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Tertiary stratigraphic palynology in Southeast Asia: current status and new directions

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Abstract: Palynology is the only biostratigraphic technique which permits crossfacies correlation, and the only micropalaeontological method for correlation of non-marine sediments. Despite its wide use in Southeast Asia, there is currently very little published information which allows the geologist to assess independently the value of palynology for correlation and dating in this area. It is hoped that this contribution will help to fill this gap, as well as indicate the groundwork which is necessary in order to build up correlation schemes which will be of value in individual basins.

Following a brief review of the history of palynological research in Southeast Asia, differences in approaches to correlation and dating of Tertiary sediments using palynology and other micropalaeontological disciplines are outlined. It is emphasised that in the Tertiary, the application of palynology is principally in correlation rather than dating; ages can often be applied to palynological zones only through independent dating using planktonic microfossils associated within transgressive sequences and distal marine facies.

The resolution of palunological zonation schemes currently applicable to the Southeast Asian region and which are based on age restricted palynomorphs is then discussed. Many of the most important age index palynomorphs actually exhibit varying stratigraphic ranges across the region and these variations can often be explained in terms of tectonic, climatic and other controls. There is some scope for the determination of additional stratigraphic markers, especially in the Palaeogene, but high resolution schemes based on stratigraphically restricted form, if they can be established, will require a great deal of work.

In order to provide palynological schemes of sufficient resolution to solve typical questions raised during petroleum exploration in Southeast Asia, an approach is required which gives greater resolution than is possible through reliance on age restricted palynomorphs alone. The methods and philosophy behind quantitative palynological zonation schemes are outlined and the stratigraphic resolution of quantitative and qualitative methods compared. Quantitative schemes can provide stratigraphic resolution comparable to that of planktonic marine microfossils, and greatly assist in the resolution of stratigraphic problems and search for hydrocarbons in non-marine, marginal marine and some marine depositional sequences.

INTRODUCTION

In the first published account of the use of palynomorphs to correlate otherwise unfossiliferous sediments to aid petroleum exploration, Kuyl, Muller and Waterbolk (1955) emphasised that palynology is the only biostratigraphic medium which can be used for cross-facies correlation, and the only

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micropalaeontological technique for correlation of non marine sediments. In the Southeast Asian region, where such sediments are prolific in oil-bearing basins, palynology is used extensively for stratigraphic purposes, although there is very little published information which allows the geologist to assess independently the value of this tool for correlation and dating. In a recent review of the application of the various biostratigraphic disciplines to petroleum exploration in Indonesia (van Gorsel, 1988) palynology was given a very brief coverage and its potential for correlation and dating considerably underestimated. It is hoped that the present contribution will help geologists to appreciate more fully the applications of palynology to stratigraphy in this area, and also will indicate what groundwork is needed in order to build up local zonation schemes which will be of value in individual basins.

This paper also has a second aim. A number of Southeast Asian Government geological institutions and University geology departments are beginning to establish their own palynological facilities and it is hoped that some of the suggestions given here might help these groups in their difficult task of building up palynological databases for their respective areas. Of particular note in this respect are recently established laboratories in the PETRONAS Research Institute in Kuala Lumpur, and LEMIGAS in Jakarta. Palynological units at the Malaysian Geological Survey at Ipoh and Indonesian Geological Survey at Bandung are mainly concerned with Quaternary studies.

BRIEF HISTORY

Up until the 1960s, the leading role in palynology of the tropical regions was taken by the Royal Dutch Shell Group of companies, and although much of their work remains unpublished, from Southeast Asia and elsewhere, their palynologists must be given much of the credit for the initial development of the use of palynology in the Tertiary of low latitude regions.

The first attempt to search for pollen and spores in Southeast Asian sediments was made by Polak (1933; 1949), who demonstrated the occurrence of rich palynomorph assemblages in Holocene peats from Java and Sumatra, but did not try to analyse or interpret her finds. The first attempts at using palynological studies to assist with correlation problems with respect to hydrocarbon exploration in this area were probably made in the early 1950s by international oil company laboratories. Few attempts to publish the early results of these studies were made; the publication of notes on the occurrence of freshwater algae in Sumatran Neogene sediments (Wilson and Hoffmeister, 1953), clearly indicates that Standard Oil were actively applying palynology at this time.

Palynology was subsequently considered for stratigraphic correlation purposes by Brunei Shell, who set up a palynological facility at Seria in 1953 (Hopping, 1967) following early remarkable successes in the immediate postwar period using miospores for cross-facies correlation in the Venezuelan Palaeogene (Kuyl, Muller and Waterbolk, 1955). Initially little progress was made in the correlations and dating of the deltaic sediments of the Brunei and Sarawak region; the first publication produced by Shell Brunei, concerning the occurrence of palynomorphs of northern temperate affinities (Van Veen 1958) was subsequently demonstrated to describe nothing more than drilling mud contamination by Muller (1961), one of the architects of the Venezuelan zonation scheme. Muller was tranferred to the Seria laboratory in 1958. Initial success for Muller in Seria was slow (Muller, 1972, discussion), but after several years work, he established a scheme of workable zones through the Oligocene to Pleistocene. Some of the stratigraphically important datums of the Sarawak/ Brunei succession were subsequently published (Germeraad, Hopping and Muller, 1968), as were generalised histories of the palynofloral succession by Muller, (1964, 1966,1972). Full details of their scheme, however, were never published, although the relationship between the Shell zonation scheme and sedimentary cycles in the Sarawak/Brunei area were presented by Fui (1978).

In the 1970s and 80s, commercial service companies handled most palynological studies from this region, and during this phase, mainly for commercial and confidentiality reasons, very little significant palynological material has been published, with the exception of general reviews (Morley, 1978; Morley and Flenley, 1987). At the present time, no adequate monographs are available for the Tertiary of the Southeast Asian region. However, welcome new contributions are being issued from Thailand (Ratanasthien, 1989; Watanasuk, 1989, 1990) and it is hoped that these can be followed by similar contributions from Malaysia and Indonesia over the next few years. Zonal schemes suggested by the above authors are compare in Fig 1.

Studies on the Late Quaternary are now becoming numerous and use increasingly advanced analytical techniques. These studies are mainly concerned with establishing the extent of climatic change in the tropics, determining temporal successions of the impact of man on vegetation. Quaternary palynological studies in the region are reviewed by Flenley (1979, 1985) and Morley and Flenley (1987). Although not of direct application to Tertiary stratigraphic studies, Quarternary studies provide valuable insights into how Tertiary data might be analysed, and provide environmental analogues with which Tertiary successions might be compared.

CHRONOSTRATIGRAPHY VERSUS CORRELATION

Palynology is frequently criticised for not being able to provide accurate dates for Tertiary samples, especially when studied in isolation of from frontier areas. These criticisms often reflected a lack of understanding by geologists as to how palynological zonation schemes are established and how later, samples are attributed to zones.

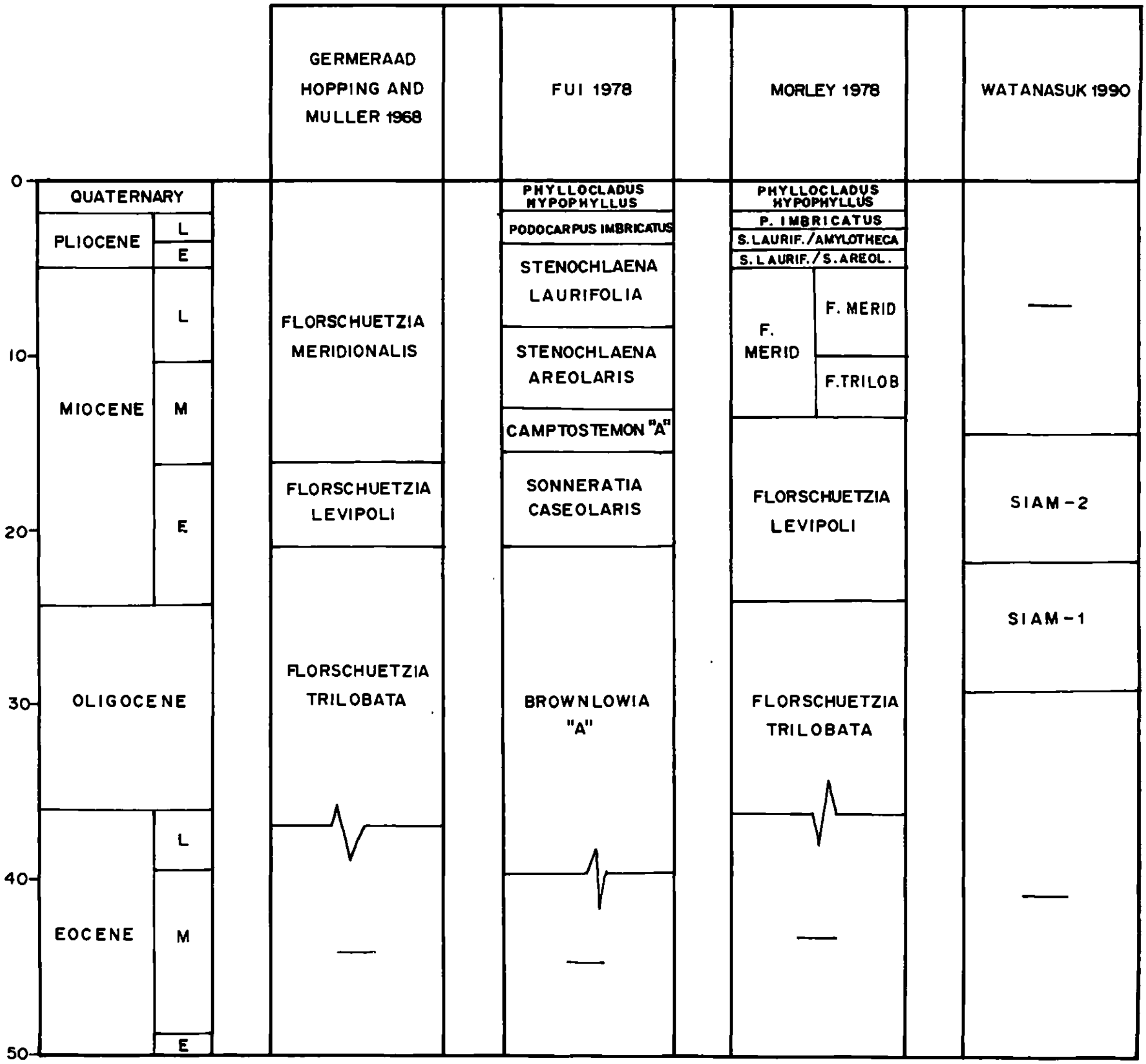

Figure 1: Some zonation schemes applied to the Southeast Asian Cenozoic.

Biostratigraphic studies based on planktonic marine microfossils, such as planktonic foraminifera, nannofossils and dinocysts, are essentially aimed at chronostratigraphic interpretations through identification of age restricted taxa and dating through reference to well established low latitude zonations (Blow, 1979; Martini, 1971). This is possible since marine planktonic microfossils often exhibit worldwide ranges, with only latitudinal and minor provincial restraints. With respect to terrestrially derived palynomorphs, the situation is quite different. Palynomorphs derived from terrestrial sources, such as pollen and spores, tend to exhibit differing stratigraphic ranges and abundances in different areas; since the opening of the Atlantic and breakup of Gondwanaland the evolution of terrestrial floras has progressed to a large degree independently in different continents. Also, vegetation distribution within individual continents is largely controlled by climate and orography. The presence of such controls are clearly illustrated by the Tertiary palynological record, and probably were also significant during the pre-Tertiary. Typically, the palynological succession will be more or less uniform within a single basin, but may vary from basin to basin.

Successive suites of palynomorphs may therefore be used to correlate sedimentary sequences within an individual basin, but in order to apply a date to individual suites, these must be dated independently in each basin by reference to marine fossils, or today perhaps through strontium isotope dating of calcareous benthonics (Rundberg and Smalley, 1989; Smalley *et al.* 1989), before accurate ages to the assemblages can be applied. Miospores are subsequently used more to correlate, rather than directly to date sediments.

RESOLUTION OF ZONATION SCHEMES BASED ON AGE RESTRICTED PALYNOMORPHS

The resolution of zonation schemes based on miospores using age index taxa in low latitude Tertiary sequences is surprisingly low in comparison to many other time intervals. Also, the resolution in Southeast Asia is less than in some other tropical regions. The reason for the reduced number of events, especially in terms of extinctions, is not altogether clear, but probably relates to the reduced effect of climatic change in the archipelagic area of Southeast Asia compared to that which would be expected to occur in an extensive continental area such as the African continent. Some of the more stratigraphically useful Southeast Asian miospore taxa are presented in Fig. 2.

Even for those taxa exhibiting reliable last appearances, many problems exist with respect to their use as age index fossils over wide geographical areas. To illustrate the problems of applying universal age ranges to individual miospores some examples are given below, for some of our most important index taxa, to show the typical geographical extent of age variation.

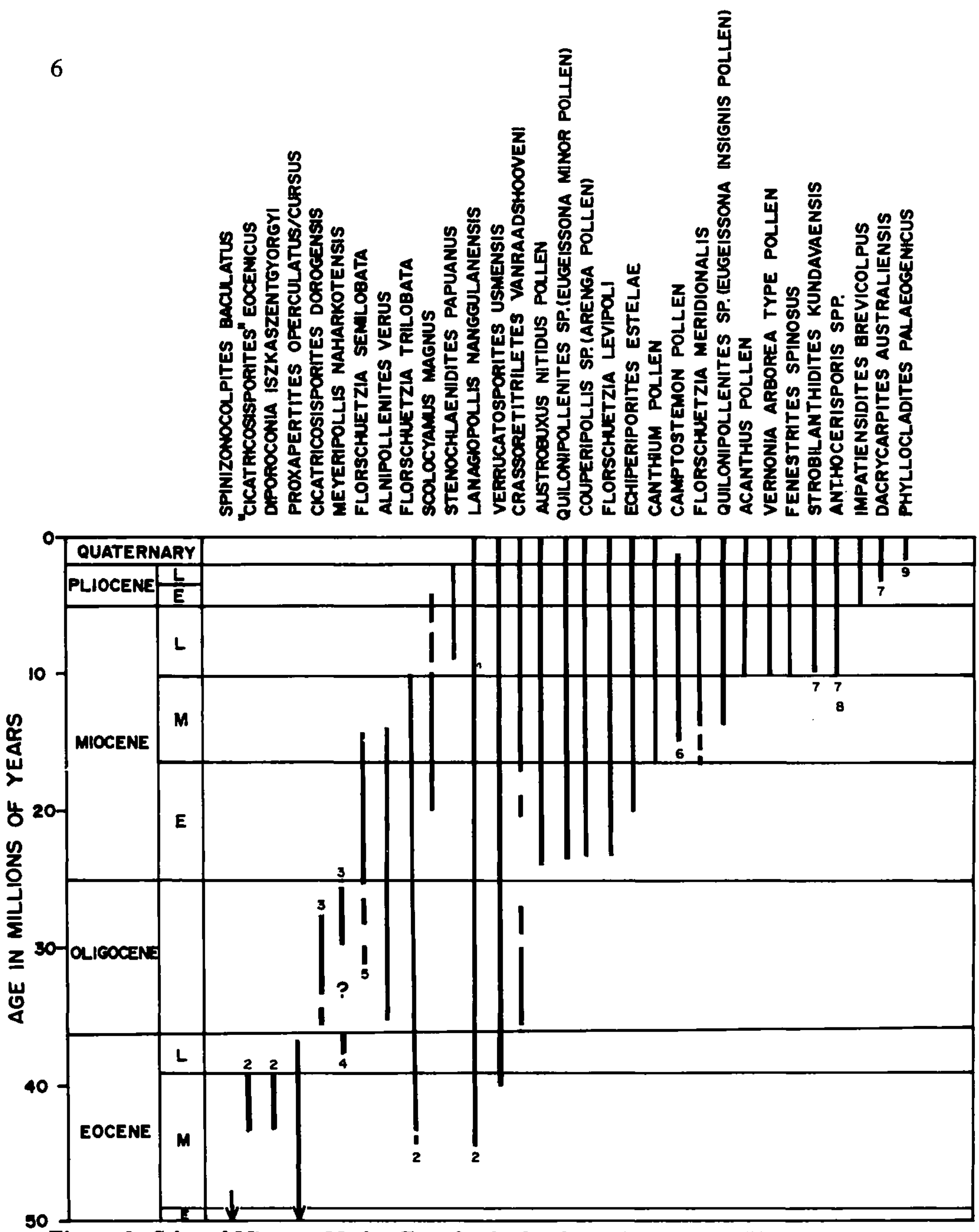

Figure 2: Selected Miospore Marker Taxa for the Southeast Asian region. Unnumbered ranges apply to the Natuna Sea and Borneo regions. Numbered ranges are based on material from the following localities, or applicable, only in the areas indicated:

1. Waripi Formation, Irian Jaya;
2. Middle Eocene occurrences from Nanggulan Formation, Central Java;
3. Talang Akar and Lower Cibulakan Formations, Java Sea;
4. Sempulu Formation equivalent, Mankalihat Peninsula;
5. Oligocene records from Talang Akar Formation, Java Sea;
6. range applicable to East Malaysia and East Kalimantan;
7. range applicable in Bangladesh, Myanmar, Thailand and Sabah;
8. range applicable in Java Sea;
9. range applicable in Borneo [1, 3–8, data from various sources; 2, Barton (1988), Morley (unpubl.)].

Stenochlaenidites papuanus

The pteridophyte spore *Stenochlaenidites papuanus* (Cookson) Kahn is identical to the spores of the fern species *Stenochlaena milnei* Underwood (formerly referred to *S. laurifolia*) and *S. cumingii* Holttum. (see Holttum, 1971). In the Sunda region the occurrence of *Stenochlaenidites papuanus* can be used as an indicator for the Late Miocene[1] and Pliocene, outside this region the species has different ranges in different areas and it these are not properly taken into account then errors in age interpretations will undoubtably occur. The author's understanding of the stratigraphic occurrence and geographical distribution of *Stenochlaenidites papuanus* is presented in Figs 3 and 4.

Stenochlaenidites papuanus was first described from Pliocene coals from Papua New Guinea by Cookson (1957) as *Schizaea papuana* (partim) and subsequently its occurrence in the Pliocene of Brunei was mentioned by Muller (1972). Its value as a stratigraphic marker for the Sunda region was brought to attention by Morley (1978) but since that date a number of both published and unpublished records have been obtained from far outside Sundaland and Papua New Guinea and hence the interpretation presented there requires revision. The earliest record of this type is from the earliest Miocene of the Philippines, and subsequently from the Middle or possibly Early Miocene of the New Guinea region; it is therefore possible that the species evolved in the Philippine region and migrated to New Guinea, prior to the collision between the Australasian and Sunda Plates in the Middle Miocene. Subsequent to this collision, within the Late Miocene, the species migrated into Sundaland, spreading rapidly to East Kalimantan (Caratini and Tissot, 1987), into Java and Sumatra, Thailand, Burma and Vietnam, and subsequently in the Pliocene into northern India (Mathur, 1986) and Southern China (Barre de Cruz, 1982). The spore type disappeared from the record at the end of the Pliocene or possibly basal Pleistocene throughout its western range, but continued in parts of Eastern Indonesia, Papua New Guinea and the Philippines up until the present day where it is currently produced by *Stenochlaena milnei* and *S. cumingii.*

The appearance of *Stenochlaenidites papuanus* in our region clearly reflects the Neogene collision of the Asian and Australian plates, with its subsequent migration across Sundaland and into Asia. No Satisfactory explanation for the Asian extinction of *S. papuanus* near the Plio-Pleistocene boundary is forthcoming, although fluctuating Quaternary sea levels and climate may have been responsible.

The Florschuetzia lineage

Pollen attributable to the genus *Florschuetzia* has been very widely used for dating throughout the Southeast Asian region. Some features of this lineage

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[1] In this paper, most discussion concern time, rather than time rock units, and hence reference is made to time units, using the suffixes "Late" and "Early". Where reference is made to time-rock units, ie. when the age of rocks is being discussed, the suffixes "Upper" "Lower" should be used (c.f. Haile, 1987).

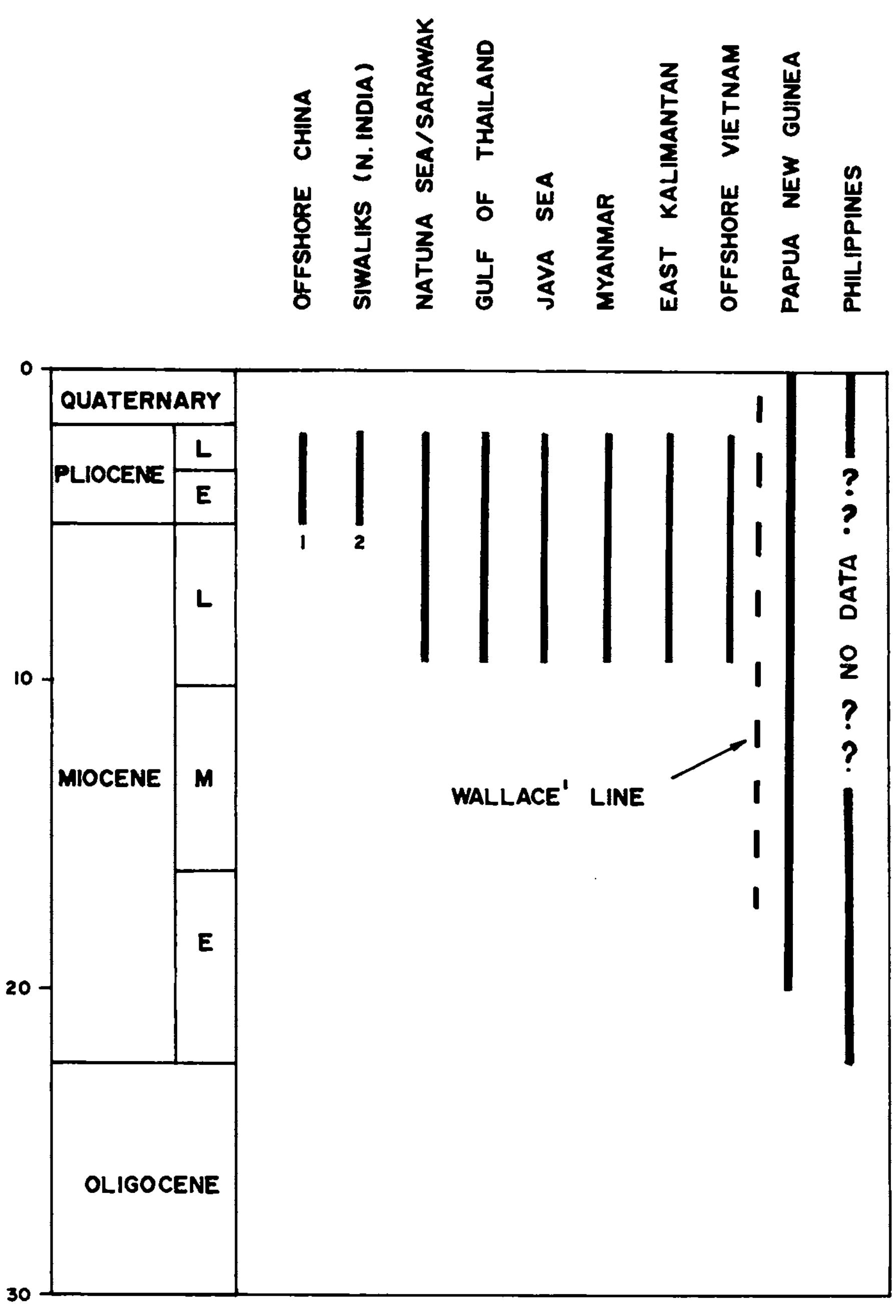


Figure 3: Variations in the stratigraphic range of *Stenochlaenidites papuanus*
1) Barre de Cruz (1982); 2) Mathur (1986); remainder, various sources.

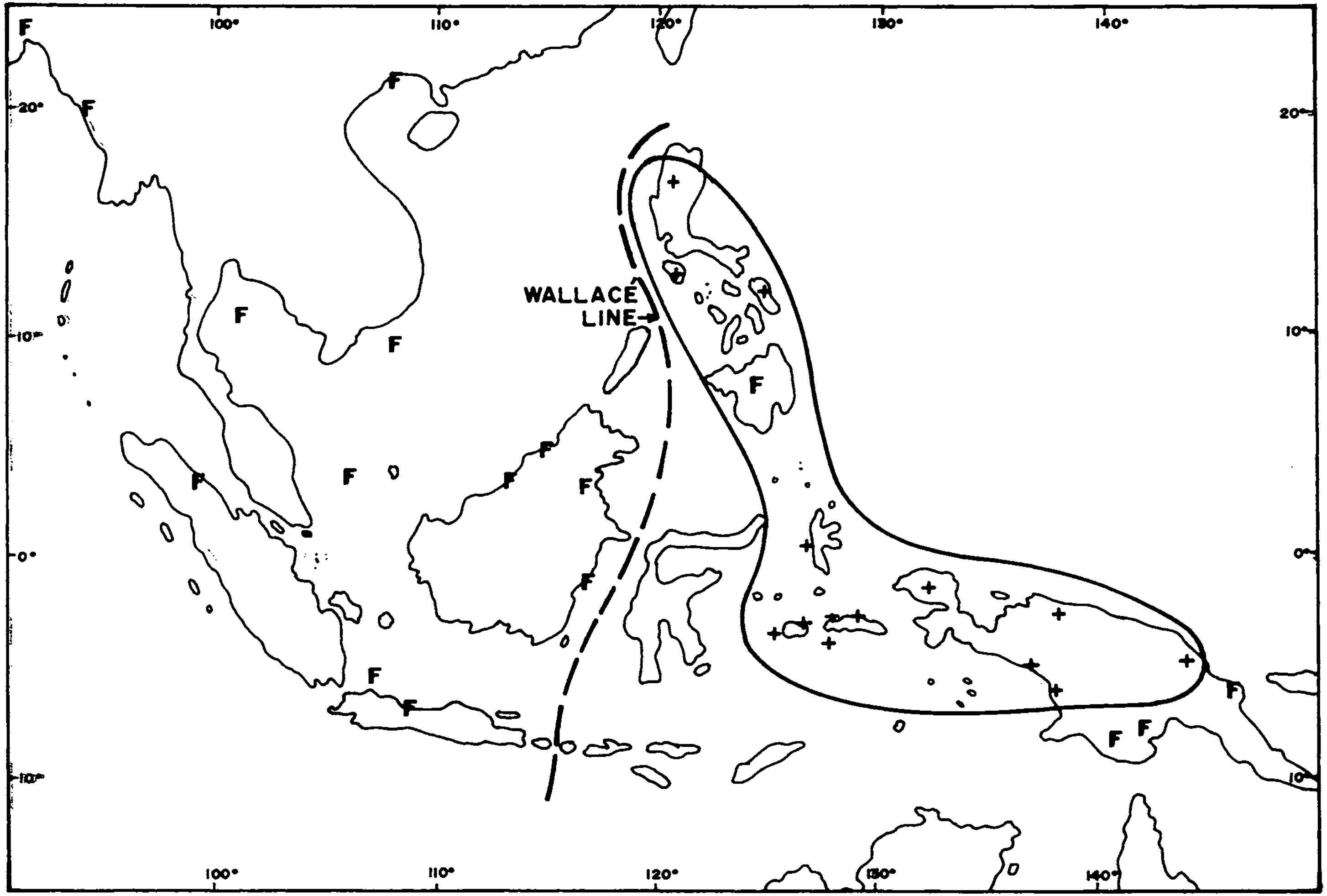


Figure 4: Past distribution of *Stenochlaenidites papuanus* (F) and present distribution of *Stenochlaena milnei / cumingii* (+) [modified from Morley (1978)]. Wallacé Line as modified by Merrill and Dickerson [(in Merrill (1923)].

(Fig. 8) have been shown to have wide stratigraphic applicability, in particular, the evolutionary appearance of *F. meridionalis* in the Middle Miocene, the appearance of *F. levipoli* near the base Early Miocene, and extinction of *F. semilobata* within the Middle Miocene. Independent dating using nannofossils places the first appearance of *F. meridionalis* close to the Middle/Early Miocene (NN5/NN4) boundary, whereas the first appearance of *F. levipoli* probably occurs within zone NN2. Many Lower Miocene sequences in Southeast Asia are transgressive, and therefore, since these forms are derived from mangrove taxa, care must be exercised to ensure that the first appearance of these species does not simply reflect the development of brackish deposition over freshwater sediments.

The extinction level of the evolutionary precursor to these pollen types, *Florschuetzia trilobata,* is also widely used for correlation in Southeast Asia (Fig 5). In much of the Sunda region, the extinction level of this form occurs near the Middle/Late Miocene boundary, where it provides a valuable datum, although Watanasuk (1990) notes its extinction in the basal Middle Miocene in Thailand. In Myanmar and Bangladesh, however, forms morphologically very close to *F.trilobata* continue through the Plio-Pleistocene and subsequently in this region the *F.trilobata* extinction cannot be used. As noted by Muller (1969) pollen closely comparable to that of *F. trilobata* occurs within the mangrove species *Sonneratia griffithii,* which is restricted to the coasts of Myanmar and Bangladesh (Fig 6), the same area as the anomalously young records of *F. trilobata.* It is thus highly probable that the precursor to *S. griffithii* produced the *F. trilobata* pollen within the Plio-Pleistocene of the Myanmar/Bangladesh region.

The pollen record of *F. trilobata* often suggests a different ecology for its parent plant compared to that of its mangrove swamp descendents, whereas the record of *F. meridionalis* suggests that its parent plant was wholly restricted to mangrove environments throughout its range, the parent plant of *F. trilobata* may have occurred in both brackish and freshwater swamp settings. It is believed that in many areas the parent plant of *F. trilobata* may have been a component of seasonal swamp forests, as is its close ally, *Lagerstroemia,* today in the Indochina region. Because of this, and since *S. griffithii* is currently restricted to areas exhibiting a monsoonal climate, the possibility of climatic control on the former distribution of the parent plant of *F. trilobata* must be considered, thus emphasising the importance of understanding the Tertiary palaeoclimatic history of the Southeast Asian region when interpreting palynological data.

Meyeripollis naharkotensis

One of the most valuable Upper Palaeogene markers for the Far East is *Meyeripollis naharkotensis* (Fig 7). This form was first described from Assam (Baksi and Venkatachala, 1971), where it ranges from the topmost Late Eocene

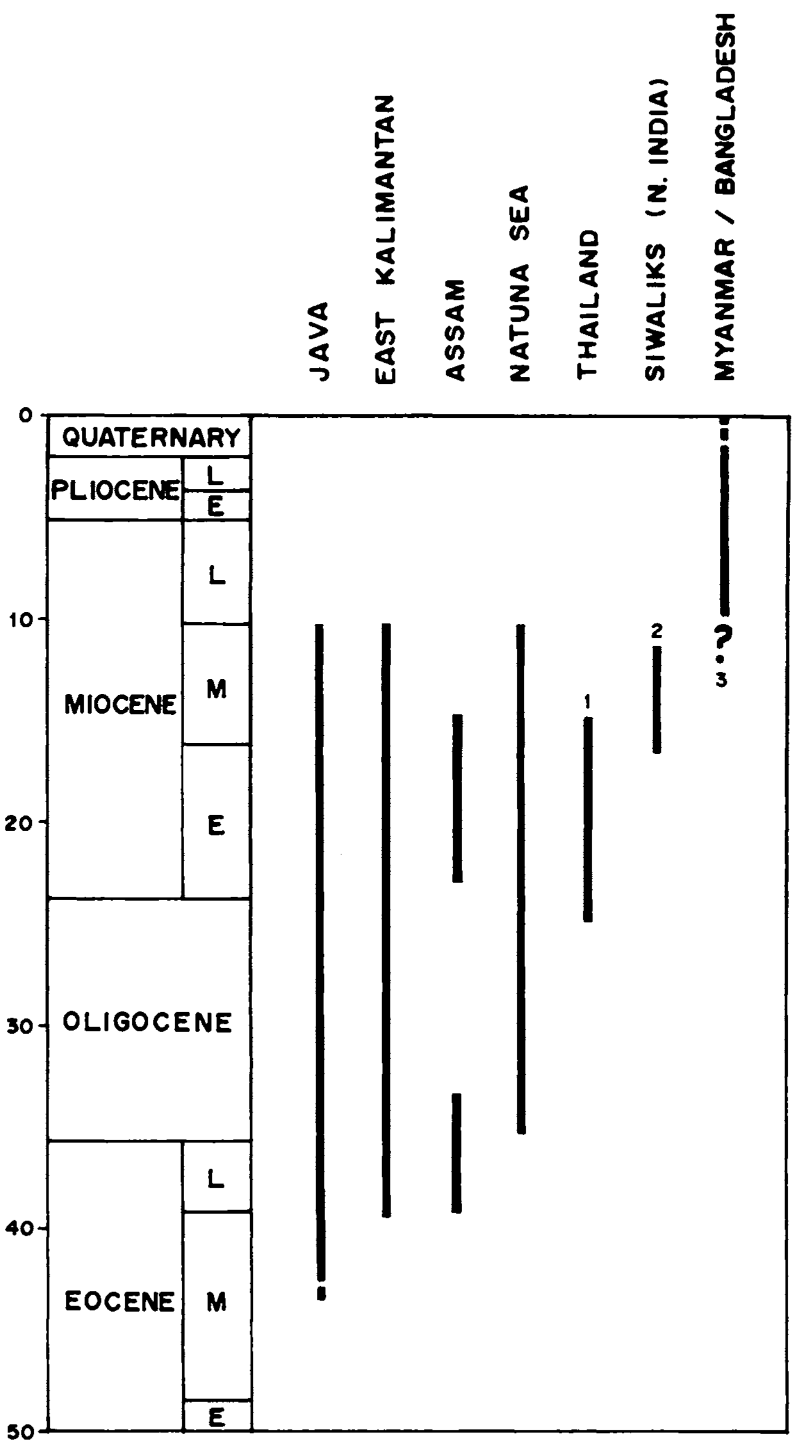


Figure 5: Stratigraphic distribution of *Florschuetzia trilobata* in Southeast Asia.
1. Watanasuk (1990); 2. Mathur (1986); 3. Morley (unpubl.).
Remainder from various sources.

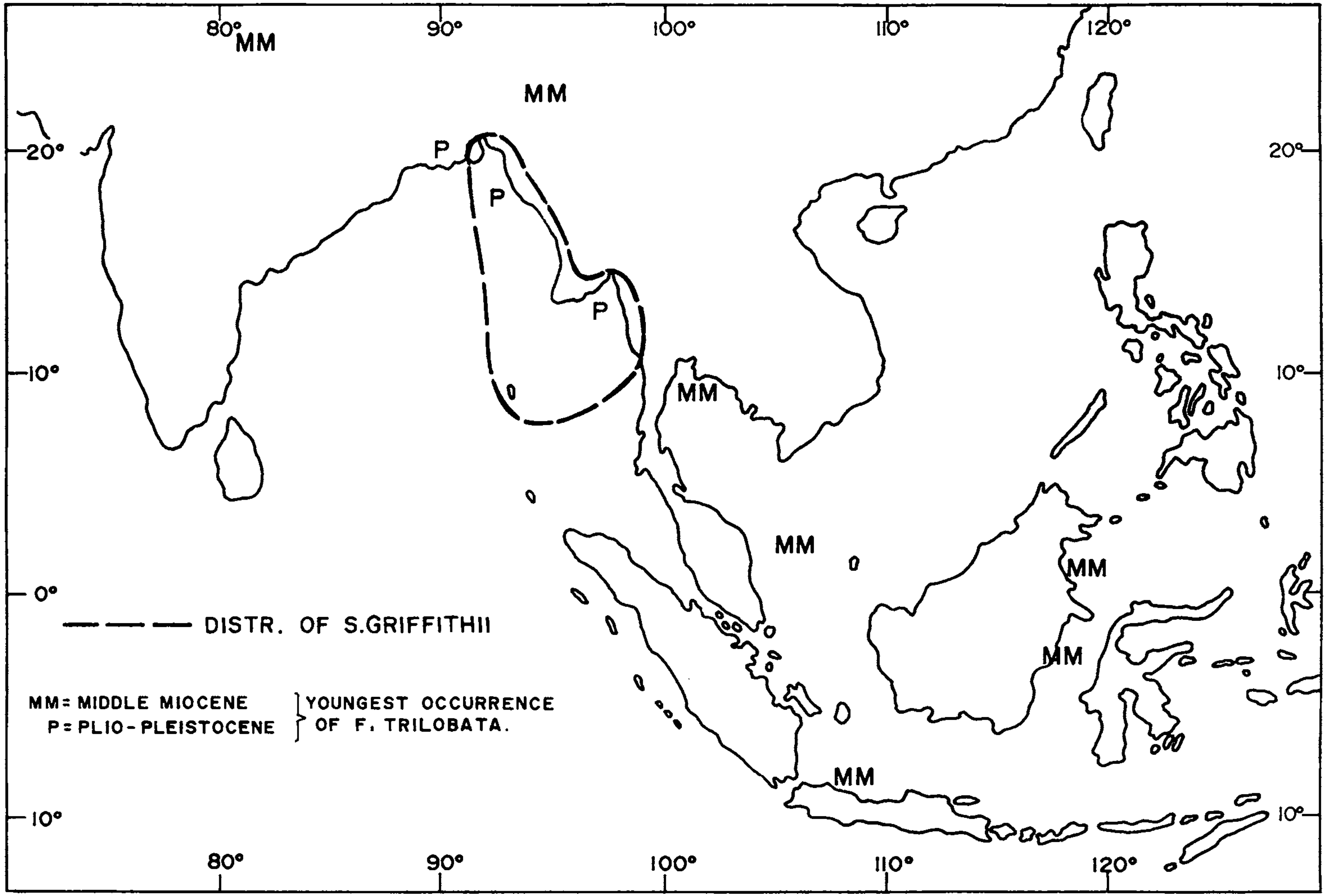


Figure 6: Youngest occurrence of *Florschuetzia trilobata* and distribution of *Sonneratia griffithii* (after Muller, 1969).

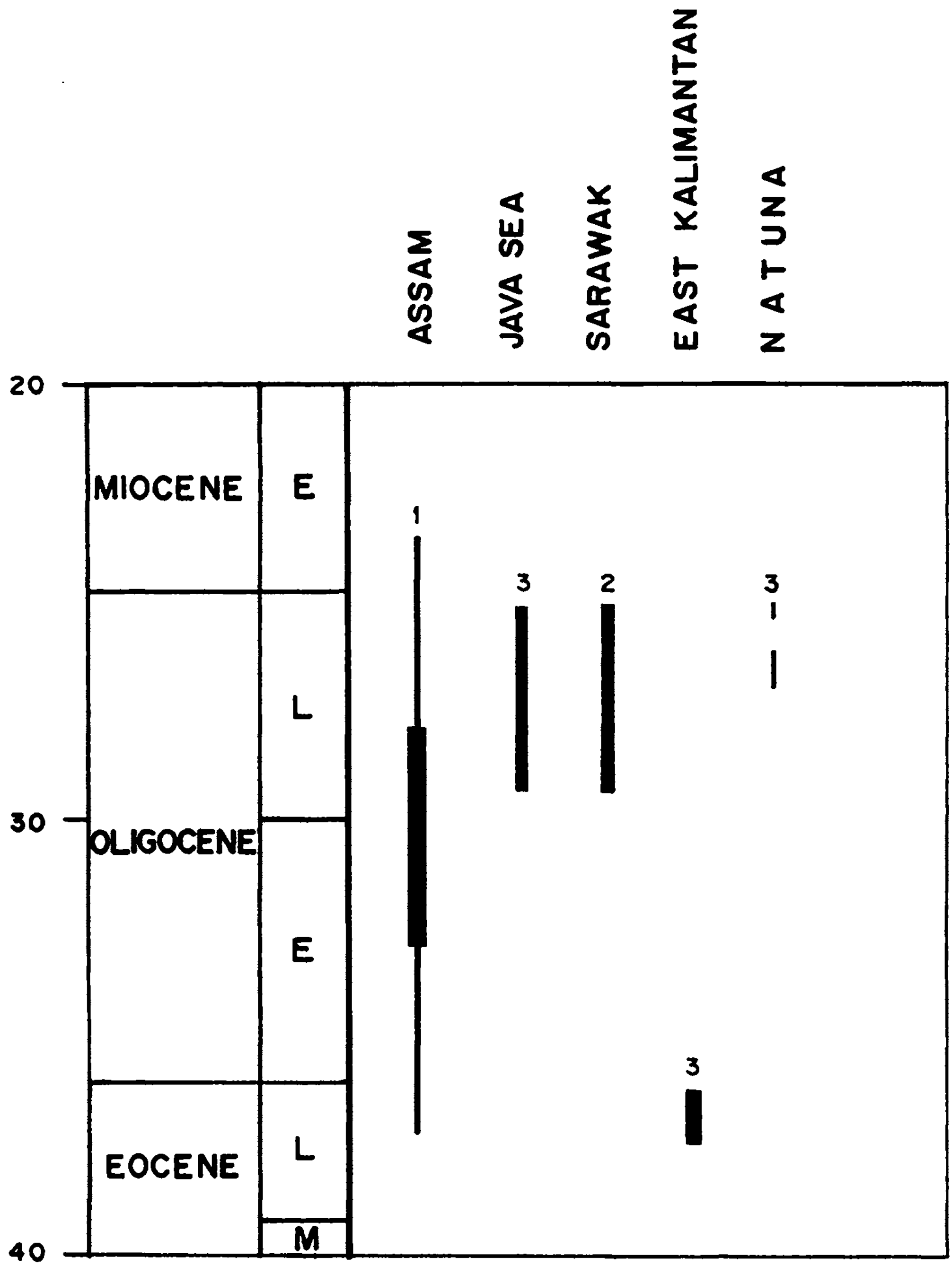


Figure 7: Variations in the stratigraphic range of *Meyeripollis naharkotensis*.
1. Baksi (1962); Mathur and Mathur (1986); 2. Kemp (1974), Muller (personal communication); 3. Morley (unpubl.).

to basal Miocene (Baksi, 1962) and peaks in the mid Oligocene (Mathur and Mathur, 1982; Morley, unpublished). In Assam it is associated with the occurrence of coals, and hence its parent plant may have formed an element of Upper Eocene/Oligocene peat swamp vegetation and also may have been an indicator of an everwet climate. The form is widely recorded but not universally encountered through the Southeast Asian region, where again it is generally associated with coals, and a similar moist climatic regime, for instance, in the Upper Oligocene coaly Talang Akar Formation in the West Java Sea region. It also occurs in the Upper Oligocene of the Brunei Sarawak region (Kemp, 1974, Muller pers. comm.), but is an extremely rare element of the Natuna Sea Upper Oligocene, where a more strongly seasonal climatic regime persisted at this time (Morley and Flenley, 1987). Remarkably *M. naharkotensis* also occurs commonly in Upper Eocene coals from Mankalihat Peninsula, East Kalimantan (Morley, unpublished), where again it is associated with an everwet climatic regime, and more anomalously, in the Middle Miocene of the Tarakan Basin, also associated with coals.

The occurrence of *Meyeripollis naharkotensis* therefore forms an excellent age marker in those areas where its representation is well established. However, because of the marked climatic control over the distribution of this species, it could by no means be considered to have a universal range in the Far East.

Dinocysts

Dinocysts are the resting cysts of dinoflagellates, which are predominantly marine phytoplankton, although today there are many freshwater dinoflagellates. They are much less affected by continental configurations and climate than miospores, and hence their stratigraphic ranges are more consistent between regions than miospore ranges. Up until ten years ago low latitude younger Tertiary dinocysts were virtually unstudied but now their stratigraphic indicator value is becoming better establised. In the Southeast Asian region Tertiary dinocyst studies have been applied principally by Brown (1988, and in preparation); in the Sumatran Neogene he proposes a scheme of four zones and six subzones, but has not indicated how these are defined. The dinocyst succession for the Upper Eocene and Oligocene of Southeast Kalimantan which he has studied, but not yet published, is eagerly awaited. Matsuoka (1981, 1984) has published notes on dinocysts from the Palaeogene of Java.

Current studies show that dinocysts may be stratigraphically important in a number of marine sequences, for instance, the Java Sea, but enigmatically, dinocysts cannot be relied upon to date all marine clastic deposits. They are virtually absent, for instance, from marine turbidite sequences from Sabah.

Because the controls on the distribution of dinocysts in this area are not fully understood, their representation cannot always be relied upon to interpret palaeoenvironment.

A group of algal bodies of possible dinoflagellate affinity occurs in the Oligocene of the Natuna Sea and Malay Basin. This group is thought to comprise freshwater cysts, occuring also in freshwater lacustrine deposits in China (China Petroleum Industry Oil Exploration Research Centre, 1978). They are of little value as age index microfossils, however, but are of considerable stratigraphic value in the Natuna Sea and Malay Basin when considered from a quantitative viewpoint.

Looking for new markers

Virtually all of the stratigraphically restricted post-Eocene miospores which are useful in Southeast Asia are thought to have been derived from taxa close to the plant species level, rather than higher taxa (e.g. from genera or groups of genera). It has previously been suggested (Morley, 1978) that new markers may be found through looking for additional pollen types which are most likely to have been produced from plant species rather than higher taxa and studies from Nigeria following this approach have met with considerable success through the search for lineages, as in the genera *Verrutricolporites* and *Retibrevitricolporites* (Legoux, 1978). The only subsequent attempt to establish additional index fossils through the search for lineages in our area is the study by Morley (1982) for the genus *Lanagiopollis.*

The most important lineage which still requires extensive study is the *Florschuetzia* lineage (Fig. 8), which when properly documented using well dated whole rock samples, rather than cuttings, should provide a number of additional stratigraphic datums which may have wide applicability. In the Middle and late Eocene, many varieties of *Florschuetzia trilobata* occur. These are much smaller than younger forms, and grade into pollen comparable to that of *Lagerstroemia* and related lythraceous forms. The precise character of the size variation seen within *F. meridionalis* and *F. levipoli* in the Late Miocene and Pliocene and brought to attention by Germeraad *et al.*, 1968 also needs thorough documentation using biometrics. Particularly away from equatorial locations, within the Oligo-Miocene a wide range of "*Florschuetzia*" morphotypes are observed which are often colporate and with structured walls. These frequently grade into pollen comparable to that of *Lagerstroemia* and *Ammania*. Very few of these variants have been described in the literature. The latter taxa are characteristic of seasonal freshwater swamp forests of Indochina and emphasise the origins of the mangrove genus *Sonneratia* from freshwater swamp ancestors. Within the Myanmar and Bangladesh region, pollen comparable to *Sonneratia apetala* have been recorded from the Plio-Pleistocene. Its full range in this region needs to be properly established.

It is believed that although the pollen flora for the Neogene of the Sunda region is relatively well known, that of the Palaeogene is very poorly understood, with few published accounts (e.g. Muller, 1968; Takahashi, 1982). Current studies now underway at LEMIGAS are intended to clarify the representation

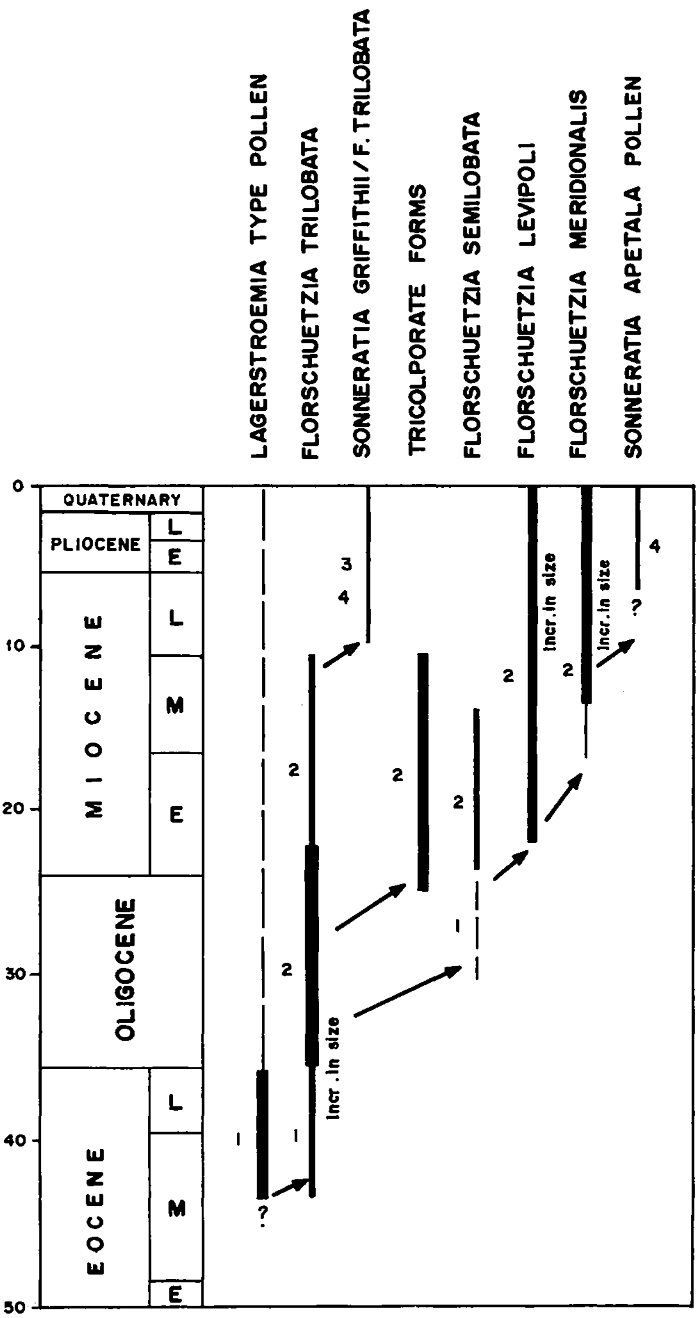


Figure 8: Some trends seen within the form genus *Florschuetzia trilobata* and its allies.
1. Central Java (M. Eocene) and East Kalimantan (Lt. Eocene), Barton (1988) and Morley (unpubl.) 2. Natuna Sea, various sources; 3. Myanmar, Morley (unpubl); 4. Bangladesh, Morley (unpubl.).

of additional stratigraphically restricted forms from the Oligocene and Eocene.

Although there may be opportunities for some expansion in the number of stratigraphically useful miospores in the Southeast Asian region, it is clear that reliance on age-restricted miospores generally gives insufficient resolution to answer typical problems of stratigraphic correlation which might be encountered in our area. Also it is clear that the distribution of some index palynomorphs is in some part controlled by palaeoclimate. In order to provide the necessary resolution to resolve stratigraphic problems more satisfactorily, palynological studies need to be approached from a different direction. An approach which would permit a better understanding of the extent of palaeoclimatic change and other controls which might have affected the distribution of former vegetation but without resulting in the widespread extinction of taxa, might provide better results.

CORRELATION BASED ON QUANTITATIVE PALYNOLOGICAL DATA

Although many tropical Tertiary sequences include few age restricted palynomorphs, assemblages often exhibit substantial quantitative variation. Such variation may be due to a number of factors, but basically two will predominate; a high proportion of the variation will be due to environment and facies controls, and will be of little stratigraphic use, at least in the initial stage of correlation, whereas a second component will relate directly or indirectly to climatic and other regional controls and this clearly will have considerable stratigraphic utility since climatic changes would be effective over wide geographical areas. Quantitative variation can be illustrated through the use of frequency diagrams in terms of percentages, or in terms of number of specimens per unit of sample. To achieve objective results a statistically viable number of specimens needs to be logged in each sample. Analysis can be performed on cuttings alone, but a combination of equal numbers of cuttings and sidewall core samples provides optimum results.

The use of quantitative analysis in palynology is by no means new. Many of the principles used today were established as early as 1916 by von Post (1916). With respect to improving stratigraphic resolution in petroleum studies, the natural progression in Tertiary studies from qualitative to quantitative methods was laid out by Kuyl *et al.*, (1955) and zonations developed by Shell for the Niger Delta (Evamy *et al.*, 1978) and that developed for use in Brunei (Fui, 1978), clearly demonstrate a considerable improvement in resolution over qualitative methods. However, it must be noted that the criteria on which these zones were based have never been published. In Tertiary sequence, the fact that detailed zonation schemes are directly applicable only in the basins in which they have been set up has done much to hinder the publication of such schemes. They have been developed largely in oil company laboratories and service companies and require a considerable material and financial input by both parties before a workable scheme materialises. Publication of such schemes requires release of well data and extensive proprietory palynological analyses and hence publication of such data is rarely encountered. Publications are usually limited to general concepts and models (eg. Morley, 1986, Poumot, 1989).

Palynomorph assemblage variation across facies

In order or utilise the quantitative variation relating to palaeoclimatic change, it is necessary to make a clear separation between palynomorph assemblage variation relating to local facies and that from the river catchment which will reflect regional changes. This initially daunting process is simplified through examination of the mode of palynomorph transport and deposition along a river system (Fig. 9). Although minor variations may occur as a result of differential sorting of palynomorphs, due to size variation etc. emphasis needs to be placed on those pollen and spore types derived from hinterland vegetation rather than from coastal vegetation, since this will be more sensitive in reflecting climatic change. To achieve this, it is necessary to obtain statistically viable counts of palynomorphs from the hinterland region. Since palynomorphs from coastal facies will tend to predominate palynomorphs assemblages, it is useful to determine the palynomorph content of a sample in two stages: initially 100 specimens are counted to give an idea of the representation of edaphically derived palynomorph, following which mangrove pollen is ignored, and subsequently 100-150 specimens of the remaining palynomorphs are counted. It may also be necessary to exclude some other miospores for the second sum, such as undifferentiated monolete fern spores, which may occur in such abundance as to distort pollen spectra of climatically more sensitive forms. Data is presented using two separate pollen sums, hinterland palynomorphs are illustrated in terms of percent of total freshwater miospores, whereas mangrove pollen is illustrated in terms of total miospores (Fig. 10). The choice of the correct "pollen sum" permitting separation of local and regional assemblage variation is perhaps the most important single stage in planning a quantitative palynology analytical programme.

Use of computers to aid data handling

Prepapration of quantitative palynology charts is greatly facilitated through the use of computers. Palynological studies are ideally suited to computer handling since they deal with large numbers of samples, each of which yields a number of palynomorph types within statistically viable populations, and since presentation requires statistical manipulation in order to present data in a manner suitable for interpretation.

Computers can also assists the palynologist in the storage and retrieval of data, and in the analysis of data using ordination, cluster techniques of specially devised zonation programmes; Birks and Birks (1980) summarised the main techniques which have been applied to palynological studies. Up until a few

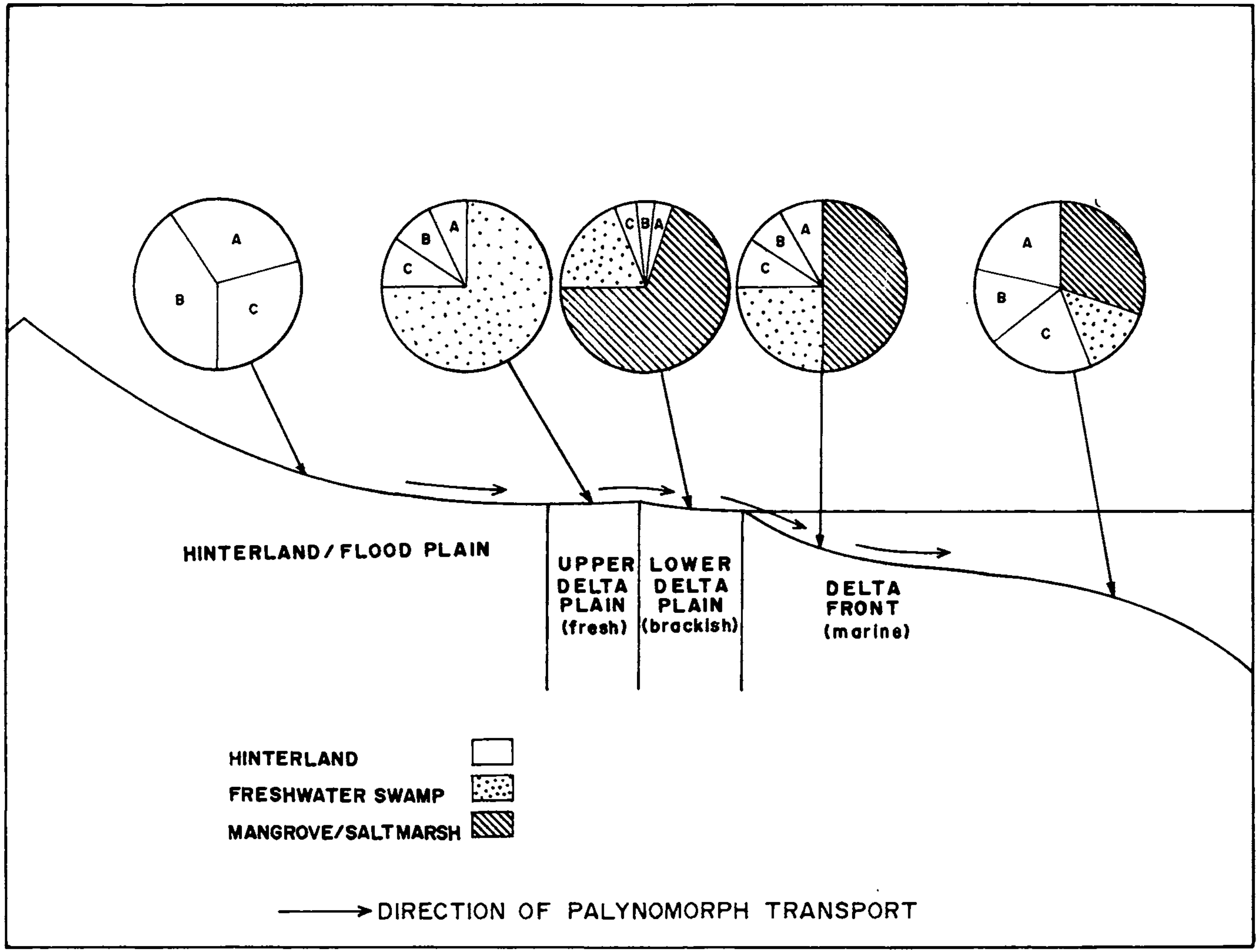


Figure 9: Model for pollen transfer in a major delta system. Locally produced palynomorphs swamp out the regionally produced component, the internal composition of the regional component remains relatively uniform in different facies (although some size sorting will invariably occur) and through removal of the local component from the pollen sum, a fair representation of the regional palynomorph signature can be obtained for any time interval.

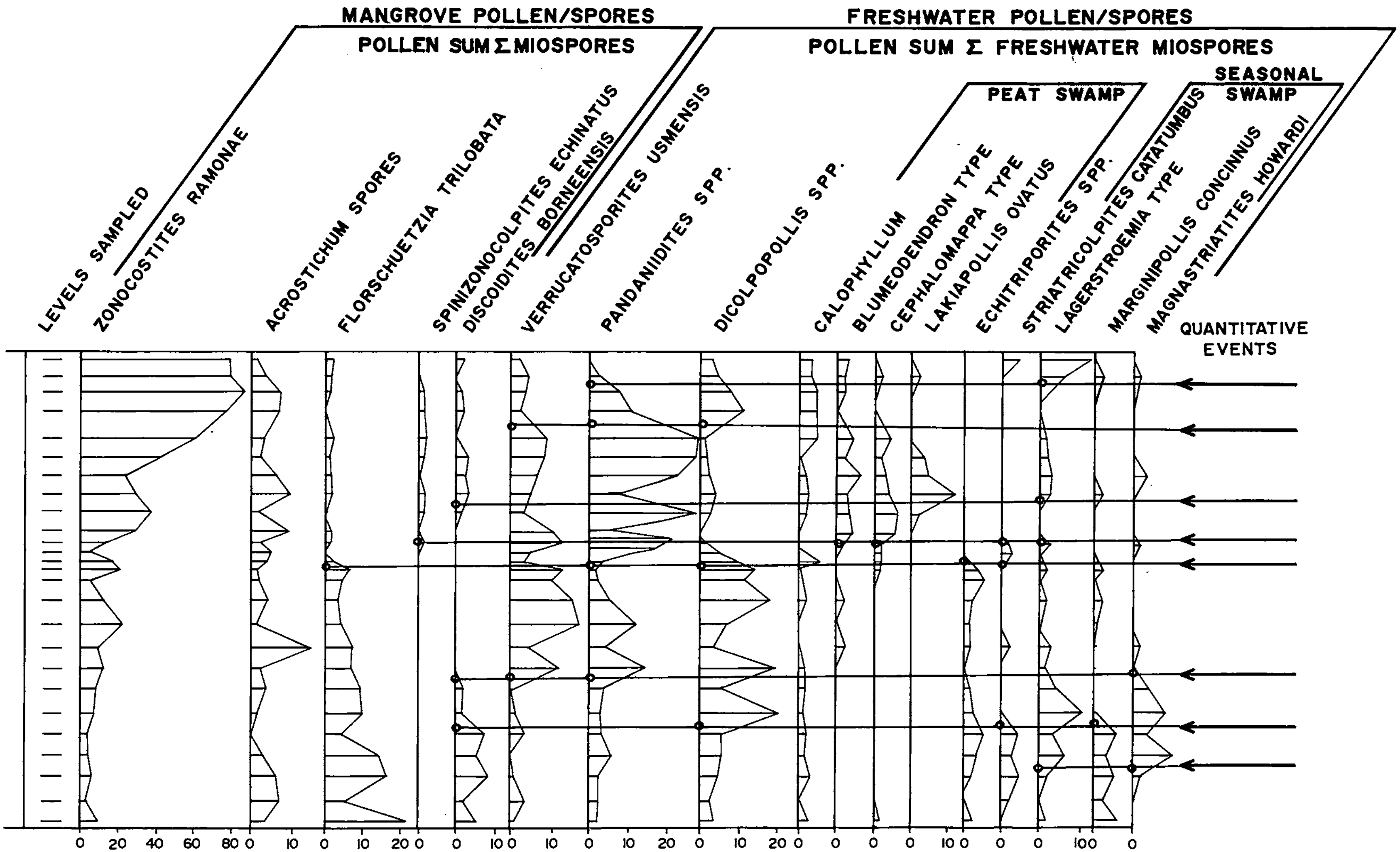


Figure 10: Presentation of quantitative palynological data and determination of quantitative palynological events. Quantitative events of regional (and hence of possible stratigraphic) significance may be revealed using a pollen sum of "total freshwater palynomorphs", whereas events of environmental significance will be reflected using a pollen sum of "total miospores" (selected palynomorphs only are shown for a typical South China Sea mid-Tertiary sequence).

years ago, many of these processes required an expensive mainframe computer, but today, most functions can be performed using readily available desktop machines. The ability to process data using a computer is must for any palynological laboratory.

In a review of the application of palynology to Tertiary stratigraphy within the Shell group of companies, Hopping (1967) emphasised that the main breakthrough in applying palynology to resolving Tertiary biostratigraphic problems came with the application of computer techniques to the handling and analysis of palynological data. In Shell the turning point was in 1957! Few operators working in the Southeast Asian region currently use computers to their full extent for the presentation and interpretation of their data.

Building up a zonation scheme

In planning a programme to establish a quantitative zonation scheme an initial selection of a minimum of four stratigraphically related wells should be made ensuring that the wells chosen include the most complete stratigraphic intervals and with a minimum of missing sections due to faulting. Incorporation of heavily faulted sections in the early stages of development of a scheme will invariably lead to subsequent major difficulties since the faulted well will act as a "type" section and bias subsequent interpretations. If seismic sequence studies have been undertaken, it is necessary to ensure that the well coverage is such that each seismic sequence is sampled, preferably in its area of greatest development.

When two wells have been analysed, and results presented on sawtooth diagrams using a pollen sum excluding obvious locally derived environmentally sensitive spectra, all quantitative assemblage variation from two well sections should be compared and examined in relation to the representation of age restricted palynomorphs, foraminifera and nannofossils as are available, which might place restraints on the position of possible correlation lines (Fig. 11). Those events which exhibit paralellism, or internal consistency with age restricted forms are highlighted and tested against the sequence of quantitative events seen in additional wells. Those event which appear in a consistent sequence in each of the wells are chosen to form the basic building blocks of the zonation scheme.

The sequence of datums established is then tested against lithologies and wireline logs, and also seismic data. Individual palynological assemblage units sometimes show a close relationship with genetic lithological units, the precise significance of which may not be apparent until brought into alignment through palynological correlation.

The confidence with which such a scheme can be applied generally goes through two stages, initial establishment, followed by an elaboration stage after perhaps eight wells have been studied, after which a scheme may become

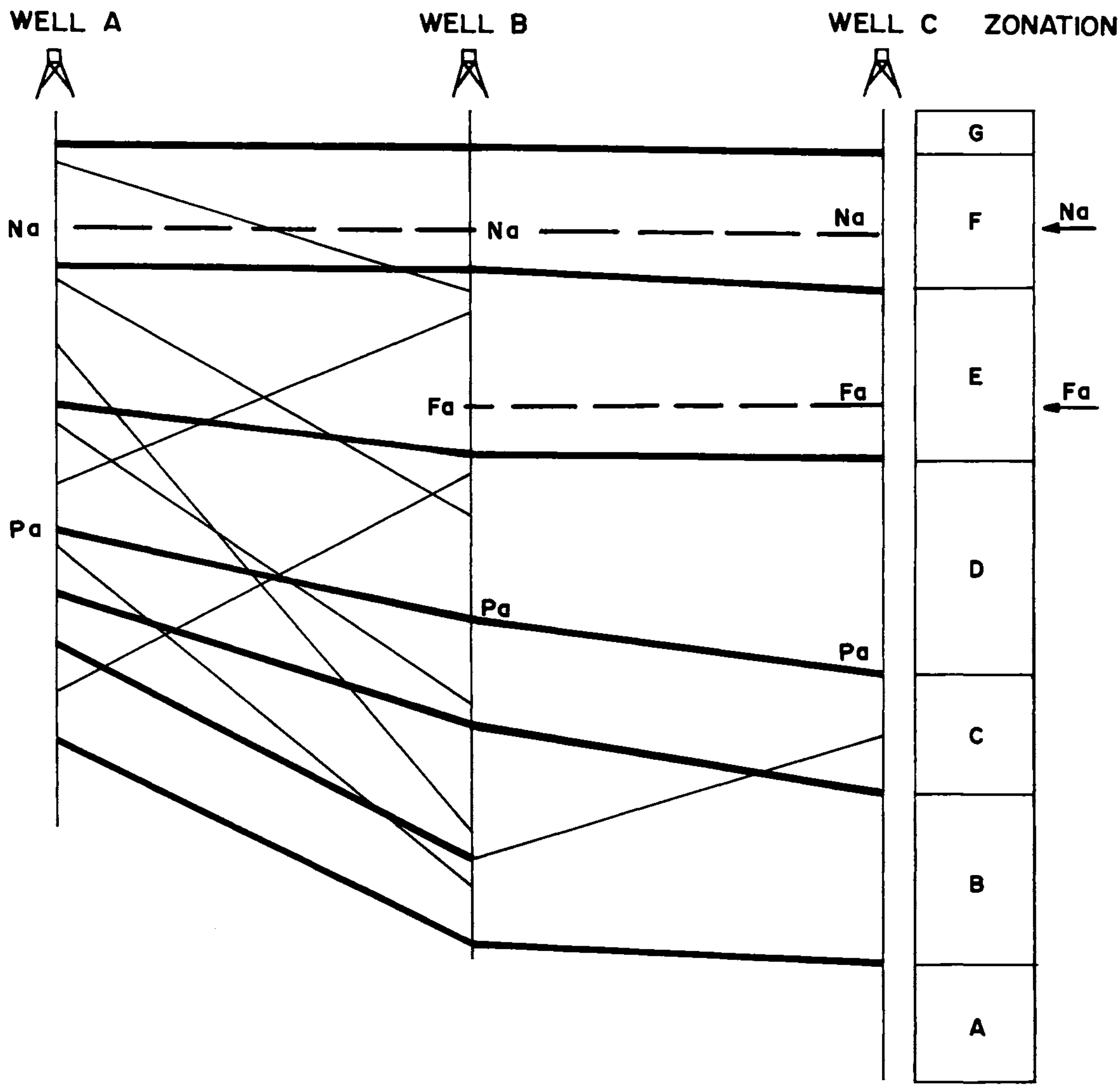


Figure 11: Elimination of non-stratigraphic quantitative events. All regional palynomorph assemblage changes common to wells "A" and "B" are tested against nannofossil (Na), palynological (Pa) and foraminiferal (Fa) events of known correlative value. Quantitative assemblage changes which exhibit parallelism or internal consistency with these events are highlighted (thick lines) and similarly tested in a third (and fourth) well before a quantitative zonation scheme is constructed.

highly predictive. Once a scheme reaches the predictive stage, it may be used without further interpretation, such as in the case of the internal Shell scheme in Sarawak. However, new events not initially appreciated, or outside the initial area of coverage will be frequently encountered and require further interpretation and expansion of a scheme. As a result, a typical zonation scheme is being continually updated as new wells are studied.

In assessing the value of a correlatable event, it is advisable to model each event in terms of controls; does the event reflect an evolutionary change, a climatic event or an orographic or tectonic control?

Events used for correlation

Evolutionary changes

Evolutionary changes within pollen types exhibited by lineages are rare in the fossil record. Examples are the *Florschuetzia* and *Lanagiopollis* lineages already mentioned from Southeast Asia, and the *Verrutricolporites* and *Retibrevitricolporites* lineages from West Africa. Since evolutionary changes are gradual it is often difficult to accurately define boundaries.

Climatic Change

Climatic changes may result from changes in moisture availability or temperature. At sea level in the equatorial tropics temperature changes would not have had a major effect on lowland vegetation (Climap, 1976), although beyond 10 degrees North or South temperature changes at sea level may have been significant. Evidence for temperature changes has been presented for the Javanese Miocene by van Gorsel and Troelstra (1981) based on foraminiferal data. In our area, changes in seasonality of climate and moisture availability are thought to have been responsible for many vegetation changes reflected in the Southeast Asian palynological record. Changes in palaeoclimate can be identified through the plotting of the percentage of pollen derived from vegetation types which develop only under everwet climates against those derived from vegetation types which develop only under seasonal or dry climates.

Ombrogenous peat swamp develops only under everwet climates, and bears a very characteristic flora in Southeast Asia which can easily be recognised on pollen characters (Table 1), thus providing an excellent indicator for everwet climates. Other indicators of everwet climates climated include many pteridophytes, such as Gleischeniaceae, many Lycopodiaceae, and Hymenophyllaceae and *Nepenthes*.

Under seasonal climates true ombrogenous peats do not form (Morley, 1981), although carbonaceous muds and topogenous peats may develop locally. Freshwater swamp environments under seasonal climates include two

Table 1. Some pollen taxa characteristic of peat swamps (form taxon names in parentheses)

A. Pollen types derived from plants which show high degree of fidelity to peat swamps (form taxon names in parentheses).

Alamgium havilandii (= *Lanagiopollis emarginatus*)
Austrobuxus nitidus
Blumeodendron type
Cephalomappa type
Combretocarpus
Ctenolophon parvifolius (= *Retistephanocolpites williamsi*)
Garcinia rostrata
Gonystylus type
Lophopetalum multinervium type (= *Triporotetradites campylostemonoides*)
Neoscortechinia
Parastemon type (= *Psilatricolporites undulatus*)
Stemonurus type

B. Pollen types derived from plants which are often common in peat swamps, but also in other vegetation types

Calophyllum
Campnosperma
Casuarina (= *Casuarinidites cainozoicus*)
Dacrydium (= *Lygistepollenites florinii*)
Durio type (= *Lakiapollis ovatus*)
Lithocarpus type
Melanorrhoea beccarii type
Myrtaceae (= *Myrtaceidites* spp)
Palaquium type (= *Sapotaceoidaepollenites* spp.)
Pandanus (= *Pandaniidites* spp.)
Shorea type
Terminalia type (= *Heterocolpites* spp)
Xanthophyllum type (= *Polygalacidites* sp.)

categories: herbaceous swamps and seasonal swamp forests. Some possible palynological indicators of seasonal climates are presented in Table 2.

Table 2: Some pollen types indicative of seasonal climates (form taxon names in parentheses).

A.	Various habitats
	common Acanthaceae
	Aegialites (= *Warkallipollenites erdtmanii*)
	Anthoceraceae (= *Anthocerisporis* spp.)
	Cedrus (= *Cedripites* spp.)
	Compositae sect. Liguliflorae (= *Fenestrites spinosus*)
	Consistent Compositae sect. Tubiflorae (= *Echitricolporites spinosus* group) excluding *Vernonia arborea* type
	Ephedra (= *Ephedripites* spp.)
	Regular Gramineae (= *Monoporites annulatus*)
	Regular Merremia (= *Perfotricolporites digitatus*)
	common *Pinus* (= *Pinuspollenites* spp.)
B.	Seasonal freshwater swamp forests
	Common *Barringtonia* (= *Marginipollis concinnus*)
	Common *Crudia* type (= *Striatricolpites catatumbus*)
	Lagerstroemia
	Common *Pentace* type (= *Discoidites borneensis*, also from mangrove taxon *Brownlowia*)

Herbaceous swamps dominated by grasses and sedges occur widely in Indochina (Dy Phon, 1981) and the Fly River area of New Guinea (Whitmore 1984). They are virtually absent from areas exhibiting everwet climates except where created by man through burning (Van Steenis, 1957). In the Oligocene of the Natuna Sea, pollen of grasses and sedges are locally common suggesting the development of extensive herbaceous swamps around the lakes of the Gabus Formation, and a markedly seasonal climatic regime.

Seasonally inundated freshwater swamp forests are best described from Indochina, and are currently well developed around the Tonle Sap in Kampuchea (Dy Phon, 1981) the Mekong, and Irrawaddy (Stamp, 1925). Among taxa which leave a palynological record, *Lagerstroemia, Barringtonia (Marginipollis concinnus), Crudia (striatricolpites catatumbus)* and *Pentace (Discoidites borneensis)* are prominent. All of these taxa are well represented in the Oligocene and in some areas, basal Miocene of the Natuna Sea, Java Sea and in Sumatra (Nugruhaningsih and Bartram, 1990) in the absence of pollen of peat swamp taxa and again lend support for a markedly seasonal climatic regime in many areas during the Oligocene.

It must be noted that one of the above pollen types, *Discoidites borneensis*, is generally considered a mangrove indicator; this pollen type is also derived from the mangrove shrub *Brownlowia*. Dogged attribution of this pollen type to the mangroves would transform many non marine Oligocene sequences into brackish swamps rather than fluvial plain or lacustrine sequences. Many pollen types are derived from more than one plant genus, and special care needs to be exercised in palaeoenvironmental interpretation with respect to such pollen types since they may be derived from more than one vegetation type. Another example is pollen of the mangrove genus *Avicennia*. This genus is from the family Verbenaceae, and within this family many genera have the same pollen, hence we normally refer to this pollen as *Avicennia* type pollen. Many of these genera are characteristic of monsoonal vegetations and freshwater swamps in areas with a seasonal climate. The results of erroneously suggesting a mangrove origin for this pollen are obvious.

Many seasonal climates in Southeast Asia are characterised by monson forests, and under strongly moisture deficient situations, by open woodland and savannas with grassland. The pollen of present day monsoon forests requires further study in order to facilitate recognition of pollen from this source. One very characteristic component of monsoonal vegetation in Indochina and the Philippines is Pine.

Bisaccate pollen identical to the genus *Pinus* is commonly met in the Southeast Asian Oligo-Miocene, in association with lesser frequencies of other gymnosperm pollen types such as *Piceapollenites* spp., *Keteleeria*, *Abiespollenites* spp., *Cedripites* spp., *Tsugaepollenites* spp., *Ephedripites* spp. and the angiosperms *Alnipollenites verus* and *Pterocarya*. Previously this association has been interpreted as being derived wholly from a montane source and associated with everwet climates (Muller, 1966, 1972).

Explaining all of the conifer pollen in the Tertiary record in terms of a moist montane origin is difficult, since in many shallow marine sequences it occurs abundantly, and huge mountain ranges without vegetated coastal plain areas would be necessary to explain these assemblages using an everwet montane model. The possibility of an alternative source should therefore be carefully examined. Today *Pinus khesiya* and *P. merkusii* occur at low and intermediate altitudes in Thailand and the Philippines in areas exhibiting a distinctly seasonal climate (Whitmore, 1975) and since many conifers frequent xerophytic situations as well as montane ones, a palaeoclimatic control over the Oligocene gymnosperm pollen - producing vegetation is thought to be more likely.

The climatic requirements of the gymnosperms other than *Pinus* and "temperate" angiosperms need to be more carefully established through examination of their current areas of occurrence in Indochina before their fossil record can be fully interpreted. Some were clearly derived from moist montane environments, such as *Alnipollenites verus* and *Abiespollenites* spp., but for others, the climatic requirements are less clear. Pollen of *Ephedripites* spp. and *Cedripites* spp. may have been derived wholly from seasonal climatic regimes.

Tectonics and orographic changes.

Tectonic events create uplift, resulting in new niches for mountain floras. Erosion results in the destruction of high altitude niches and the gradual disappearance of these floras.

The increase in representation of pollen of temperate montane plants, such as *Alnipollenites verus*, in the Oligocene and Middle Miocene of the Natuna Sea, may relate to periods of uplift. Other than these, most changes in the representation of pollen which has probably been derived from montane sources reflect the gradual erosion of former mountain systems and the gradual reduction of high altitude montane elements. The emphasis here, however, is of gradual change, which rarely provides sharp palynomorph assemblage breaks which can be used for correlation.

Continental collisions create pathways along which plants can migrate. The result is sudden appearances, such as the immigration of the parent plant of *Stenochlaenidites papuanus* from the region of the Australian plate, which has already been discussed. Other examples of migration into Sundaland through continental collision are reflected in the appearances of *Phyllocladites palaeogenicus* in the base Pleistocene, *Dacrycarpidites australiensis* in the mid Pliocene, *Scolocyamus magnus* in the Early Miocene, *Lygistepollenites florinii* in the basal Oligocene, and subsequent to the collision of India and Asia in the Late Eocene, the appearances of *Magnastriatites howardi* and the palm pollen *Quillonipollenites* spp. (*Eugeissona*).

Sea Levels

Sea level fluctuations should theoretically provide the most accurate basis for time stratigraphic correlation since sea level variations affect wide geographical areas, or are global. The main problems in using sea level fluctuations for correlation are, firstly, ensuring that water depth variation relate to real eustatic changes and not to sedimentological factors such as switching of delta lobes, and secondly, especially in the Southeast Asian region, the effects of sea level changes are often overprinted by tectonic events. The latter, however, will not affect local zonation schemes.

Sea level changes will have two effects on the palynological record. Firstly, they will affect climate. During high sea levels the climate is likely to have been more oceanic and wetter, whereas during low sea levels, more continental climates would be more likely (e.g. Morley and Flenley 1987, Van Steenis, 1939, 1961). The development of wetter climates and formation of coals in the Arang Formation in Natuna coincides with such a rise in sea levels.

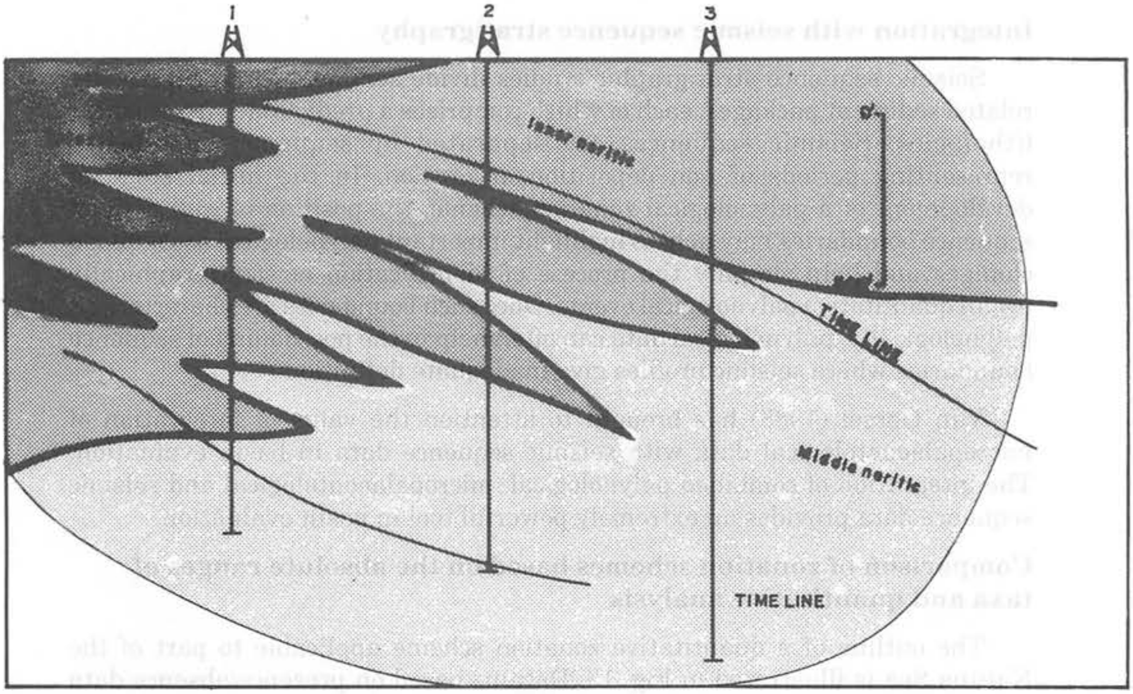
Secondly, they will have an effect on coastal geomorphology and the representation of brackish and freshwater swamp vegetation, depending on whether sea levels are rising, falling or at still-stand. During periods of still-stand, coastal mangrove swamps will expand, whereas during periods of sea level fall or rise, their area will be reduced. Also, during periods of drier climate, the representation of mangroves may be less than during wet periods. Subsequently, sea level changes will have an effect on both the pollen produced from the river catchment, and also that produced by coastal vegetation and hence the effects of sea level changes be examined in both the regional and local pollen component. Poumot (1989) has made a tentative model to suggest how sea level changes might affect vegetation and palynomorph productivity in the Southeast Asian region and suggested for Sarawak that sea levels may have fluctuated in 400 000 yr "palynocycles" in that area during the Miocene.

The presence of mangrove swamps and other vegetation types within a delta plain setting will also bear a relationship to the style of delta position. Fluvial and wave dominated deltas will have minimal mangroves, whereas tidal dominated settings may bear vast mangrove tracts. Changes in the style of deltaic regimes may subsequently find an expression in the palynological record through changes in the character of delta plain vegetation, and sometimes such changes may also be of value for the purposes of correlation (Morley, 1986).

Integration with benthonic foraminifera

In the interpretation of marine environments, palynology will determine whether deposition occurred in a fluviomarine of holomarine setting, or whether deposition was proximal or distal relative to a shoreline, whereas water depths are best determined using benthonic foraminifera. Relative changes in water depths as indicated from foraminifera should provide a good basis for correlation, but often, where a number of changes in water depth are demonstrated within a single, sequence, and age restricted microfossils are missing, these events can rarely be correlated.

With the addition of a limited number of time stratigraphic datums from palynology, it is often possible to place water depth changes identified using micropalaeontology into a time stratigraphic perspective and develop a local stratigraphic model based on degrees of sea level change (Fig. 12). In looking for correlatable benthonic foraminiferal assemblages, it is important to look for data which suggests comparable degrees of water depth change with time, rather than similar foraminiferal assemblages correlations using foraminifera to identify eustatic changes will be based on degrees of change rather than similarity of foraminiferal assemblages.



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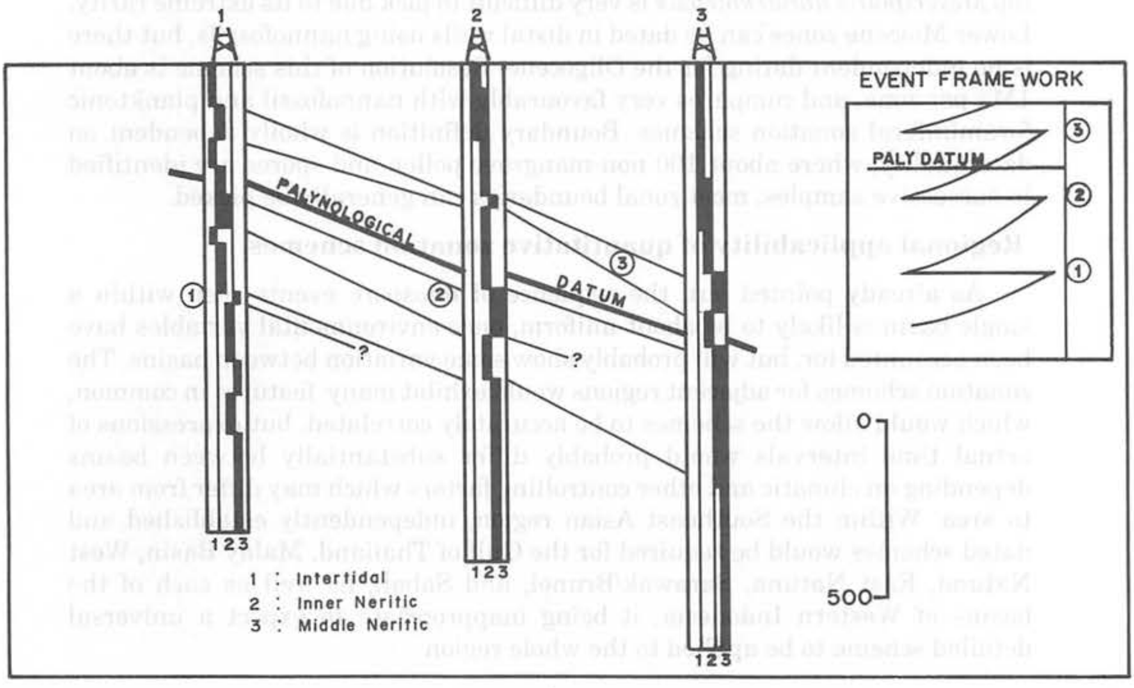

b

Figure 12: Integration of palynology and benthonic foraminifera. 12a. Hypothetical deltaic sequence with transgressions and three wells located against strike. 12b, Water depth interpretation from foraminifera for the above wells tied into a stratigraphic model through the determination of correlation line using quantitative palynological datum.

Integration with seismic sequence stratigraphy

Seismic sequence stratigraphic studies divide sediments into genetically related sediment packages, each of which comprises a predictable succession of lithofacies. Seismic sequences are separated by sequence boundaries representing periods of non deposition or erosion. In the initial stage of development of a palynological zonation scheme, the position of well defined sequence boundaries may help to highlight important palynological assemblage changes and help simplify the process of identification of stratigraphically useful quantitative palynological events. Once such boundaries are characterised palynologically, palynological data can often help in the positioning of sequence boundaries where seismic profiles give inadequate definition.

Van Gorsel (1988) has brought to attention the value of integration of micropalaeontological data with seismic sequence data in basin evaluation. The integration of combined palynological. micropalaeontological and seismic sequence data provides an extremely powerful tool in basin evaluation.

Comparison of zonation schemes based on the absolute ranges of taxa and quantitative analysis

The outline of a quantitative zonation scheme applicable to part of the Natuna Sea is illustrated in Fig. 13. Datums based on presence/absence data are also presented. In this area, probably as a result of climatic restraints, the top *Meyeripollis naharkotensis* is very difficult to pick due to its extreme rarity. Lower Miocene zones can be dated in distal wells using nannofossils, but there is no independent dating for the Oligocene. Resolution of this scheme is about 1Ma per zone, and compares very favourably with nannofossil and planktonic foraminiferal zonation schemes. Boundary definition is wholly dependent on data quality; where about 100 non-mangrove pollen and spores are identified in successive samples, most zonal boundaries can generally be picked.

Regional applicability of quantitative zonation schemes

As already pointed out, the sequence of miospore events seen within a single basin is likely to be about uniform, once environmental variables have been accounted for, but will probably show some variation between basins. The zonation schemes for adjacent regions would exhibit many features in common, which would allow the schemes to be accurately correlated, but expressions of actual time intervals would probably differ substantially between basins depending on climatic and other controlling factors which may differ from area to area. Within the Southeast Asian region, independently established and dated schemes would be required for the Gulf of Thailand, Malay Basin, West Natuna, East Natuna, Sarawak/Brunei, and Sabah, as well as each of the basins of Western Indonesia, it being inappropriate to expect a universal detailed scheme to be applied to the whole region.

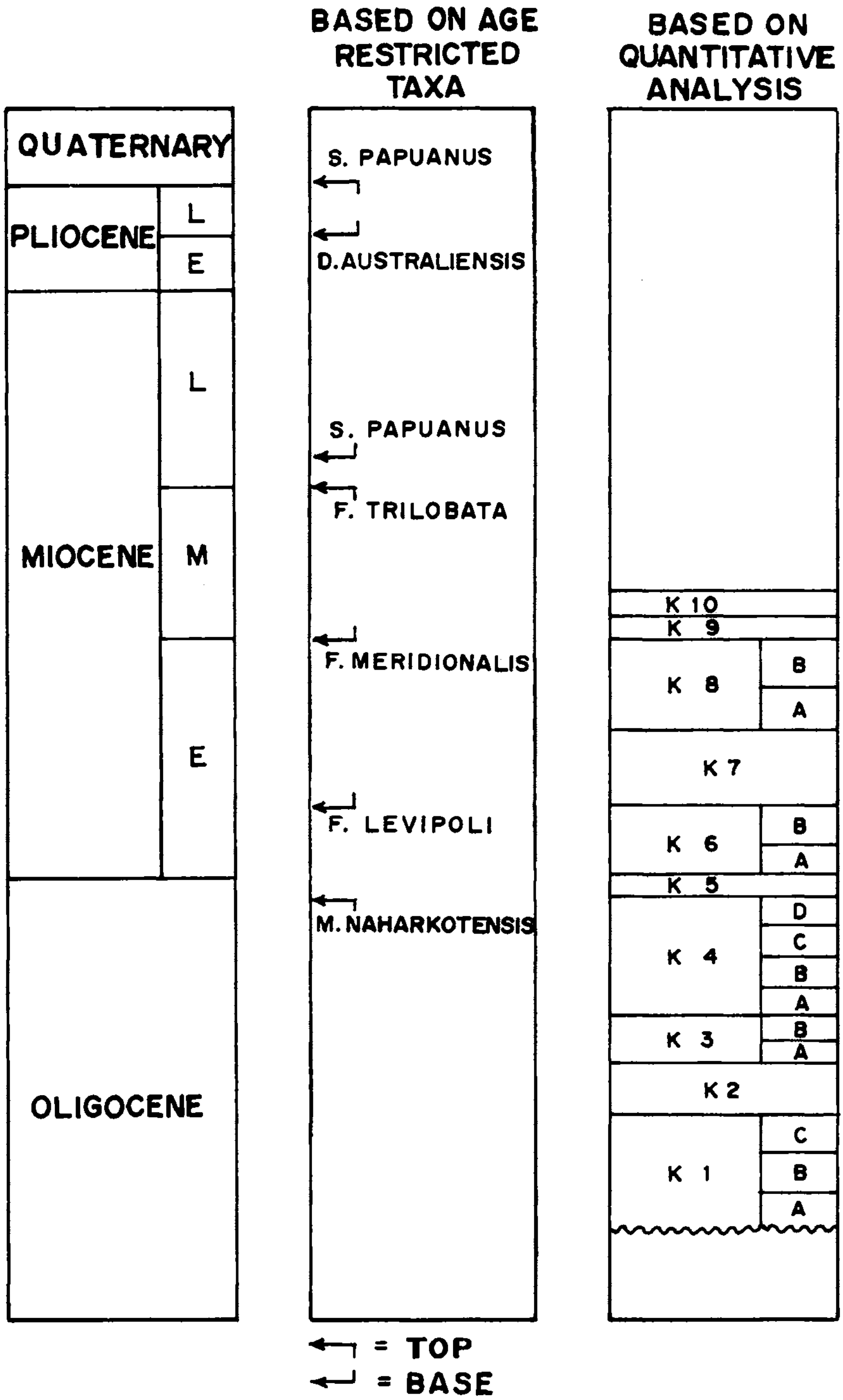

Figure 13: Stratigraphic resolution for an area of the Natuna Sea comparing the use of age-restricted forms and of quantitative methods.

High resolution zonation schemes established in other regions, e.g. Niger Delta or North Sea, tend to be applicable only over relatively small areas in comparison to the Southeast Asian region. When considered from the point of view of geographical scale, it is therefore not suprising that only low resolution schemes are produced for the broad Southeast Asian region.

CONCLUSIONS

Despite intensive palynological studies with respect to petroleum exploration, zonation schemes for Southeast Asia based solely on the presence of age restricted palynomorphs have a low resolution and accuracy with respect to correlation. Also, many of the most important palynomorphs used for establishing ages exhibit varying stratigraphic ranges across the region which can be explained in terms of tectonic and other controls, but which may possibly lead to misinterpretations of age during routine palynological studies. There is some scope to determine additional stratigraphic markers, especially in the Palaeogene, which has been poorly studied, and among the dinocysts, but high resolution scheme suitable for resolving typical geological problems based on stratigraphically restricted forms, if they can be established, will require a great deal of work.

Stratigraphic resolution can be substantially improved through the application of quantitative palynological methods, which are aimed at the identification of events reflecting climatic, tectonic, orographic and sea level changes but without resulting in widespread extinction of plant taxa. Quantitative methods permit the separations of environmentally and stratigraphically related palynomorph assemblage variation through the careful choice of "pollen sums". Palynomorphs which are derived from plants which were clearly growing in close proximity to a depositional site, such as mangrove pollen in a typical deltaic depositional setting, are presented using a pollen sum of "total miospores", and palynomorph spectra presented using this sum principally reflect environmental change. Palynomorphs derived from vegetation distant from the site of deposition are presented using a pollen sum of "total freshwater miospores". Palynomorph spectra presented using the latter sum are more likely to reflect vegetational changes of regional significance, which might relate to climatic and other events, and these events will be much more useful for the purpose of stratigraphic correlation.

Using such an approach, zonation schemes can be established which are perhaps of basinal extent, which have a resolution of in the order of 1Ma per zone, comparable in terms of stratigraphic resolution to planktonic microfossil zonation schemes. Quantitative zonation schemes are initially aimed at correlating rather than dating sediments; once established, however, zonation schemes can be calibrated by reference to any planktonic foraminifera of nannofossils which might occur in transgressive sequences or distal marine facies. Calibration can also be achieved through strontium isotope dating of shallow marine calcareous benthonic foraminifera. The process of integration of quantitative palynological data and other disciplines such as foraminiferal and seismic studies may result in the development of integrated "stratigraphic models", the resolving power of which may be considerably greater than any individual discipline used in isolation. The establishment of a zonation scheme requires an initial development phase, involving the study of at least four wells. Once perhaps six or eight wells are studied, a quantitative zonation scheme can become a highly predictive tool which can greatly assist in the resolution of stratigraphic problems and search for hydrocarbons in non marine, marginal marine and some marine sequences.

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