

Sequence stratigraphy applied to the hydrocarbon productive basins of western Indonesia

S. COURTENEY

124 Wangford Road
Reydon, Suffolk, IP18 6NZ, England

Abstract: Oil exploration began in Indonesia in 1870 and the first commercial discovery was made in 1885 in the North Sumatra Basin. Since then over 3,000 exploratory wells have been drilled in Western Indonesia with some 750 discoveries reported. By the end of 1992 over 300 fields in eleven geological basins were producing in Western Indonesia and a further 100 fields were either shut-in or had been abandoned. However, despite the fact that Western Indonesia is a mature hydrocarbon province, all published work of a regional nature, and indeed most internal company reports, use lithostratigraphy and to a lesser extent biostratigraphy.

Lithostratigraphy is based, often unwittingly, on pre-1960's work when only relatively shallow wells and limited seismic were available. Additional difficulties arise from companies using alternative names for a rock unit and the same formation name for different rock units. Biostratigraphy is handicapped by the lack of age diagnostic fossils in the Early Miocene and older sediments in most of Sumatra and Natuna. In Java and Kalimantan, where the older section tends to be more marine and age diagnostic fossils are present, significant errors in age determination occur due to reworking of sediments.

As a consequence the 'hydrocarbon system' in Western Indonesia is inadequately understood and exploration efforts are often poorly applied. This paper proposes a correlative framework using sequence stratigraphy for the hydrocarbon productive basins of Western Indonesia, which should contribute to a better understanding of the 'hydrocarbon system' and significantly reduce exploration risk in Western Indonesia.

INTRODUCTION

Fourteen geological basins in Western Indonesia (Fig. 1) can be considered as being hydrocarbon productive. Oil exploration began in West Java in 1870 and since the first commercial discovery at Telaga Said, North Sumatra, in 1885, over 3,000 exploratory wells have been drilled in Western Indonesia. By the end of 1992 over 300 fields in eleven geological basins were producing in Western Indonesia and a further 100 fields were either shut-in or had been abandoned.

The three basins which did not contain producing fields at the end of 1992 are the Central Java-Pati, Lombok and East Natuna basins. The Tjipluk field in the Central Java-Pati basin produced oil from 1903 until 1912 and may have also continued producing small quantities of oil until 1941 (Van Bemmelen, 1949).

In the Lombok basin the Pagerungan gasfield, which was being developed in 1992/1993, began commercial production in January 1994 with the first delivery of gas to the Gresik power station in East Java.

The East Natuna basin has yet to produce hydrocarbons commercially, but is included due to the fact that the basin has estimated in-place

reserves of 3.20 billion barrels of oil equivalent (excluding carbon dioxide). Most of the reserves can be considered as 'proven' as a result of the extensive testing of the giant 'L' gas field which has yet to be developed due to the high carbon dioxide content of the gas.

Before discussing the proposed correlative framework using sequence stratigraphy for Western Indonesia, the drawbacks of correlations using lithostratigraphy and biostratigraphy will be reviewed.

LITHOSTRATIGRAPHY

At present lithostratigraphy is still commonly used as a means of correlation within and between basins in Western Indonesia. Figure 2 shows a common 'problem' when using lithostratigraphy to correlate between two wells in different exploration blocks. Though this is an example from the North Sumatra basin, analogues can be found in all basins in Western Indonesia and the rest of the world. Such 'miss-ties' most commonly occur at block boundaries (in this example the old block boundary was located in the middle of the seismic line), but also in blocks when the new wells are not correctly integrated with earlier wells.

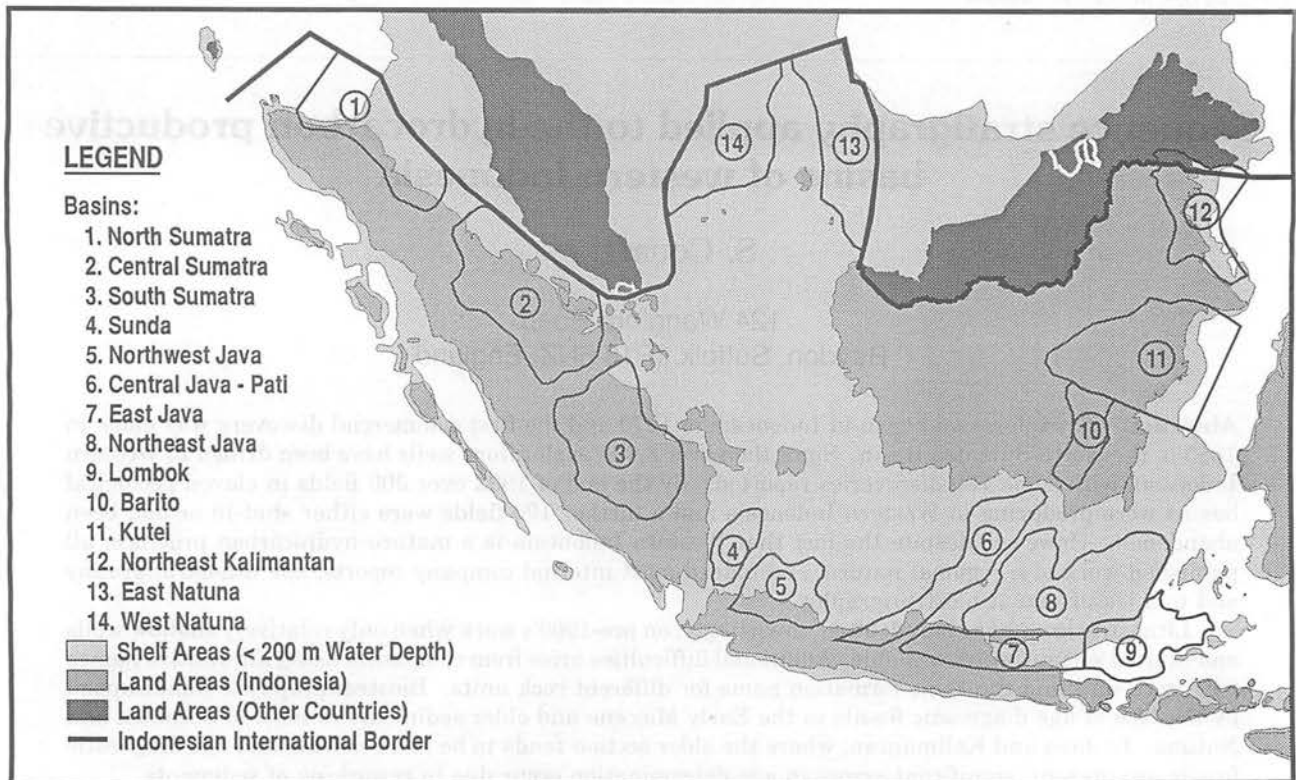
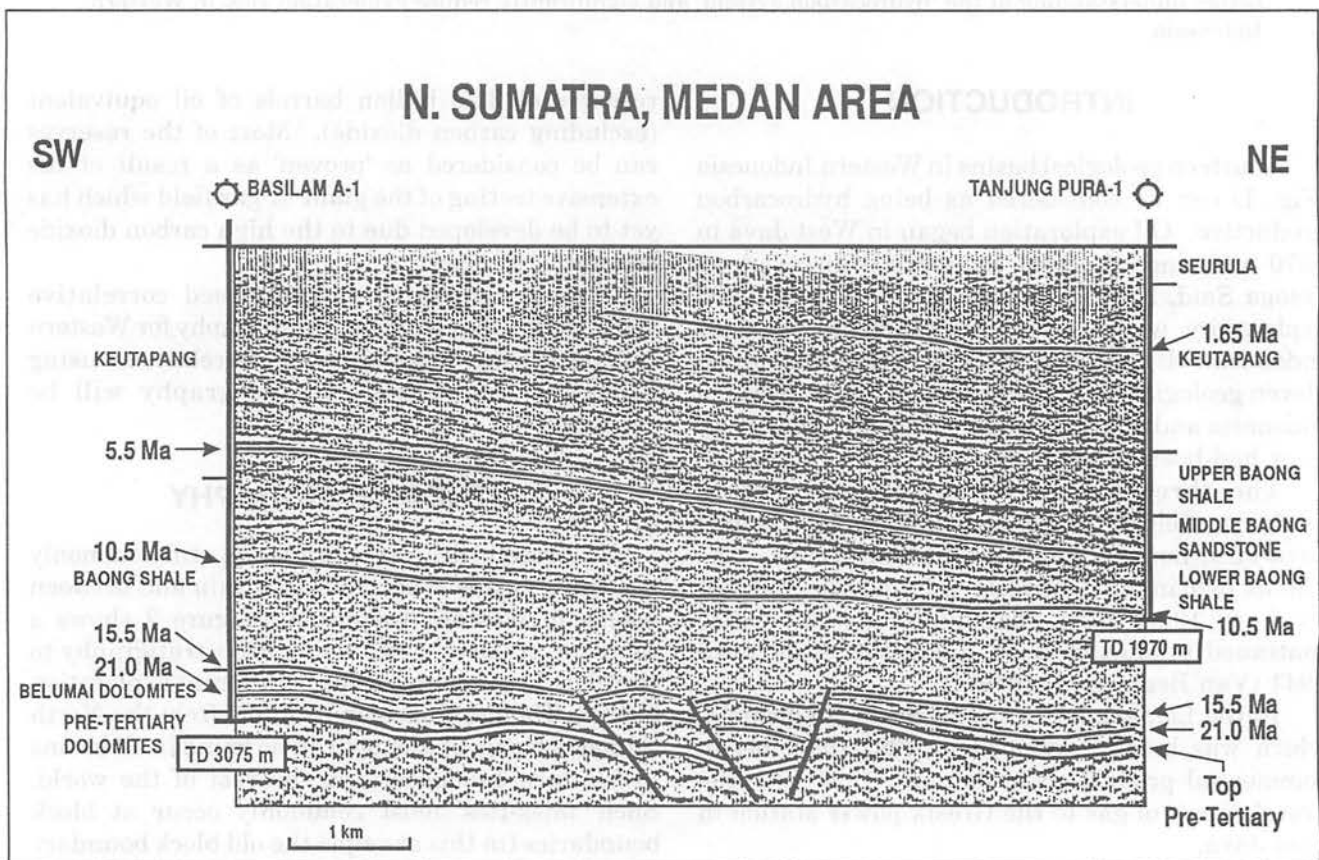


Figure 1. The hydrocarbon productive basins of Western Indonesia.



Lithostratigraphy from Kirby *et al.*, 1989.

Figure 2. North Sumatra, Medan area.

Very few formations in Western Indonesia have well defined type sections and often the origin of a formation name has been lost.

For example, the Julu Rayeu, Seurula and Keutapang Formations which contain the main clastic producing horizons in the North Sumatra basin were first described by T'Hoen (1922) on the basis of surface outcrops, samples from shallow trenches, and cores from the two fields and limited exploratory drilling carried out in East Atjeh until that time. Though this nomenclature was later adopted for use throughout the North Sumatra basin, problems in correlations had been identified by the 1930's when the application of micro-palaeontology became more widespread. The introduction of electric well logs and reflection seismic in the late 1930's confirmed the correlation problems. Meyer (1943) notes that R. Koch carried out a basin wide study of the planktonic foraminifera of the Late Tertiary in the North Sumatra basin during 1941. This work apparently corroborated earlier work by Meyer and demonstrated that the lithostratigraphic correlations of the Seurula and Keutapang Formations were between 158 m and 240 m high to the biostratigraphic correlations in the wells (e.g. Kr. Merbau, Gebang-1 and Lho' Soekon-1) which were located some distance from the surface outcrops in the foothills of the Barisan mountains. Unfortunately, neither the earlier work of Meyer nor that of Koch has ever been published.

The Sihapas Formation of the Central Sumatra basin has, or rather had, a type section in the foothills of the Barisan mountains to the west of the main basin. This was first described by Durham (1939) from a stream section in the Aek Si Hapas. Cameron (1983) downgraded the type section to the Yang Asli Member of the new Sihapas Formation which had previously been assigned to the Kampar Group (Aspden *et al.*, 1982). The Kampar Group was named after a river that rises in the Barisan mountains and was assigned to the outcrops along its upper course. Cameron (1983) demonstrated that the sandstones of the redefined Sihapas Formation in this part of the Central Sumatra basin have a provenance area to the southwest. Other authors (Wongsosantiko, 1976) have demonstrated that the prolific sandstone reservoirs in the Central Sumatra basin have a provenance area to the north or northeast. The use of the Sihapas Formation, or Group, for these reservoirs thus bears little to no relevance to the supposed type section.

The Baturaja Formation of the Sumatra Forearc, South Sumatra, Sunda and Northwest Java basins is a further example of the 'misuse' of lithostratigraphy. The greatest distance between reported occurrences of this formation is over 950

km. The first use of the Baturaja Formation can be traced back to Gsell (1930), who in an internal Bataafsche Petroleum Maatschappij (BPM — the forerunner to SHELL) report describes, in German, the limestone outcrops near the town of Baturaja in South Sumatra. The first use of the Baturaja Formation in a publication in the English language was by Westerveld in 1941.

Hadi and Simbolon (1976) described the Baturaja Formation at its type locality in some detail. They established its age range as Te.5 to Tf.1 of the East Indian Letter Classification. Using the Biostratigraphic Correlation Sheet of van Gorsel (1988) this equates to the Early-Middle Miocene (i.e. 25.2 Ma–15.0 Ma). Van Bemmelen (1949) cites an earlier Te.4–Te.5 (Late Oligocene–Early Miocene) age for the Baturaja outcrops further west in the foothills of the Gumai and Garba mountains. To the northwest Wahab (1986) indicates a Middle Oligocene age for the Baturaja Formation in the area of the Musi-Klingi High. Thus the reported ages for the top of the Baturaja Formation vary from around 28.0 Ma (Late Oligocene) to 15.0 Ma (Middle Miocene) over only 160 km. The Baturaja Formation is thus very diachronous and cannot be reliably correlated over the four basins as implied in the literature. This is perhaps the best example of the application of the same formation name to different rock units.

The South Sumatra basin also provides a good example of the use of alternative names for the same rock unit. PERTAMINA-BEICIP (1985) show in their Figure 20 the nomenclature of the lithostratigraphic units in the South Sumatra basin. Taking the latest Middle Miocene (N.13–N.15) sandstone unit as an example, PERTAMINA apply the name Air Benakat Formation (Upper), STANVAC the name Lower Palembang Formation and both TOTAL and SHELL assign the same unit to the Upper Palembang Formation.

BIOSTRATIGRAPHY

The following three biostratigraphic zonation schemes have been regularly applied to wells in Western Indonesia:

1. East Indian Letter Classification introduced by van der Vlerk and Umbgrove (1927) for larger foraminifera and subsequently modified.
2. The planktonic foraminifera zonation proposed by Blow (1969). An earlier planktonic foraminifera zonation proposed by Bolli (1966) is often used in the East Java area.
3. The calcareous nannoplankton zonation scheme of Martini (1971).

The salient features of each scheme are described below. For a detailed discussion of the

methods and pitfalls, together with other biostratigraphic zonation schemes that have been applied locally, the reader is referred to van Gorsel (1988).

East Indian Letter Classification

The East Indian Letter Classification is still used today. However, since it can only be applied to carbonate sequences and since it is principally of value in the recognition and dating of Early and Middle Tertiary sediments (Adams, 1970), the East Indian Letter Classification can only be reliably applied to:

- The extensive Late Eocene to early Miocene carbonate province that extends from Central Java to the southern Kutei basin and smaller carbonate developments in the Mangkalihat Peninsular and western Northeast Kalimantan basin.
- Early Miocene carbonates in all but the Central Sumatra and West Natuna basins.
- Isolated Late Oligocene carbonate developments in the western parts of the North and South Sumatra basins and the onshore part of the Northwest Java basin.

Adams (1970) also makes two points that are of pertinence to the later discussion on sequence stratigraphy of Western Indonesia. These are:

1. No type sections exist.
2. Van Doornink's record (1932) of Early Eocene faunas from Java is incorrect. The beds contain *Pellatispira* a characteristic larger foraminifera genus of Late Eocene age.

The second point may also be of relevance to the Barito basin where the East Indian Letter Classification has been applied since the 1930's. No detailed descriptions have been published, but the fact that the first datable marine micro-fossils of the Lower Tanjung Formation cited by Kusuma and Darin (1989) are described as Mid-Late Eocene suggests that the micro-fossils are larger foraminifera. It is equally probable that the palaeontologist assigned a T.ab age to them, since T.ab is a common 'catch all' first introduced by BPM geologists for pre-Oligocene sediments. The term T.ab was used widely by many companies in Indonesia until the early 1980's (Bishop, 1980). This is discussed in detail later.

Planktonic Foraminifera Zonation

The planktonic foraminifera zonation of Blow (1969) is a world wide scheme that is now the most frequently applied zonation scheme in Indonesia. However, as with the East Indian Letter Classification it has drawbacks. The planktonic foraminifera tend to be found and preserved in marine sediments which were deposited in water

depths greater than 100 m. Such sediments, if deposited, have only been preserved since the Early Miocene N.4 zone in the basins of western Java, Natuna and most of Sumatra (Wight *et al.*, 1986). De Coster (1974) gives examples of two wells and surface outcrops in the southwest of the South Sumatra basin where planktonic foraminifera of the N.3 zone (Late Oligocene) have been identified. Burnaman *et al.* (1985) cited Late Oligocene benthonic and planktonic faunal assemblages from the Bampo Formation in the Jeuku A-1 well, and Jordan and Abdullah (1992) cite recent palaeontological studies that assign a Late Oligocene age to the Bampo Shale below the Arun gas field. These studies imply that planktonic foraminifera of the Blow's N.2/N.3 zones have been identified.

Elsewhere in Sumatra, western Java and Natuna the sediments below the N.4 zone are lacustrine, alluvial plain, delta plain and shelfal where planktonic fauna are either absent or scarce. The latter three of course contain the major reservoir units throughout the area. The thickness of sediments below the N.4 zone varies from 0–1,200 m in wells to over 1,500 m on seismic sections (e.g. Fig. 8).

In eastern Java and the adjacent areas together with Kalimantan, planktonic foraminifera zones as old as P.9–P.10 (Early-Middle Eocene) are known (Brandsen and Matthews, 1992). In Kalimantan dating problems have arisen due to the reworking of Cretaceous and Jurassic fossils in Eocene sediments (Mouret, 1987) and similar problems have been reported from the Sumatra Forearc basin (Karig *et al.*, 1979).

In Java and Kalimantan particularly, significant errors in age determination using planktonic foraminifera occur due to the reworking of sediments or the absence of index species in the Late Miocene and younger sediments (e.g. Badak-44 type log shown as Figure 2 in Ade *et al.*, 1988). Though not documented, the author believes that such errors also occur in Sumatra especially near the Barisan mountains in the North and South Sumatra basins.

The additional apparent advantage of using the planktonic foraminifera is the existence in Indonesia of a type section, which is often used by palaeontologists as a local reference point. This will shortly be discussed, but unfortunately in terms of significant age errors!

Calcareous Nannoplankton Zonation

The calcareous nannoplankton zonation (Martini, 1971) is widely used in the low latitude Cenozoic and is applied in Indonesia to the same marine sequences as the planktonic foraminifera

zonation. Use of the two schemes together often leads to a more accurate age determination and a better understanding of the palaeoenvironments. The application of calcareous nannoplankton zonation suffers from the same geographic and age restrictions as the planktonic foraminifera. At first it appears that the calcareous nannoplankton zones NN.1 to NN.3 and NN.8 have been correlated to the Indonesian section, implying perhaps, the existence of an Indonesian type section.

Indonesian Type Section

The existence of a reliable Indonesian type section for either planktonic foraminifera or calcareous nannoplankton is of great importance since it would provide a vital control point for sequence stratigraphy. The type section of the planktonic foraminifera can be traced from Blow (1969) to Bolli (1966) and back to a dissertation at the University of Utrecht by Boomgart (1949).

The planktonic foraminifera type section is in fact the Bodjonegoro-1 well drilled by BPM in 1934 in Northeast Java (Fig. 3 — inset). It is perhaps worth noting that in the same year as Boomgart completed his dissertation, van Bemmelen (1949) published *The Geology of Indonesia*. In the *Economic Geology* section of this work van Bemmelen states, when describing the stratigraphy of the oilfields in Northeast Java: "*The sequence of the Neogene sediments in NE Java differs strongly from the stratigraphy of the oil terrains in Sumatra and Borneo.*" (Volume II, Page 33). The Bodjonegoro-1 well is located on the same anticlinal axis as the Kawengan oilfield around 25 km to the ESE. Since the Kawengan field is the largest field in Northeast Java, the choice of a type section on the same regional trend in an area with obvious stratigraphic correlation problems is worrying.

Notwithstanding the above, Bolli (1966) stated: "*No similarly complete Lower Miocene to Pliocene section rich throughout in planktonic foraminifera is known to the author. Bodjonegoro-1 therefore offered a unique opportunity to restudy the planktonic foraminifera in the light of present day knowledge*" The Bodjonegoro-1 well has thus become established as a type section even though Blow (1969) also expressed some reservations.

Before examining the Bodjonegoro-1 well in detail the results of two modern wells in the East Java basin will be reviewed. The two wells are:

MS-1-1: Drilled in 1970 by CITIES to test the Kawengan ("GL") Formation of Late Miocene-Pliocene age (using the zonation of Bolli) which produced some 10.8 million barrels of oil in the onshore Kruka oil field (Courteney *et al.*, 1989) situated some 53 km to the west. Both the MS-1-

1 and Kruka structures are shale enhanced inversions. MS-1-1 reached a total depth of 2662 m in a marl which is reported as being Middle Miocene in age. A seismic line across the Kruka field was published by Patmosukismo *et al.* (1985) and this is shown in Figure 4. The MS-1-1 structure is represented at the surface by Kambing Island and is more elongate than the Kruka structure. Its flanks are also steeper, but the structure appears not to be as faulted as the Kruka structure.

BD-1: Drilled by MOBIL in 1987 to test a suspected Early Miocene reefal buildup. A seismic line across the 'BD' reef published by Widjonarko (1990) is shown in Figure 5. The ages on Figure 5 have been converted from the series ages using the Mesozoic-Cenozoic Cycle Chart of Haq *et al.* (1987).

The difference between the post and pre-drilling interpretations is very significant bearing in mind that the MS-1-1 well is only 7.5 km NNW of BD-1 and has apparently reliable palaeontological control to the Middle Miocene. There are no major faults between the two wells, just the steep flank of the MS-1-1 structure which is seen on the northern end of each panel in Figure 5. Whereas the difference in the deeper and older sequences can be explained by lack of local control, the difference of around 430 milliseconds TWT (approximately 410 m) at the Base Pliocene is much harder to explain. The palaeontological data from the MS-1-1 well indicate a reliable correlation back to the type section of the Bodjonegoro-1 well. It is thus necessary to examine fully the palaeontological data in the Bodjonegoro-1 well which is only 150 km west of MS-1-1.

Figure 6 shows the distribution of planktonic foraminifera in Bodjonegoro-1 which has been simplified so that only the index species of Bolli (1966) are included. It is apparent that Bolli (1966) and Blow (1969) assign significantly different ages to the planktonic foraminifera as is shown in Table 1.

In justifying the differences between their interpretations Blow (1969, page 90) states: "*It is evident that Bolli and Bermudez (1965) did not correctly assess the complete stratigraphic ranges of the taxa used by them* Further, Bolli (1965, 1966) and Bermudez (1965) did not relate their 'biostratigraphy' sufficiently to local geological conditions and were misled by heterogeneous assemblages, incomplete knowledge of the ranges of the taxa they used and by using too few taxa in their zonation: thus, they had insufficient stratigraphic control over the actual taxa used in the distinction and differentiation of the 'zones' they proposed".

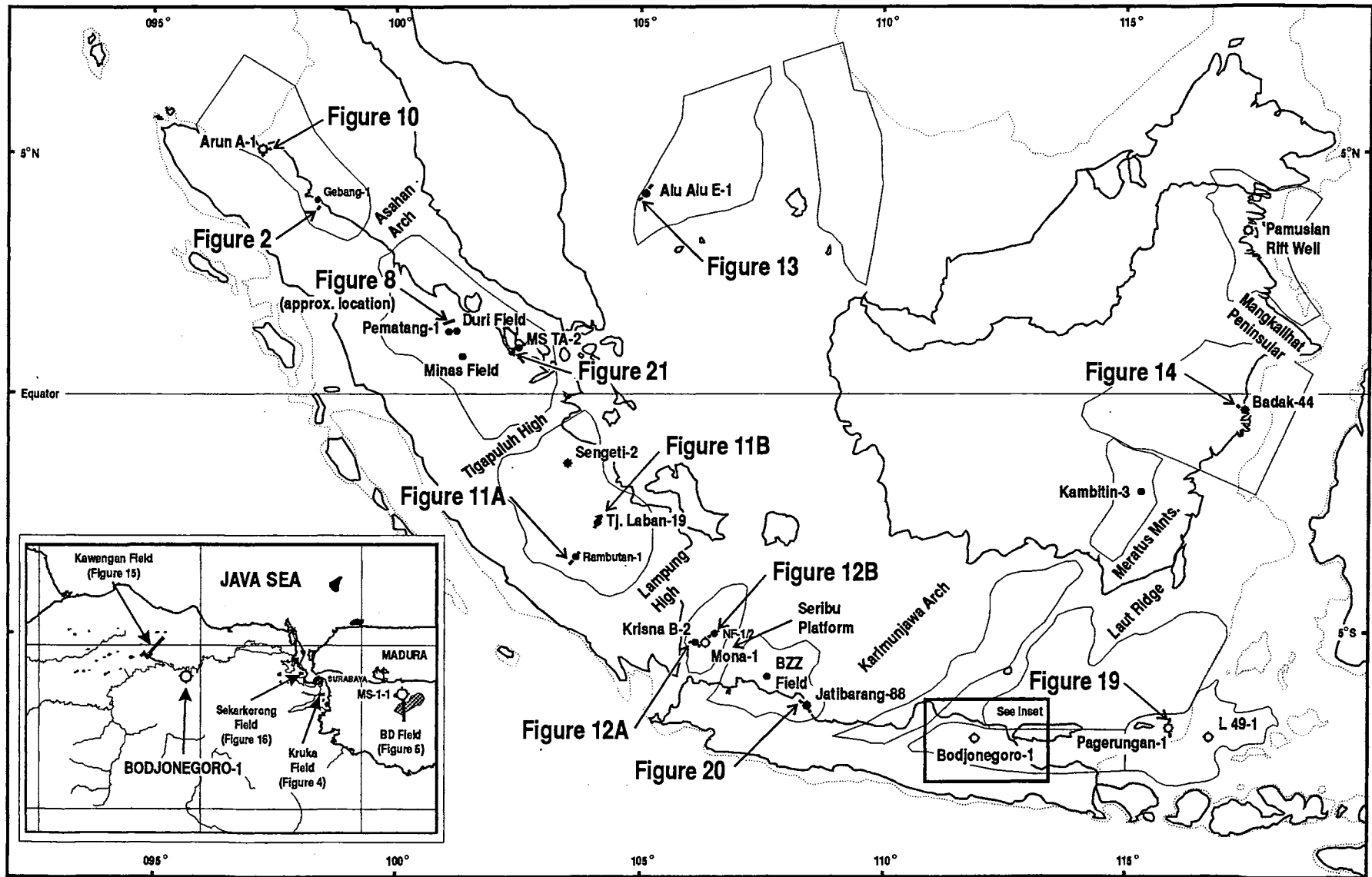
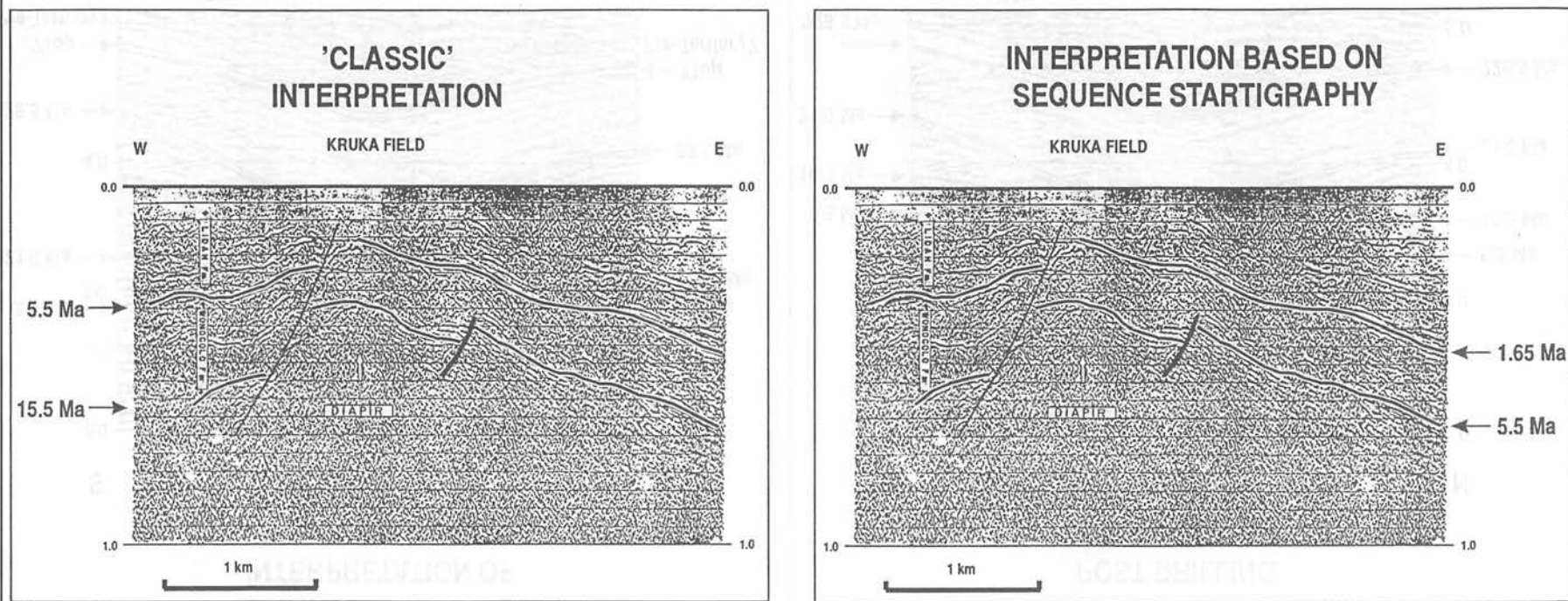


Figure 3. Location of figures and wells.

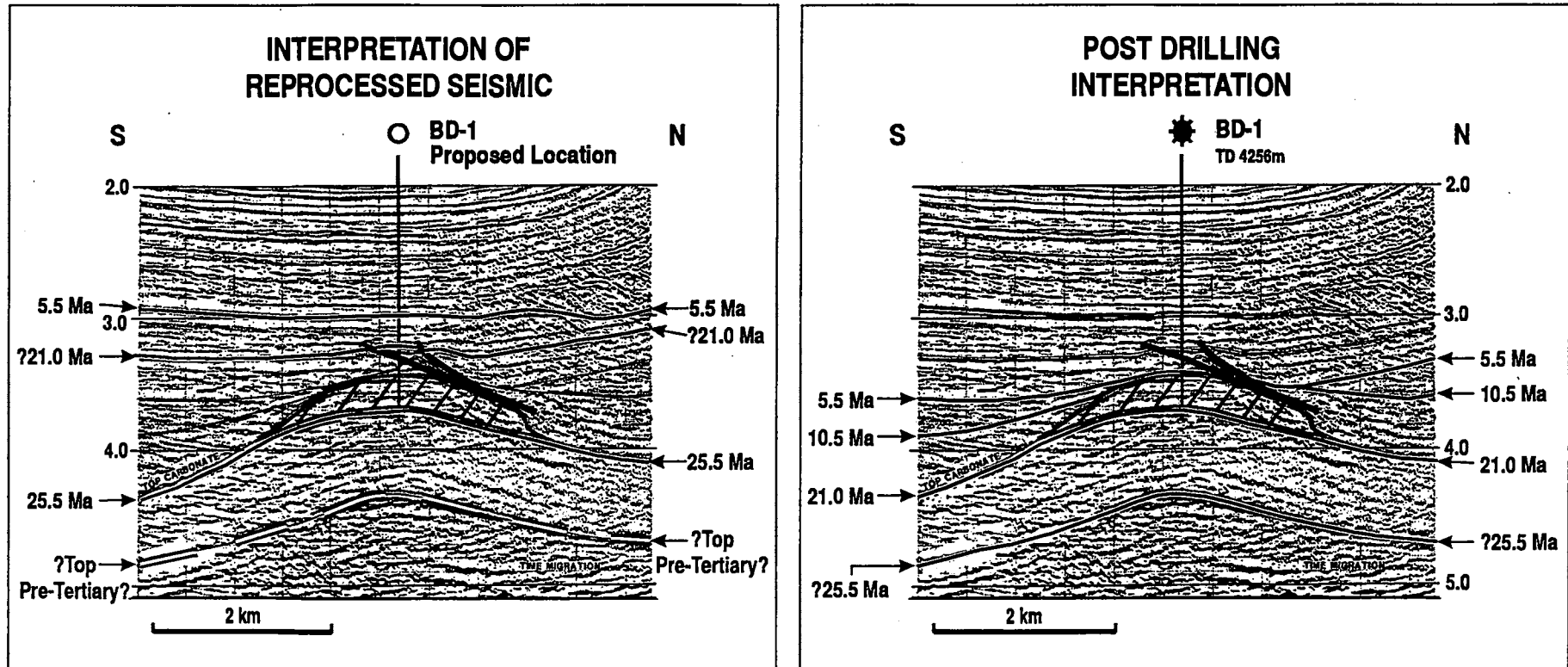
E. JAVA, KRUKA FIELD



Reinterpretation of seismic section from Patmosukismo *et al.*, 1985.

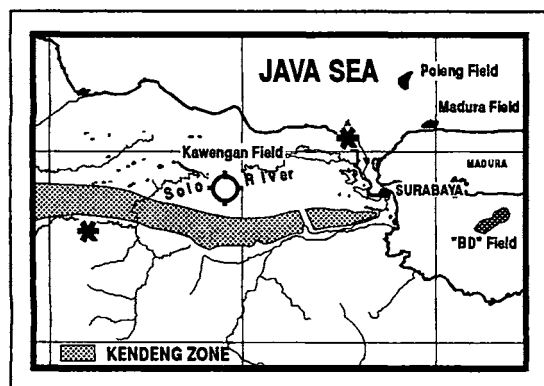
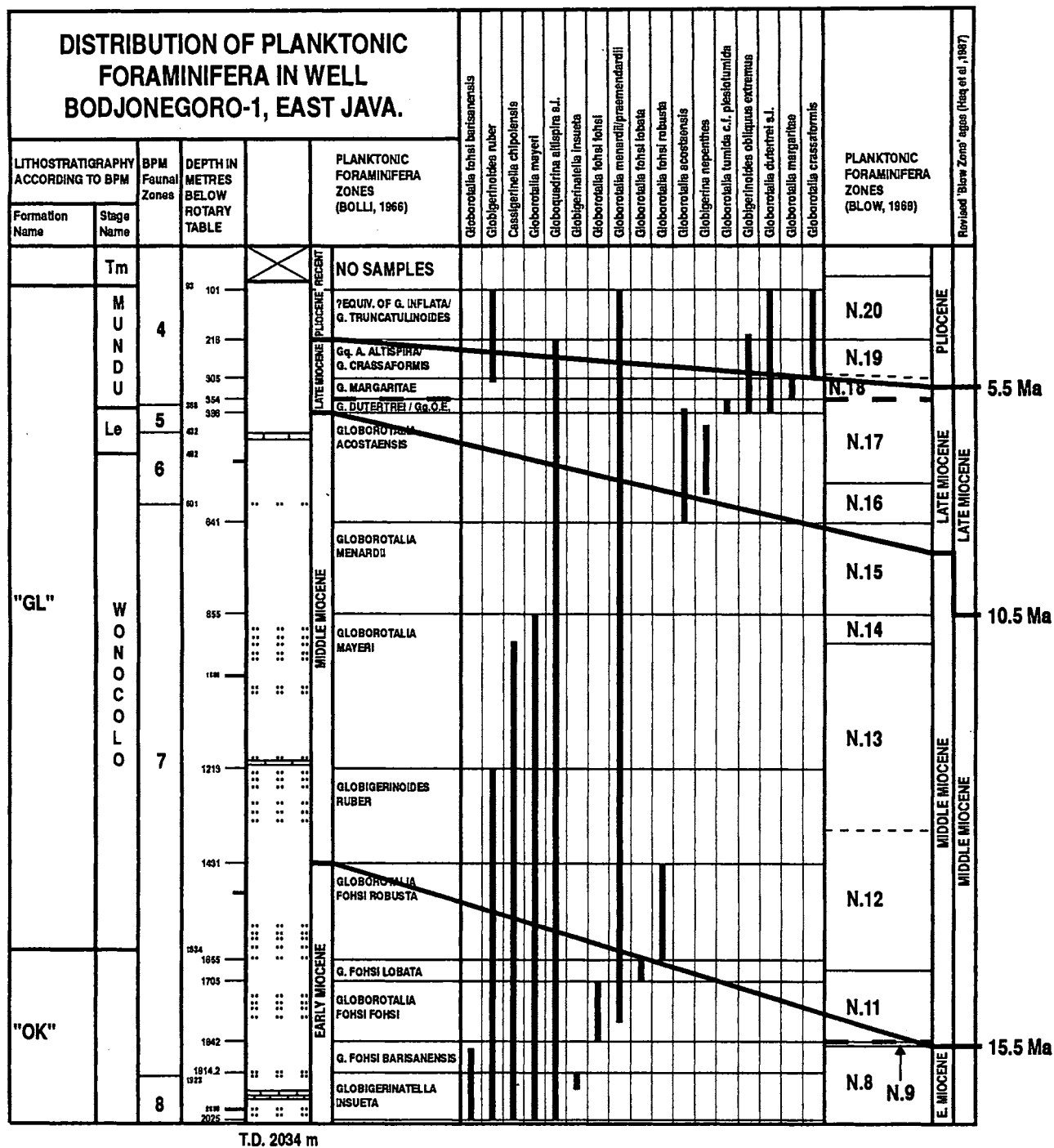
Figure 4. The differing interpretations of the Kruka field, East Java.

E. JAVA, BD-1 WELL



Modified from Widjonarko, 1990.

Figure 5. Pre and post drilling interpretations of BD-1 well, East Java.



Notes

1. Tm = Tambakromo, Le = Ledok.
2. Part of N.9, all of N.10 and part of N.11 missing.
3. Hiatus marked as: — — —

Map Legend

- Bodjonegoro-1 Well Location.
- ★ Fossil Localities.
- Oil Fields.
- Gas Fields.

Figure 6. Bodjonegoro-1 Well.

Table 1. Comparison between age determinations of Bolli and Blow for the well Bodjonegoro-1.

Series	Chronostratigraphy (Haq <i>et al.</i> , 1987)	Bolli (1966)	Blow (1969)	Difference
Base Pliocene	5.5 Ma	216 m	254 m	38 m
Base Late Miocene	10.5 Ma	286 m	670 m	384 m
Base Middle Miocene	15.5 Ma	1431 m	1916 m	485 m

Figure 36 of Blow (1969) correlates Bodjonegoro-1 to Kawengan-9 which is located 25.2 km to the west. This well in the large Kawengan oil field is located 670 m northwest of Kawengan-1 which is shown on the seismic section in Figure 15. The main production in the Kawengan field comes from the Ngrayong sands at the base of the 'GL' (*Globigerina* Marls) Formation which are interbedded with deep water marls.

It is interesting to note in Bolli (1964) that adverse ecological conditions are invoked to explain an absence over 899 m of the *Globigerinoides ruber* in Bodjonegoro-1 and that similar conditions are again invoked to explain why the *Globorotalia tumida* complex in Bodjonegoro-1 continue to the present, whereas in Venezuela (Cubagua-1) the species disappears after a short but distinct occurrence.

In view of the reported difference in stratigraphy between NE Java and other areas of Western Indonesia (van Bemmelen, 1949), the presence of over 3,300 m of Pliocene and younger sediments in the well BD-1 (Widjonarko, 1990), the correlation by Blow (1969) between the Kawengan field and Bodjonegoro-1 and the rapid facies changes in the NE Java area reported by several authors, an alternative interpretation is possible: namely, that most of the Bodjonegoro-1 section is reworked!

Strong evidence to support this interpretation is provided by van Gorsel (1988) who states: "*Uplift of the Kendeng zone in NE Java caused erosion of the rich Late Miocene-Pliocene Globigerina marls and deposition of locally abundant reworked deep marine foraminifera in the Pleistocene lacustrine and fluvial Pucangan and Kabuh Formations to the South. At first sight preservation is good, but close inspection reveals common dissolution pits. Also, most species are thick-walled Globorotalia and Pulleniatina: small fragile Globigerina are absent. Recent sediments of the Solo River delta North of Surabaya also contain such reworked Kendeng zone material (S.R. Troelstra pers. comm.).*"

The two localities mentioned by van Gorsel are marked on the map in Figure 6. The Bodjonegoro-1 well is located between them. The planktonic foraminifera distribution chart in Figure 6 shows a preponderance of *Globorotalia*. This author therefore believes that the Bodjonegoro-1 well has penetrated a section of Pleistocene sediments containing abundant reworked Miocene and Pliocene fauna (both benthonic and planktonic foraminifera). Such an interpretation also explains the fact that good porosity reservoirs have been encountered in the oil fields in the area despite the fact that palaeontologically the sediments would appear to be deep marine. The Bodjonegoro-1 well is thus not suitable as a type section for planktonic foraminifera in Indonesia.

Mention was made earlier of a possible Indonesian type section for calcareous nannoplankton. However, when the references of Martini (1971) are checked the Indonesian examples are traced back to Bramlette and Wilcoxon (1967) who state that: "*the many (95) samples from Indonesia were from drilled wells, with their location and depths unavailable, but their original stratigraphic assignments are indicated under the discussion of Biostratigraphic Zonation and shown in Table 2.*" Their Table 2 cites the East Indian Letter Classification, which has been discussed earlier, and the section of their discussion of Biostratigraphic Zonation dealing with Indonesia ends with the comment: "*The letter assignment of these samples was based, however, on the results of field exploration, drilling, and accompanying study by biostratigraphers in areas of Java and Borneo over a period of many years.*" While this does not necessarily mean that a full circle back to the Bodjonegoro-1 well has been made, it is highly likely that the Miocene and younger samples were from the NE Java area. There is thus no suitable Indonesian type section for the calcareous nannoplankton that can be used for sequence stratigraphy.

PROPOSED CORRELATIVE FRAMEWORK USING SEQUENCE STRATIGRAPHY

All the hydrocarbon producing basins of Western Indonesia are underlain by rifts or rift systems (Courteney and Williams, 1994) and generally these basins are separated by wide arches comprising Pre-Tertiary metasediments and intrusives. Consequently, the limitations of biostratigraphy described earlier are further compounded by the fact that sequence boundaries visible on seismic and tied to biostratigraphy in wells in one basin cannot often be followed on seismic to the adjacent basin. This is particularly true of the pre-Early Miocene sequences (pre-N.4). Older units in the non-marine basins of Western Indonesia have been correlated by applying the principles of 'non-marine' sequence stratigraphy to well logs and seismic with support, when available, of Kr/Ar age determinations of volcanics.

The major 'geological hurdles' to this correlative framework were the Karimunjawa Arch (separating the Northwest Java basin from the basins of the greater East Java area), the Meratus Mountains (and their extension, the Meratus Ridge) and the Laut Ridge (separating the greater East Java basins from the Barito and Kutei basins), the Mangkalihat Peninsular (separating the Kutei and Northeast Kalimantan basins), the Lampung High (separating the Sunda and South Sumatra basins) and the Asahan Arch (separating the North and Central Sumatra basins). Lesser 'hurdles' were occasioned by the Tigapuluh High, which separates the Central and South Sumatra basins, and the Seribu Platform, which separates the Sunda and Northwest Java basins. These are all shown in Figure 3. The isolated nature of the Natuna basins on the northern margin of Sundaland also presented difficulties.

Notwithstanding the above, the Tejas A3, A4, B1, B2 and B3 Supercycles of Haq *et al.* (1987) can be recognised in Western Indonesia. Sediments from the earlier Tejas A2 Supercycle are also present locally. Using log and seismic data within the constraints of the available and reliable age determinations (from biostratigraphy, strontium isotope data, radiometric data), boundaries approximating to the 39.5 Ma, 30.0 Ma, 21.0 Ma and 10.5 Ma sequence boundaries of these Supercycles have been correlated throughout Western Indonesia. Additionally, perhaps as a function of the better age determination through the application of planktonic foraminifera, the 25.5 Ma, 15.5 Ma and 5.5 Ma Sequence Boundaries have also been correlated. Other sequence boundaries have been used locally.

Figure 7 shows the thicknesses (after

compaction) of each third order cycle of Haq *et al.* (1987) from some 500 wells throughout Western Indonesia. It is interesting to note that even after allowing for the effects of compaction the late Neogene sequences are considerably thicker than the earlier sequences. The convergence of the Average and "Weighted" Average curves around 19.5 Ma shows the point at which the Early Tertiary rifts have been filled. The reason for this is that the "Weighted" Average curve only includes those wells where the earlier sequences have been deposited and preserved. The later divergence of the two curves in the late Tejas B2 and in Tejas B3 indicates the erosion caused by the uplift and/or inversion particularly in the Barisan Mountains, Sumatra, the Natuna area and Central Kalimantan during those times.

Prior to discussing the Supercycles in detail a further 'key' point needs to be addressed: namely, what is 'Basement'? Many authors imply that Basement is synonymous with Pre-Tertiary. This interpretation is usually based on the interpretation of a low frequency/high amplitude seismic event (PERTAMINA-BEICIP, 1994; Soeparyono and Lennox, 1989) or significant changes in electric log character (Mulhadiono and Sutomo, 1984). In many cases this interpretation is valid, however, there are some significant cases where it is not. Figure 8 shows a question first posed by Santoso *et al.* in 1990. The Top Pre-Tertiary reflector is in fact at around 1.65 seconds TWT in the centre of the section. The packet of low frequency/high amplitude events that reach a time of 1.15 seconds TWT near the centre of the section represent the Brown Shale Member (or Formation) of the Pematang Formation (or Group). In the Central Sumatra basin this is the main source rock (Williams *et al.*, 1985). Thus many authors have interpreted the top of the source rock interval as the top of basement (or Pre-Tertiary)!

PERTAMINA-BEICIP (1994) and Soeparyono and Lennox (1989) have made similar error in the Asri sub-basin of the Sunda Basin and in the Cepu area of the East Java basin. Seismic data in the Medan area also suggests that a more optimistic interpretation to that of Mulhadiono and Sutomo (1984) is possible. They are by no means the only authors which have made the same error and, for example, a detailed comparison of earlier publications containing Pre-Tertiary or basement maps with the well results in the AAPG International Developments (MASERA-AAPG Data Systems, 1991) shows similar misidentification.

Tejas B2 (TB2) Supercycle

The discussion of the supercycles of Haq *et al.* (1987) will commence with the least controversial.

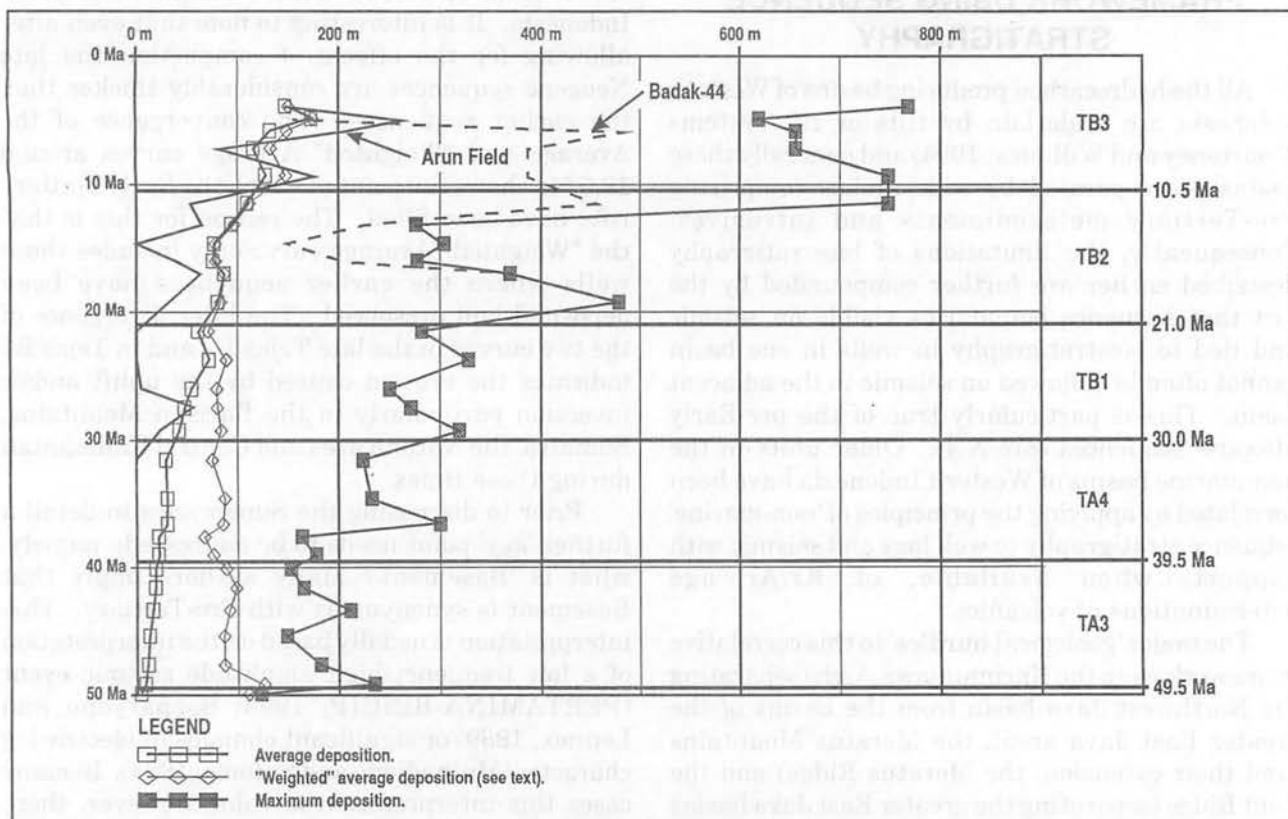
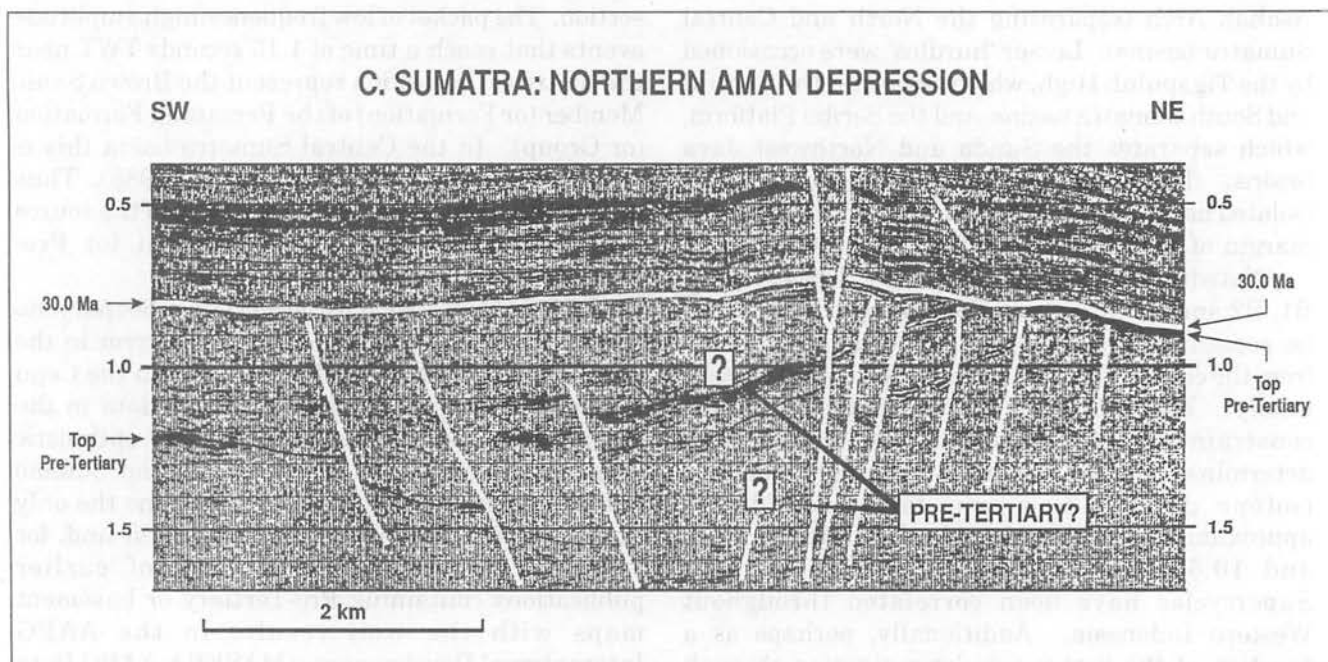


Figure 7. Graph of sediment thickness versus age.



Modified from Santoso *et al.*, 1990.

Figure 8. The Pre-Tertiary/Basement Enigma.

The TB2 Supercycle is tied to the giant Arun gas field (Figs. 9A and 10) by palaeontological and strontium isotope data (Jordan and Abdullah, 1992) and its base, the 21.0 Sequence Boundary, is tied to the N.5 Zone of Blow (1969) elsewhere.

Figures 9A–9C show a regional correlation using well logs through significant fields in the North, Central and South Sumatra, Sunda and West Natuna basins. In Figure 9A the TB2 Supercycle is generally transgressive until the 15.5 Ma Sequence Boundary. In the Arun field reefal limestones of the Peutu Formation were developed. Reefal limestones were also developed in the early part of the Supercycle in the Tanjung Laban field (Fig. 9B) and the nearby Rawa and Ramba fields (Fig. 11B) which are locally assigned to the Baturaja Formation. A similarly thin reefal limestone is also developed above the 21.0 Ma Sequence Boundary on the Krisna High in the Sunda basin (Figs. 9C and 12A). A much thicker reefal development is the reservoir of the 'BD' gas field in the East Java basin (Fig. 5).

In the Central Sumatra basin retrogradational sandstones were deposited and are the main reservoirs for the giant Duri field (Fig. 9A). These are in turn overlain by the progradational sands of the regressive late TB2 Supercycle which are also reservoirs in the Duri field and some nearby much smaller fields. In the West Natuna basin, sands of the Lower Arang Formation are productive in the Belida field (Figs. 9C and 13). These laterally very discontinuous sands were probably deposited in incised valleys. The overlying shales record the first marine transgression in this part of the West Natuna basin. In the giant Badak gas field, Kutei basin, the G61 Reservoir is a progradational sandstone in the early transgressive part of the TB2 Supercycle (Fig. 14).

The early TB2 Supercycle (21.0 Ma–15.5 Ma) contains 14.87% of the estimated 'in-place' reserves of Western Indonesia (Fig. 22). The majority of these are reservoired in the Arun and Duri fields. The late TB2 Supercycle (15.5 Ma–10.5 Ma) contains 18.80% of the estimate 'in-place' reserves which are mostly reservoired in the Kutei basin.

Tejas TB3 (TB3) Supercycle

Using planktonic foraminifera located away from major uplifts such as the Barisan Mountains of Sumatra and the Kendeng Zone in East Java, it is possible to correlate the 5.5 Ma and 10.5 Ma Sequence Boundaries into areas of significant reworking like the oil fields of Northeast Java mentioned earlier.

Figure 15 shows the resulting interpretation of the area between and around the Kawengan and Sebogo oil fields, E. Java. The major producing

interval of the Kawengan field, the Ngrayong sands, is located above the 10.5 Ma Sequence Boundary and is some 5.5 million years younger than the age assigned to the Ngrayong sands in the literature (normally earliest Middle Miocene).

Similar correlations through to the Kruka oil field (Fig. 4, right panel) and the Sekarkorong oil field (Fig. 16, right panel) near Surabaya in East Java indicate an error of around 10 million years in the 'classic' interpretation of these fields.

Reservoirs of the early TB3 Supercycle contain 22.57% of the estimated 'in-place' reserves of Western Indonesia (Fig. 22), the vast majority being in the clastic reservoirs of the Kutei basin (e.g. Fig. 14 and Duval *et al.*, 1992). Other significant fields in the same interval include: the Telaga Said oilfield, N. Sumatra; the Kawengan oilfield, E. Java and the giant 'L' gasfield, E. Natuna (Sarg, 1988) which has reservoirs in a large reefal carbonates. Only minor hydrocarbon potential remains in the early TB3 Supercycle.

The late TB3 Supercycle includes the Pleistocene clastic reservoirs of the Central Java-Pati (Tjipluk oil field), East Java and Northeast Kalimantan basins which account for 0.065 of the estimated 'in-place' reserves of Western Indonesia together with the Pliocene clastic reservoirs which account for a further 2.94% of the 'in-place' reserves. Such major fields as Rantau, North Sumatra, and Pamusian, Northeast Kalimantan are produced from Pliocene reservoirs. The reservoirs of the late TB3 Supercycle are only of historical interest since no remaining potential exists.

Tejas B1 (TB1) Supercycle

The TB1 Supercycle is also tied to palaeontological and strontium isotope data in the Arun gasfield (Fig. 9A) where the interval from 25.5 Ma to 21.0 Ma is missing. However, as mentioned earlier in the section on Biostratigraphy, elsewhere in Sumatra planktonic foraminifera are rare below the N.4 Zone. In Figures 9A–B the Duri field has no age diagnostic foraminifera, in the Minas, Sengeti and Tanjung Laban fields planktonic foraminifera allow the dating of the shales above the 25.5 Ma Sequence Boundary. No age diagnostic fossils are present in the lacustrine shales of the Alu Alu E-1 well in the West Natuna basin, whereas the shales interbedded with the thick carbonates of the Lower Baturaja Formation (above the 25.5 Ma Sequence Boundary) in the Krisna field can be reliably dated to the N.4 Zone.

In South Sumatra sediments above the reef build-ups on the Musi-Klingi Platform have been dated as Late Oligocene, N.3/P.22 and N.2/P.21 (de Coster, 1974; Wahab, 1986). Figures 11A and 11B again illustrate the diachronous nature of the

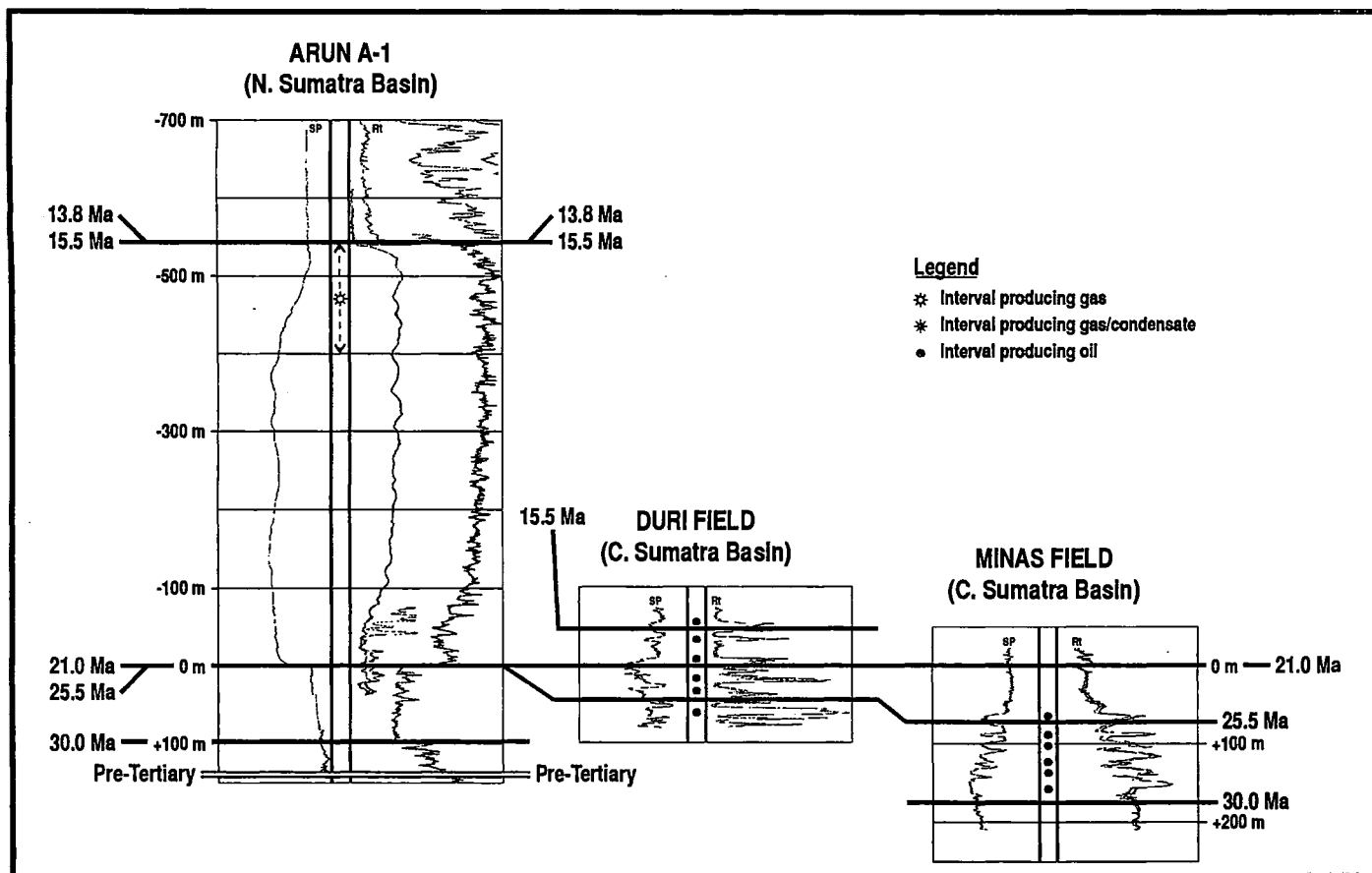


Figure 9A. Correlation of TB1 and TB2 Supercycles.

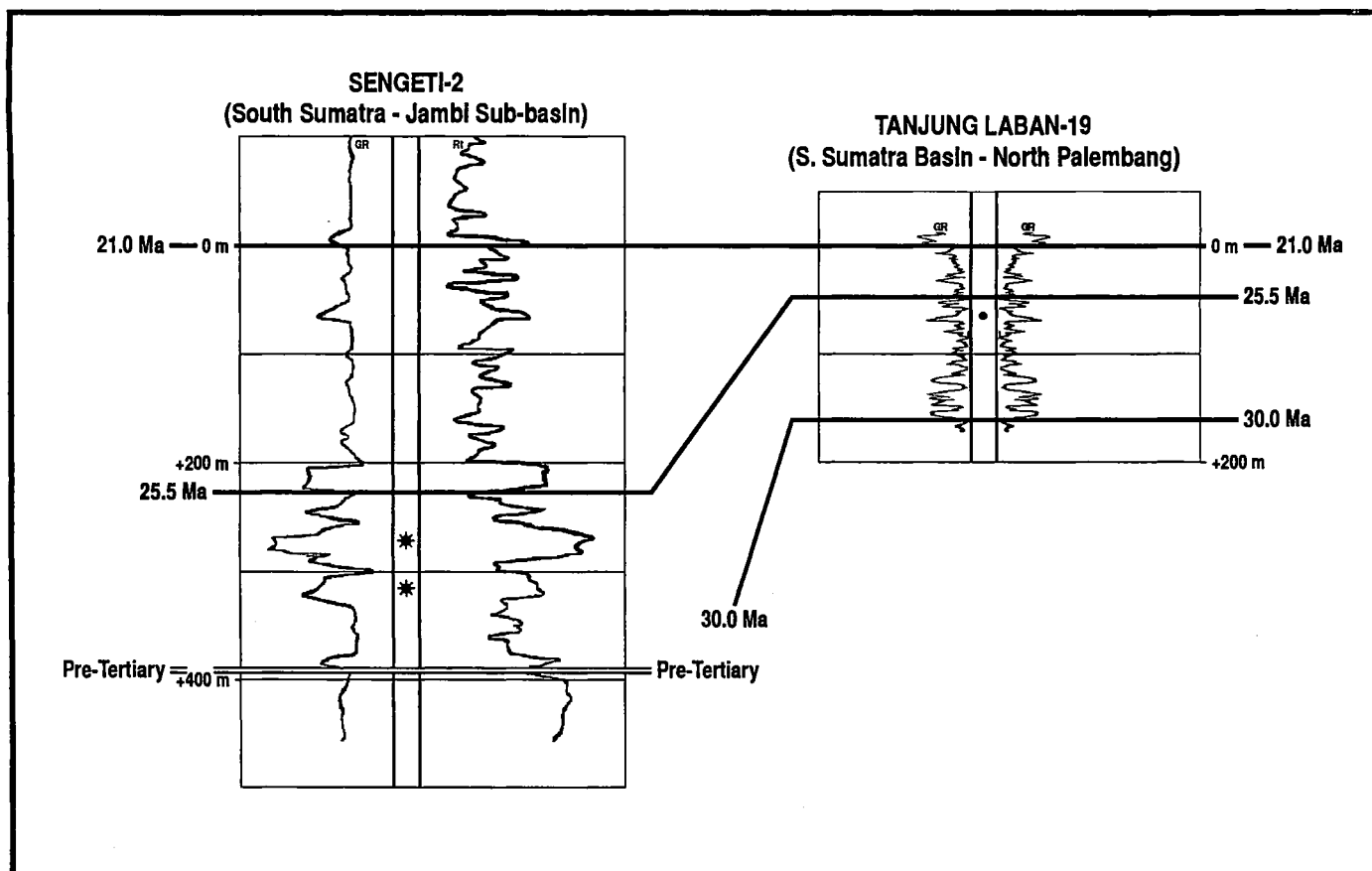


Figure 9B. Correlation of TB1 and TB2 Supercycles, continued.

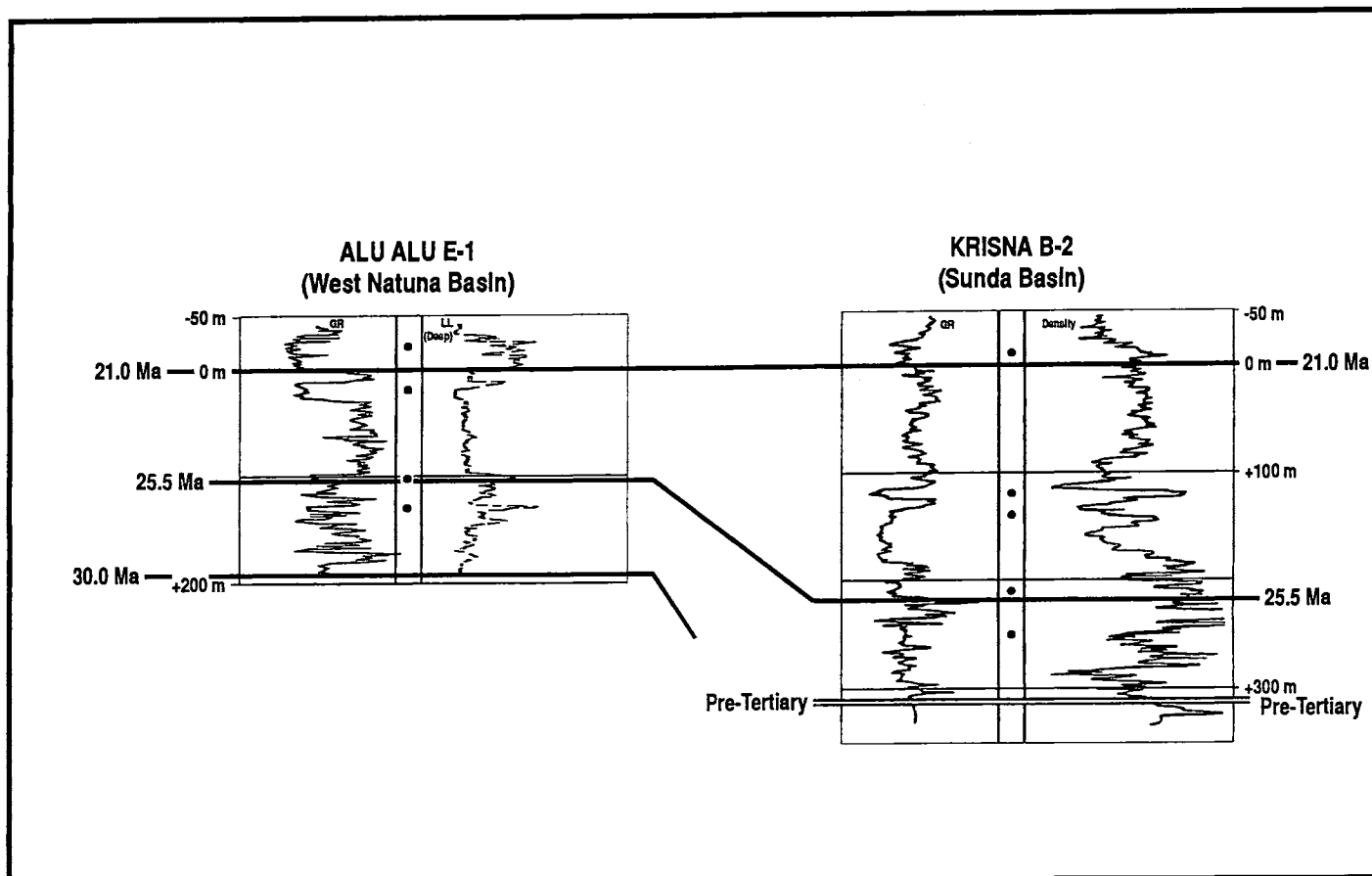
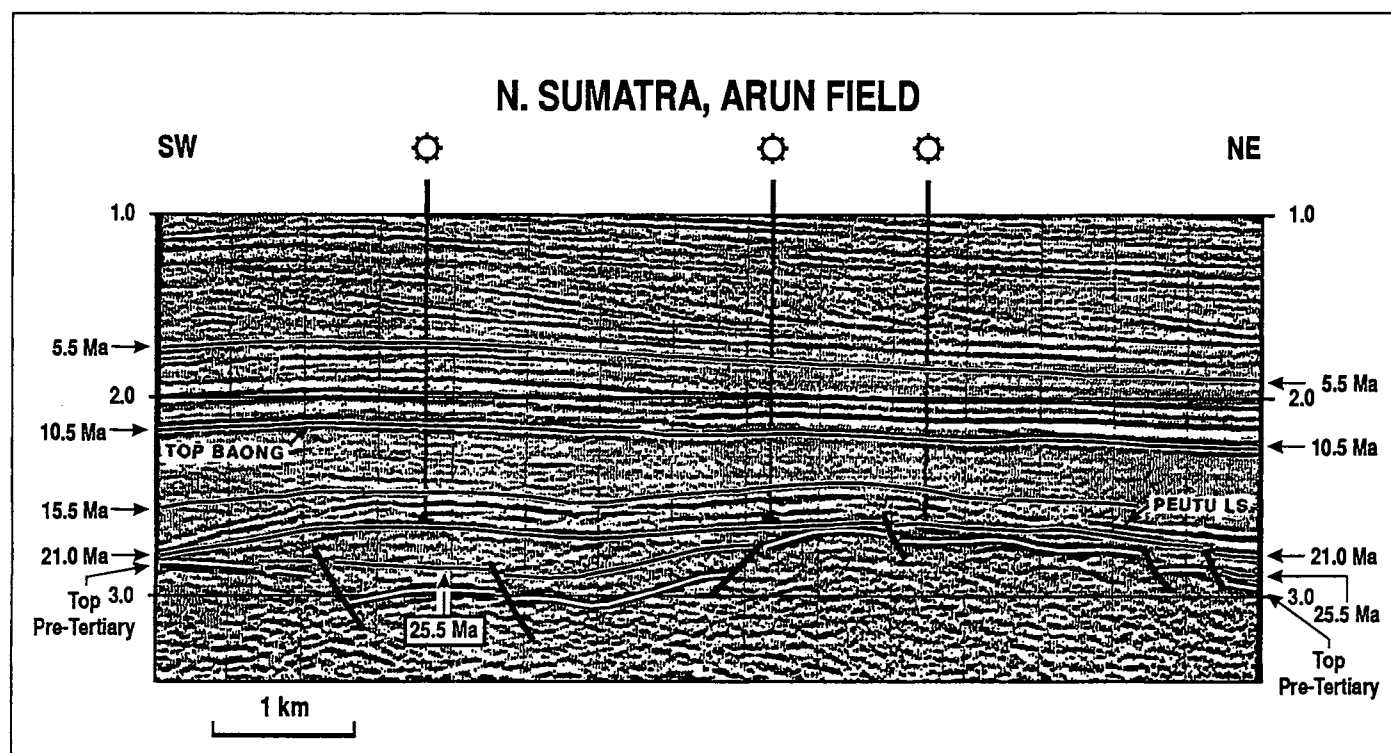


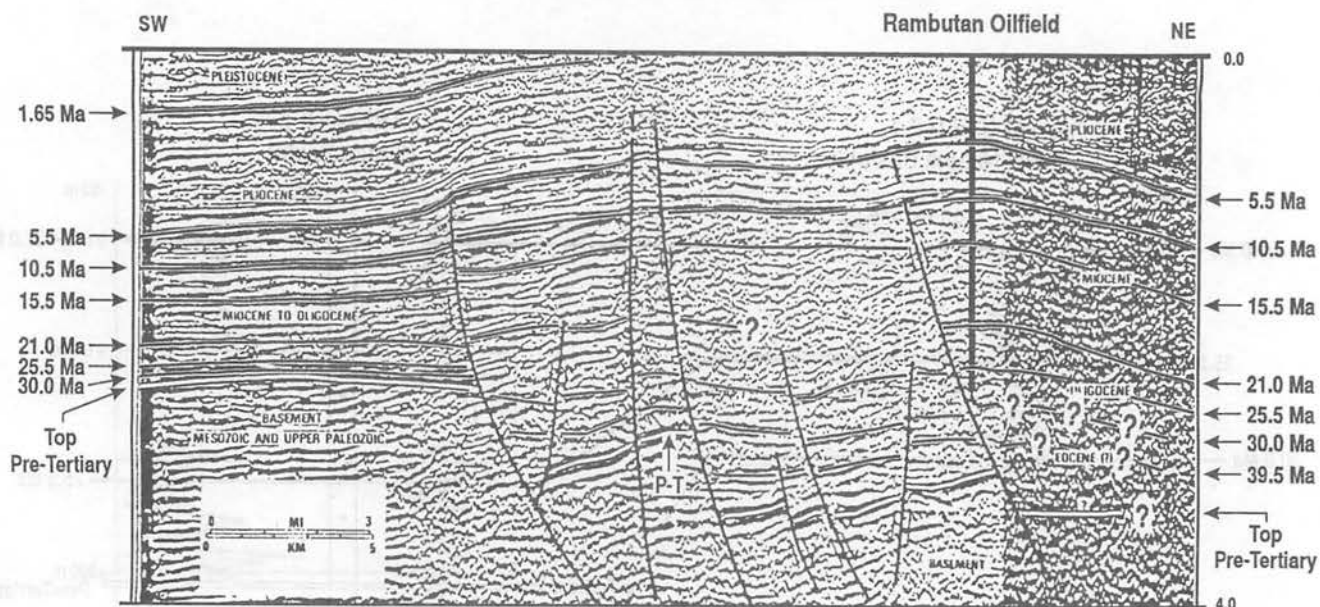
Figure 9C. Correlation of TB1 and TB2 Supercycles, continued.



Reinterpretation of seismic section from Wirjodihardjo, 1992.

Figure 10. Sequence stratigraphy of the Arun gas field, N. Sumatra.

S. SUMATRA, BENAKAT GULLEY



Modified from Harding, 1983.

Figure 11A. South Sumatra basin sequence stratigraphy, Part 1.

S. SUMATRA, RAWA AREA

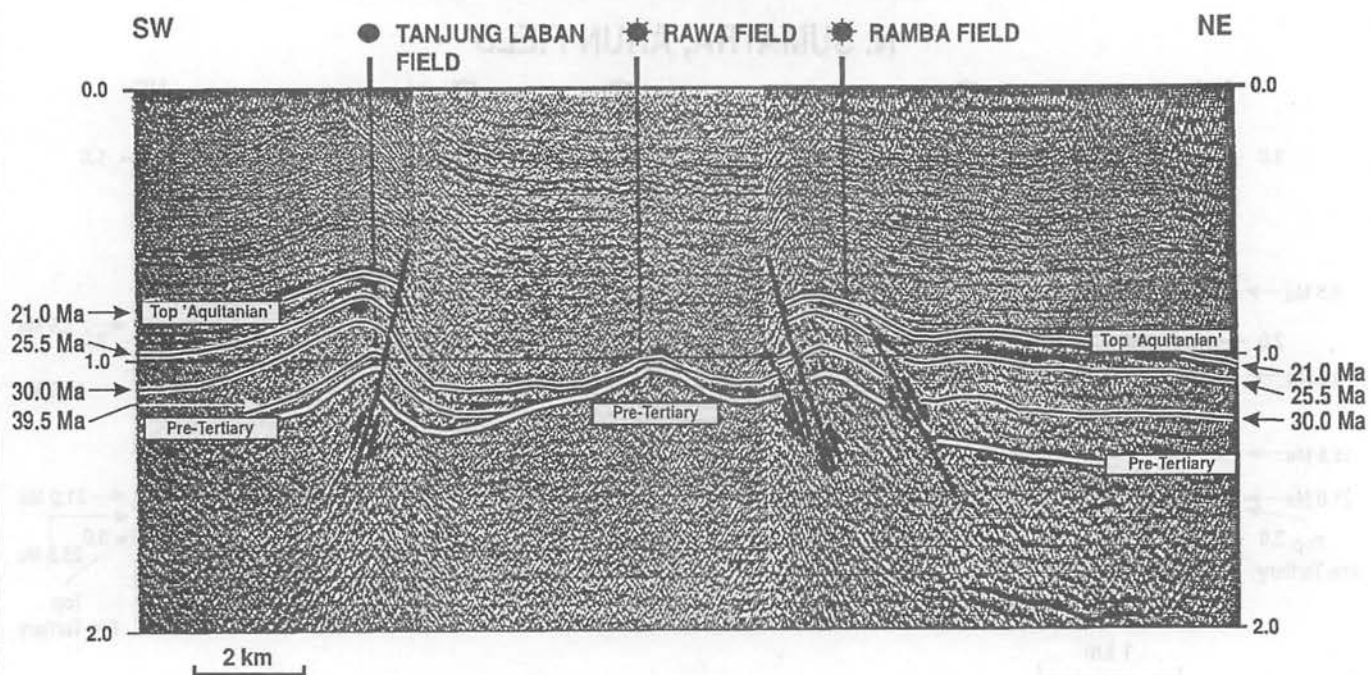
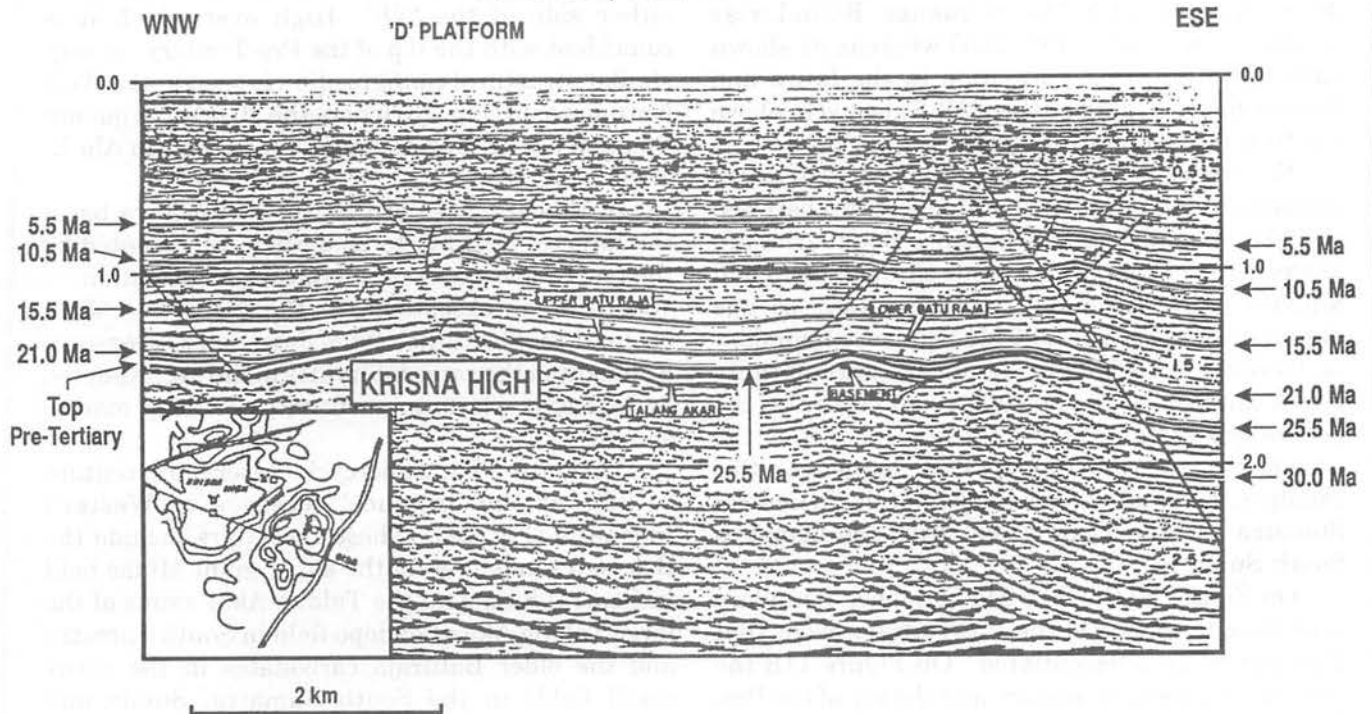
Reinterpretation of seismic section from Zelff *et al.*, 1985.

Figure 11B. South Sumatra basin sequence stratigraphy, Part 2.

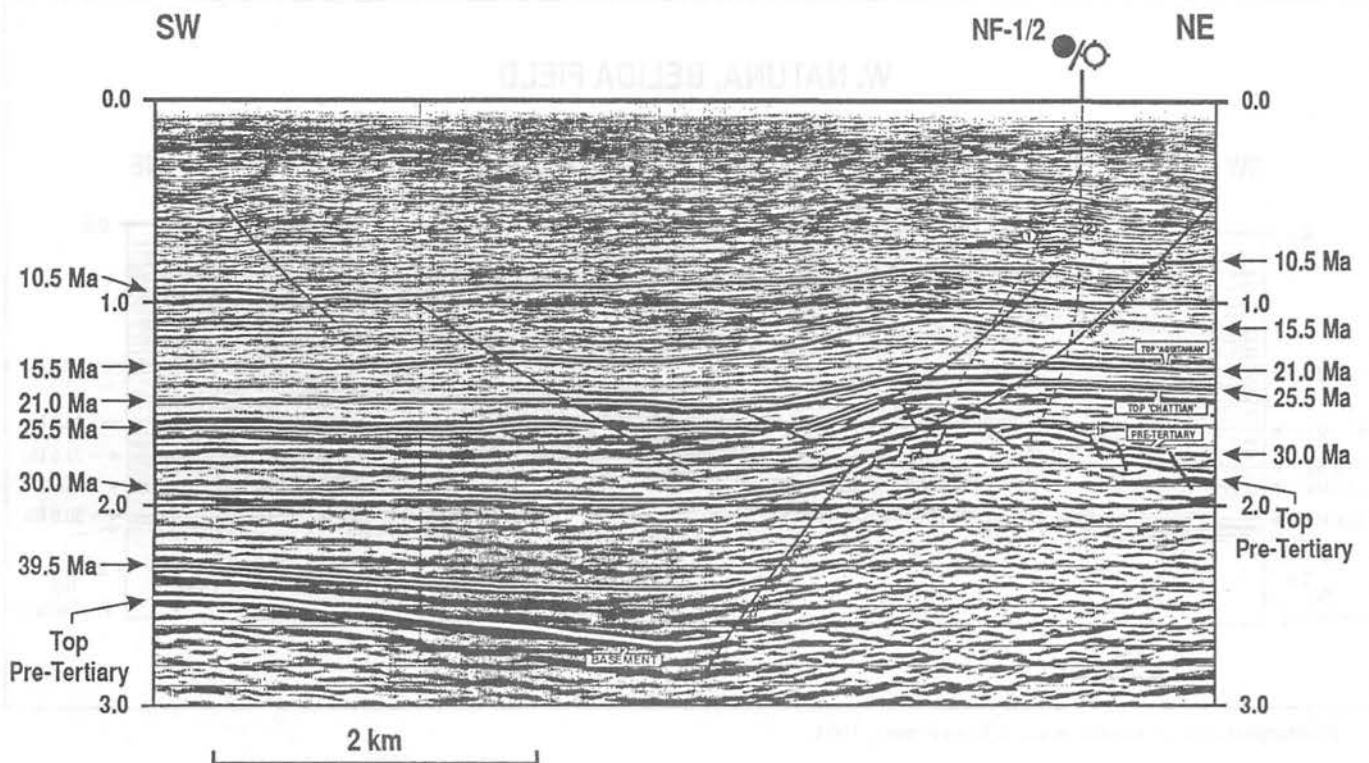
SUNDA, KRISNA FIELD



Reinterpretation of seismic section from Ardila, 1983.

Figure 12A. Sunda basin sequence stratigraphy, Part 1.

EAST SUNDA BASIN: SEQUENCE STRATIGRAPHY



Reinterpretation of seismic section from Fainstein, 1987.

Figure 12B. Sunda basin sequence stratigraphy, Part 2.

Baturaja Formation. On the Musi-Klingi Platform the Baturaja Formation is developed between the 30.0 Ma and 25.5 Ma Sequence Boundaries (southwestern end of Fig. 11A) whereas as shown earlier the Baturaja Formation in the Rawa and Ramba fields is part of the T2B Supercycle above the 21.0 Ma Sequence Boundary (Fig. 11B).

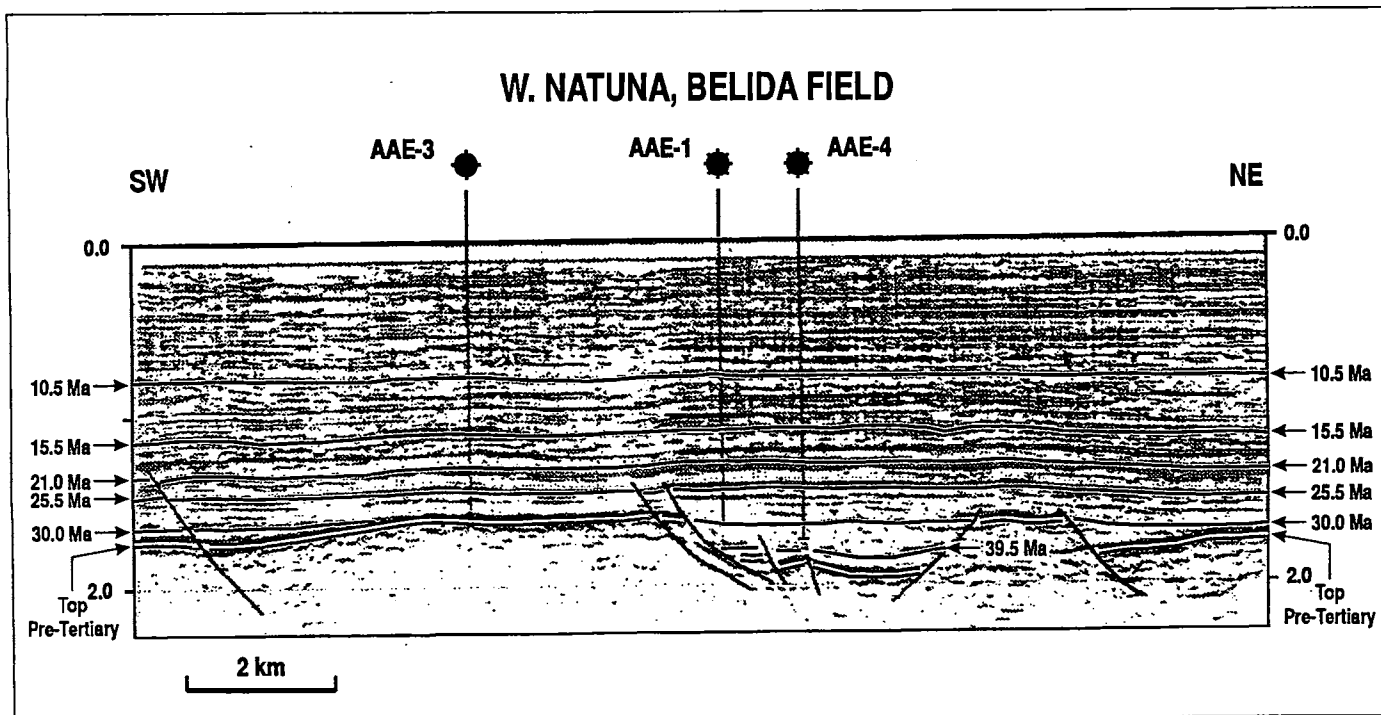
Elsewhere in the North, Central and South Sumatra and the Sunda basins the strata between the 30.0 Ma and 25.5 Ma Sequence Boundaries are represented by marginal marine through delta and alluvial plain sediments which contain no age diagnostic fossils. The 30.0 Ma Sequence Boundary is, however, a regionally significant unconformity which can be followed on seismic. It separates the generally more marine rift fill sequences from the underlying non-marine syn-rift sequences (for example, the Sihapas from the Pematang in Central Sumatra and the Talang Akar from the Lemat in South Sumatra).

On Figure 10 the 30.0 Ma Sequence Boundary is so close to the top of the Pre-Tertiary event that they cannot be differentiated. On Figure 11B the 30.0 Ma Sequence Boundary and the top of the Pre-Tertiary are coincident below the Rawa field and the same situation occurs below the Krisna field (Fig. 12A) where the Talang Akar sandstones which onlap the Krisna High represent sequences between the 30.0 Ma and 25.5 Ma Sequence Boundaries.

Figure 12B shows the 30.0 Ma Sequence Boundary truncating earlier syn-rift sequences either side of the 'NF' High over which it is coincident with the top of the Pre-Tertiary. A very similar structural configuration is seen in the West Natuna basin (Fig. 13) where the 30.0 Ma Sequence Boundary is interpreted near TD in the Alu Alu E-1 well (Fig. 9C).

In the BZZ area of the Northwest Java basin the interval 30.0 Ma to 25.5 Ma is represented by the reefal carbonates of the Baturaja Formation (!). With similar exceptions in the Northwest Java basin, throughout the rest of Java and also eastern Kalimantan the same interval is mainly represented by extensive platform carbonates or deep marine shales.

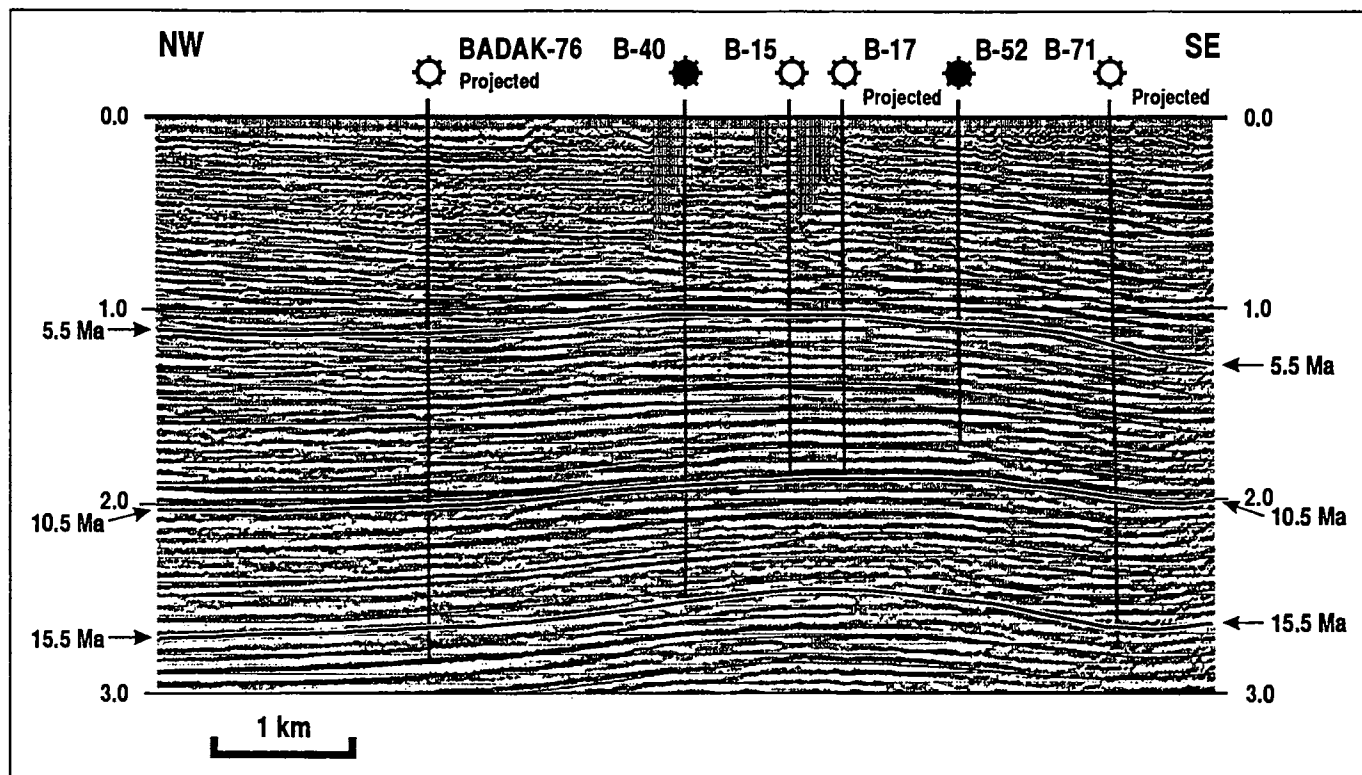
The late TB1 Supercycle reservoirs contain 21.96% of the 'in-place' reserves of Western Indonesia (Fig. 22). These reservoirs include the Bekasap sandstones of the super giant Minas field in Central Sumatra, the Talang Akar sands of the large Talang Akar-Pendopo field in South Sumatra and the older Baturaja carbonates in the many small fields in the South Sumatra, Sunda and Northwest Java basins. The early TB1 Supercycle reservoirs contain 12.81% of the 'in-place' reserves. The early TB1 reservoirs include both carbonates and clastics which are more geographically restricted since they are deeper in the rift fill sequences.



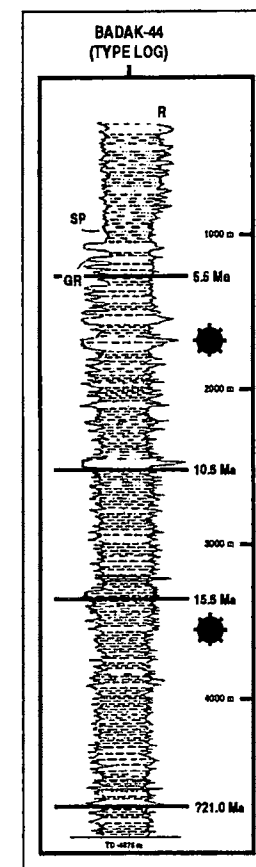
Reinterpretation of seismic section from Sutoto, 1991.

Figure 13. West Natuna basin sequence stratigraphy.

KUTEI BASIN, BADAQ FIELD



Reinterpretation of seismic section and type log from Ade *et al*, 1988



Tejas A4 (TA4) Supercycle

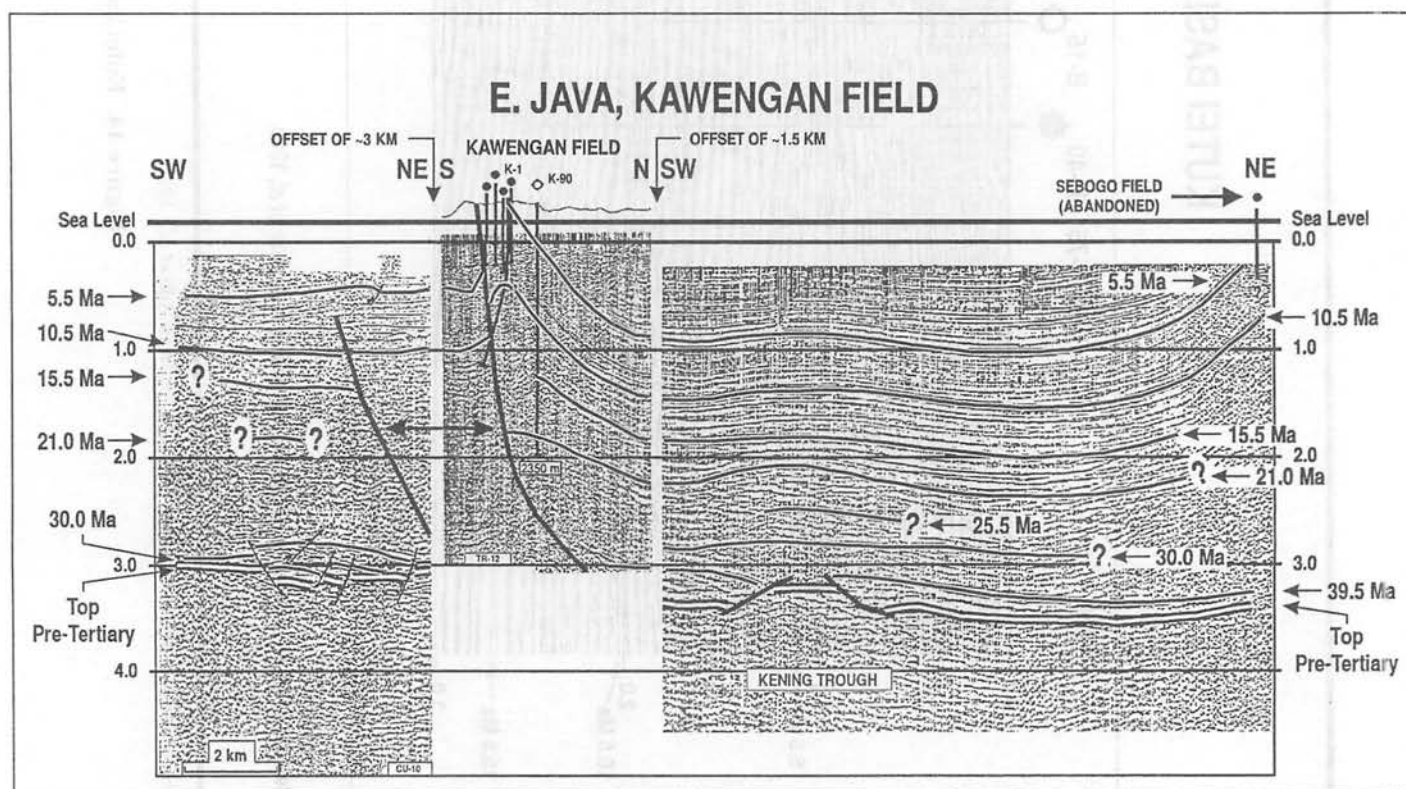
The TA4 Supercycle is the most critical and controversial since its lower sequence boundary (39.5 Ma) is the top of the major effective source interval throughout Western Indonesia (Courtney and Williams, 1994). By implication it makes the age of these underlying syn-rift source rocks significantly older than is published in the literature.

Figure 17 shows all wells drilled to December, 1992 which have been reported as having drilled into, or through, Late Eocene sediments; surface outcrops of Middle and Late Eocene sediments; and the approximate extent of the Late Eocene in the subsurface. As can be clearly seen the main occurrences of unequivocally dated Eocene sediments are in Kalimantan and the Lombok and East Java basins (for example: PERTAMINA-BEICIP, 1982 and 1985, Mouret, 1987, Sunaryo *et al.*, 1988, Phillips *et al.*, 1991, Bransden and Matthews, 1992 and van de Weerd and Armin, 1992). Surface outcrops have been reported from Java which range from near shore clastics and limestones to bathyal shales and range in age from Middle to Late Eocene (van Bemmelen, 1949 and references therein, and Shiller *et al.*, 1991). The Ujung Kulon-1A well offshore Southwest Java reached TD in the Eocene (MASERA-AAPG Data

Systems, 1991) and the sediments penetrated by this well are believed to include Middle Eocene fluvio-deltaics similar to those which crop out in the Bajah area onshore.

In the Northwest Java basin the Jatibarang field produces from the Jatibarang Volcanic Formation which is dated as Late Eocene to Early Oligocene (PERTAMINA-BEICIP, 1985 and Nutt and Sirait, 1985). This age range is supported by Soeria-Atmadja *et al.* (1994) who report a series of K/Ar age determinations of surface outcrops of volcanic rocks in Java from the Late Eocene (e.g. 39.86 ± 3.31 Ma) to the Early Oligocene (e.g. 29.24 ± 2.38 Ma).

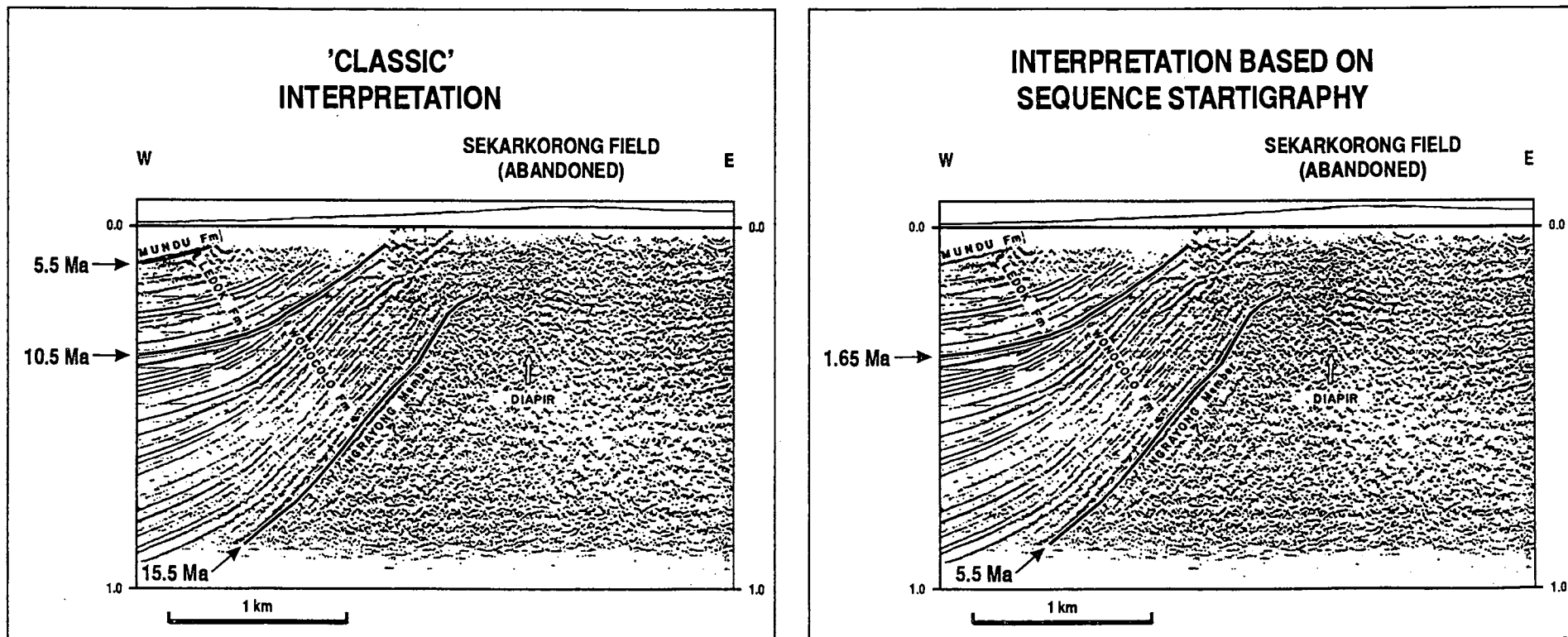
In the South Sumatra basin de Coster (1974) cites probable Late Palaeocene-Early Oligocene ages for the Lemat Formation on the basis of spore-pollen and K/Ar age dating of some samples of shale and tuff. In the Benkulu segment of the Sumatra Fore-arc the FINA Arwana-1 well apparently reached TD in Eocene sediments and Karig *et al.* (1979) reports the bathyal shales and turbidites in four wells in the Sibolga segment of the Sumatra fore-arc as having been redetermined as Late Eocene to Early Oligocene in age. Onshore Central Sumatra many papers have been published on the Eocene section in the Ombilin sub-basin and Koning and Aulia (1985) also describe the results of



Reinterpretation of seismic sections from Sutarso and Suyitno, 1976, and Soeparyono and Lennox, 1989.

Figure 15. East Java basin sequence stratigraphy.

E. JAVA, SEKARKORONG FIELD



Reinterpretation of seismic section from Patmosukismo *et al.*, 1985.

Figure 16. The differing interpretations of the Sekarkorong field, East Java.

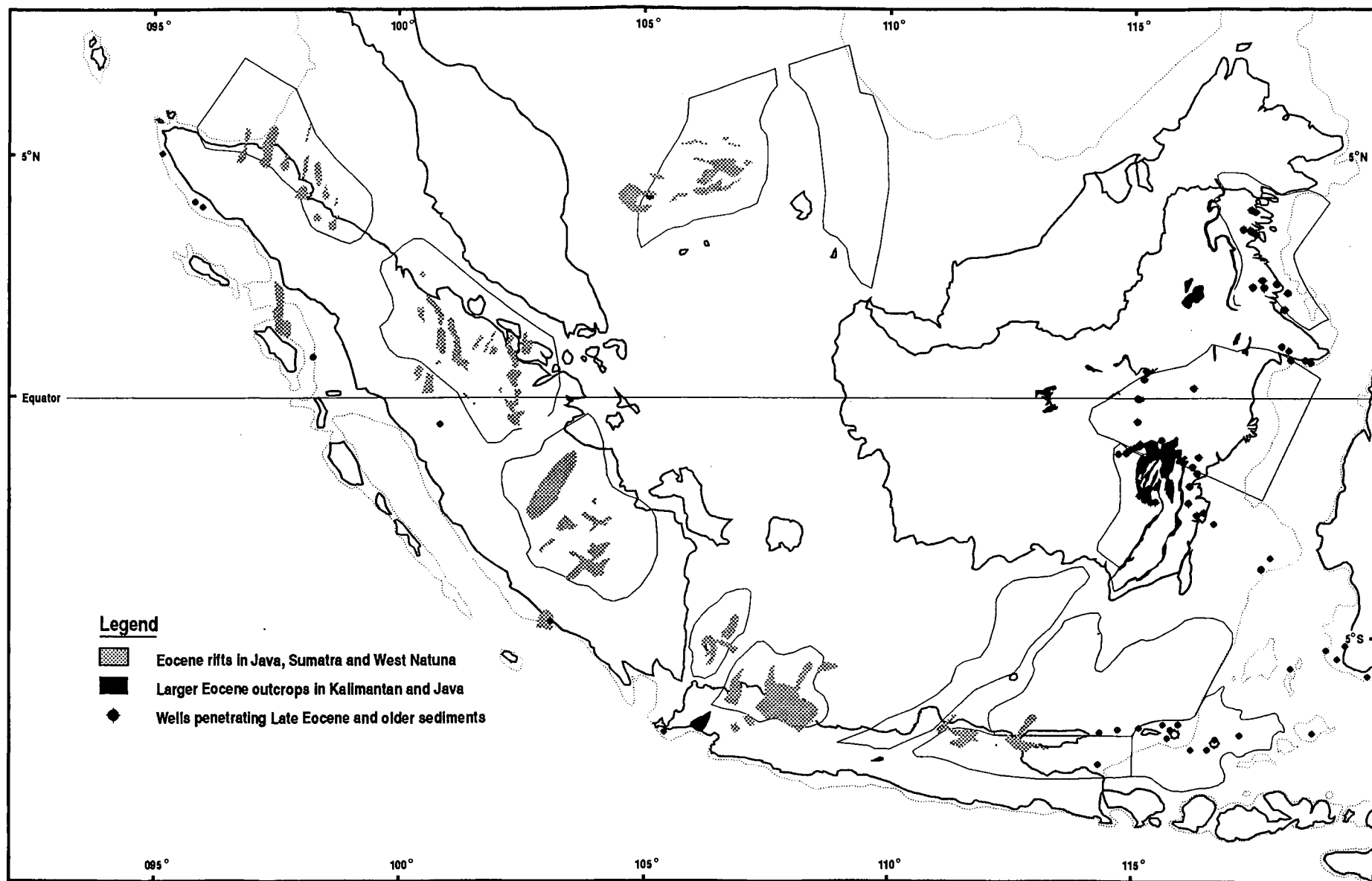


Figure 17. The Eocene of Western Indonesia.

the Sinamar-1 well which penetrated over 1200 m of Eocene sediments without reaching the Palaeocene or Pre-Tertiary. The lower 877 m of the drilled section comprised continental sediments with minor littoral influx. Further north ?Eocene to Early Oligocene marine sediments are reported from Central and North Aceh (Cameron *et al.*, 1980) and offshore Northeast Sumatra the ONS D-1 well is reported to have reached TD in volcanics which are apparently of Middle Eocene age.

Several authors (Blum, 1994) have highlighted the fact that base level changes in the marine part of a basin affect the non-marine section more than 100 km landward of the shoreline. It is thus reasonable to expect that the non-marine equivalents of these many examples of Late Eocene to Early Oligocene marine sediments may be preserved in what were the landward parts of the palaeo-drainage systems and are now the deeper syn-rift sections of the North, Central and South Sumatra, Sunda, Northwest Java, Central Java-Pati and East Java Basins. It is also to be expected that these non-marine sediments will exhibit the major sequence boundaries on seismic sections and on electric logs. With this in mind and using the additional control of K/Ar age determinations of volcanics, where volcanics are present and age determinations are available, a log correlation of the TA4 Supercycle is shown in Figures 18A-D.

Reliable biostratigraphic data is available for the well from the Pamusian Rift in the Northeast Kalimantan basin (Fig. 18D) allowing a reliable tie to seismic (see Courteney and Williams, 1994). To the south many wells in the Kutei basin penetrated Middle Eocene and Late Eocene sediments and volcanoclastics. For example, the Jelmusibak-1 well drilled through 1,300 m of Early Oligocene deep marine shales, about 410 m of Late Eocene shallow marine clastics and 2000 m of non-marine conglomerates, sandstones and shales (van de Weerd *et al.*, 1987). The well reached TD in these non-marine sediments. The combined thickness of over 3710 m is one of the thickest sections known in Western Indonesia. No age determinations older than P.12 (Middle Eocene) are known (PERTAMINA-BEICIP, 1985), however, thick basal conglomerates and non-marine sandstones are reported by many authors (van Bemmelen, 1949; Wain and Berod, 1989; van de Weerd *et al.*, 1987) which underlie the marine sediments. A more detailed review of the available data on the Early Tertiary sediments of the Kutei basin is given in Courteney and Williams (1994).

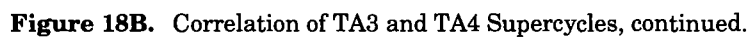
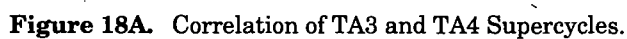
In the Barito basin barren red beds underlie the deepest Eocene producing zone in the Tanjung field (Kusuma and Darin, 1989). The first datable foraminifera occur some 400 m higher in the

Tanjung-1 well in the marine part of the Tanjung Formation. Kusuma and Darin (1989) cite a Middle-Late Eocene age for the foraminifera and then assign the whole Stage 3 of the Tanjung Formation in which they occur to the Middle Eocene (47.5 Ma–44.5 Ma) and their overlying Stage 4 (Middle Eocene-Early Oligocene) is “*terminated by a drastic eustatic sea level fall*”. As noted earlier there is a strong possibility that Kusuma and Darin are using the old BPM T.ab interpretation as BPM were the original operators of the Tanjung field.

In contrast PERTAMINA-BEICIP (1985) cite the earliest datable larger foraminifera as being of T.b (Late Eocene) and T.cd (Early Oligocene) age. Volcanics are reported from the Tanjung field in the zone immediately below the foraminifera, but as far as is known they have not been dated. Several authors (van de Weerd and Armin, 1992) give a Late Eocene age to the Keliam volcanics some 250 km to the North of the Tanjung field and Bauman (1972) has described Late Eocene and Oligocene deep marine shales with rare basalt flows overlying Middle Eocene non-marine to shallow marine clastics. In addition a weak Middle Oligocene unconformity is reported by van de Weerd *et al.* (1987) and Saller *et al.* (1992) point out that the major eustatic sea level fall predicted by Haq *et al.* (1987) is not recognised in Central Kalimantan.

A review of all available data and a re-correlation of the data provided by Kusuma and Darin (1989) with the data included in Waluyo *et al.* (1986) combined with the alternative interpretations above, strongly suggests that Stage 3 of the Tanjung Formation as defined by Kusuma and Darin (1989) is in fact located just below the 36.0 Ma Sequence Boundary. This is illustrated by the Kambitin-3 well on Figure 18D. The main producing zone in the Kambitin field is from sands of the third order cycle above the 39.5 Ma Sequence Boundary and they can be correlated to the sands in the main producing zone of the Tanjung field. The sands are designated ‘Z-860’ are described by Kusuma and Darin (1989) as: “*tributary channel sands incised into the underlying unconformity surface*”. They are interpreted by the author as being Late Eocene in age as opposed to the Middle Eocene of Kusuma and Darin (*ibid*).

A correlation with the Late Eocene Ngimbang clastics of the Lombok basin is suggested by lithological descriptions alone. The sequence stratigraphy log correlations are shown in Figure 18C. The Pagerungan-1 well is tied to biostratigraphy and the source rock intervals reported by Phillips *et al.* (1991) have been marked on the log. The L-49-1 is reliably tied to planktonic foraminifera zones (Brandsen and Matthews, 1992) and a possible source rock interval, attributed to



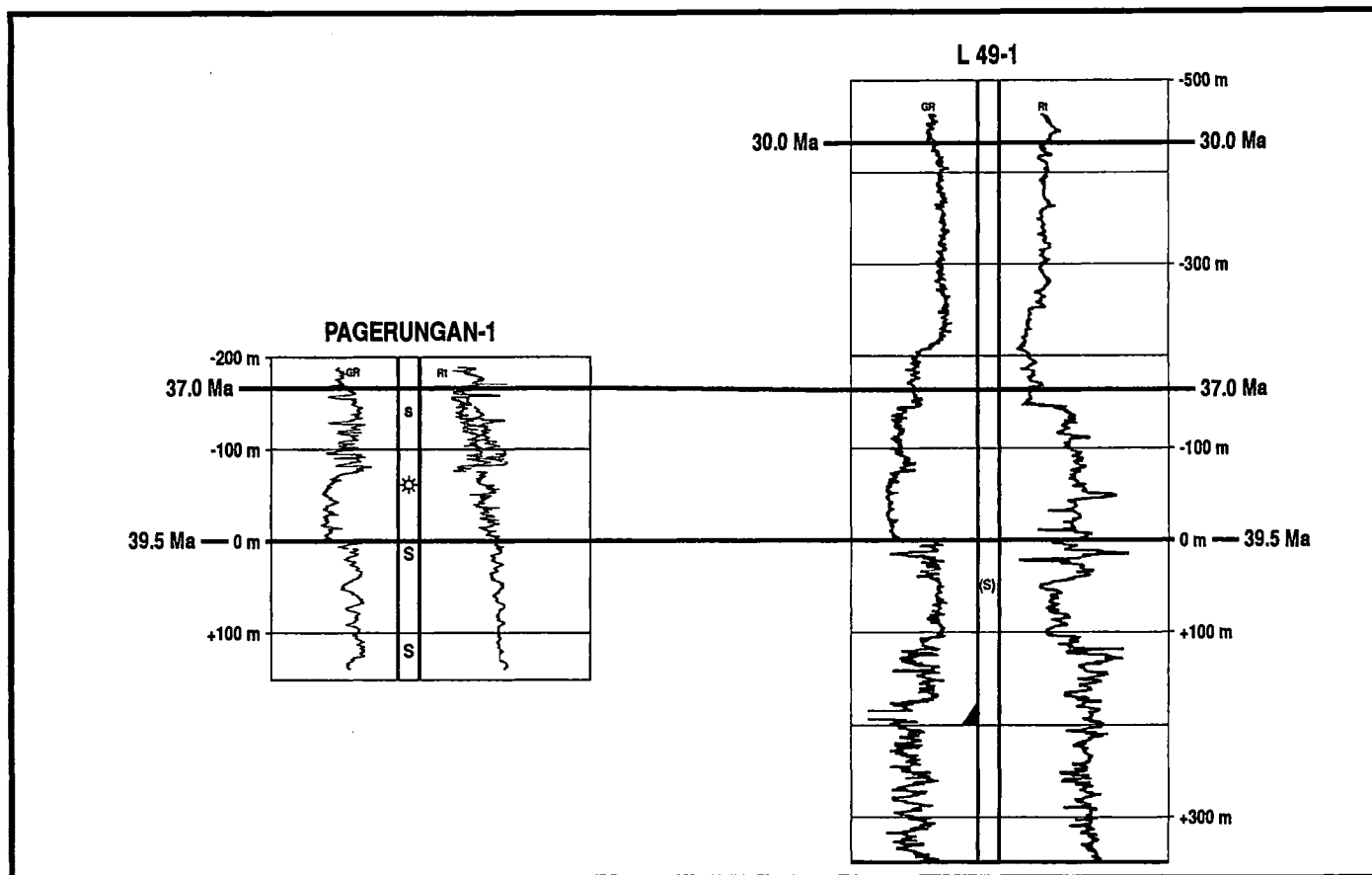


Figure 18C. Correlation of TA3 and TA4 Supercycles, continued.

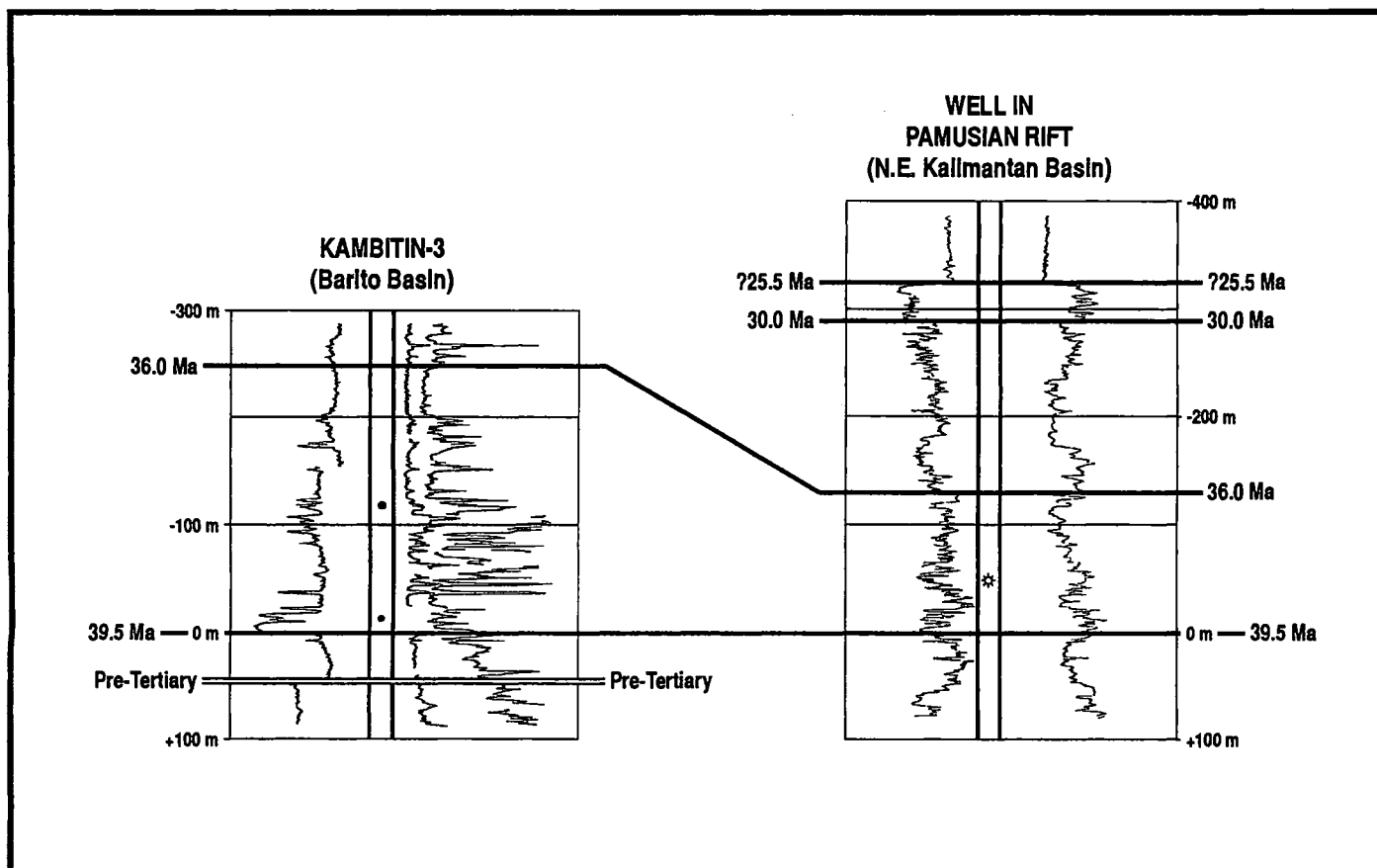


Figure 18D. Correlation of TA3 and TA4 Supercycles, continued.

the well's operator, is also indicated. Figure 19 shows a seismic line extending northward from the eastern end of the Pagerungan gas field. The localised nature of the pre-39.5 Ma sediments and the thinning of the TA4 Supercycle is clearly visible.

To the west in the Northwest Java basin the sequence stratigraphy interpretation of the Jatibarang-88 log (Fig. 18B) is constrained by the age of the volcanics. The Jatibarang structure is an inversion as shown in Figure 20. Thinning of the TA4 Supercycle is visible over the structure. To the west in the offshore part of the Northwest Java basin and in the Central Sumatra and Sunda basins the TA4 Supercycle sediments are barren of fossils and volcanics are also scarce. However, the correlation between Jatibarang-88 and the 'BZZ' field is felt to be reliable even though few seismic lines have been published in the area. The 'BZZ' log is in fact a composite of the BZZ-1 and BZZA-9 wells (Suria, 1991) in order to facilitate the integration into the sequence stratigraphy framework of the source rock data of Noble *et al.* (1991).

In the Sunda basin the 39.5 Ma Sequence Boundary in Mona-1 (Fig. 18A) can be tied to a regional seismic event that can be followed to the eastern flank of the basin (Fig. 12B). The thickness of the TA4 Supercycle in this basin is more regionally consistent than the interpretation of Prayitno *et al.* (1992) which assigns the same sediments to the interval 32.0 Ma to 26.0 Ma and does not recognise the Middle Oligocene unconformity, which, unlike Central Kalimantan, is regionally significant in the Western Java-Sumatra area.

In the Central Sumatra basin Longley *et al.* (1990) published detailed well to seismic correlations of the Pematang source rocks in the Melibur – "TA" Trough area. Figure 21 has been modified from the original of Longley *et al.* (1990) to show the sequence stratigraphy interpretation. The regionally significant 30.0 Ma Sequence Boundary is clearly visible and the more localised 39.5 Ma Sequence Boundary is represented by the 'classic' low frequency/high amplitude seismic event. Figure 18A shows the Pematang type section from the Pematang-1 well (PERTAMINA-BEICIP, 1985) in the northern Aman Depression, Central Sumatra. The relatively thin TA4 Supercycle in the well indicates that it is also an inversion similar to the one illustrated in Figure 8 which is also from the northern Aman Depression.

Similar log responses from wells drilled on inversion structures (e.g. the Limau fields) and seismic events deep within the syn-rift can be recognised in the South Sumatra basin. For example, the reflections around 3.0 seconds TWT

in the centre of Figure 11A. In the West Natuna basin the seismic event below the Alu Alu E-1 and Alu Alu E-4 wells is an example of the 39.5 Ma Sequence Boundary (Fig. 13). The TA4 Supercycle can also be correlated to the East Java basin on the basis of the characteristic seismic signature below the 39.5 Ma Sequence Boundary. Soeparyono and Lennox (1989) implied that this signature represented a different type of 'basement'.

The reservoirs of the TA4 Supercycle are extremely restricted geographically in the basins of west Java, Natuna and Sumatra since they are within the syn-rift sequences. In the basins of the greater east Java area and Kalimantan, where the rifts were filled and drowned earlier, the clastic reservoirs tend to be very thin and discontinuous and the later carbonate reservoirs tend to be developed on localised Pre-Tertiary highs in front of the main carbonate platforms (e.g. Kerendan gasfield).

TA4 Supercycle reservoirs account for only 5.24% of the 'in-place' reserves of Western Indonesia (Fig. 22). The largest field producing from this Supercycle is the Pagerungan gasfield in the Lombok basin.

Tejas A3 (TA3) Supercycle

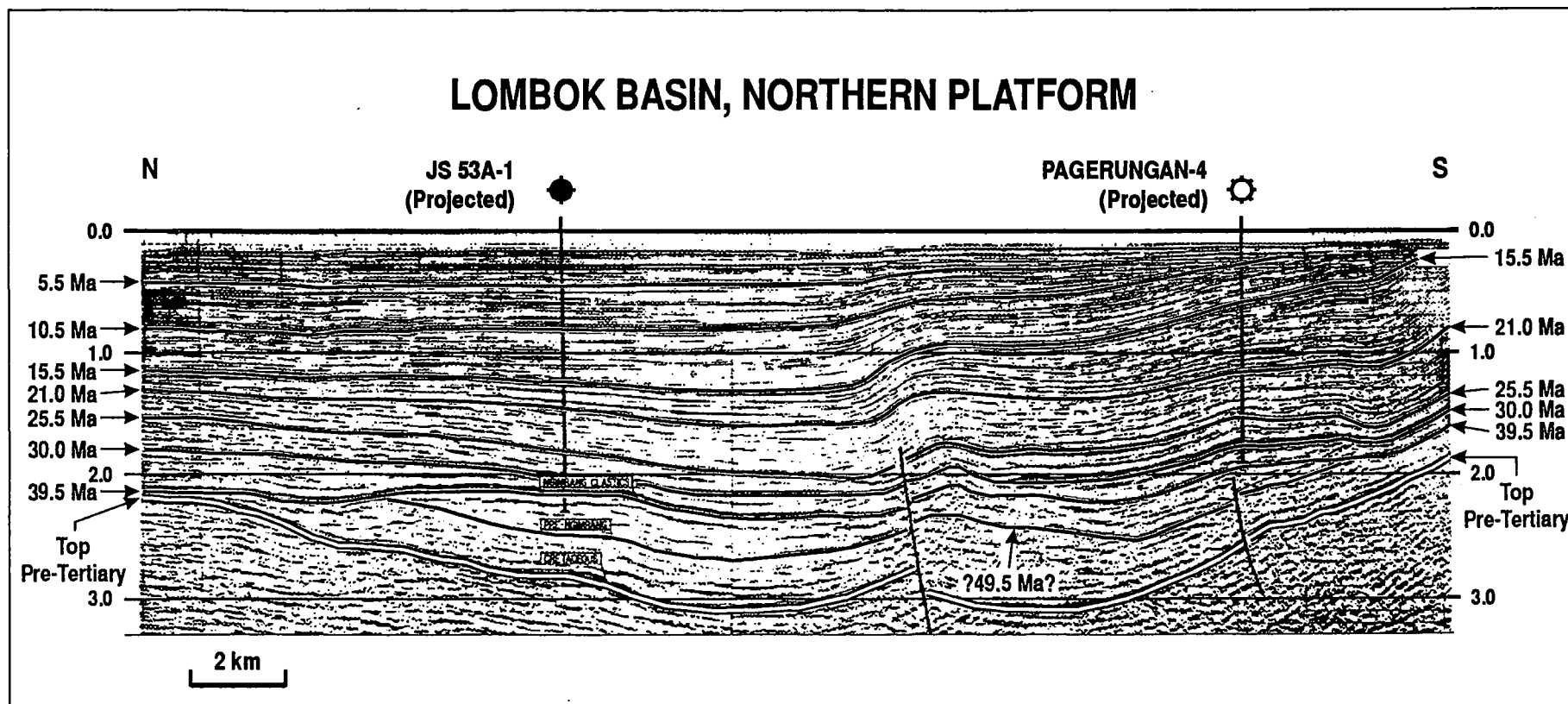
The identification of the 39.5 Ma Sequence boundary implies that sediments between it and the Pre-Tertiary, assuming a further major sequence boundary is not recognised, are part of the TA3 Supercycle.

Such sediments can be seen in the Central Sumatra (Figs. 8, 18A and 21), South Sumatra (Figs. 11A and 11B), Sunda (Figs. 12B and 18A), Northwest Java (Figs. 18B and 20), East Java (Fig. 15), Lombok (Figs. 18C and 19), Barito (Fig. 18D), Northeast Kalimantan (Fig. 18D) and West Natuna (Fig. 13) basins. Sediments from this Supercycle are known from the Kutei basin and Courteney and Williams (1994) have identified them on seismic data in the North Sumatra basin. Courteney and Williams (1994) further argue that the TA3 Supercycle contains the main effective source rocks of Western Indonesia.

The reservoirs of the TA3 Supercycle account for 0.67% of the estimated 'in-place' reserves of Western Indonesia. They are normally very poor reservoirs deep in the syn-rift sequences and produce in such fields as the Pematang oilfield, Central Sumatra (Fig. 18A), and in the Tanjung oilfield, Barito basin.

Tejas A2 (TA2) Supercycle

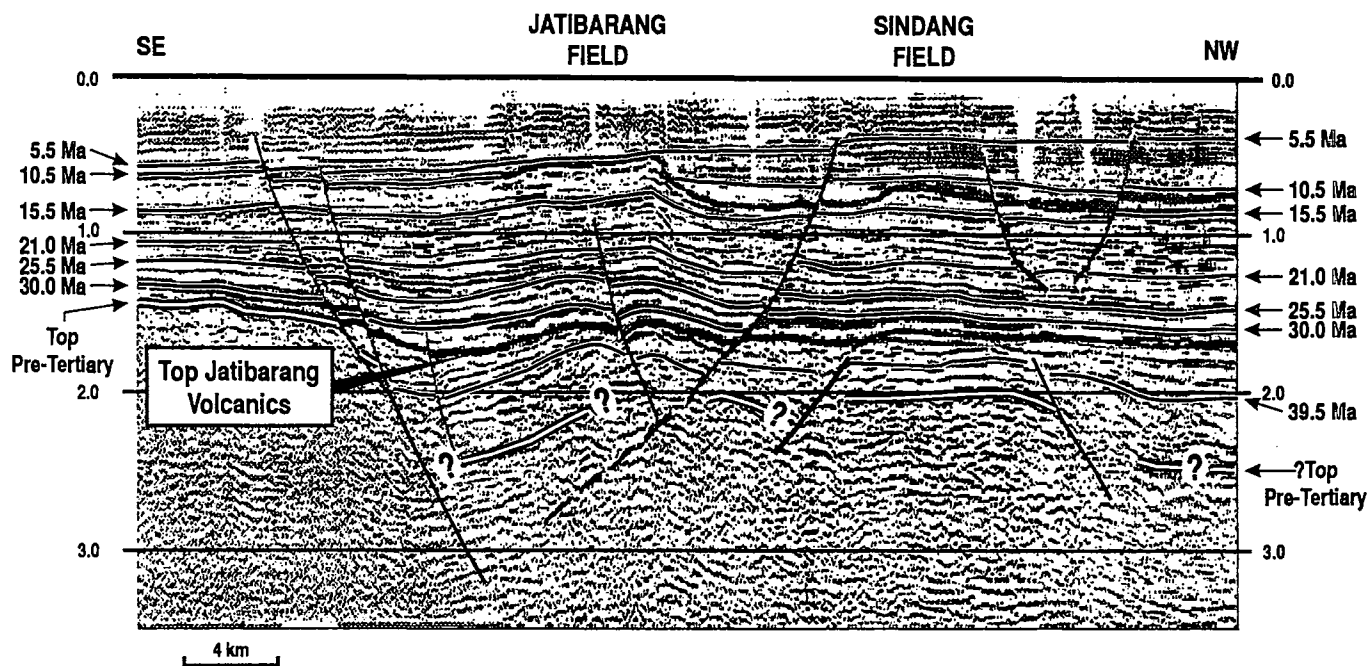
Sediments belonging to the TA2 Supercycle have been reported from the Lombok basin and are possibly present in the rift remnant shown in Figure



Reinterpretation of a seismic section from Phillips *et al.*, 1991.

Figure 19. Lombok basin sequence stratigraphy.

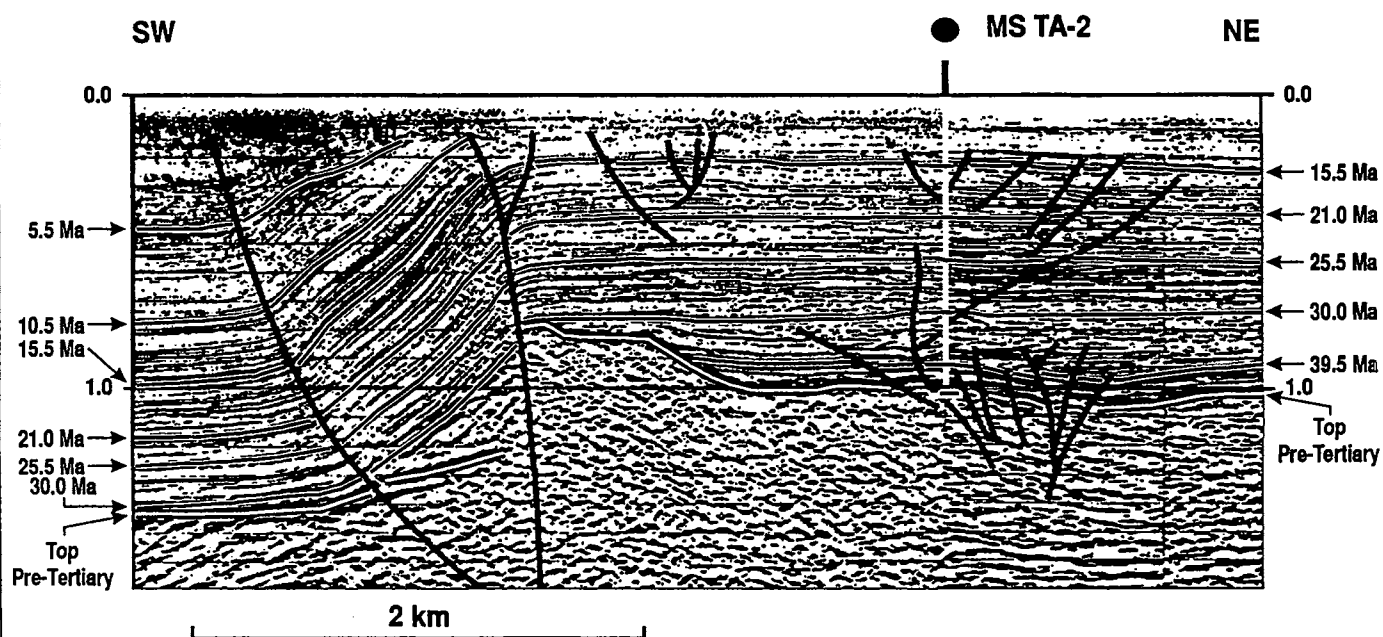
N.W. JAVA, JATIBARANG AREA



Reinterpretation of seismic section from Adnan *et al.*, 1991.

Figure 20. Northwest Java basin sequence stratigraphy.

CENTRAL SUMATRA: MELIBUR - "TA" TROUGH



Modified from Longley *et al.*, 1990.

Figure 21. Central Sumatra: Melibur — "TA Figure Captions, Page 2" Trough.

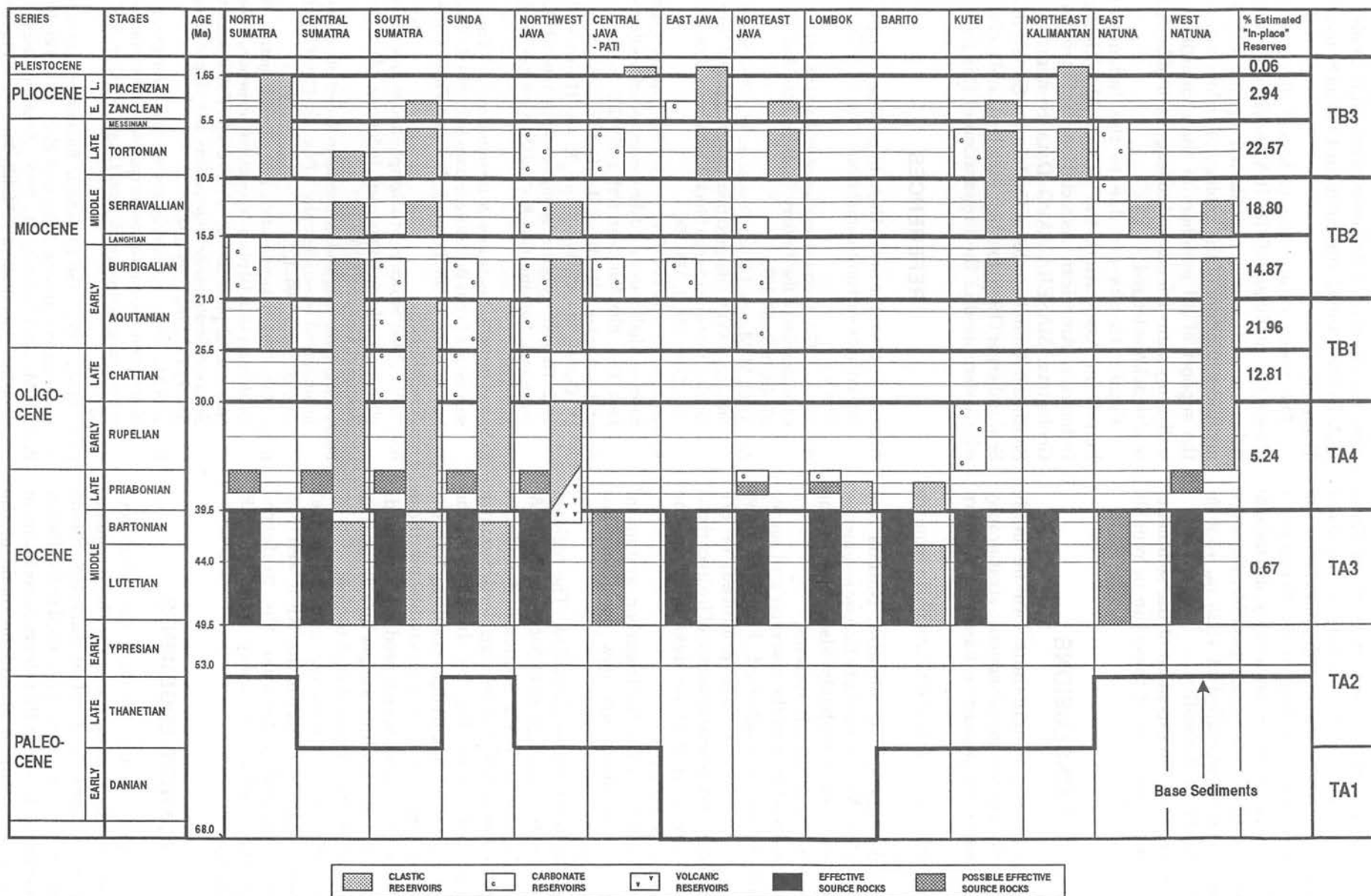


Figure 22. Correlation of the hydrocarbon productive basins of Western Indonesia using sequence stratigraphy.

19. The thick non-marine sequences of the Kutei and Barito basins may also include sediments of this supercycle. The 800 m of sediments below the 39.5 Ma Sequence Boundary in the Pematang-1 well (Fig. 18A) in Central Sumatra may also include sediments of this cycle, since possible sequence boundaries can be identified at +325 m, +530 m and near the TD of the well.

However, with the exception of the sediments in the Lombok area none of these can be reliably dated.

CONCLUSIONS

The following conclusions can be made concerning the application of sequence stratigraphy to the hydrocarbon productive basins of Western Indonesia:

1. The stratigraphy of the East Java basin requires revision.
2. The rift sequences of Sumatra, Natuna and Java include Middle and Late Eocene sediments. Older sediments probably also exist in the deeper parts of the rift systems.
3. A better correlation of the reservoir and source sequences has been achieved. Figure 22 shows all reservoirs that have produced, or are producing, commercial amounts of hydrocarbons and those that will be developed in the foreseeable future.
4. New insights to the 'hydrocarbon system' of Western Indonesia are now possible. For example:
 - Regional seals can be identified. The regional seal over the Arun gasfield between the 15.5/13.8 Ma and 10.5 Ma Sequence Boundaries (Fig. 10) can be followed through North Sumatra to the Medan area (Fig. 2). In addition, the lowstand prograding wedges resulting from the Barisan uplift are clearly visible on these sections. The fields which produce from sands within the prograding wedges are located in areas where the regional seal is thin.
 - The migration pathways can be better constrained. The failure of the 'NF-2' well (Fig. 12B) is probably because the preferred migration pathway is away from the 'NF' structure.

ACKNOWLEDGEMENTS

The inspiration for the work described here came from the discussions about the three regional seismic lines, from the Central Sumatra, Sunda and Northwest Java basins, presented at the Poster Session of the Indonesian Petroleum Association in 1989. Special mention should be made of the

contributions of my fellow co-workers: M.R. Cholidy, M.A. Bridden and U. Irawan to the Central Sumatra Transect.

The many interesting technical discussions among the members of the IPA Oil & Gas Fields Atlas Committee also contributed significantly to my understanding of the geology of Indonesia and the support of all members of the committee as well as my many friends and colleagues in Indonesia is also acknowledged.

Finally thanks are due to the Indonesian Petroleum Association, the Ikatan Ahli Geologi Indonesia, American Association of Petroleum Geologists, MASERA-AAPG Data Systems, the Southeast Asian Petroleum Exploration Society and Schlumberger (1986) for their excellent publications which were used in the preparation of this paper.

REFERENCES

- ARDILA, L.E., 1983. The Krisna High: Its geologic setting and related hydrocarbon accumulations. *Proc. SEAPEX, VI*, 10-23.
- ADAMS, C.G., 1970. A reconsideration of the East Indian Letter Classification of the Tertiary. *Bull. Br. Mus. Nat. Hist. (Geol.)*, 19(3), 85-137.
- ADE, W.C., McMAHON, I.T. AND SUWARLAN, W., 1988. Seismic lithology (AVO) interpretation at the Badak and Nilam fields in the Sanga-Sanga block, Kalimantan. *Proc. 17th Ann. Conv. IPA*, 1, 323-358.
- ADNAN, A., SUKOWITONO AND SUPRIYANTO, 1991. Jatibarang sub-basin — A half graben model in the onshore of Northwest Java. *Proc. 20th Ann. Conv. IPA*, 1, 279-297.
- ASPEN, J.A., KARTAWA, W., ALDISS, D.T., DJUNUDDIN, A., DIATMA, D., CLARKE, M.C.G., WHANDOYO, R. AND HARAHAP, H., 1982. The geology of the Padangsidempuan and Sibolga quadrangle, Sumatra. *Geol. Res. and Dev. Centre, Bandung, Indonesia*.
- BAUMANN, P., 1972. Les faunes de foraminifères de l'Eocene supérieur à la base du Miocene dans la bassin de Pasir, Sud de Kalimantan (Borneo). *Rev. Inst. Franc. Petrole*, 27(6), 817-829.
- BISHOP, W.F., 1980. Structure, stratigraphy and hydrocarbons offshore Southern Kalimantan, Indonesia. *Bull. Am. Assoc. Pet. Geol.*, 64(1), 37-58.
- BLOW, W.H., 1969. Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. *Proc. 1st Plankt. Conf., Geneva 1967*, 1, 199-422.
- BLUM, M.D., 1994. Glacio-eustatic and climatic controls on Quaternary alluvial plain depositional sequences, Texas Gulf coastal plain (USA). *Proc. Conf. High Resolution Sequence Stratigraphy: Innovations and Applications*, Abstract Volume, 295-299.
- BOLLI, H.M., 1964. Observations on the stratigraphic distribution of some warm water planktonic foraminifera in the young Miocene to Recent. *Eclog. Geol. Helv.*, 57(2), 541-552.
- BOLLI, H.M., 1966. The planktonic foraminifera in well Bodjonegoro-1 of Java. *Eclog. Geol. Helv.*, 59(1), 449-465.
- BOLLI, H.M. AND BERMUDEZ, P.J., 1965. Zonation based on planktonic foraminifera of Middle Miocene to Pliocene

- warm-water sediments. *Bol. Informativo, Assoc. Venezolana de Geol., Min. y Pet.*, 8, 5.
- BOOMGART, L., 1949. Smaller foraminifera from Bodjonegoro (Java). *Diss. Univ. Utrecht*, 175p.
- BRAMLETTE, M.N. AND WILCOXON, J.A., 1967. Middle Tertiary calcareous nanoplankton of the Cipero section, Trinidad, West Indies. *Tulane Studies in Geology*, 5(3), 93–131.
- BRANDEN, P.J.E. AND MATTHEWS, S.J., 1992. Structural and stratigraphic evolution of the East Java Sea, Indonesia. *Proc. 21st Ann. Conv. IPA*, 1, 417–453.
- BURNAMAN, M.D., HELM, R.B. AND BEEMAN, C.R., 1985. Discovery of the Cunda gas field, Bee block, North Sumatra: an integrated geological seismic stratigraphy case history. *Proc. 14th Ann. Conv. IPA*, 1, 453–496.
- CAMERON, N.R. CLARKE, M.C.G., ALDISS, D.T. ASPDEN, J.A. AND DJUNUDDIN, A., 1980. The geological evolution of Northern Sumatra. *Proc. 9th Ann. Conv. IPA*, 149–187.
- CAMERON, N.R., 1983. The stratigraphy of the Sihapas formation in the northwest of the Central Sumatra basin. *Proc. 12th Ann. Conv. IPA*, 1, 43–65.
- COURTENAY, S., COCKCROFT, P., MILLER, R., PHOA, R.S.K. AND WIGHT, A.W.R. (Eds.), 1989. *PERTAMINA — IPA Oil & Gas Fields Atlas, Volume IV, Java*.
- COURTENAY, S. AND WILLIAMS, H.H., 1994. The Palaeogene rifts of Western Indonesia. Paper presented at AAPG Annual Meeting — *Analogs for the World*, Denver.
- DE COSTER, G.L., 1974. The geology of the Central and South Sumatra basins. *Proc. 3rd Ann. Conv. IPA*, 77–110.
- DURHAM, J.W., 1939. Mountain Front stratigraphy in Central Sumatra. *NPPM internal report*.
- DUVAL, B.C., CHOPPIN DE JANVRY, G. AND LOIRET, B., 1992. The Mahakam delta province: An ever changing picture and a bright future. *Proc. 24th Ann. OTC*, 393–404.
- FAINSTEIN, R., 1987. Exploration of the North Seribu area, northwest Java sea. *Proc. 16th Ann. Conv. IPA*, 1, 191–214.
- GSELL, R., 1930. Geologische Untersuchungen in der Umgebung von Batoeradja. *BPM internal report*.
- HADI, T. AND SIMBOLON, B., 1976. The carbonate rocks of the Baturaja Formation in its type locality, Baturaja, South Sumatra. *Proc. IPA Carbonate Seminar*, 67–78.
- HAQ, B.U., HARDENBOL, J. AND VAIL, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science* 235, 1156–1167.
- HARDING, T.P., 1983. Structural inversion at Rambutan oil field, South Sumatra basin. In: Bally, A.W. (Ed.), *Seismic Expression of Structural Styles, AAPG Studies in Geology*, 15(3), 3.3-13 – 3.3-18.
- JORDAN, C.F., JR. AND ABDULLAH, M., 1992. Arun Field — Indonesia. In: Foster, N.H. and Beaumont, E.A. (Eds.), *Stratigraphic Traps III. Treatise of Petroleum Geology, Atlas of Oil and Gas Fields*, 1–39.
- KARIG, D.E., SUPARKA, S., MOORE, G.F. AND HEHANUSSA, P.E., 1979. Structure and Cenozoic Evolution of the Sunda Arc in the Central Sumatra Region. In: Watkins, J.S., Montadert, L. and Wood Dickerson, P. (Eds.), *Geological and Geophysical Investigations of Continental Margins. AAPG Mem.* 29, 323–358.
- KIRBY, G.A., SITUMORANG, B. AND SETIARDJA, B., 1989. Seismic stratigraphy of the Baong and Keutapang Formations, North Sumatra basin. *Proc. 18th Ann. Conv. IPA*, 1, 289–301.
- KONING, T. AND AULIA, K., 1985. The petroleum geology of the Ombilin intermontane basin, West Sumatra. *Proc. 14th Ann. Conv. IPA*, 1, 117–137.
- KUSUMA, I. AND DARIN, T., 1989. The hydrocarbon potential of the lower Tanjung Formation, Barito basin, S.E. Kalimantan. *Proc. 18th Ann. Conv. IPA*, 1, 107–138.
- LONGLEY, I.M., BARRACLOUGH, R., BRIDDEN, M.A. AND BROWN, S., 1990. Pematang lacustrine petroleum source rocks from the Malacca Strait PSC, Central Sumatra, Indonesia. *Proc. 19th Ann. Conv. IPA*, 1, 279–297.
- MARTINI, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. (Ed.), *Proc. 2nd Conf. Planktonic Microfossils Rome 1970*, 2, 739–785.
- MASERA-AAPG DATA SYSTEMS, 1991. *International Developments in Exploratory Drilling, 1950–1990 (AAPG Bulletin)*, A set of CD ROMs.
- MEYER, H., 1943. A compilation of the results of geological and geophysical exploration work done during recent years in the Tertiary basin of North Sumatra. *Report for the Japanese Imperial Army Engineers*, incomplete, GRDC Library, Bandung, Indonesia.
- MOURET, C., 1987. Stratigraphy and structural evolution of the Melawi basin (West Kalimantan, Indonesia) in its regional setting. *Paper presented at the 16th Ann. Conv. IPA*.
- MULHADIONO AND SUTOMO, J.A., 1984. The determination of economic basement of rock formation in exploring the Langkat-Medan area, North Sumatra basin. *Proc. 13th Ann. Conv. IPA*, 1, 75–107.
- NOBLE, R.A., WU, C.H. AND ATKINSON, C.D., 1991. Petroleum generation and migration from Talang Akar coals and shales offshore N.W. Java, Indonesia. *Org. Geochem.*, 17(3), 363–374.
- NUTT, W.L. AND SIRAIT, J., 1985. Application of offset seismic profiles in the Jatibarang volcanic reservoir. *Proc. 14th Ann. Conv. IPA*, 2, 385–406.
- PATMOSUKISMO, S., SYAHBUDDIN, A. AND ALAMEDA, G., 1985. New seismic method in populated areas (a case study in the Surabaya area, East Java, Indonesia). *Proc. 14th Ann. Conv. IPA*, 1, 405–435.
- PERTAMINA-BEICIP, 1982. Petroleum Potential of Eastern Indonesia. *Multiclient Report*.
- PERTAMINA-BEICIP, 1985. Petroleum Potential of Western Indonesia. *Multiclient Report*.
- PERTAMINA-BEICIP, 1994. Global geodynamics, basin classification and exploration play-types in Indonesia. *Multiclient Report*.
- PHILLIPS, T.L., NOBLE, R.A. AND SINARTIO, F.F., 1991. Origin of hydrocarbons, Kangean block Northern Platform, offshore northeast Java Sea. *Proc. 20th Ann. Conv. IPA*, 1, 637–661.
- PRAYITNO, W., ARMON, J.W. AND HARYONO, S., 1992. The implications of basin modelling for exploration — Sunda basin case study, offshore Southeast Sumatra. *Proc. 21st Ann. Conv. IPA*, 1, 379–415.
- SALLER, A., ARMIN, R.A., ODE ICHRAM, L. AND GLENN-SULIVAN, C., 1992. Sequence stratigraphy of Upper Eocene and Oligocene limestones, Teweh area, Central Kalimantan. *Proc. 21st Ann. Conv. IPA*, 1, 69–92.
- SANTOSO, H., BERMAWI, A. AND MURHANTORO, E., 1990. Combined interpretation of gravity with seismic and well data using stripping technique. *Proc. 19th Ann. Conv. IPA*, 1, 131–146.
- SARG, J.F., 1988. Carbonate sequence stratigraphy. In: Wilgus,

- C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and van Wagoner, J.C. (Eds.), Sea-level changes: An integrated approach. *SEPM Spec. Pub.* 42, 155–181.
- SCHILLER, D.M., GARRAD, R.A. AND PRASETYO, L., 1991. Eocene submarine fan sedimentation in southwest Java. *Proc. 20th Ann. Conv. IPA*, 1, 125–181.
- SCHLUMBERGER, 1986. *Formation Evaluation Conference, Indonesia*, 332p.
- SOEPARYONO, N. AND LENNOX, P.G., 1989. Structural development of hydrocarbon traps in the Cepu oil fields northeast Java, Indonesia. *Proc. 18th Ann. Conv. IPA*, 1, 139–156.
- SOERIA-ATMADJA, R., MAURY, R.C., BELLON, H., PRINGGOPRAWIRO, H., POLVE, M. AND PRIADI, B., 1994. Tertiary magmatic belts of Java. *Jour. SE Asian Earth Sciences*, 9(1/2), 13–27.
- SUNARYO, R., MARTODJOJO, S. AND WAHAB, A., 1988. Detailed geological evaluation of the hydrocarbon prospects in the Bungalon Area, East Kalimantan. *Proc. 17th Ann. Conv. IPA*, 1, 423–446.
- SURIA, C., 1991. Development strategy in the BZZ field and the importance of detailed depositional model studies in the reservoir characterisation of Talang Akar channel sandstones. *Proc. 20th Ann. Conv. IPA*, 1, 419–452.
- SUTARSO, B. AND SUYITNO, P., 1976. The diapiric structures and its relation to the occurrence of hydrocarbon in North-east Java basin. *Paper presented a 5th Ann. Meet. IAGI*, 46p.
- SUTOTO, A., 1991. Reservoir geology of the Belida field, south Natuna Sea, Block 'B'. *Proc. 20th Ann. Conv. IPA*, 1, 453–478.
- 'T HOEN, C.W.A.P., 1922. De tertiaire petroleum terreinen ter Oostkust van Atjeh (Atjeh II). *Jaarb. Mijnw. Ned. Ind.*, 1919, *Verh. I*, Batavia.
- VAN BEMMELEN, R.W., 1949. *The geology of Indonesia*. The Hague, Government Printing Office, 732p.
- VAN DE WEERD, A., ARMIN, R.A., MAHADI, S. AND WARE, P.L.B., 1987. Geologic setting of the Kerendan gas and condensate discovery, Tertiary sedimentation and palaeogeography of the northwestern part of the Kutei basin, Kalimantan, Indonesia. *Proc. 16th Ann. Conv. IPA*, 1, 317–338.
- VAN DE WEERD, A. AND ARMIN, R.A., 1992. Origin and evolution of the Tertiary hydrocarbon-bearing basins in Kalimantan (Borneo), Indonesia. *Bull. Am. Assoc. Pet. Geol.*, 76(11), 1778–1803.
- VAN DER VLERK, I.M. AND UMBGROVE, J.H.F., 1927. Tertiaire gidsforaminifera van Nederlandsch Oost-Indie. *Wetensch. Meded. Dienst Mijnbouw Ned. Oost-Indie*, 6, 3–31.
- VAN DOORNINK, H.W., 1932. Tertiary nummulitidae from Java. *Verh. Geol. Mijnb. Gen.* 9.
- VAN GORSEL, J.T., 1988. Biostratigraphy in Indonesia: methods, pitfalls and new directions. *Proc. 17th Ann. Conv. IPA*, 1, 275–300.
- WAHAB, A., 1986. Hydrocarbon potential of Klingi Area, South Sumatra. *Jour. Ikatan Ahli Geologi Indonesia (IAGI)*, 11, 2, 7–10.
- WAIN, T. AND BEROD, B., 1989. The tectonic framework and paleo-geography of the upper Kutei basin. *Proc. 18th Ann. Conv. IPA*, 1, 55–78.
- WALUYO, YULIAN, B. AND HADI, T., 1986. Aplikasi interval velocity untuk menentukan sand shale ratio dalam hubungannya dengan eksplorasi minyak dan gas bumi di daerah Kambitin-Bagok, Kalimantan Selatan. *Proc. XV Ann. Conv. IAGI*, 35p.
- WESTERVELD, J., 1941. Three geological sections across South Sumatra. *Kon. Ned. Akad. v. Wetensch., Amsterdam, Proc.*, 44, 1131–1139.
- WIDJONARKO, R., 1990. BD Field — A case history. *Proc. 19th Ann. Conv. IPA*, 1, 161–182.
- WIGHT, A.W.R., SUDARMONO AND IMRON, A., 1986. Stratigraphic response to structural evolution in a tensional back-arc setting and its exploratory significance: Sunda basin, West Java Sea. *Proc. 15th Ann. Conv. IPA*, 1, 77–100.
- WILLIAMS, H.H., KELLEY, P.A., JANKS, J.S. AND CHRISTENSEN, R.M., 1985. The Paleogene rift basin source rocks of Central Sumatra. *Proc. 14th Ann. Conv. IPA*, 2, 57–90.
- WIRJODIHARDJO, K., 1992. Seismic reef expressions in the North Sumatra basin. *Proc. 21st Ann. Conv. IPA*, 1, 117–144.
- WONGSOSANTIKO, A., 1976. Lower Miocene Duri Formation sands, Central Sumatra basin. *Proc. 5th Ann. Conv. IPA*, 133–150.
- ZELIFF, C.W., TROLLOPE, S.W. AND MAULANA, E., 1985. Exploration cycles in the Corridor block, South Sumatra. *Proc. 14th Ann. Conv. IPA*, 1, 379–400.

Manuscript received 24 October 1994