fig. 20). The Bunyu Formation is missing by erosion and non-deposition on Tarakan island and the mainland, where Miocene and older sequences outcrop. The Pleistocene reservoirs of the Bunyu island fields demonstrate a very young phase of migration (also predicted from geothermal maturity modelling). This phase, however, may be the remigration of gas, as indicated by geochemical studies and it is possible that migration could have begun by the end of the Pliocene. The traps on Bunyu island are believed to be successful due to the fact that they had already begun to form in the Miocene or early Pliocene as shown by Sceptre's mapping of older structures which are discordant with the younger, re-activated fault structures. This interpretation is also supported on Bunyu by Heriyanto *et al.* (1992).

Carbonates also formed in the Pleistocene, mainly in the clearer waters to the east, distal from the deltas, as at Mayne-1, where a thick carbonate developed on a footwall uplift of the Mayne fault (Fig. 21) The thickest sandstone distribution pattern

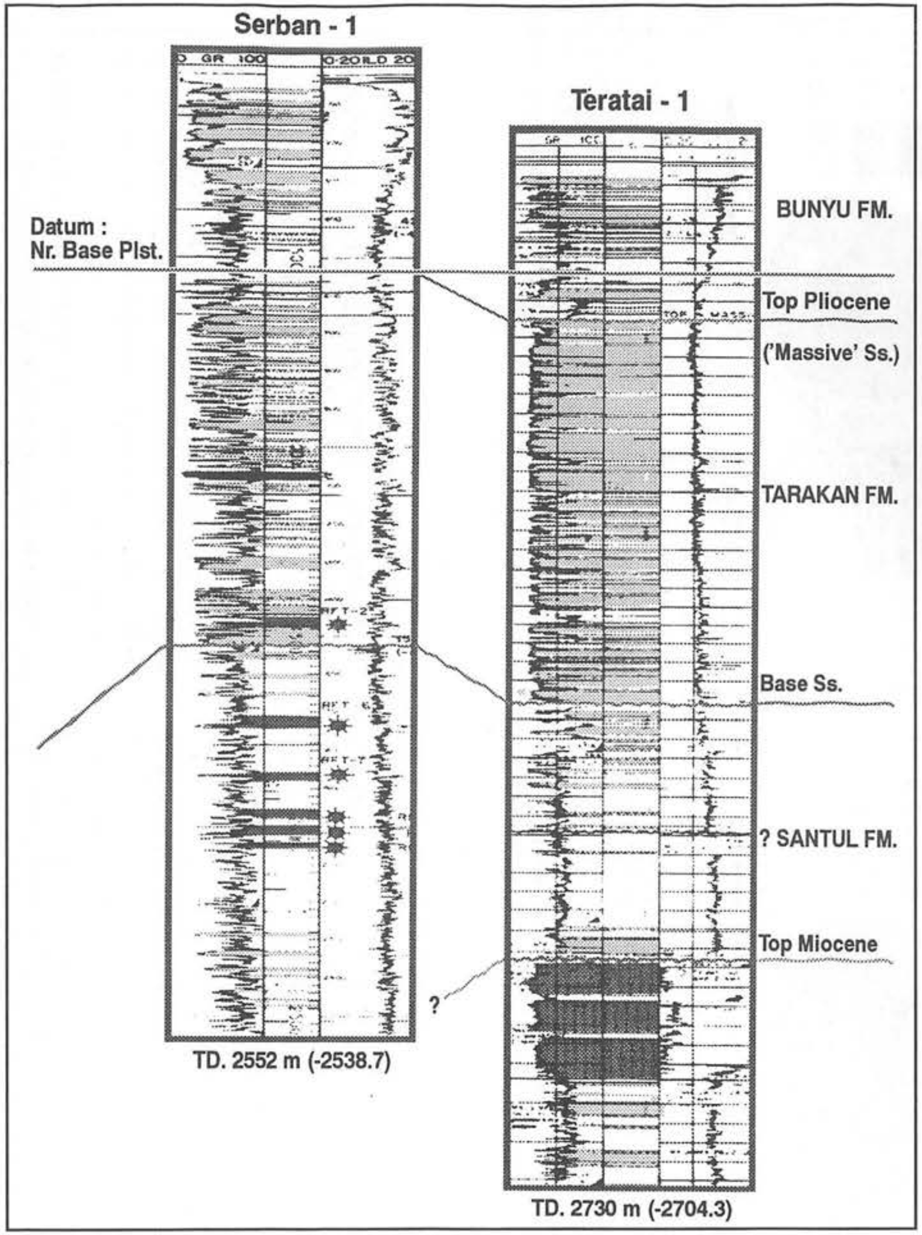

Figure 17. Stratigraphic cross-section north. The thick, massive sandstones of the Pliocene, Tarakan Formation are shown by the 'cylindrical' gamma-ray log pattern. These overlie thinner, but still frequent, marine sandstones and shales which in turn overlie the Miocene carbonates in the northern, Ahus arch, or clastics further south.

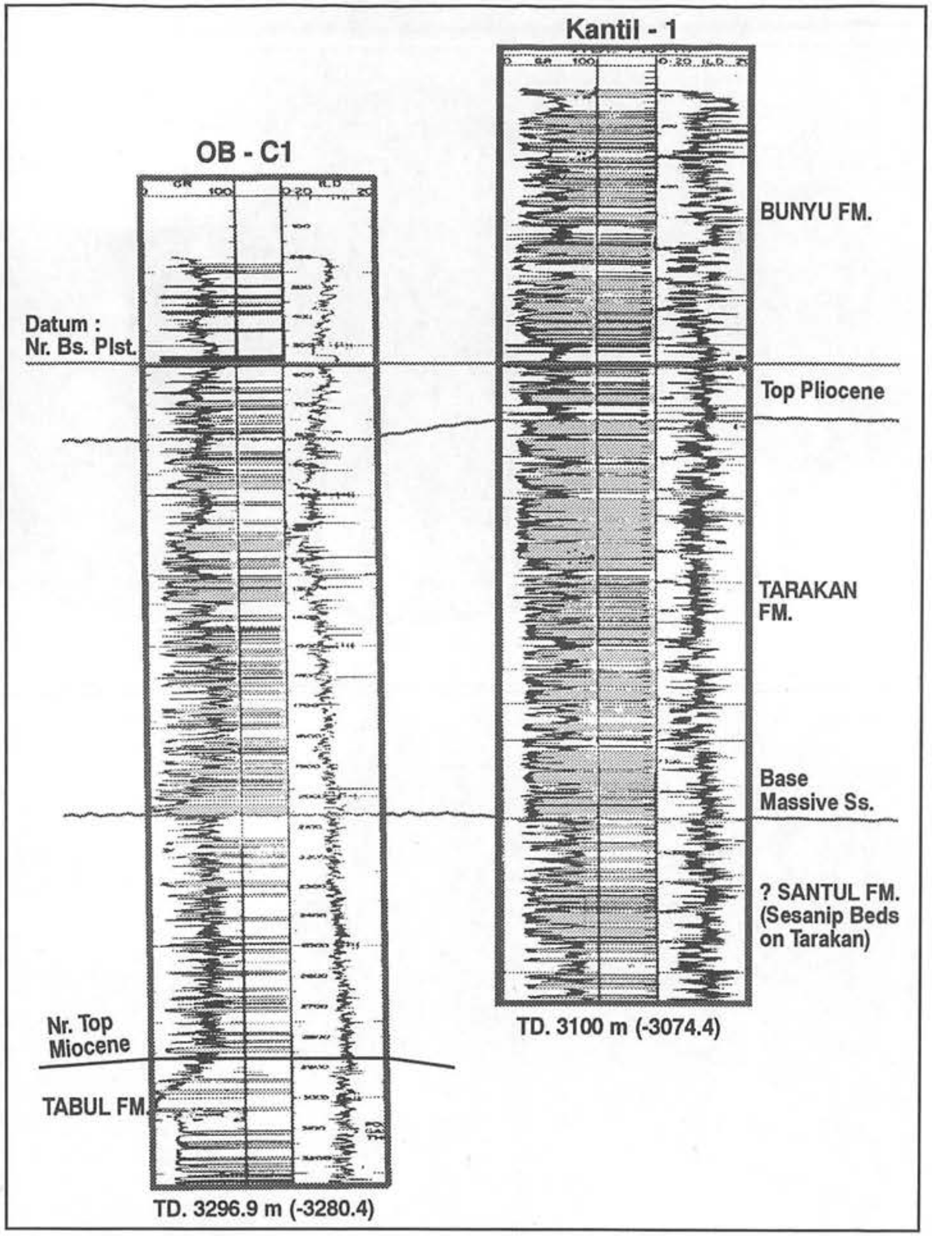

Figure 18. Stratigraphic cross-section south. A similar sequence to that shown in Fig. 17 is present in the south, although there, the sandstones contain pay zones not only in the Tarakan Formation but also in the Bunyu, Santul and Tabul formations. The Miocene contains little carbonate this far south and east, but there are platform carbonates to the west, along an earlier shelf-edge.

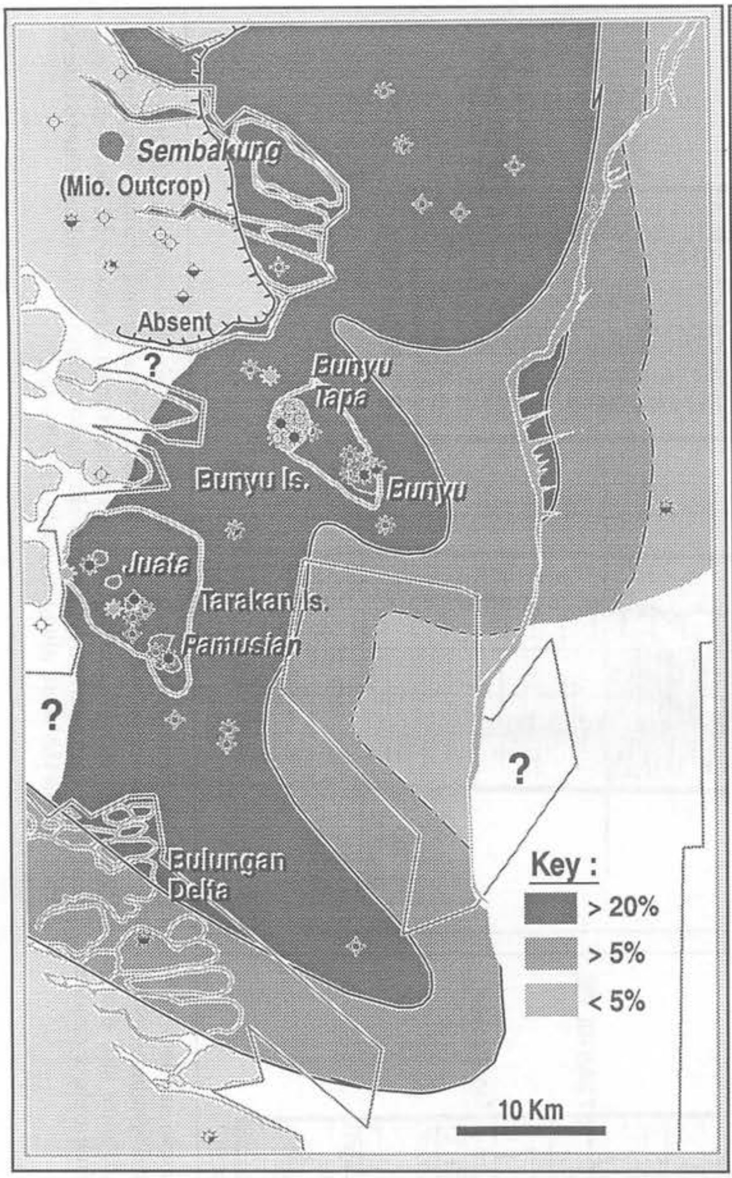

Figure 19. Pliocene sandstone percentage. There are three main lobes of high sandstone content; those in the south were derived from the paleo-Sesayap river west of Bunyu Island. The northern lobe had provenance in the volcanic area to the northwest. An increase in sandstone percentage is predicted at the Mayne fault, where two fairways intersect in a growth-fault zone.

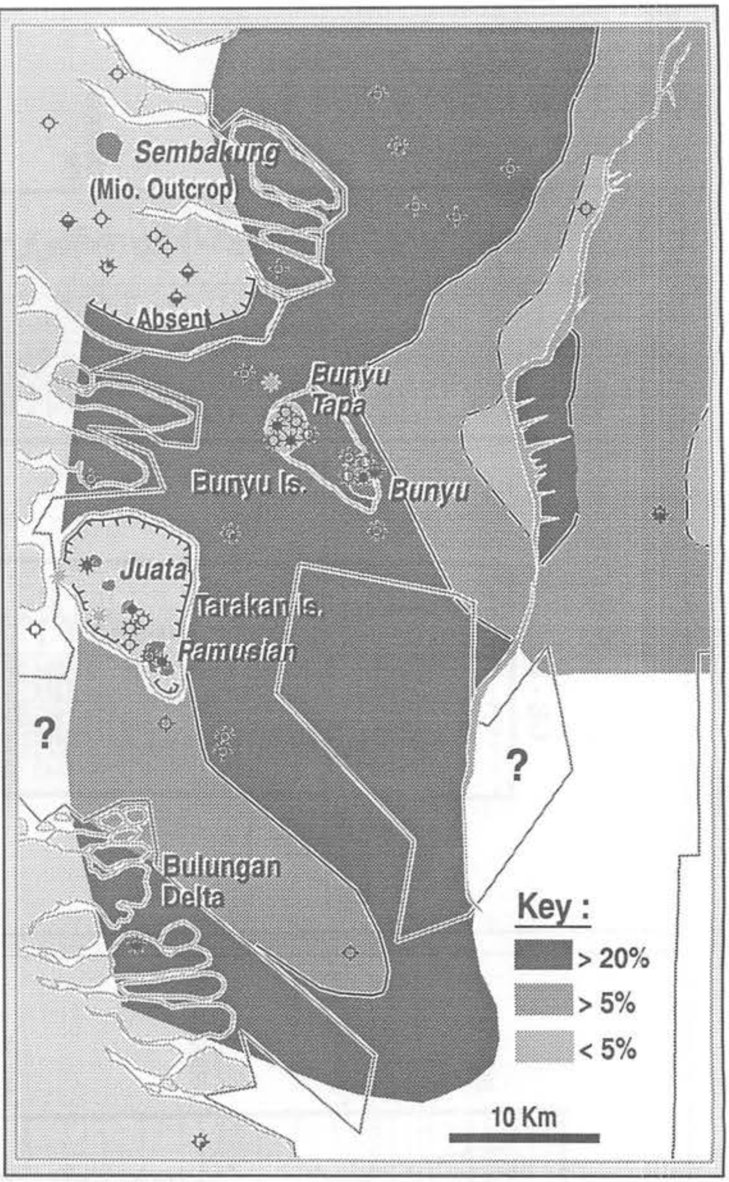

Figure 20. Pleistocene sandstone percentage. Pleistocene sandstone distribution is different to that of the Pliocene and was affected by the emergence of islands offshore from the Sesayap river mouths. The thickest sandstones so far encountered are in the Kantil trough but may also be present east of the Mayne fault.

is different to that of the Pliocene, being predominantly into the deep Kantil trough (Fig. 20) where thick sandstones were deposited (for example 574 m in Kantil-1, Table 2). Also, east of the Mayne fault, thick, lignitic, lowstand sandstones were deposited beyond an earlier shelf-edge, in the Vanda-1 area.

Overall, the offshore late Miocene to Pleistocene stratigraphic sequence exhibits a gradual shallowing from proximal shallow to distal deeper marine environments in the late Miocene and early Pliocene, to continental braided and point bar, fluviatile ones in the west during the late Pliocene to Pleistocene. Minor transgressions interrupted both Pleistocene and Pliocene deposition, however, with occasional intercalations of shallow marine deposits. The presence of growth-faulting and subsequent inversion of the major anticlines caused the formation of islands, which diverted the otherwise eastwards flow of the Sesayap river sediments, for example towards the northeast near Bunyu island.

Sedimentary environments thus range generally from coarsening-upward, shallow deltaic

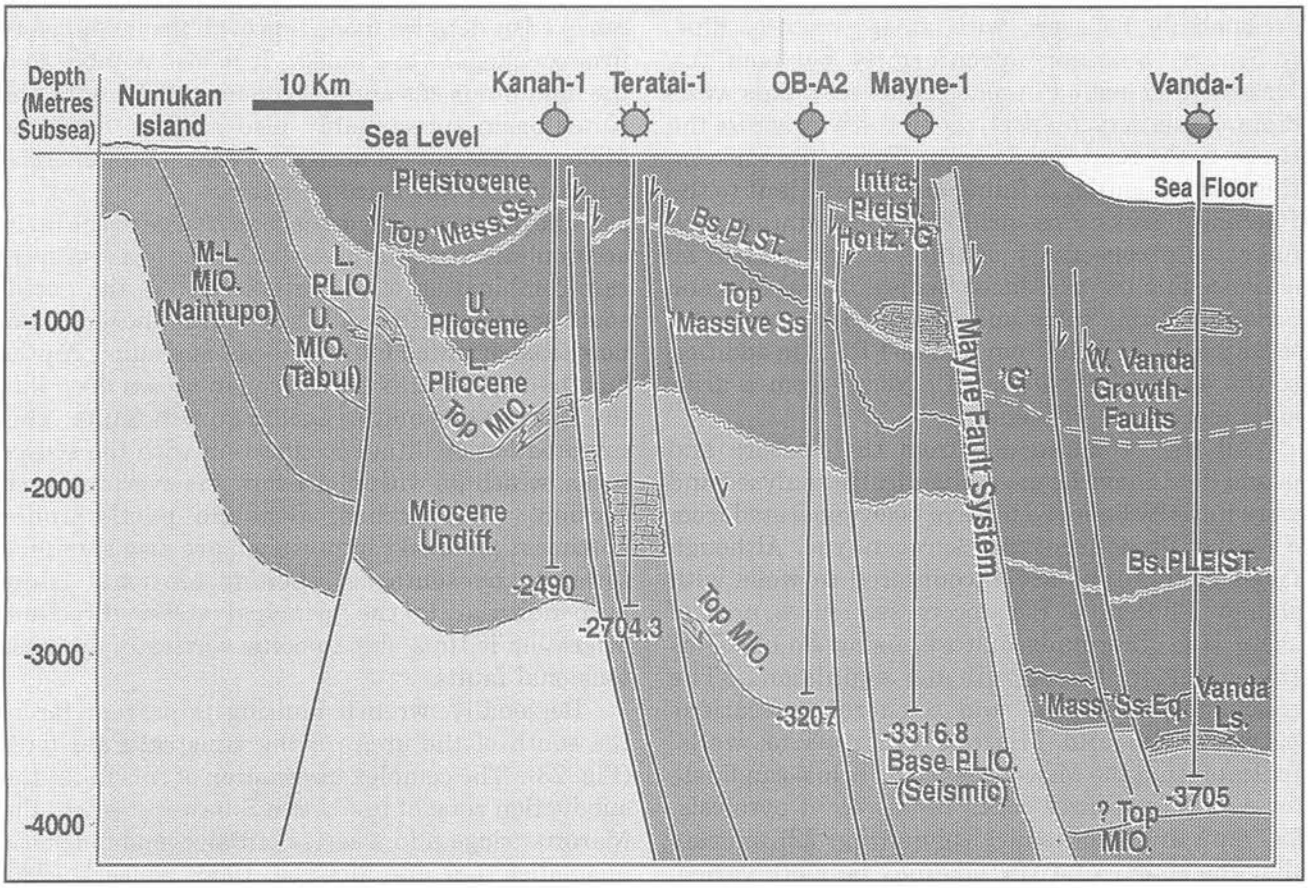

Figure 21. Structural cross-section (W-E). This geological interpretation of line C (Fig. 15) shows the wide vertical and lateral distribution of carbonates throughout the section, in Miocene platform (Kanah-1), Pleistocene pinnacle (Mayne-1) and Pliocene delta-front (Vanda-1) environments.

sandstones (Tabul, Santul Formations) up to massive and eventually discrete, fining-upwards fluvial sandstones (Tarakan and Bunyu Formations). Peripheral to these deltas, platform, patch and delta-front carbonate developed sporadically. To date, however, none of these carbonates has yet produced hydrocarbons, although gas was tested from a thin porous zone at the top of Teratai-1 and oil shows observed in the Vanda-1 carbonate. There are also several untested carbonates which may still have potential in certain areas.

HYDROCARBON GENERATION AND TRAPPING IN RELATION TO BASIN DYNAMICS

The structural features, the western compressional and eastern tensional tectonic regimes and the effects of tectonism on sediment dispersal described above are intimately related to hydrocarbon trapping mechanisms. The Tarakan basin is a complex combination of major arches comprising Pliocene and Pleistocene inverted depocentres which were filled with regressive, sand-prone sediments which host all the major hydrocarbon accumulations except the late Miocene deltaics of the onshore Sembakung field. The growth of the three major arches caused sediment-switching as channels were diverted away from the predominant east-west flow of the paleo-Sesayap river.

An unfortunate result of the orientation of the major fold axes, (which is the Kutei basin are perpendicular to the main depocentre and thus contain long, areally large traps), is that the Tarakan fold axes formed sub-parallel to sand fairways. This resulted in areally small closures, reliant on rare, down-to-margin faults or giving fault-independent closures, also rare and often small. This is considered to be the main reason for the lack of discovery of major accumulations offshore to date. The principal successful trapping mechanism appears to be downthrown, probable growth-fault structures, but many of these are unsuccessful due to lack of preservation of rollover towards the axial crests of anticlines.

Although the Miocene offshore basin is poorly defined, due to lack of good, continuous reflectors and partly to the great depths below the thickened Plio-Pleistocene sequences, reflections can occasionally be seen, with steep westerly dips, indicating a major unconformity between the Miocene and early Pliocene sequences. This west-dipping relationship persists all the way across the basin, to the East Vanda high. There, the Pliocene thins significantly, defining an eastern limit to the Pliocene basin. Post-drilling interpretation now indicates prospectivity of this eastern area to be enhanced by the presence of supralittoral Miocene beds containing coals and source rocks correlated to tested 35° API oil (from Vanda-1 RFT) in addition to the 44° API condensates covered from a drill-stem test in the Pliocene.

All the produced oils from the onshore and island fields have been geochemically analysed and were initially believed to have been generated from a similar, fluvio-lacustrine kerogen type. Although facies of this type are encountered in wells with shallow Pliocene to Pleistocene sequences, none of these is geothermally mature, using *R*o of 0.7 as the criterion for significant expulsion. The conclusion from this and onshore correlations between oils and Miocene outcrops or wells, indicates that the Miocene is the principal candidate for a suitable source rock. More recent pyrolysis-GC data and geochemical plots (Fig. 22) indicate that the sources for the oils may be more varied, ranging from types II/III or IV (Juata-IV, Pamusian, Mengatal and Bunyu-II/III) to Type I/II (Sembakung, Bunyu Tapa, Bangkudulis and Vanda-1 oil and condensate). The source rocks thus appear to be more complex and from more varied depositional environments than earlier believed. They are also apparently widespread, occurring from Bangkudulis in the west to Vanda-1, 110 km to the east and between Sembakung in the north 70 km to Mamburungan in the south, as well as at Muara Makapan-1 (condensate) and oil seeps still further south, onshore in the Berau sub-basin.

Although it is beyond the scope of this paper to dwell in detail on the geochemical aspects of the basin, geothermal modelling indicates depths to the peak oil window (*R*o = 0.7), vary from approximately 2,350 m to 3,100 m+ on structural highs and down to 3,900 m+ in depocentres. Attainment of maturity, modelled from several wells, is in the range of 0.5 to 1.8 Ma ie. latest Pliocene to Pleistocene. These models, however, lack well paleotemperature data from the main fields and depocentres and are sensitive to the inclusion of the undrilled Miocene source sequence below, so conclusions as to depth of oil window and timing could be inaccurate. Also, heat flow below certain fields is almost certainly higher than the averages available from the dry holes; this would invalidate all results except the (as yet unmodelled) fields themselves. This uncertainty needs to be removed by detailed modelling of all the fields before firm conclusions are made. It is also notable that the ubiquitous gas and gas condensate found in the Kutei basin (presumably also sourced from the Miocene), has not yet been discovered in commercial quantities in the Tarakan basin.

The question of hydrocarbon charge to the main accumulations is interpreted to be due to a relatively rare combination of the intersection of the north-south and the northeast sets of faults. The tensional, northeast oriented faults sole out at shallow depths but the north-south set appear to access deep into the Miocene and may be earlier growth-faults. This combination facilitates connection with the source rocks, which lie within or below the overpressured section. The arches, although partly under northeast directed compression, are also slumping towards the southeast opening tensional faults perpendicular to the principal stress direction. Migration is thus able to occur vertically up these tensional faults.

Regionally, wrench faulting is present far to the south of the area, in the sinistral Palu fault (Fig. 23). The complex association of this fault, the subduction zone of the North Sulawesi trench, the Maratua ridge and a series of Paleogene magnetic anomalies (Lee and McCabe, 1986; Weissel, 1980; Hutchison, 1992) are tentatively suggested to be linked, along an arc-trench junction, by a very deep, major Paleogene transform fault running along the coast of NE Kalimantan. Subsequent Neogene thrust or strike-slip motion along this line of weakness may have affected parts of the Tarakan basin, generating sub-vertical faulting and higher heat flows. The orientation of the postulated Miocene half-grabens is also extremely uncertain, but may represent an early phase of east-west extension.

Although traps so far explored offshore are mainly downthrown fault closures, Juata and Sesanip fields are upthrown traps and Ahus-1 and Mayne-1 were both upthrown, fault-dependent tests. Downthrown closures without clear independent rollover were unsuccessful and the largest accumulations (Pamusian, Bunyu and Sembakung), appear to have maintained counter-basinal dip despite inversion and tilting. Original rollover to the north was generated by growth across north-south faults. Most plays had sandstone objectives, although five wells had carbonate objectives, however the latter encountered very little porosity. The search for other trap types has broadened — elements of stratigraphic trapping is probably present in at least three accumulations, all within the lower sand: shale ratio "Santul" marine facies. These traps, however, lack sufficient volume to be commercially viable offshore.

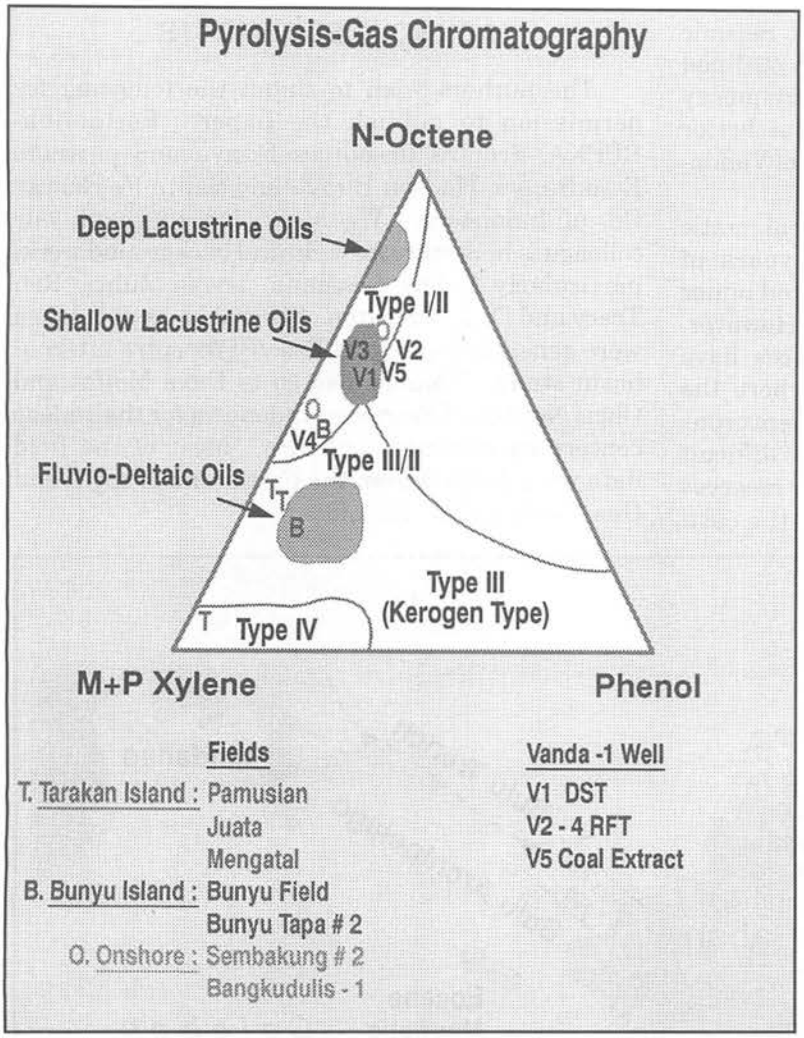

Figure 22. Tarakan Basin oil types. Type I/II and II/III oils (lacustrine and fluvial) are present in the basin and most were generated at relatively low maturities (Ro < 0.9). Oils are thus spatially widespread and from many depositional environments. Few gas condensates, so common in the Kutei, have so far been found.

PAST PROBLEMS AND FUTURE EXPLORATION POTENTIAL

Technical obstacles experienced in the exploration of the Tarakan basin are: lack of good reflectors or geological sequence boundaries, reworking of sediments, lack of age-diagnostic fauna, poor seismic data zones and sea-bottom multiples. Operational constraints include the high expense of drilling deep wells in deep water or into overpressure and of shooting transition zone seismic. Natural obstacles are mainly the lack of closures, especially shallow, areally large structures perpendicular to the reservoir depositional fairways. Others are young migration and lack of competent lateral seals.

Recent work has therefore concentrated on shooting high-technology seismic data, reducing costs of transition zone seismic, enhancing paleontological age determinations with strontium isotope dating and finally, by drilling different play types. Modern techniques, utilizing workstations, more sophisticated geochemical analyses, geothermal history modelling, improved seismic acquisition and processing/reprocessing, have improved data significantly.

The basic problem of lack of structure, however, has focused exploration into a search for new play types such as growth-faults, or other types of carbonates and a search for lowstand or turbidite deposits. For example growth-fault blocks east of Vanda-1, near the Mayne fault system, constitute a major, as yet untested structural play, with additional stratigraphic trapping probably present in the up dip feather-edge of the gas condensate-productive Pliocene sandstones. Still other plays exist in deep, pre-Pleistocene structures, below a subcrop unconformity in the northwest, in large carbonate build-ups in the northeast and in half-grabens in the southeast corner (Fig. 24).

Given that mature source rocks of many types exist in the basin, it is probable that considerable reserves remain trapped in a basin which has so far yielded only 320 million barrels of oil, but little gas condensate. It is considered likely that more oil and significant new gas condensate reserves remain to be discovered, especially in the eastern areas. Decreased future drilling and seismic costs will be necessary to promote future exploration. Seismic stratigraphy, made difficult by the factors outlined above, may be made possible by higher frequency seismic, multiple-removal techniques and better acquisition in a large poor data zone south of Vanda-1.

In conclusion, this large and still enigmatic basin has had nearly one hundred years of exploration, with only one large gas find and minor oil discoveries during the last 20 years. However, recent drilling and technological advances have increased our knowledge to the point where the stage has been set for committed and adventurous explorers with sufficient funds to brave the difficult drilling conditions and discover large new reserves and hopefully even a new oil province in the east!

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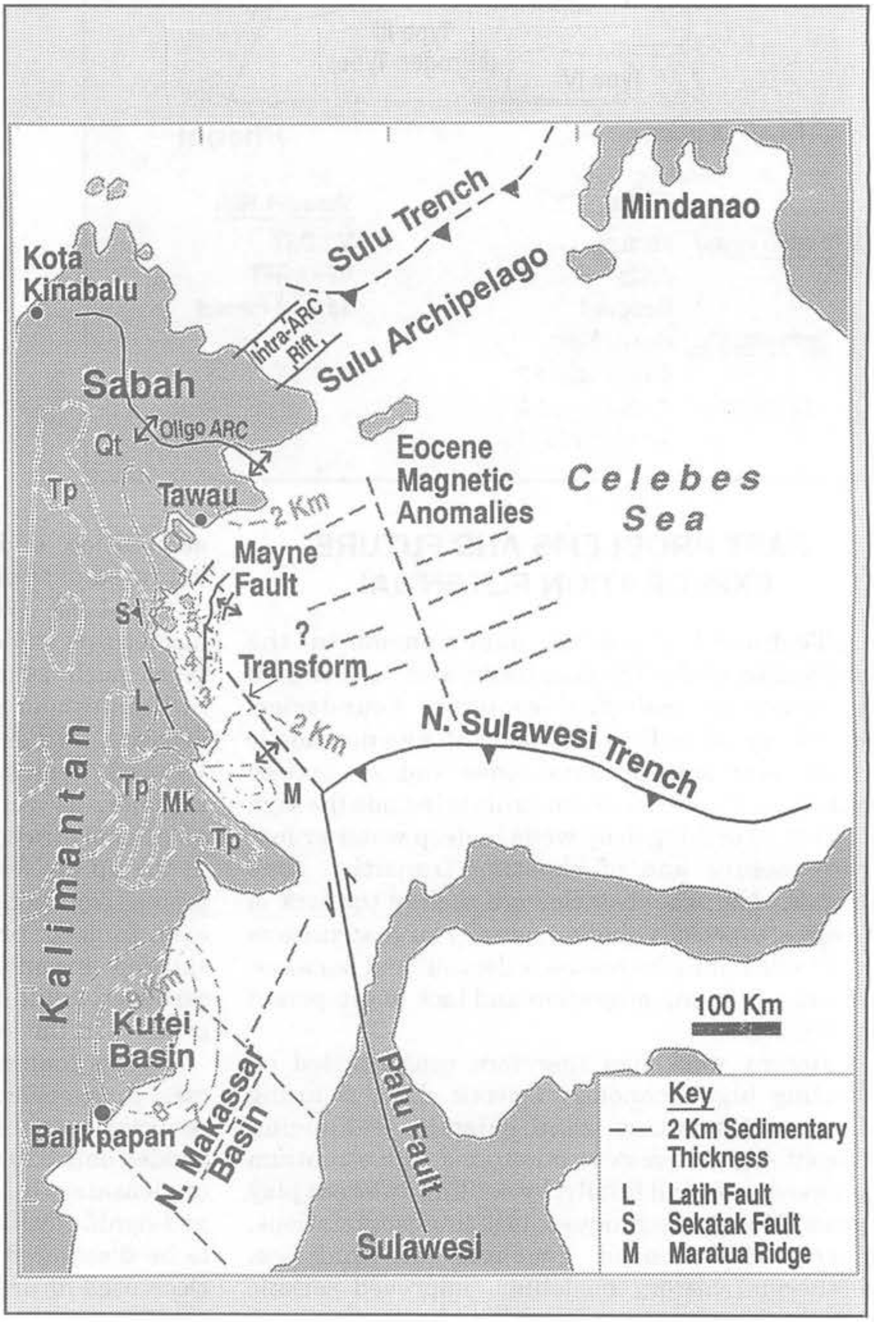

Figure 23. Regional tectonics. The NE Kalimantan basinal area is outlined by the 2 km isopach. The Latih and Sekatak thrust faults are sub-parallel to the fold axes of the Tarakan and Bunyu arches, which similarly may have been generated by deep thrusts. This caused the inversion of Pliocene and perhaps also Miocene extensional depocentres formed by growth-faulting. Inversion was also concomitant with minor strike-slip movements parallel to the coastlines of Bunyu and Tarakan islands, associated with southeasterly tensional slumping towards the passive margin, into the Celebes Sea. Strike-slip faulting could also be the shallow expression of deeper wrenching, originating from a very tentatively proposed, deep Eocene transform perpendicular to the magnetic anomalies present in the Celebes Sea. Such a transform could then provide a trench-arc link between the junction of the N Sulawesi subduction trench and the Palu wrench fault in the south, via the Tarakan basin, to the Oligocene collision arc (Hamilton 1979, shown by the curved trace with double arrows) in Sabah.

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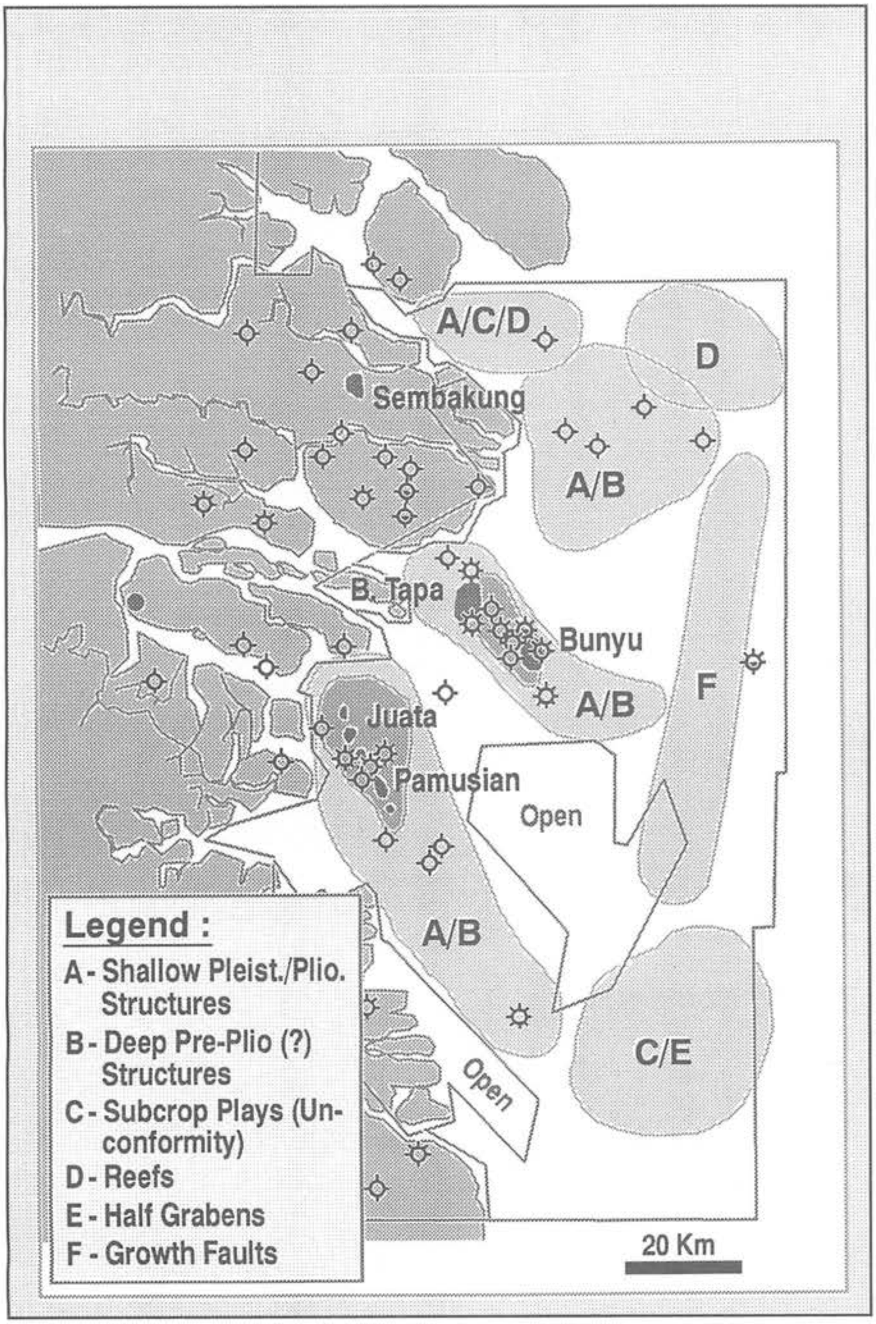

Figure 24. Tarakan Basin future exploration plays. Six varied play types still exist in this relatively unexplored area, the largest potential, in terms of structure, being the growth-fault area (F) east of the Mayne fault. Many small undrilled features exist around the productive arches (A/B) and the southeast (C/E) is completely virgin territory, with DHI's and potentially thick reservoirs.

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