Tertiary source rocks, coals and reservoir potential in the Asem Asem and Barito Basins, Southeastern Kalimantan, Indonesia

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CHAPTER ONE

INTRODUCTION

1.1. LOCATION

The Asem Asem and Barito Basins are situated in southeastern Kalimantan (Fig. 1.1), covering the area between $1^\circ$S and $5^\circ$S latitude and $114^\circ$E and $117^\circ$E longitude. The Asem Asem Basin is about 180 km east of the provincial capital of Banjarmasin, the commercial centre of South Kalimantan. The Barito Basin extends about 250 km northwards from Banjarmasin (Figs 1.2 and 1.3).

Access to the Asem Asem Basin is by regular flights to the main district town, and then by car (usually landcruiser) and boat to reach villages and small places along the coast.

Much of the Asem Asem Basin consists of a series of hills and intervening low-lying floodplain or swamppy regions, although the crest of the northeast-trending Meratus Range is a conspicuous feature.

1.2. GENERAL GEOLOGY OF SOUTHEASTERN KALIMANTAN

The northeast-trending Tertiary Asem Asem Basin has previously been called the Pasir or Asem Asem Sub-basin of the larger Barito and Kutei Basins. The basin is bounded by the Meratus High in the west, the Laut High and Paternoster
Shelf in the east, and the Paternoster High in the north (Fig. 1.2). The Barito Basin is separated from the Asem Asem Basin by the Meratus High in the east, from the Kutei Basin by the Paternoster and Kuching Highs in the north, from the Melawi and Ketungau Basins by the Schwaner Block in the west and Kuching High in the northwest.

Both the Asem Asem and Barito Basins (the southeastern Kalimantan basins) are underlain by Early to Late Cretaceous basement rocks. In general, the basement consists mainly of ophiolite complex and metamorphic rocks, plus volcanic and sedimentary rocks which are well exposed along the present core of the Meratus High (Figs 2.5 and 2.6).

Tertiary sedimentation commenced with the Eocene Tanjung Formation sediments deposited over most of the southeastern Kalimantan basins (Fig. 2.4). The Tanjung Formation unconformably overlies the pre-Tertiary basement rocks. This formation was succeeded by the predominantly carbonate succession of the Berai Formation (Oligo-Miocene). Subsequently, during a regressive phase, the Warukin Formation (Middle-Late Miocene) was deposited conformably on the Berai Formation. The Plio-Pleistocene Dahan and Martapura Formations were later laid down unconformably on the Warukin Formation.

1.3. PREVIOUS WORK

The first geological reports on the Asem Asem and Barito Basins and surrounding area were by Krol (1918, 1920, 1925) and Gollner (1924). The most comprehensive early
synthesis of the geology of Kalimantan (Borneo) was by Van Bemmelen (1949).

In the period 1970 to 1982, further geological investigations were carried out in the Asem Asem and Barito Basins by Power and Reiser (1970), Austin (1970), and Pertamina UEP IV (1976, 1981). The Geological Research and Development Centre, Bandung, has also published preliminary geological maps at a scale of 1:250,000 covering the Asem Asem and Barito Basins (e.g. Supriatna et al., 1980; Sikumbang and Heryanto, 1981; Rustandi et al., 1981; and Umar et al., 1982).

1.3.1. Petroleum Exploration

Oil exploration in the Barito Basin was commenced in 1930 by the Dutch oil companies, Nederlandsche Koloniale Petroleum Maatschappij (NKPM) and Bataafsche Petroleum Maatschappij (BPM). Exploration drilling in the southern Barito Basin began in 1937 with the drilling of the Kahayangan #1, #2, #3, and #4, and Kuripan #1 wells. All five wells were plugged and abandoned as dry holes. In the same year, the first oil discovery in the northern Barito Basin occurred in the Tanjung #1 well, followed later by development drilling. To date, over 20 oil wells have penetrated the Tertiary successions in the area and along the northern margin of the Barito Basin, west of the Meratus Range, four oil fields have been identified: Tanjung, Kambitin, South Warukin and East Tapian. A cumulative production of over 114 million barrels of crude oil and over
141 thousand MMCF of gas had been reported prior to August 1985 (Kusuma and Nafi, 1986). In the offshore area of southern Kalimantan, Bishop (1980) reported that of the three oil fields one has produced nearly 100 million barrels of oil and 1.8 MMCF methane per day.

Recent geological investigations in the Asem Asem Basin, together with the known petroleum deposits in the Barito Basin, suggested that the Asem Asem Basin is also a prospective area for hydrocarbon accumulations. On the basis of these investigations, the Team Basin Study Group of PPTMGB Lemigas reinvestigated the area in 1983. No oil and gas is produced in the Asem Asem Basin at present.

Prospective reservoirs are in the Tanjung Formation and equivalent basal Tertiary sandstones, the Berai Formation (limestone) and the Warukin Formation (sandstone). Future integrated exploration efforts in the Asem Asem Basin are expected to locate accumulations of oil and gas.

1.3.2. Coal Exploration

Preliminary assessment of the Eocene coal measures was carried out by a Dutch engineer, J.A. Hooze, in 1886. This investigation was followed by the work of E.R.D. Gollner in 1921. The last sustained episode of data collection in the Asem Asem Basin was implemented by Sigit (1959, 1963) during his expedition to the Laut and Sebuku Islands. Some contributions were also made by Large (1973). Siregar (1975) produced an inventory of all coal seams in eastern Kalimantan.
Siregar (1975) reported that coal occurs over an area of about 700 km² in the Asem Asem Basin and that total coal reserves are approximately 1,430 million tonnes at a depth of less than 500 m. West of the Meratus Range, the Barito Basin contains more than 447 million tonnes of coal ranging in rank from typically brown to bituminous coals. The distribution of coal seams exposed in southeastern Kalimantan is shown in Fig 4.5 (Chapter 4).

In 1981, an agreement for the exploration, evaluation and development of coal resources within Block 6 in the Asem Asem Basin, southeastern Kalimantan, was signed between P.N. Tambang Batubara and P.T. Arutmin Indonesia. Geological summary reports during the exploration program were produced (i.e. Aero Service Division Western Geophysical Company of America, 1982; Cozens, 1982; Bennett, 1982; Johnet, 1983; Mucalo, 1984; Friederich, 1984; and Robins, 1985).

A drilling program over the coal prospect in the Block 6 area commenced in 1982, and by the end 1985 over 350 holes had been drilled to define the coal seam distribution and characteristics. In a more recent investigation, P.T Arutmin Indonesia has identified over 80 million tonnes of Eocene Senakin coal to a production depth of 60 m (P.T. Arutmin, 1986) in the Block 6 coal concession in the Sangsang area. Significant coal reserve potential also exists in other areas, notably Kintap (Fig. 4.5, Chapter 4), with indicated resources similar to the Senakin coals. The exploration program indicated that commercial development of coal on the Senakin Peninsula (Sangsang area) would be feasible. Initial mining began at Sangsang in September
1985 in areas with minimal overburden. Since that time 80,000 tonnes of coal has been mined and 65,000 tonnes were ready for shipment at Air Tawar Port Site. The Eocene coal is currently mined by P.T. Arutmin in Satui area, north of Kintap (B. Daulay, pers. comm., 1990).

1.4. AIMS OF THE STUDY

The major objective of this study is to investigate the petroleum source and reservoir rock potential, the coal potential and the deposition environments of Early Tertiary sequences in the Asem Asem and Barito Basins. The study is based on data and material collected from shallow boreholes drilled by P.T. Arutmin; oil well samples from Pertamina, Trend Energy Co., Phillip Petroleum and Union Carbide Co.; outcrop samples; and field data collected in 1987. The main aims of the study in this basin are listed below.

a. Elucidation of the basin setting and its development, including facies analysis, palaeogeography and provenance during the deposition of the Early Tertiary Tanjung Formation through the Plio-Pleistocene Dahor Formation.

b. Determination of the type, rank and distribution of organic matter in coals and source rocks, including local and regional coalification, and burial metamorphism.

c. Assess the relationships between coal macerals and dispersed organic matter (d.o.m) in associated sediments.

d. Assess detailed information on the lateral, vertical and temporal variation of organic maturation.
e. Determine the type of porosity and the diagenetic features which might affect permeability and porosity of the reservoir rocks.

f. Determine the primary and secondary clay minerals and their relationships to diagenesis (or low grade metamorphism).

g. Assess the relationship between organic metamorphism of coal and dispersed organic matter and the occurrences of oil and gas; and thus determine the sequence of maturation and hydrocarbon generation, and the source rock potential of strata in the basin.

1.5. METHODS AND DATA EVALUATION

Data and material for this study were supplied from subsurface drilling and include geological and geophysical logs, core and cuttings from shallow coal exploration wells and deeper oil wells. Additional samples were obtained from outcrops.

A detailed geological map of the area was constructed by compiling previous data and adding the results of field observations, airphoto and satellite imagery interpretations (SIR-B). Lineaments, faults, joints and cleats were analysed to assess the main tectonic compressive strain direction that influenced the area.

Detailed measured sections and well logs provide the data for facies analysis, palaeocurrents, provenance and the sedimentary framework of the basin. Organic petrological methods have been employed for the assessment of source rock
samples and coals. Vitrinite reflectance was used as an indicator of source rock maturation and for the determination of vertical and lateral patterns of rank variation. It was also used to estimate palaeotemperatures, the timing of coalification and the possibility of hydrocarbon generation. Organic matter contents of coals and source rocks were identified and point counted by using reflected white light and fluorescence mode microscopy.

Geochemical analyses, such as gas chromatography and mass spectrometry were required to identify source rocks and to determine biomarkers and the maturation level of hydrocarbons.

Full petrographic descriptions from thin sections were produced to assess reservoir rock quality, including composition, cement, porosity, permeability and diagenetic features. X-ray diffraction analyses were carried out to study the mineral composition of fine-grained rocks and mineral matter of coals. Some cements or matrices from sandstones were also examined to identify minerals and variations in the clay mineral suites by using the peak intensity of the diffractograms. Scanning electron microscopy (SEM) is considered to be a good method to aid the study of diagenetic features, such as authigenic minerals, cement, overgrowths and the nature of pore spaces.

All data compiled from the laboratory work were evaluated by use of statistical methods including cluster analysis and linear regression.
1.6. SUMMARY

The Asem Asem and Barito Basins are considered to be feasible areas for coal exploitation and they show good potential for hydrocarbon accumulations. This study will evaluate the coal, hydrocarbon source rock and reservoir rock potential of the basins and assess their relationship to basin development. An understanding of the palaeogeography of the basins should highlight the areas having the greatest potential for economic development.
CHAPTER TWO

GEOLOGICAL SETTING

2.1. INTRODUCTION

The geological evolution of Kalimantan can only be meaningfully discussed in terms of the complete tectonic framework. On the basis of early geological information, together with more recently produced geological maps, numerous papers have been written about the tectonic evolution of southeastern Kalimantan, in particular, the Cretaceous subduction complex in the Meratus Range (e.g. Katili, 1973, 1978; Rose and Hartono, 1978; Hamilton, 1979; Suhaeli et al., 1980; Situmorang, 1982; Lemigas, 1983; Pryomarsono, 1984; Hartono, 1984; and Katili and Asikin, 1985). However, the mechanisms and timing of events are still poorly understood. For example, it has not been conclusively proved whether the ophiolite complex in the Meratus Range resulted from rifting or collision. New geological evidence has recently been presented by Sikumbang (1986) and will be considered in this section.

2.2. TECTONIC FRAMEWORK AND GEOLOGICAL STRUCTURE

2.2.1. Tectonic Framework

To explain the tectonic evolution of Kalimantan, especially southeastern Kalimantan, it is necessary to
consider the interaction between Southeast Asia, India and Australia. It has currently been well documented that the present extremely active tectonics in the Indonesian Archipelago are controlled by the convergent interaction of three main lithosphere plates, i.e. the Pacific plate moving roughly westwards, the Indian-Australia plate moving northwards, and the Eurasian plate which is relatively stationary (Katili, 1973, 1978; and Hamilton, 1979).

The main pre-Tertiary cratonic core of Southeast Asia (Sundaland) was formed by the amalgamation of numerous microcontinental blocks during the Permo-Triassic (Stauffer, 1974, 1985; Sengor, 1985; Nur and Ben-Avraham, 1982; Barber, 1985; Pulunggono and Cameron, 1984; Audley-Charles, 1983, 1984; and Archbold, 1987). During the Late Mesozoic and Tertiary, other additional terranes or small continental fragments were joined to the Sundaland core in Sumatera, Kalimantan and eastern Indonesia.

Although the affinities and original positions of the Southeast Asian continental terranes are still being debated, many papers suggest that the terranes have separated from the Gondwana continental nucleus (e.g. McElhinny et al., 1974; Powell and Johnson, 1980; Audley-Charles, 1983; 1984; Stauffer, 1985; and Powell et al., 1984).

Sikumbang (1986) presented the most recent model for the pre-Tertiary tectonic development of southeastern Kalimantan (Fig. 2.1). The model indicates that tectonic activity commenced in the late Early Cretaceous when the Tethyan oceanic crust was subducted westwards and
northwestwards beneath the eastern margin of the Sunda continental plate resulting in the development of an island arc system. During Late Cretaceous (90 Ma), the island arc collided with the continental plate and a narrow slab of oceanic crust was obducted. Sikumbang (1986) believed that the collision developed due to a period of spreading in the Wharton Basin (Falvey, 1972; and Johnson et al., 1976). Paleocene regional uplift in the collision zone was followed by the commencement of volcanic and magmatic activities. At the end of magma activity, probably in the Late Paleocene or Early Eocene, rifting occurred on the southeastern margin of the Sunda continent and the region drifted east and southeastwards (Sikumbang, 1986). At the same time, the Tertiary basins in southeastern Kalimantan were formed. Rose and Hartono (1978) proved that the Kutei Basin was connected to the Melawi-Ketungau area during the Paleogene. The rifting stage was also responsible for the formation of Meratus graben (Barito and Asem Asem Basins) and the Makassar Strait underwent extension and subsidence from the early Middle Eocene (or possibly earlier) until the Early Miocene (Situmorang, 1982).

In the late Middle Miocene (10 Ma) most of western Indonesia appears to have consolidated into its present form, while the eastern part of Indonesia was undergoing rapid evolution as a result of the convergence of the Australia-New Guinea and Southeast Asian continental plates. Late Miocene orogeny activity began to separate the southern Kutei Basin from the Barito and Asem Asem Basins. The orogenic climax, probably in the Late Pliocene, resulted in
regional uplift of Meratus Range and Kuching High. The obduction zone in east Sulawesi and Sabah, combined with the major transcurrent fault movements in eastern Indonesia, was probably responsible for the formation of the present Meratus Range.

2.2.2. Geological Structure

The major structural elements of Kalimantan (Fig. 1.2) consist of the Schwaner Block in the west, the Meratus and Laut Highs in the east, and the Paternoster High, Mangkalihat Ridge, Kuching and Semporna Highs in the north.

The Schwaner Block and Kuching High are composed of pre-Tertiary igneous, metamorphic and sedimentary rocks. The blocks have been stable throughout the Tertiary, being emergent since Late Cretaceous, and they acted as important sources of Early Paleogene and Neogene clastic sediments to the Melawi, Ketungau, Barito, Asem Asem and Kutei Basins.

The main structural elements in southeastern Kalimantan are faults, folds and lineaments (Fig. 2.2). Most faults consist of northeast-trending thrust faults that are sub-parallel to the general trend of fold axes. Other thrust faults are present in the Tertiary successions in the Tanjung area, Barito Basin. The latter faults have been clearly identified in the seismic section reported by Kusuma and Nafi (1986).

Normal and block faults occur mainly in pre-Tertiary rocks and only a few are present in the Tertiary successions. These faults have either northeasterly or
southeasterly trends. Lineaments have been identified mainly from airphoto and SIR-B interpretation. They are most prominent in carbonate rocks (Berai Formation) in the east Meratus Range, although a few are present in the pre-Tertiary rocks on the Senakin Peninsula and Pulau Laut (Laut Island). These karst sequences contain fractures, minor faults and bedding traces.

A rose diagram of fault orientations (Fig. 2.3) shows that faults in southeastern Kalimantan have a mean trend of about 035°, while lineaments are oriented at approximately 028°. This indicates the close tectonic relationship between the faults and lineaments. Most faults are thought to have formed during the Late Cretaceous to Late Paleocene, or during phases of Neogene arc-continent collision (Sikumbang, 1986).

Fold structures are also prominent in southeastern Kalimantan. In general, the pre-Tertiary rocks have been strongly folded to form asymmetrical anticlines and synclines which have steeper east-southeastern flanks. The general trend of fold axes is approximately northeastwards, although numerous variations in trend exist due to differential responses to compressional forces during folding.

The trends of folds in the Tertiary sequences are essentially parallel to the eastern coastline and the Meratus Range, i.e north-northeast in the northern part of the basin and east-northeast in the southeastern area. The folds are generally open with the fold limbs being inclined at low to moderate angles. A few folds are tighter and rare
folds are overturned.

Two phases of folding are proposed to account for the structures in this area. The first corresponds to the phase of thrust faulting in the Late Cretaceous or Paleocene while the second was formed during or after the Meratus orogenic uplift, i.e. Late Neogene.

2.3. STRATIGRAPHY

2.3.1. Pre-Tertiary

The Tertiary Asem Asem, Barito and Kutei Basins are underlain by pre-Tertiary basement rocks consisting of an ophiolite complex and metamorphic, volcanic and sedimentary rocks. Detailed field investigations were carried out on the Tertiary sequences by Koolhoven (1935), Supriatna et al. (1980, 1983), Sikumbang and Heryanto (1981), Rustandi et al. (1984), Nila and Rustandi (1984), Umar et al. (1984) and Sikumbang (1986) and resulted in the production of a number of geological maps.

The ophiolite complex (Fig. 2.4) consists typically of dunite, harzburgite, lherzolite, serpentinite, gabbro, dolerite and microdiorite (Sikumbang, 1986). Metamorphic rocks comprise quartz-muscovite schist, metaquartzite, biotite-epidote schist, hornblende-epidote schist and amphibolite (Supriatna et al., 1983; Rustandi et al., 1984; Sikumbang and Heryanto, 1981; and Sikumbang, 1986).

The pre-Tertiary volcanic suite consists of volcanic
breccia, tuff and basalt lava, together with volcaniclastic mudstone and sandstone. The sedimentary successions are typically turbidite sequences and carbonate rocks; the former are comprised of conglomerate, pebbly sandstone, sandstone, siltstone and radiolarian chert. The carbonate rocks consist of Orbitolina limestone, crystalline limestone, bioclastic micrite and calcarenite. The ages of the pre-Tertiary rocks were determined by Sikumbang (1986) to range from Early Cretaceous (Berriasian - early Alban) to Early Paleocene.

Apart from ultramafic, volcanic, metamorphic and sedimentary rocks, plutonic rocks including diorite, granodiorite and granite also occur in southeastern Kalimantan. The age of these intrusions, based on radiometric dating, is early Late Cretaceous (95.3 Ma; Sikumbang, 1986).

2.3.2. Tertiary

Tertiary rock units have a widespread distribution throughout southeastern Kalimantan (Figs 2.5 and 2.6). Many previous workers described and subdivided the Tertiary rock units (e.g. Pelton, 1974; Samuel and Muchsin, 1975; Rose and Hartono, 1978; Sirerag and Sunaryo, 1980; Sikumbang and Heryanto, 1981; Marks et al., 1982; Bennett, 1982; Umar et al., 1982; Large, 1973; Lemigas, 1983; Pangestu, 1983; Supriatna et al., 1983; Friedrich, 1984; Johnet, 1983; Mucalo, 1984; Rustandi et al., 1984; Robins, 1985; P.T. Arutmin, 1985; and Kusuma and Nafi, 1986).
The oldest rock unit in the Tertiary sequence is the Eocene Tanjung Formation in the Asem Asem and Barito Basins. The most common lithologies above the basal conglomerate in this formation are quartz-lithic sandstone, sandy claystone, siltstone, mudstone and shale, with bituminous rank coal seams. Marl and limestone are locally present. A detailed description of this unit is given in Chapter 3.

The overlying rock units constitute the Oligo-Miocene succession, comprising predominantly carbonate facies plus marl, claystone and sandstone (Berai, Pamaluan, Montalat, Tuyu and Bebulu Formations). The Berai Formation is prominently exposed in the Barito and Asem Asem Basins and partly exposed in the Kutei Basin. Pelton (1974) noted that the lower Berai Formation was built up of barrier reef facies, while the upper part consists of lagoon and patch reef facies. The entire sequence was deposited in an open reef shoal environment (Lemigas, 1983).

The Middle to Late Miocene units conformably rest on the Berai, Pamaluan, Montalat and Bebulu Formations. The units include the Warukin Formation in Asem Asem Basin, and the Pulubalang and Balikpapan Formations in Kutei Basin.

The Warukin Formation consists of alternating successions of quartz sandstone and claystone, thin bedded shale and limestone, and coal seams which were deposited in a deltaic environment. The coal seams are up to approximately 40 m thick in the Sarongga area (Johnet, 1983) whereas in other places the coal seams are only 10 cm to 5 m thick. Total thickness of the Warukin Formation is 2600 m as indicated in the Brk-1 and Mrtp-IX wells.
2.3.3. **Late Tertiary - Quaternary**

Rock units of Late Tertiary to Quaternary age were unconformably deposited on the Warukin and Balikpapan Formations. They include the Dahor and Martapura Formations in both the Barito and Asem Asem Basins, and the Kampung Baru Formation in the Kutei Basin. The lithology of all these formations consists predominantly of sandstone, mudstone, claystone, gravel, sand, marl and locally brown coal or lignite. The formations were deposited in fluviatile to neritic environments.

2.4. **SUMMARY**

The Tertiary Asem Asem and Barito Basins in southeastern Kalimantan are underlain by rocks belonging to an ophiolite complex, plus other associated metamorphic, plutonic, volcanic and sedimentary rocks.

In the Late Paleocene or Early Eocene, the southeastern margin of the Sunda continent rifted and drifted east and southeastwards. This rifting stage led to subsidence in southeastern Kalimantan and the creation of the Tertiary sedimentary basins.

Prominent structural features including folds, thrusts and normal faults developed during the Late Cretaceous to Paleocene and the Late Tertiary. The Meratus Orogenic event has been responsible for the formation of most geological structures in the Tertiary sequences.
CHAPTER THREE

SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENTS

3.1. INTRODUCTION

This section discusses the sedimentary features and outlines the cyclic sedimentation patterns within the Eocene to late Middle Miocene sequences (Tanjung, Berai and Warukin Formations) in the southeastern Kalimantan basins. This study is based mainly on examination of core samples from 160 shallow drill holes, and cuttings and side wall cores from 12 deep wells. Continuous lithological successions are poorly exposed, although six measured sections through the Eocene Tanjung Formation were available for study.

The Eocene sequence represents a transgressive depositional phase with the peak of the transgression in the Oligocene to Early Miocene being recorded by the deposition of a widespread limestone overlain by marl. Deposition of the Middle Miocene Warukin Formation took place during the subsequent regression.

3.2. FACIES ANALYSIS

For this project, facies analysis encompasses mainly the study, description and interpretation of the sedimentary structures, textures and lithologic associations in the few available outcrop and well sections. The techniques for
recording, and the terminology used for describing, the sedimentological features are based on appropriate figures and tables from Conybeare and Crook (1968), Pettijohn and Potter (1964), Reading (1978), Walker (1981, 1984), Miall (1984a,b) and Anderton (1985). The most common sedimentary structures recorded in each rock unit are given in Table 3.1.

3.2.1. Tanjung Formation

The Tanjung Formation is widely distributed in the Senakin Peninsula, Pulau Laut (Laut Island) and on the eastern and western flanks of the Meratus Range. A maximum thickness of 2250 m was recorded at the Pararawen Anticline, in the northern Barito Basin (Siregar and Sunaryo, 1980). In the investigated area, a maximum thickness of 802.5 m was penetrated in MYA-1 (Fig. 3.5) in the Barito Basin. In the Senakin Peninsula and Pulau Laut areas shallow wells drilled by P.T. Arutmin penetrated up to 200 m of the formation.

Five main lithofacies have been recognized from the outcrops, cores, cuttings and geophysical log profiles. They are conglomeratic sandstone, sandstone, mudstone-shale-claystone-siltstone, coal and limestone-marl. Vertical and lateral lithological variations within the formation are shown in Figs 3.1 to 3.5.

Lower Sequence

The lower sequence of the Tanjung Formation is defined
as the succession of lithofacies between the pre-Tertiary basement rocks and the top of the lower coal seam beds. The entire thickness of the lower sequence varies between 5 m and 90 m in the Laut Island, Tanjung Dewa and Senakin Peninsula areas.

In general, the lower sequence is divided into three main lithofacies, i.e. lower sandstone, mudstone and lower coal facies. The typical vertical section given in Fig. 3.1 shows a sequence that can be classified using the lithofacies code scheme described by Miall (1978, 1984b). The lower sequence in the lower Tanjung Formation includes lithofacies codes comprising Gm, Gm/Gt, Sp, Se, Sr, Sl, Sh, Fsc, Fr, Fm and C.

**Lower Sandstone Facies**

The lower sandstone facies comprises two major cycles of sandstone beds. The first is the lowermost cycle having a thickness ranging from 2 m to 60 m. It unconformably overlies the pre-Tertiary basement rocks as can be seen in SP-1 (Fig. 3.1), several shallow drilling (Figs 3.2-3.3) and deep wells MRTP-1X and MYA-1 (Fig. 3.5). The beds comprise medium- to coarse-grained sandstone and conglomeratic sandstone with lenses of conglomerate at the base. Siltstone and claystone are present as very thin intercalations within the sandstone beds, but they are very minor.

Sedimentary structures consist predominantly of massive bedding and medium scale cross-bedding. The succession
appears to fine upwards, with flat parallel lamination and ripple marks being the dominant structures in the upper portion.

On the basis of lithological features and textures, including grain size, sedimentary structures and bedding characteristics, the lower sandstone Facies can be equated with the lithofacies codes Gm, Gm/Gt, Sp, Se, Sr, Sh and Fsc of Miall (1984b). The lithofacies Gm, Gm/Gt are common in the lowermost beds. These are succeeded by the lithofacies Sp, Se and Sr followed by Sh and Fsc in the uppermost portion.

The facies probably represents channel lag and point bar deposits. The sequence of structures indicates that the sandstone facies accumulated under decreasing flow regime conditions, probably reflecting a response to filling and progressive abandonment of the alluvial channel.

The second cycle of sandstone deposits consist of fine-to medium-grained sandstone beds having a thickness ranging from about 1 m to 10 m. These sandstone beds are typically characterised by the lithofacies Sp and Se, which are commonly succeeded by Sr, Fl, Fr or Fm that usually occur as thin discrete beds. Sedimentary structures include massive bedding, small to medium scale cross-bedding and scours hollows filled with mudclasts. Parallel, wavy and ripple laminated beds are also present. Slump structures and contorted bedding are rare to sparse in the fine-grained sandstone beds.

The sandy facies of this cycles appears to represent lateral accretion in channels and probably splay sand sheets
deposited predominantly under lower flow regime conditions. Other finer grained lithofacies probably indicate overbank or waning flood vertical accretion deposits laid down under lower flow regime conditions.

**Mudstone Facies**

This facies consists predominantly of mudstone, shale and claystone with interbeds of siltstone and fine- to medium-grained sandstone. The mudstone, shale and claystone beds range in thickness from 1 m to 20 m. The siltstone and sandstone beds are 5 cm to 50 cm thick.

The lithofacies recognized in this succession are mostly equivalent to Fm, Fsc and Fr of Miall (1984b). Sr and Se are associated with siltstone and sandstone beds. The main sedimentary structures observed in this unit are massive beds, fine parallel lamination and rootlets. Burrows and bioturbated beds are less common. The mudstone facies probably represents overbank flood plain deposits laid down during waning flood conditions.

**Interrelationship between the Sandstone and Mudstone Facies**

The thickness ratio between the sandstone and mudstone facies in the lower sequence of the Tangung Formation is approximately 3:1. A high proportion coarse-grained clastic rocks was noted in the lowermost section while fine-grained clastics consisting of siltstone and claystone are less abundant. This suggests that the first cycle in the lower
sandstone facies probably represents bed-load channel-fill deposits which are similar to those described by Galloway and Hobday (1983). This facies shows the characteristic features of sandy sequences deposited in either low sinuosity or braided channel systems.

At the top of the lower sequence, mudstone, shale and claystone are the dominant lithologies, except in the SP-2 profile in Fig. 3.1. Overall, this upper section probably represents deposits of a mixed-load fluvial system where flood plain and backswamp environments were more prominent during deposition. Galloway and Hobday (1983) pointed out that in the mixed-load fluvial system, sandstone proportions can be high along main fluvial axes where channel-fill units are vertically stacked and amalgamated. In addition, channel-fill deposits are commonly flanked by crevasse splay and levee sandstone and siltstone. Abandoned channels are commonly filled with mudstone, claystone and siltstone containing common organic matter. According to Coleman and Prior (1982), mud and clay filled channels tend to isolate sand bodies in the overall meander belt system.

Lower Coal Facies

This facies is generally underlain by mudstone, shale and siltstone beds, with sandstone in some areas. These lithologies contain abundant plant material or organic matter with in situ rootlets being more prolific towards the floor of coal seams. The lithofacies C, Fr and Fl are most common in this unit.
The lower coal facies has been well documented in the Sangsang area, Senakin Peninsula, by P.T. Arutmin. The thickness of the coal seam ranges from 0.20 m to 6 m, but the general average thickness is 5.1 m. The seam is well developed in the Senakin Peninsula, Ata River and Kintap areas, but reduces in thickness to the northwest of Pulau Laut (Fig. 3.4), in the Tanjung Dewa area (TD profile, Fig. 3.1) and partly north of Sepapah. It extends continuously for 35 km along strike on the eastern flank of the Senakin Peninsula. In some places the seam has been split by the incursion of sandstone, siltstone and mudstone lenses.

Splitting may have occurred when the site of peat accumulation was inundated by water, with the hollow subsequently being filled with clastic sediment and finally recovered by the peat swamp. Fenn and Staub (1984) gave a detailed description of similar seam splitting in a major coal-bearing formation in the Appalachian region.

In contrast, coal seams in the southeast Barito Basin do not appear to be extensively distributed. They are only intersected in the MRTP-1X and MYA-1 wells (Fig. 3.5).

The lower coal facies is probably indicative of peat accumulation in swamps on a broad flood plain with some accumulations in abandoned channels.

**Upper Sequence**

The upper sequence in the Tanjung Formation is defined as the lithofacies occurring above the lower coal seams.
The entire thickness is about 125 m. Four main facies are recognized, consisting of the upper sandstone, mudstone, coal and limestone facies. The lithofacies codes (Miall, 1984b) commonly found in this sequence are Sp, Sr, Se, Fsc, Fl, Fr, Fm and C.

Upper Sandstone Facies

In the Senakin Peninsula area the upper sandstone facies has been penetrated by several shallow drill holes. The total thickness of this facies is approximately 40 m. This facies is defined to include the sandstone bodies occurring in the upper section of the lower coal. The upper sandstone facies consists two major cycles of sandstone units.

The first cycle constitutes a unit having a thickness ranging from 2 m to 10 m, which is generally composed of white to light grey fine- to medium-grained sandstone with siltstone and mudstone interbeds 0.1 m to 2 m thick. It is locally interbedded with volcanic rocks as noted in reports for P.T. Arutmin (1985). The thickness of individual sandstone bodies ranges from 0.1 m to 8 m. The lithofacies observed in this cycle comprise Sp, Sr, Se, Fl and Fr. Sedimentary structures include massive beds, erosion channels, cross-beds and cross-laminae, wavy and parallel laminations, ripple marks and mudclasts.

Fining upward sandstone layers are commonly found in this cycle. The sedimentary structures in the sandstone and siltstone indicate that this cycle represents point bar and
channel deposits.

The second cycle in the upper sandstone facies occurs in the middle and uppermost part of the upper sequence. The thickness is about 30 m. It consists of very fine- to medium-grained sandstone having beds ranging in thickness from 0.2 m to 5 m. The sandstone is also interbedded with 5 cm to 100 cm beds of siltstone and mudstone. In this cycle lithofacies equivalent to Sp, Sr, Se and Sl occur in the sandstone beds and Fl, Fsc and Fr are common in the siltstone and mudstone.

Sedimentary structures comprise massive beds, planar and trough cross-beds, cross-laminae, scour-and-fill structures, wavy and parallel lamination, ripple marks and mudclasts. Burrows and bioturbated beds are typical and abundant structures in the siltstone beds. Contorted bedding and slump structures are only rare to sparse in some siltstone and fine-grained sandstone beds in core samples. Fine stringers and fragments of coal are usually associated with the siltstone and mudstone beds.

The erosional nature of the basal contact of the sandstone beds is conspicuous and is also indicated by the presence of mudclasts in the lower part of sandstone bodies that probably represent channel-floor lag deposits produced by bank undercutting. The abundance of mudclasts indicates that slack water deposition recurred frequently either within the channel or in channel margin positions (Rust, 1984).

The siltstone and mudstone beds may have formed in an overbank environment as vertical accretion deposits laid
down from overbank flood waters. Burrows and bioturbated beds, which are particularly abundant in the fine-grained clastic rocks such as siltstone and mudstone, indicate that brackish water probably invaded the abandoned distributary channels.

Mudstone Facies

This facies comprises mudstone, shale and claystone with subordinate fine-grained sandstone, siltstone and marl as thin intercalated beds (2-10 cm thick). The mudstone facies is vertically more prominent in the southern part of the Asem Asem Basin (A-1 and A-2 wells) and in the southeastern Barito Basin (MRTP-1X, MYA-1 and SMD-1 wells). The entire thickness of this facies is about 50 m. It is interbedded with siltstone, shale, marl, limestone and a small amount of sandstone. Lithofacies Pr, Fm, Fsc and Fl are common in this unit. Lithofacies Sl is present but it is less common.

Sedimentary structures possessed by this mudstone facies constitute massive beds, very thin parallel laminae with small ripple marks, rootlets and ferro-carbonate (ankerite) nodules. Burrow and bioturbated beds are locally common.

The presence of ferro-carbonate (ankerite) nodules in the mudstone and siltstone probably represent early diagenetic precipitation soon after burial.
Interrelationship between the Sandstone and Mudstone Facies

Compared with the lower sequence, the ratio of sandstone to mudstone in the upper sequence is much lower, i.e. approximately 2:3. In general, the thickness of the sandstone facies decreases southwards in the Asem Asem Basin and southeastwards in the Barito Basin.

Some sandstone beds show fining upwards, although coarsening upwards sequences are also present in a few sections. The geometry and compositional attributes of the entire upper sequence indicate that the sandstone facies cycles probably constitute mixed-load and suspended-load channel systems as described by Galloway and Hobday (1983). Mixed-load channel systems are indicated by prominent sand bodies consisting of channel lag and point bar deposits with repetitive fining upward successions. In contrast, suspended-load channel systems show increasing amounts of mudstone assemblage at the top of each cycle. The distributary channel model is a typical and good example of the suspended-load channel system (Galloway and Hobday, 1983).

The lithologic succession suggests that this facies was possibly deposited in interdistributary areas on a fluvial-dominated delta plain. However, minor marine incursions may have interrupted floodplain deposition and produced the thin carbonate beds.
Upper Coal Facies

The upper coal facies is not significant economically in terms of thickness. It ranges from 0.1 m to 2.0 m thick. Fifteen main coal layers have been noted in the Senakin Peninsula area but most seams do not appear to be laterally continuous. Partings and dirt bands are prominent within each seam.

Based on the discontinuity of the coal seams and the associated sedimentary sequences above and below the coal, the facies was probably deposited in interdistributary tracts within the lower delta plain.

Limestone Facies

This facies forms the uppermost unit within the Tanjung Formation. It is composed of fossiliferous limestone, marl, mudstone and calcareous sandstone. The thickness ranges from 5 m to 25 m.

The limestone contains abundant foraminifers described by Supriatna et al. (1983), Rustandi et al. (1984) and Lemigas (1983). They include Discocyclina sp., Nummulites variolarius, N. pangaronensis, N. fichteli, N. sp., Alveolina sp., Lepidocyclina sp., Operculina complenata, Pellistipira sp., Amphistigina sp., Biplanespira sp., Ostracoda and Bryozoa. The facies was deposited in a shallow marine environment during a transgressive episode.
3.2.2. Berai Formation

The lithology of the Berai Formation is dominated by a thick carbonate facies comprising typically light grey to cream massive fossiliferous limestone in the lower part, succeeded by marl, claystone and siltstone.

A detailed investigation by Pelton (1974) indicated that the lower Berai Formation is composed of a barrier reef facies, while the upper part consists of persistent lagoon and patch reef facies. Total thickness of the formation is 1200 m (as intersected in MRTP-1X, BRK-1, SMD-1 and BKO-1 wells) and it was deposited in an open reef shoal marine environment (Bishop, 1980; and Lemigas, 1983).

Some foraminifers have been reported by Lemigas (1983) and Rustandi et al. (1984). They include Austratillina asmariensis, A. howchini, Nummulites pangaronensis, N. variolarius, N. fichteli, N sp., Lepidocyclina bornensis, L. spp., Cycloclypeous sp., Heterostegina depressa, H. sp., Pelastipira sp., Spiroclypeous sp., Nephrolepidina sp., Borelis pygmaeous, Rotalia sp., Quinqueloculina sp., Globigerina sp. and other shelly marine fauna.

3.2.3. Warukin Formation

This formation is restricted to the Senakin Peninsula, being widely distributed along the eastern and western flank of the Meratus Range. Maximum thickness of this unit in the Asem Asem Basin is approximately 1000 m. In general, the lithology of the Warukin Formation consists of alternating
sandstone, shale and claystone, with thin beds of limestone and marl, and a few coal seams. From cuttings, cores, geophysical logs and the few available outcrops the following three main facies could be recognized.

**Shale Assemblage Facies**

This facies assemblage is the dominant lithology occurring beneath the main coal seam, and it consists predominantly of shale, mudstone and claystone (Figs 3.6-3.8) having a total thickness ranging from 100 m to 600 m. These lithologies are interbedded with 5 cm to 50 cm thick beds of siltstone, limestone and marl in the lower section, and 0.1 to 4 m thick sandstone, siltstone and coal beds in the uppermost section. The thickness of the coal seam ranges from 0.1 m to 2 m. Lithofacies Fl, Fsc, Fm, Fr, C and Sl of Miall (1984b) are common in this unit. Lithofacies Se, Sh and Sr are only minor and occur within sandstone and siltstone beds.

Sedimentary structures in the facies include ripple marks, cross-stratification, parallel laminae and burrows. Several sandstone beds contain granules, although they are predominantly fine- to medium-grained. These features suggest that the shale assemblage facies represents suspended-load channel deposits as described by Galloway and Hobday (1983). Overall, the sequence of structures within this facies probably accumulated in a coastal plain-delta association.
Coal Facies

The best coal facies was intersected in the Sarongga area (Fig. 3.6) and in MRTP-1X well (Fig. 3.7). The thickness of the coal seam ranges from 1 m to 40 m. In the southern Asem Asem Basin, this facies does not appear to be well developed (see A-1, and A-2 wells, Fig. 3.8). Some roots and woody tree trunks are well preserved in outcrops near Butani in the Kintap area. This indicates that the Miocene coals are autochthonous, which is in accordance with the vast majority of economic coal deposits (Teichmuller and Teichmuller, 1968; and McCabe, 1984). The main Sarongga coal was probably deposited as a raised swamp since it is comparable to raised swamp deposits from the tide dominated delta of the Klang and Langat Rivers of Malaysia (Coleman et al., 1970) and raised swamps in the Rajang delta, Sarawak (Anderson, 1964).

Sandstone Facies

This facies is defined as the clastic succession overlying the main coal seam facies (Fig. 3.6). It comprises fine- to coarse-grained sandstone interbedded with siltstone, shale, mudstone and coal. Lithofacies Sp, St, Se and Ss of Mialli (1984b) are dominant in the sandstone beds. Lithofacies Sl, Fl, Fsc, Fr and C are abundant in the fine-grained clastic rocks and coal layers.

The main sedimentary structures in the sandstone include massive beds, cross-beds, scour-and-fill structures,
cross-lamination, parallel laminae and subordinate current ripples. Burrows and parallel laminae are more prominent in the associated siltstone and mudstone. The presence of cross-bedding and scour-and-fill structures in sandstone interbedded with siltstone suggests that deposition probably occurred in a distributary channel or distal bar. Coal stringers and plant debris are also commonly found in the siltstone and mudstone. They are typically abundant in delta plain sequences and may be preserved in distributary channel sediments.

This facies represents a series of coarsening upward sequences which conform with the general characteristics of distributary mouth-bar deposits (e.g. Reading, 1978; Reineck and Singh, 1980; Coleman and Prior, 1982; Galloway and Hobday, 1983; and Miall, 1984a,b).

3.3. PALAEOCURRENT ANALYSIS

Without detailed dipmeter logs, most palaeocurrent studies are based on cross-bedding preserved in outcrops of sandstone and siltstone. This limited palaeocurrent analysis in the present study to the few available outcrops of the Tanjung Formation. Due to the poorly exposed nature of the outcrops, cross-beds could only be measured at 19 locations from a narrow outcrop belt in the Senakin Peninsula area, and a few localities in the Pulau Laut and mainland areas.

Methods for collecting data for palaeocurrent analysis were outlined by Potter and Pettijohn (1977). Azimuths and
dips of cross-beds and the regional structure were measured from the Senakin, Tanjung Dewa, Pulau Laut and Kintap areas (Fig. 3.9).

All data were manually corrected for tectonic tilt of the region, using an equal angle stereo net (Wulff-net) and a lower hemisphere projection as modified by Jones (1980). Directional features were analysed vectorially and the simplified equations for a group of individual readings are also adopted from Jones (1970). The results are given in Appendix 3.1 and current rose diagrams are represented on a map (Fig. 3.9).

The current rose diagrams for each location show bimodal and unimodal palaeocurrent patterns in the Senakin area, while in the Tanjung Dewa, Pulau Laut and Kintap areas the patterns are entirely unimodal. The vector mean palaeocurrent directions are south, southeast and southwest. Nevertheless the grand mean palaeocurrent trend is obviously towards south (172°S).

Sandstone grain size and the coarse- to fine-grained clastic ratio (sandstone : shale + mudstone + claystone) is also indicated in Fig. 3.9. The largest grain size occurs in the northern Senakin Peninsula, and the size gradually decreases towards both flanks of the Meratus Range. The pattern follows the general orientation of the basin (i.e. northeast to southwest) and suggests that the river system probably followed the trend of the palaeo-rift valleys forming the basins.

The flow depth for some cross-strata sets in the Tanjung Formation was determined using the formulae of Allen
(1970) and Collinson and Thompson (1982). Allen (1970) provided the empirical formula $H=0.086d^{1.19}$, where $H$ is the dune amplitude and $d$ is the flow depth. Collinson and Thompson (1982) suggested ratios of 1:6 and 1:2 for dune height to flow depth. The flow velocity for a given depth of flow was calculated using Froude numbers between 0.3 and 0.8, since Leeder (1982) suggested that dunes composed of medium-grained sand formed in this Froude number range.

The results of calculations of the flow depth and flow velocity, using the preserved set thickness as a minimum estimate of the dune height, are given in Table 3.3. The average flow depth for the planar cross-strata sets is 1.56 m and the maximum depth is 2.22 m, with flow velocities ranging from 1.00 m/s to 3.60 m/s. The trough cross-strata sets have average and maximum flow depths ranging from 1.60 m to 2.34 m, and the flow velocities vary between 1.18 m/s and 3.86 m/s. Overall, the values of flow velocity in the Tanjung Formation suggest that the prevailing hydrodynamics are typical of fluvial environments, especially meandering river systems (Maizels, 1983).

Figure 3.10 shows the equivalent clastic ratio and sandstone grain size for the Warukin Formation. Although the pattern shows a slightly more north-south trend, the depositional pattern is similar to that of the underlying Tanjung Formation. Data from the A-1 and A-2 wells indicate that the clastic ratio becomes still smaller where fine-grained clastic cycles become more prominent in the southern Asem Asem Basin.
3.4 PETROGRAPHY AND ROCK CLASSIFICATION

Petrographic analysis of the Tanjung, Berai and Warukin Formations involved the detailed examination of 126 thin sections using transmitted light microscopy combined with point count analysis. The method of point counting follows Chayes (1949, 1955, 1956), Chayes and Fairbairn (1951), Bayly (1960) and Ireland (1971).

Of the total samples examined, 107 comprise fine- to very coarse-grained sandstone and the remainder consist of limestone. The framework grains of sandstone in the Tanjung and Warukin Formations are composed of variable amounts of quartz, feldspar, volcanic and metamorphic rock fragments (see Plates 5-6). Accessory minerals, such as muscovite, chlorite, tourmaline and opaque minerals are rare to sparse in all the clastic samples. Detailed results of the petrographic analyses are listed in Appendix 3.2.

3.4.1. Composition

A. Tanjung Formation

Quartz grains

Quartz is the most prominent detrital component in both the upper and lower sandstone in the formation (see Fig. 3.11 and Appendix 3.2). The quartz content of the samples ranges from 19% to 85% with a mean of 54.3% and a standard deviation of 16.34%. The average grain size ranges from 0.06 mm (4.0 phi) to 1.2 mm (-0.25 phi). A variety of the empirical quartz types of Folk (1980, p. 73) are present
in almost all samples. Approximately 75% of detrital quartz in the Tanjung Formation exhibits undulose extinction but extinction angles are generally less than three degrees. The quartz grains with undulose extinction occur as single, semicomposite and composite crystals. The individual grains contain rare to sparse vacuoles and microlite inclusions. The semicomposite and composite quartz grains comprise less than 15% of quartz in both upper and lower sandstone facies of the Tanjung Formation. Grains with vacuoles and low extinction angles probably represent reworked granite, vein quartz, metaquartzite or schist.

Simple grains of quartz with straight extinction are the second most abundant constituent in the sandstone. Unlike the quartz with undulose extinction, the grains with straight extinction contain a variable number of microlite inclusions but rare to absent vacuoles. Straight extinction is rare to absent in semicomposite and composite quartz grains. The general roundness (subangular to rounded) of the quartz grains indicates that they are presumably of a recycled sedimentary origin.

Feldspar

Feldspar constitutes a relatively minor mineral ranging in abundance from 0.4% to 5.2% with an average of 0.7%. Both potassium and plagioclase feldspar are present. The K-feldspar is predominant in all samples, with orthoclase being more frequent than microcline in all samples. The K-feldspar grains are usually angular to subrounded. Some
orthoclase grains show signs of alteration to sericite or clay.

Plagioclase is less abundant than K-feldspar, and 90% of all samples are barren of this mineral. It is predominantly subangular to subrounded and sodic in composition. All grains exhibit a conspicuous peripheral development of clay minerals due to diagenetic alteration. Most feldspar grains are probably first cycle constituents derived from volcanic, plutonic and metamorphic rocks.

**Rock Fragments**

Volcanic, metamorphic and sedimentary rock fragments are the important lithic fragments found in all sandstone samples in this formation. They vary in abundance from 0.6% up to 22%. On average rock fragments are more abundant in the lower sandstone facies than in the upper sandstone facies.

Volcanic rock fragments are generally found throughout all the thin sections that were examined. They range in abundance from 0.2% to 8%, with a mean value of 2.0%. The fragments are commonly subangular in shape, consisting mainly of devitrified andesite, basalt and tuff. However, the volcanic rock fragments are very rarely found as fresh grains. They were probably derived from an intermediate to basic volcanic terrain that may be part of a subduction complex.

The most common metamorphic rock fragments are metaquartzite and schist ranging in abundance from 0.4% to 10%, with a mean of 3.0%. Both metaquartzite and schist
grains are usually subrounded to well rounded and presumably represent primary detritus from a metamorphic basement terrain.

Sedimentary rock fragments are composed of shale, slate, fine-grained quartz sandstone and chert. Chert fragments form up to 5% of several samples, particularly in the lower sandstone. The chert grains are composed characteristically of radiolarian fossils.

Accessory Minerals

These constituents comprise up to 1% of each thin section. Micas (both muscovite and biotite) are the most prominent accessory minerals in many samples. Other accessory minerals include chlorite, epidote and tourmaline, but they are only rare or trace components.

The opaque minerals comprise mainly pyrite, magnetite and hematite which form less than 1% of each sample. Finely dispersed organic matter occurs as black to reddish brown detritus in thin sections. Some organic matter is concentrated on stylolites and also occurs as coal fragments and thin coal layers. The abundance of organic matter ranges from less than 1% to 20% of the samples. A detailed account of the occurrence of organic matter and its significance for petroleum generation is covered in Chapters 4 and 5.
B. Berai Formation

Framework Grains

Nine thin sections from the Berai Formation were examined and are listed in Appendix 3.2. Most of the samples analysed contain framework grains ranging in abundance from 16% to 53%, with an average 36%. The framework grains consist predominantly of detrital fossil fragments. A few detrital quartz grains (less than 8%) were found only in sample HP797.

Detrital fossils consist of common large and planktonic foraminifers, bryozoans, corals and molluscs. Echinoid spines, ostracods and algae are also present but they are less common. The grain sizes vary from 0.1 mm to 16 mm. Many grains are floating or disconnected in the matrix, but some samples show an interconnected grain supported fabric. Some skeletal fossils have been replaced by spar and micrite calcite crystals.

Matrix/cement

Micritic calcite is the most prominent cement found in samples from the Berai Formation. This cement ranges in abundance from 20% to 84%. Microspar calcite is the second most abundant cement ranging from 8% to 18%.

Siderite and dolomite cements are rare to sparse throughout the samples examined. Other cements include clays (less than 8%) found in sample HP628.
C. Warukin Formation

Quartz grains

Like the Tanjung Formation, this formation is also dominated by quartz grains. The quartz content ranges from 33% to 74%, with a mean of 48% and a standard deviation of 18.7%.

A number of quartz types are also present in the thin sections. More than 80% of the quartz grains have undulose extinction and most of these grains occur as single crystals. The extinction angle is generally less than 3°. Very few grains contain vacuoles, but microlite inclusions are occasionally present. Grains with straight extinction are present only in small amounts. Semicomposite and composite quartz grains comprise less than 10% of the total detrital quartz. The grains vary in shape from subangular to rounded and contain rare vacuoles and microlite inclusions. All quartz types are interpreted to be derived from granite, vein quartz, metaquartzite or schist terrains and many represent a recycled sedimentary origin.

Feldspar

The Warukin Formation contains 0% to 10% detrital feldspar, with an average abundance of 3%. Orthoclase and microcline are the only feldspar constituents in the samples; plagioclase being absent from all samples. However, possibly plagioclase minerals were present but have been altered during early burial diagenesis. The feldspar
crystals probably represent primary detritus from a volcanic and plutonic terrain.

**Rock Fragments**

The most abundant rock fragments are volcanic grains, while metamorphic rock fragments are the second most abundant type. The volcanic rock fragments are composed of chloritic devitrified andesite, basalt and tuffaceous material. They have generally been weathered and altered. The amount of volcanic rock grains ranges from 1% to up to 8%, with a mean value of 3%. The grains are mostly subrounded to rounded.

The metamorphic rock fragments range in abundance from less than 1% to 6% of all samples examined. Metaquartzite grains are the dominant constituent, whereas fragments of schist are present but they do not form a significant amount in the samples. Most metamorphic rock fragments are subangular to subrounded in shape. Sedimentary rock fragments include detrital siltstone, fine-grained quartz sandstone, mudstone and limestone. These components form only 0% to 2% of the framework grains and are commonly subrounded in shape. As in the Tanjung Formation, the rock fragments are assumed to be derived from a first cycle intermediate to basic volcanic terrain or subduction complex and a metamorphic basement terrain.

**Accessory Minerals**

Accessory minerals comprise mainly tourmaline, mica and opaque minerals (0-1% of the framework grains). Chlorite is
present but it mainly occurs as a matrix and cement. The mica grains are nearly always recognizable as 0.01-0.05 mm flakes and most are weathered and altered. Opaque minerals include pyrite and hematite which, although rare to sparse, can be found throughout the samples.

Dispersed organic matter is found in almost all samples and includes coal stringers and concentrations along stylolites. The abundance of organic matter ranges from less than 1% up to 14%.

3.4.2. Rock Classification

Classification of the 117 sandstone samples in this study is based on the ternary system of Folk (1980) which is independent of textural shapes. The classification is comparatively specific and it employs a well accepted terminology. The system is based on the proportion of the detrital components: monocrystalline quartz plus metaquarzite or polycrystalline quartz (Q-pole); all single potassium and plagioclase feldspar grains together with granite and gneiss rock fragments (F-pole); and all supracrustal rock fragments such as chert, limestone, sandstone, shale, slate, schist and volcanics (R-pole). The Q, F and R components are recalculated to 100 percent and drawn by an IBM P-C using a turbo-basic program made by Susilohadi (pers. comm., 1990) results of the QFR ternary diagrams are provided in Figs 3.11 and 3.14.

Sandstone from the Tanjung Formation is made up of three main classes, i.e. quartzarenite, sublitharenite and
litharenite. Quartzarenite and sublitharenite are the most abundant sandstone types in the formation (Fig. 3.11), while litharenite is a minor component. One sample just falls into feldspathic litharenite class. The standard deviations for all the samples plotted from the Tanjung Formation are 13.53% (Q), 1.78% (F) and 13.17% (R) respectively. QFR ternary diagrams reveal that the upper sandstone facies contains more abundant quartzarenite than the lower sandstone facies (Figs 3.12 and 3.13). The standard deviations of the total samples plotted in the diagrams are 6.72% (Q), 1.78% (F) and 5.79% (R) respectively. Most of the sandstone is mature to submature.

For the Warukin Formation, the QFR ternary diagram (Fig. 3.14) shows that the samples consist of mature quartzarenite, sublitharenite, feldspathic litharenite and subarkose. Approximately 65% of the sandstone consists of quartzarenite and sublitharenite and the remainder is feldspathic litharenite and very minor subarkose. The standard deviations for the samples plotted in the diagram are 8.86% (Q), 4.32% (F) and 5.60% (R) respectively.

The carbonate rocks of the Berai Formation are classified on the basis of depositional texture following Dunham (1962). The samples from the Berai Formation consist mainly of wackestone, packstone and grainstone. One sample is classed as mudstone since it contains less than 10% framework grains. The grain-supported fabrics are composed predominantly of fossil fragments, while the matrix is mainly micrite, microspar carbonate and clay.
3.4.3. Matrix and Cement

Matrix

The matrix includes all material finer than 32 microns (5 phi), including fine detrital quartz and feldspar grains, opaque and accessory minerals, particularly mica flakes, and detrital clays.

The proportion of matrix in the Tanjung Formation is variable, with the lower and upper sandstones having a matrix content of 1% to 16%, whilst sandstone in the Warukin Formation contains more than 15% matrix.

Scanning electron microscopy and X-ray diffraction analyses have been conducted to examined the clay minerals which consist predominantly of kaolinite, illite, mixed-layer clay minerals and chlorite (see Chapter 6).

Cement

Cements comprises mainly carbonate, silica, clay, limonite and hematite which are found in the Tanjung, Berai and Warukin Formations. Carbonate cement content ranges from 0% to 22%, comprising calcite, siderite and dolomite. Calcite is the dominant cement in all formations and usually occurs as micrite or microspar, with rare spar cement. Both early and late diagenetic calcite occurs in all three formations. Siderite is the second most abundant carbonate cement in the Tanjung Formation, whereas dolomite occurs only in trace amounts. In contrast late diagenetic siderite and dolomite form minor or trace cements in the Berai and Warukin Formations.
Silica cement is the second most abundant cement in the Tanjung Formation, and includes chalcedony, chert and authigenic quartz occurring as overgrowths. It ranges in abundance from 0% to 6%, with an average of 1% for all the samples. The amount of silica cement decreases in the upper sandstone of the Tanjung Formation (less than 1% on average) and is rare from most samples of the Warukin Formation.

Limonite and hematite cements are most abundant in the lower sandstone of the Tanjung Formation where they form up to 20% in several samples. However, only few samples in the upper sandstone contain this cement (maximum 3%) and the samples from the Warukin Formation contain only traces of limonite and hematite cements.

3.5. PROVENANCE

Provenance in sedimentary petrography was defined by Suttner (1974) and Basu (1985) as a function of source rock, relief, climate and transportation. Dickinson and Suczek (1979) and Dickinson (1985) established that quantitative detrital mineralogy from point count analysis could be used to determine sandstone provenance.

The results of quantitative analyses, from point counts of all thin sections that were examined in the studied area, can be used to determine the provenance of the Tertiary sequence using the method proposed by Dickinson and Suczek (1979) and Dickinson (1985). All main detrital constituents were recalculated to 100% based on the classification of grain types (Qm, Qp, P, K, Lv and Ls) proposed by Dickinson.
(1985; see Table 3.4). A summary of provenance types and key compositional aspects of derivative sands is given in Table 3.5.

Sandstone from the Tanjung and Warukin Formations (using the ternary diagram Qm-F-Lt; Figs 3.15 and 3.16) plots in the compositional fields for recycled orogen provenance suites, although few samples fall near the margin of the continental block provenance areas. However, the mean and standard deviation (13.53% (Qm), 1.78% (F) and 13.17% (Lt)) plots for all samples from the Tanjung Formation are within the recycled orogen provenance area. Similar results also indicate that sandstone from the Warukin Formation was derived from a recycled orogen, with no samples in the continental block provenance field.

The second test employs the three components Qp-Lv-Ls plotted as a ternary diagram for both the Tanjung and Warukin Formations (Fig. 3.17). The diagram shows that the samples are scattered throughout the diagram which means, according to the fields defined by Dickinson and Suczek (1979), that the source for the Tanjung Formation could have included a collision suture and fold-thrustbelt, a mixed orogen and subduction complex areas, whilst the Warukin Formation may have been derived from an arc orogen, subduction complex and a collision suture and fold-thrustbelt source. The standard deviations for end members in this ternary diagram are high, i.e. 29.60% (Qp), 34.76% (Lv) and 22.11% (Ls) respectively for the Tanjung Formation and 17.09% (Qp), 17.42% (Lv) and 13.54% (Ls) respectively for the Warukin Formation. Figure 3.17 shows
that most samples from both units are slightly enriched in chert. According to Dickinson and Suczek (1979) this is characteristic of some recycled orogenic suites.

Finally, the QFR ternary diagram (Figs 3.11 and 3.14) can also be applied to determine the provenance categories of Dickinson (1985). The results indicate that the sandstone in the Tanjung and Warukin Formations were derived from recycled orogenic sources and to lesser extent from continental block sources.

3.6. MATHEMATICAL ANALYSES OF PETROGRAPHIC DATA

Cluster analysis was preformed using a PC computer program devised by Dr B.G. Jones (pers. comm., 1990). The main data files and the results of the computer calculation are given in Appendix 3.3.

Cluster analysis is a method of multivariate classification which attempts to infer the structure within a data array by linking together those variables (R-mode) or objects (Q-mode) which are most strongly positively correlated (Harbaugh and Merriam, 1968; Davis, 1973; and Buttler, 1978). A perfect positive linear correlation, where the correlation coefficient \( r = 1.00 \), means that knowing one factor, the other factor is predictable with both factors increasing together. In contrast, \( r = -1.00 \) indicates a perfect negative correlation and \( r = 0.00 \) indicates no linear correlation. After calculating a full correlation coefficient matrix the relationship between the variables or objects can be simplified by progressively
combining the variables with the greatest positive correlation to produce a dendritic network or dendrogram (e.g. Figs 3.18 to 3.21).

3.6.1. R-Mode Cluster Analysis

In the R-mode cluster analysis, the data were examined using a Pearson Product-Moment correlation coefficient with 39 variables (lower sandstone, Tanjung Formation; Fig. 3.18A), 43 variables (upper sandstone, Tanjung Formation; Fig. 3.19B), 15 variables (Berai Formation; Fig. 3.20A) and 33 variables (Waruki Formation; Fig. 3.21B).

In the lower sandstone of the Tanjung Formation (Fig. 3.18A), the dendrogram for the R-mode cluster analysis can be divided into four groups (A, B, C and D). The groups are linked with low similarity coefficients ranging from -0.04 to 0.10. The four major cluster groups are subdivided into one to four subgroups, each having between subgroup similarity coefficients of between 0.09 and 0.31. The cluster dendrogram indicates that, within the major groups, clusters 2, 3 and 4 in group C and clusters 1 and 2 in group D are characterized by strong linkage among variables, whereas those variables in the other clusters show less significant linkage. For example, K-feldspar, volcanic rock fragments, plagioclase, fine quartz sandstone and siderite cluster together. With the exception of fine quartz sandstone and siderite, the feldspar and volcanic rock fragments generally have a close association indicating a similar origin.
In the upper sandstone of the Tanjung Formation (Fig. 3.19B) the cluster dendrograms are divided into A, B, C, D and E groups having similarity coefficients of between -0.007 and 0.03. Group A, consists of most of the carbonate constituents, such as micrite, microspar and limestone rock fragments, that cluster together with variables including colour, chlorite matrix, hematite and limonite cement. In group B, variables such as K-feldspar, fine quartz sandstone fragments, quartz overgrowths, silica cement, mudclasts and clay matrix are closely linked with each other. However, significant relationships are found between mudclasts and clay matrix, and between quartz overgrowths and silica cement. Variables such as packing, compaction, grain shape, tourmaline, quartz, plagioclase, fossils, organic matter and chlorite form a cluster in group C. The similarity coefficients range from 0.09 to 0.68. In this cluster, quartz grains show a strong relationship with grain shape, packing and compaction. This probably means that the grain shapes recorded are predominantly for quartz grains and most samples are closely packing and compact since quartz is the dominant framework constituent. Furthermore, a close linkage between grain size, porosity and pore size is represented in the group D cluster.

The R-mode cluster analysis for carbonate rocks in the Berai Formation is given in Fig. 3.20A. The dendrogram shows two major groups (A and B) that have similarity coefficients of between 0.06 and 0.11. In group A, a close relationship is found between micrite and microsparite at 0.66 similarity coefficient. This means that these
constituents are always obviously present together in similar proportions in the carbonate samples studied. The second group (B) represents grain size (maximum and average), clay and spar calcite cement which are strongly associated having high positive similarity coefficients of 0.87 to 0.98. As in the upper and lower sandstone of the Tanjung Formation, porosity and pore size are also strongly linked since porosity was visually determined from pores visible under the microscope.

The R-mode dendrogram for the Warukin Formation (Fig. 3.21B) is divided into three groups that have similarity coefficients ranging from 0.03 to 0.34. In group A, the greatest positive cluster occurs between carbonate components, such as limestone, micrite and microsparite, with similarity coefficients of 0.98 and 0.99. Other variables are found in group B (i.e. quartz, metaquartzite, siltstone rock fragments, silica cement, porosity and sorting). Thus, the quartz, metaquartzite and siltstone grains are probably the most essential components for determining sorting values, while silica cement and porosity are related to each other since the pore size partly depends on the amount of silica cement between the framework grains.

3.6.2. Q-Mode Cluster Analysis

Q-mode cluster analysis is especially useful for comparison between sedimentary facies and mineral assemblages (Harbaugh and Merriam, 1968). Samples which have similar mineralogical composition, grain size, texture,
structure and provenance tend to become clustered together. The results of the Q-mode analyses is presented as four dendrograms (see Figs 3.18B, 3.19A, 3.20B and 3.21A).

The first Q-mode cluster dendrogram (Fig. 3.18B) represents the analysis of the lower sandstone samples from the Tanjung Formation and shows three main cluster groups (A, B and C). The three groups have positive similarity coefficients of between 0.30 and 0.40. Group A consists of samples which are characterized by a slightly higher content of rock fragments and feldspar grains. Most samples in this group consist of sublitharenite, litharenite and feldspathic litharenite. The dendrogram for group B shows samples clustered with positive similarity coefficients ranging from 0.33 to 0.83. This cluster comprises only sublitharenite, which is considered to represent interdistributary channel and point bar deposits. Finally, group C is the largest group and samples have strong positive similarity coefficients of between 0.40 and 0.88. This group contains an assemblage of quartzarenite and sublitharenite samples which probably represent channel and point bar deposits.

The Q-mode cluster analysis for the upper sandstone of the Tanjung Formation is given in Fig. 3.19A. It comprises four groups (A, B, C and D) having positive similarity coefficients ranging between 0.01 and 0.09. Group A can be subdivided into two subgroups. Subgroup 1 contains samples that are mostly composed of very fine- to fine-grained sublitharenite with moderate sorting and subangular to subrounded grain shapes. Subgroup 2 consists of 10 samples having a close relationship characterized by high quartz
contents; they are mainly quartzarenite and sublitharenite. Most framework grains in the sandstone are very fine- to fine-grained, moderately to well sorted and subrounded. The sedimentary structures and textures of these samples suggest that subgroup 2 consists of interdistributary channel, bar or crevasse splay deposits.

Group B contains four subgroups related by positive similarity coefficients of between 0.28 and 0.58. Subgroup 1 consists of samples which are mainly sublitharenite with a slightly lower quartz grain percentage. Similarly subgroup 2 is composed of sublitharenite but the samples contain a higher percentage of quartz and significant porosity. Subgroup 3 comprises samples which are predominantly well sorted, fine-grained sublitharenite. Subgroup 4 is also composed mostly of sublitharenite. Overall, the sedimentary structures and textures associated with this strongly linked group of sandstone samples indicate a probable interdistributary mouth bar, channel and river bank depositional environment.

Group C is divided into three main subgroups linked by positive similarity coefficients ranging from 0.13 to 0.28. Subgroup 1 indicates that the samples are closely related based on their characteristic framework grains. It is composed entirely of coarse- to very coarse-grained sublitharenite with poor to moderate sorting and subrounded to rounded grains. In subgroup 2, the six samples have a close relationship at 0.28 similarity coefficient and they are composed of sublitharenite and litharenite. Subgroup 3 consists of three samples that are clustered with positive
similarity coefficients between 0.13 and 0.41. It comprises entirely medium-grained sublitharenite.

Finally, group D is divided into three subgroups. The first subgroup is characterized by a significant strong linkage of well sorted, subrounded, medium-grained quartzarenite samples. Subgroup 2 has samples linked with similarity coefficients between 0.25 to 0.66 and comprises medium-grained sublitharenite and quartzarenite. Seven samples are clustered in subgroup 3 having positive similarity coefficient of between 0.33 and 0.75. From the petrographic analysis subgroup 3 consists of an assemblage of medium- to coarse-grained sublitharenite and quartzarenite. The sandstone usually has good to excellent porosity, with subrounded to rounded grain shapes and is moderately to well sorted. The combination of petrology, sedimentary structures and textures suggests that the sandstone represents a channel or point bar deposit. It was probably derived from a recycled orogenic provenance area.

The result of Q-mode cluster analysis of the Berai Formation is provided in Fig. 3.20B. Two major groups (A and B) are linked by similarity coefficient between 0.36 and 0.54. Group A comprises three samples containing 16% to 53% of framework fossil fragments by volume. They generally consist of wackestone and packstone supported by a large amount of muddy micrite matrix with less abundant microspar cement. Group B consists of six samples characterized by strong positive similarity coefficients which range from 0.61 to 0.91. The group is composed of coarse-grained fossil fragments supported by muddy micrite, microspar and
spar calcite cements, i.e. they are mostly classified as grainstone.

Q-mode analysis of samples from the Warukin Formation (Fig. 3.21A) indicates subdivision into two groups (A and B) having similarity coefficients in the range from -0.08 to 0.11. Group A consists of samples which clustered in two subgroups linked with a low (-0.007) similarity coefficient. Subgroup 1 is composed predominantly of quartzarenite with several samples of sublitharenite. These samples are very fine- to fine-grained, poorly to moderately sorted and are generally composed of subrounded grains. The sandstone probably consists of distributary channel bars. Subgroup 2 comprises three samples of medium-grained sublitharenite having positive similarity coefficients in the range 0.04 and 0.22.

Group B has three well defined clusters of samples comprising medium- to coarse-grained sublitharenite. The similarity coefficients range from 0.11 to 0.49 and the rocks in this group were probably deposited as channels or point bars.

3.7. DISCUSSION

The Tanjung, Berai and Warukin Formations comprise the Eocene stratigraphic units that filled the Barito and Asem Asem Basins (Fig. 3.22). The oldest unit is the Eocene Tanjung Formation that unconformably overlies pre-Tertiary basement rocks. The formation accumulated in the mildly downfaulted widening rift zone of the Meratus graben (Rose
and Hartono, 1978). The most recent study of the Melawi and Ketungau Basins, West Kalimantan, by Heryanto and Jones (1990) suggested that the Tanjung Formation can be correlated with the Payak and lower Tebidah Formations which is in contrast to the regional correlations of Pieters et al. (1987) which equated the Tanjung Formation with the Ingar and Kantu Formations. However, deposition of the Tanjung Formation in southeastern Kalimantan probably commenced in the Early Eocene since the lower part of the formation overlies the Cretaceous basement rocks whilst the upper part contains Late Eocene foraminiferal faunas (see Siregar and Sunaryo, 1980; Supriatna et al., 1983; Rustandi et al., 1984; and Lemigas, 1983).

The initial cycle of deposition consisted of the lower sandstone facies succeeded by coal seams. This was succeeded by the upper sandstone and mudstone assemblage, the upper coal seams and the limestone. The thick basal sandstone in the Senakin Peninsula probably resulted from the initiation of a deep major fluvial channel complex on the basement subjected to river floods. This facies is mainly characterized by the presence of channel lag deposits, cross-beds, massive beds, ripple marks and parallel laminae. The channel lag deposits may be associated with point bar accumulations as noted by Reineck and Singh (1980). The sandstone facies was overlain by a fine-grained clastic sequence of predominantly mudstone, shale, claystone and siltstone. Meandering rivers are normally characterized by fining upward sequences from lag gravels to sand, silt and mud, followed by vertical
accretion of overbank fine deposits (Cant, 1982; and Walker and Cant, 1984). In addition, rivers with meandering channel systems have sediment accumulating on point bars and in well defined pools (Reineck and Singh, 1980). All the evidence from the lower succession in the Tanjung Formation indicates a fluvialite deposit laid down by a meandering river system. The lower coal seam would have been deposited on the interchannel floodplain.

After deposition of the lower coal seam, a second fining upward cycle is found in the upper sandstone facies. This cycle consists predominantly of fine-grained clastic sediments with a few coal beds and subordinate sandstone and siltstone capped by limestone beds in the uppermost section. Sedimentary structures in the upper part of this second cycle suggest that the depositional environment was dominated by distributary channels, mouth bars and interdistributary bay facies of the lower delta plain (as described by Coleman and Prior, 1982). Burrows and bioturbated structures are also more intense in this sequence. Deposition of the cycle ended with shallow marine carbonate rocks deposited during a marine transgression.

Coal deposits occurring in the Tanjung Formation were considered to have formed in intra-montane basins (Koesoemadinata et al., 1978) and would, therefore, be comparable to coals found in the Ombilin Basin, West Sumatera, which was described in more detailed as a fan-delta and lacustrine deposit (Whateley and Jordan, 1989).
This study has proved that features characteristic of fan-delta deposits are not associated with the coal facies in either the Barito or Asem Asem Basins. Detailed vertical profiles showing the association of lithofacies and sedimentary features, and the reconstruction of a depositional model for coal formation within the Eocene Tanjung Formation is summarized in Fig. 3.23. Two distinct phases of ancient peat formation are proposed in this study. The lower coal seams are considered to represent deposition in low-lying back swamps adjacent to meandering river systems where large amounts of vegetation may be concentrated and lead to peat accumulation (see McCabe, 1984; and Haszeldine, 1989). The upper coal seams are interpreted to have accumulated in low-lying swamps and marshes associated with filled interdistributary bay sequences in a lower delta plain setting.

Most of the Eocene coals in southeastern Kalimantan may have developed in raised swamp systems which are common in tropical peat forming areas where the annual rainfall is greater than annual evaporation (Teichmuller and Teichmuller, 1982; and McCabe, 1984). Recent workers, such as Esterle et al. (1989) and Moore and Ferm (1990), have suggested that the dome peat deposits ("pulling up" sequences) of the Baram River, Sarawak, can be compared to some Eocene coals in Kalimantan based on the vertical and lateral distribution of bright bands within well preserved woody tissues. Some evidence gathered in this study suggests that the ancient peat forming the Eocene coal in the southeast Kalimantan basins might have formed under
similar condition to modern peat formation in Sarawak.

Sandstone in the Tanjung Formation is classified as quartzarenite, sublitharenite, subordinate litharenite and minor feldspathic litharenite. The QFR plot demonstrated that the quartzarenite is less abundant in the lower sandstone. Cluster analysis indicates that many components of the sandstone are closely related to each other and most samples have similar grain framework features and textures and are positively clustered together. Restricted palaeocurrent analyses reveal that the mean current direction was southwards which is in marked contrast to the palaeocurrent study by Tjia (1970) in a local area near Tanjung, in the northern part of the Barito Basin. The latter study was based on long pebble axes at the base of Tanjung Formation and he concluded that the palaeocurrent direction was toward north-northeast or northeast.

Following the model of Dickinson and Suczek (1979) and Dickinson (1985), sandstone samples were mainly derived from recycled orogen areas, presumably mostly the Kuching High and part of the Mangkalihat Ridge and Sundaland continent or Schwaner Block.

The Berai Formation mainly consists of carbonate facies deposited during an Oligocene-Early Miocene transgression which followed deposition of the Tanjung sequence. Few samples were analysed but they are composed predominantly of wackestone, packstone and grainstone with subordinate mudstone. Deposition of the Berai Formation probably took place in an open shallow marine environment containing reefs, as shown in Fig. 3.22.
In comparison with the Tanjung Formation, facies variations in the Warukin Formation show a greater dominance of shale assemblages and carbonate rocks. An interesting feature is that the facies show an overall upward coarsening which suggests a deltaic environment. Coal seams within the Warukin Formation probably represent raised swamp deposits in a tide-dominated delta comparable to the Klang and Rangat deltas in Malaysia and the Rajang delta in Sarawak (Coleman et al., 1970; and Anderson, 1964). Sandstone in the Warukin Formation mainly consists of quartzarenite and sublitharenite with subordinate feldspathic litharenite and subarkose. Although a palaeocurrent study could not be conducted, the grain size and ratio of shale to sandstone show a significant trend which suggests that palaeocurrent patterns were almost identical to those for the Tanjung Formation.

The provenance for the Warukin Formation is similar to that for the Tanjung Formation and probably included the Kuching High and part of the Mangkaliat Ridge and Sundaland continent as the main source areas. This contrasts with the suggestion by Kusuma and Nafi (1986) that the formation was derived from the Meratus Range which only became elevated after deposition of the Warukin Formation, i.e. during the Late Miocene or Pliocene.

3.8. SUMMARY

Tertiary deposition in the Barito and Asem Asem Basins commenced with a meandering river system which gave way to a
fluvial-dominated delta and shallow marine environment at the top of the Tanjung Formation. The peak of the Late Eocene transgressive phase is represented by carbonate facies (Berai Formation) which was followed by the regressive lower delta plain and possibly fluviatile succession of the Warukin Formation.

Sandstone from both the Tanjung and Warukin Formations consists mainly of quartzarenite and sublitharenite, whilst litharenite, feldspathic litharenite and subarkose form minor components. In contrast, the Berai Formation samples consist of grainstone, packstone and wackestone with subordinate carbonate mudstone.

The clastic rocks of the Tanjung and Warukin Formations were transported southwards from a predominantly recycled orogen that possibly included the Kuching High, and part of the Mangkalihat Ridge, Sundaland continent or Schwaner Block.
CHAPTER FOUR

ORGANIC PETROLOGY

4.1. INTRODUCTION

Organic petrology is an optical microscopy technique to examine the occurrence and properties of organic matter in coal, oil shale and dispersed organic matter in sedimentary rocks, which is of particular value in the coal and oil industries. Definitive texts on optical microscopy for this study were given by Cook (1980, 1982), Stach et al. (1982), International Committee for Coal Petrology (1963, 1971, 1975) and Bustin et al. (1983).

A total of 365 cuttings, sidewall core, core and hand-specimen (outcrop) samples were examined from the Tanjung, Berai, Warukin and Dahor Formations. Of the samples, 191 consisted of coal or shaly coal, and a total of 174 samples are shale/claystone, siltstone, sandstone, marl or limestone. All selected cuttings and core samples were collected from twelve oil wells: A-1, A-2, MRTP-1X, MYA-1, BRK-1, SMD-1, BKO-1, DS-1, DS-2, PRN-2, PB-1 and PB-2 (see Fig. 4.1), or from shallow drilling by P.T. Arutmin.

portion of each sample was crushed (<0.2 mm in size) and mounted in a block approximately 2 x 1.5 cm in cold setting polyester resin (ASTIC), mixed in the ratio of 90 parts resin to four parts hardener. The mounted blocks were then ground on 120 to 220 grit on mechanical laps, and with carborundum abrasive papers in sequences ranging from 400 to 1200 grit. They were then polished firstly chromium sesquioxide and secondly magnesium oxide both in water slurries on selvyt cloths.

The blocks were mounted on a plasticene (modelling clay) and levelled for microscopic examination. Oil immersion objective lenses were used for maceral analyses, with nominal magnifications in the range 25x to 125x and oculars with a magnification of 10x. The prepared samples were examined with reflected light microscope techniques using both normal incident reflected white light (Leitz MPV1 system) for measuring vitrinite reflectance, and reflected UV/violet/blue light fluorescence mode (Leitz Orthoplan microscope MPV2 system) for determining liptinite and vitrinite macerals and bitumens.

The Leitz Orthoplan microscope is fitted with a Leitz Vario-Orthomat camera which incorporates a 5x to 12.5x zoom used for photomicrographs. Photographic techniques were described by Cook (1980).

Reflectance measurements were carried out using plane polarized light of 546 nm wavelength and oil immersion with a refractive index of 1.518 at a room temperature of 23±1°C. Synthetic garnet standards (YAG 0.917% and GGG 1.726% reflectances) and a synthetic spinel (0.413% reflectance)
were used to calibrate the microphotometer. The galvanometer was set to give a reading of one half the reflectance multiplied by 100. The normal procedure for reflectance measurement was given by Cook (1982).

A maximum of thirty measurements were made on coal grains or on discrete phytoclasts of vitrinite occurring as dispersed organic matter. Readings were predominantly made on telovitrinite in coal and the total vitrinite population of the dispersed organic matter in clastic rocks. Each reading comprised two measurements with a stage rotation of 180° between the first and second maximum values. The results were accepted if the two readings were within 5% relative of each other. The mean maximum reflectance (\%R_{V\text{max}} or \%R_{O\text{max}}), including variance and standard deviation for acceptable maximum pairs, were calculated using a Texas Instrument PC-100C calculator.

4.2. DISPERSED ORGANIC MATTER (DOM)

For samples of clastic and carbonate rocks having low contents of dispersed organic matter, the volumetric composition of macerals was examined by careful visual estimation using reflected white light and fluorescence mode illumination. Hence the analysis provides semiquantitative data on the relative amounts of the different macerals within the total dom. The organic matter abundance gives a measure of the relative amounts of the maceral groups
assessed at different levels of abundance (absent = 0; rare = <0.1 %; sparse = 0.1 - 0.5 %; common = 0.5 - 2.0 %; abundant = 2 - 10 %; major = 10 - 40 % and dominant = >40 %). The abundances were visually estimated in approximately fifty grains from several traverses across each sample. The assessment of abundance was given by the following formula:

\[
\text{OMAV} \ (\%) = \frac{(V_{m}.Am) + (V_{a}.Aa) + (V_{c}.Ac) + (V_{s}.As) + (V_{r}.Ar)}{\text{N}(=50)}
\]

where:

- OMAV = Total organic matter abundance for vitrinite(%)  
- N = Total clastic grains counted in the sample  
- Vm = % of grains with vitrinite in the major category  
- Va = % of grains with vitrinite in the abundant category  
- Vc = % of grains with vitrinite in the common category  
- Vs = % of grains with vitrinite in the sparse category  
- Vr = % of grains with vitrinite in the rare category  
- Am = % mid-point value for the major category - 25%  
- Aa = % mid-point value for the abundant category - 6%  
- Ac = % mid-point value for the common category - 1.3%  
- As = % mid-point value for the sparse category - 0.3%  
- Ar = % value for the rare category - 0.1%

Similar formulae were used for calculating the proportions of liptinite and inertinite macerals. For coal and shaly coal grains occurring in the clastic and carbonate rocks, the amount of each maceral was visually estimated and then
the average was calculated by dividing summed percentages by
the total number of grains.

The maceral classification used for this study (Table
4.1) follows the Standards Association of Australia (1986)
and is based on the work of Smith (1981). He recommended a
humic coal maceral classification which is largely
independent of coal rank. This classification is based on
the maceral concept as defined by the International
Committee for Coal Petrology (1963, 1971, 1975). The
classification of coal microlithotypes is adopted from the
terminology given by Stach et al. (1982).

4.2.1. Types of Maceralls and Abundance

A. Tanjung Formation

Detailed descriptions of the organic matter type and
the relative abundance of maceral groups are given in the
Appendix 4.1. Dispersed organic matter (dom) content of the
Tanjung Formation varies between 0.5% and 2.35% (sparse to
abundant) in shale, claystone, siltstone and fine-grained
sandstone. In general, the most abundant maceral in the dom
is vitrinite (0.35% to 1.8%). Liptinite is the next most
abundant, ranging from 0.1% to 0.6% (rare to common), while
inertinite is only rare to sparse (less than 0.1% to 0.2%).
The highest proportion of dom occurs in shale and claystone.

Most vitrinite comprises telovitrinite and
detrovitrinite. Telovitrinite generally forms stringers and
bands more than 30 um in length. Detrovitrinite is usually found as small phytoclasts and rarely as thin bands. These vitrinite macerals are probably derived from woody, bark and leaf tissues of higher plant origin.

Inertinite consists predominantly of inertodetrinite, semifusinite and micrinite. Sporinite, resinite and cutinite are the most abundant liptinite macerals found in dom (Plates 1f-i). Liptodetrinite is a minor proportion of the liptinite macerals.

B. Berai Formation

Thirty five carbonate samples from the Berai Formation were examined for dom. Five samples are barren of organic matter. In the remainder, dom ranges from 0.1% to 0.85%, but the average abundance of the dom is sparse. Inertinite is the dominant maceral in this formation, followed by vitrinite. Liptinite is generally rare, except in one sample from PB-2 well where it is sparse.

Inertinite consists of inertodetrinite and rare semifusinite and micrinite. Vitrinite usually occurs as very fine phytoclasts less than 5 um in size. Liptodetrinite is the most common liptinite maceral in the samples examined. Although sporinite, cutinite and resinite are present in some of samples, they are only minor components. The proportions of dom from each well are shown in Fig. 4.2.
C. Warukin Formation

The Warukin Formation was examined in 129 block samples from twelve petroleum exploration wells. Twenty samples were coal which will be discussed in the coal section. The three main maceral groups of vitrinite, inertinite and liptinite are present in all samples as dom in shale, claystone, siltstone, fine-grained sandstone and carbonate rocks. Dom content of the Warukin Formation ranges from 0.6% to 3.5% by volume which is categorized as common to abundant (Fig. 4.3). It is mainly restricted to the shale, claystone and siltstone with lesser amounts in the sandstone and carbonate samples.

Vitrinite is the dominant maceral and its content ranges from 0.3% to 2.8% in the wells studied. The second most abundant maceral group is liptinite which varies between 0.2% and 0.6%. Inertinite comprises less than 0.2%. As in the Tanjung Formation, the vitrinite is composed predominantly of telovitrinite with subordinate detrovitrinite. The telovitrinite is usually found as stringers and moderately thick bands more than 30 µm in length, while other vitrinite occurs as fine grains and more rarely as thin layers or stringers. These vitrinite macerals are derived from well preserved woody, bark and leaf tissues of largely higher plant origin. Liptinite macerals in dom comprise sporinite, resinite, cutinite, liptodetrinite, suberinite, exsudatinite, fluorinite and lesser amounts of telalginite and phytoplankton. Sporinite, resinite, cutinite and liptodetrinite are the most common
liptinite macerals found in the samples studied (Plate 1a-e). Suberinite, exsudatinite and fluorinite are only rare to sparse.

Rare to sparse telalginite is present in a few samples and occurs in carbonaceous shale and siltstone. Cell structure in the alginite is usually poorly preserved, but in several occurrences show an affinity to *Botryococcus* sp. can be seen.

Phytoplankton related organic matter is rare to sparse, but is found in several samples. Some of the phytoplankton resembles fragments of dinoflagellate/acritach cysts.

Inertinite typically occurs as inertodetrinite, semifusinite, sclerotinite and micrinite which are generally rare to sparse in most of the samples examined. Inertodetrinite is more common in the dom, whereas semifusinite, sclerotinite and micrinite are present, generally associated with vitrinite in coal fragments.

D. Dahor Formation

Samples of the Dahor Formation contain sparse to common dom and abundant coal. The dom comprises sparse to common vitrinite, sparse liptinite and rare to sparse inertinite.

Vitrinite typically occurs in shale, siltstone and sandstone as stringers and thin bands of telovitrinite, and as lenses and fine grains of detrovitrinite. Liptinite consists mostly of cutinite, sporinite, resinite and liptodetrinite.

Inertodetrinite and sclerotinite are the main
components of inertinite group in the Dahor Formation, but are rare to sparse. Rare semifusinite is also present in several samples. Fig. 4.3 illustrates the average abundance of each maceral group in dom and coal. Ternary diagram showing maceral group composition of the dom is given in Figs 4.4. and 4.6-4.8.

4.3. COAL PETROLOGY RESULTS

Coals are widely distributed in the Tertiary Basins of Indonesia, particularly in southeast and east Kalimantan. The occurrence of Late Tertiary coal in the Kutei Basin was discussed by Land and Jones (1987). The main coal measures in southeastern Kalimantan occur in the Eocene Tanjung and Middle Miocene Warukin Formations (see Figs 3.19, 3.20 and 3.21 Chapter 3). The distribution of coal outcrops is given in Fig. 4.5.

The majority of Indonesian Tertiary coals is typically humic coal. Studies on the organic petrology of some Indonesian coals, including southeastern Kalimantan coals, have been contributed by Daulay (1985), Daulay and Cook (1988), Moore (1987) and Moore and Ferm (1990).

4.3.1. Eocene Coal

Organic petrological examination showed that the three main maceral groups of vitrinite, liptinite and inertinite are abundant to dominant present in all the Eocene coal
samples (Appendix 4.2). The proportions of maceral components in the lower and upper coal sections of the Eocene Tanjung Formation are shown in Fig. 4.9A,B.

The vitrinite contents range from 45% to 100% (average 82%). Liptinite varies between 0% and 50% with an average of 15%, whilst inertinite occurs as a minor constituent in all samples, ranging from 0% to 10% (average 3%). Hence, the coal is typically vitrinite-rich with liptinite-poor vitrite being the dominant microlithotype. Nevertheless, liptinite-rich clarites are also abundant in several samples, whilst other bimaceral and trimaceral microlithotypes are minor components.

Overall, telovitrinite (range from 12% to 100%, mean 64%) is the main vitrinite maceral in most samples (Fig. 4.11B), whereas detrovitrinite is the second most abundant type of vitrinite with a mean of 24%. Gelovitrinite ranges from 3% to 20% (average 12%). Telovitrinite consists predominantly of telocollinite with sparse to common eu-ulminite and rare textinite. Desmocollinite and densinite are the most prominent components of detrovitrinite. Attrinite is present, but is not present in significant amounts in several samples. Gelovitrinite constitutes lesser amounts of the vitrinite compared with both telovitrinite and detrovitrinite (Plate 3a-b). It typically occurs as corpovitrinite and porigelinite.

The upper coal seam has a higher liptinite content than the lower seam. In several samples, the upper seam reaches up to 50% liptinite. The majority of the liptinite found in
the Eocene coals is sporinite, resinite and cutinite (Plates 2i, 3g-h). The next most abundant group of liptinite macerals comprises liptodetrinite, suberinite and fluorinite (Plates 2g-h and 3c-d).

Exsudatinite is common in most samples, and sparse to common Botryococcus-related telalginite is present in some samples (Plates 2i and 3i). Sporinite consists mainly of tenuisporinite or thin-walled microspores, although sporangia and megaspores are also found as minor components of clarites (Plate 3e-f).

Cutinite occurs dominantly as thin-walled varieties. Some samples contain sparse thick-toothed cutinite, with prominent cuticular ledges, derived from leaf tissue. Resinite is mostly confined to the liptinite-rich clarite where it is present as medium to large elongate bodies, or as small spheres (Plate 3g-h) which usually interbedded with detrovitritine.

Suberinite is a common and characteristic component of more than 50% of the Eocene coal examined. It commonly occurs in well preserved thin layers containing minute phlobaphinitic corpovitrinite. In the liptinite-poor clarite, suberinite typically forms the cell wall material surrounding gelovitrinite cell fillings. However, in many samples the suberinite macerals occurs as thick-walled varieties. Teichmuller (1982, 1989) suggested that suberinite is derived from cork tissues which occur mainly in bark, roots, stems and fruits, acting as a protection against desiccation. Liptodetrinite is usually found as scattered fine degradation products probably derived from a
range of liptinite macerals.

Fluorinite typically shows bright fluorescence and
commonly infills cell lumens, but also occurs as discrete
small bodies (Plate 2g and 2c). Exsudatinite is generally
found as resin-like or bitumen-like substances infillings in
cracks or veins within vitrinite (Plate 4f-g and 4i).
Exsudatinite is discussed in more detail in Sections 4.4 and
4.6.

Inertinite consists mainly of inertodetrinite, sclerotinite and semifusinite. Micrinite is less common
while macrinite is a very minor component throughout the
samples. Teleutospores and fungal sclerotia generally
comprise the bulk of the sclerotinite.

4.3.2. Miocene Coal

Like the Eocene coals, these coals also contain a much
higher vitrinite content than the liptinite and inertinite
macerals (Fig. 4.10). The vitrinite content varies between
74% and 99%, with an average of 84%. This is closely
comparable to the Eocene coal, as described above, and to
some Neogene coal from Bukit Asam in South Sumatera (Daulay,
1985). Telovitrinite is typically the most prominent
vitrinite constituent (average 79%) followed by
detrovitrinite (average 15%; Fig. 4.11A).

Gelovitrinite occurs as a minor component (average 6%).
Telocollinite and eu-ulminite are the most common vitrinite
types in the Miocene coal, but small amounts of textinite
are also present in some samples. Detrovitrinite consists
mainly of desmocollinite and densinite, which are commonly interbedded with thin bands of telocollinite. Many detrovitrinites are also associated with liptinite assemblages and mineral matter. Gelovitrinite comprises mostly corpovitrinite and porigelinite.

Liptinite content ranges from 1% to 21% (average 11%), which is slightly higher than Neogene coal samples examined by Daulay (1985) from Bukit Asam in the South Sumatera Basin. Liptinite consists predominantly of sporinite, cutinite and resinite. The next most abundant liptinite macerals are suberinite and liptodetrinite (Plate 2a-b), while fluorinite and exsudatinite are only sparse to common.

Sporinite occurs typically as microspores (tenuisporinite) (Plate 2e), but rare megaspores and sporangia are also present. Like the sporinite in the Eocene coal, the sporinite in the Miocene coal is characteristically associated with desmocollinite. Typically, tenuicutinite (thin-walled untoothed cutinites) is present in the Miocene coal, but crassicutinite (thick-toothed cuticle types) is present in some samples. Resinite mostly occurs as discrete small bodies and infillings in cell lumens throughout the coal. Similar features were also noted for fluorinite macerals. Liptodetrinite constitutes very fine detrital liptinite which is usually disseminated within liptinite-rich clarite coal. Botryococcus-related telalginite is present in some samples (Plate 2c-d).

Inertinite averages less than 3% throughout the coal, and in several samples it is absent. It consists
predominantly of sclerotinite and semifusinite with occasionally rare to sparse micrinite and macrinite (Plate 2f). As in the Eocene coal, teleutospores and sclerotia are the most common sclerotinite types in the Miocene coal of southeastern Kalimantan. The cells are usually filled by either resinite or mineral matter but, more rarely, bitumens infill the cell lumens. Mycorrhizomes and fungal stomata have been found in equivalent coal near Samarinda (A.C. Cook, pers. comm., 1990).

4.3.3. Mineral matter

Eocene Coals

The average abundance of mineral matter in the Eocene coal is approximately 6%, but some samples contain up to 17%. The mineral matter consists of clay-size minerals, pyrite and carbonate. X-ray diffraction analysis on two representative samples indicates that the clay-size fractions comprise predominantly quartz and kaolinite, but chlorite was also recorded (see Chapter 7).

Pyrite and carbonate minerals are more abundant components in the upper coal seam. This indicates a saline influence for a significant part of the upper seam (see Chapter 3). Pyrite in the lower seam forms less than approximately 2% of the mineral matter content, whilst in the upper seam it ranges from 2% to 10% of total mineral matter.
Miocene Coals

The Miocene coals contain up to 5% mineral matter. Clay-sized fractions generally consist of quartz and kaolinite, but pyrite and carbonate are also present in several samples. Many of the Miocene coal samples are remarkable for the absence of discrete mineral matter. In the Kutei Basin, the sections of coal being mined from some thick seams have ash yields of less than 1% and many of the seams have ash yields of less than 2% (Kaltim Prima Coal Company and A.C. Cook, pers. comm., 1990).

4.3.4. Vitrinite Reflectance and Coal Rank

The vitrinite reflectance measurement data of dom and coal are listed in Appendix 4.3. The results of vitrinite reflectance measurements on dom from petroleum exploration well data are discussed in Chapter 5. According to Smith and Cook (1980) reflectance measurements on macerals can be used as an indirect microprobe method to distinguish differences between the chemical properties of the various coal macerals. They confirmed that vitrinite undergoes changes at a consistent rate throughout the general trend of organic metamorphism, while liptinite and inertinite reflectances respectively indicate most rapid change at moderate and low maturity levels. Thus, the reflectance of vitrinite macerals is the best measure to use as a rank indicator for coal and dom, and it is also a measure which can be used to assess the extent of maturation in hydrocarbon generating rocks (Fig. 4.12). In addition,
vitrinite is widespread, is generally easy to identify and it is homogeneous in composition relative to other coal macerals (Cook, 1982; Kantsler, 1985).

Rank in coal petrology is a measure of the position on the coalification path from peat through to anthracitic coal. The type of organic matter and rank are basically orthogonal variables (Cook, 1982).

The effective heating temperature and time of heating are the essential variables controlling the degree of coalification (e.g. Hood et al., 1975 and Bostick et al., 1979). Nevertheless, Teichmuller and Teichmuller (1982) assumed that pressure can, to a great extent, promote coalification, especially in strongly folded regions. Hower and Davis (1981) and Levine and Davis (1984), following on from early work by Stone and Cook (1979), have shown how pressure regimes may be inferred from measurement of maximum and minimum reflectance.

Cook (pers. comm., 1990) has commented on the effects of the presence of liptinite macerals, bitumens, overpressured zones and the influence of host rock lithology on vitrinite reflectance. Interference effects on vitrinite reflectance are assessed as minimal for the coal examined in the present study.

A. Rank of Eocene Coal

Vitrinite reflectance measurements from the lower and upper Eocene coal seams were made on 161 selected samples from shallow drilling and outcrops. The results are
summarized in Fig. 4.13. The range of vitrinite reflectance of all samples of Eocene coal is from 0.50% to 0.73%, and the overall mean is 0.60%.

Some distinction can be made, on the basis of vitrinite reflectance values, between the lower seam and the upper seam, even though the difference in stratigraphic level is only between 5 m and 100 m. The overall mean vitrinite reflectance value for the lower seam is 0.62%, while that for the upper seam is 0.58%. The Eocene coal varies between sub-bituminous and high volatile bituminous in rank. Lateral variation in the rank of the two seams appears to be small over the area of the Senakin Peninsula.

Vitrinite reflectance measurements on some cuttings samples show that the rank of the Eocene coal in the Barito Basin increases to over 0.80% $R_v^{\text{max}}$ at depths greater than 3700 m in SMD-1 well (see also Section 5.5). It should be noted that if equivalent the Eocene section continued below the seam examined in outcrop, reflectances of 0.80% would be expected at depths of about 1000 m or less.

B. Rank of Miocene Coal

Mean maximum vitrinite reflectance of 30 coal samples from outcrop, shallow drilling and petroleum well samples was measured (Fig. 4.13) indicate that the $R_v^{\text{max}}$ varies between 0.28% and 0.70%, with the average reflectance of all the samples 0.43%. Two ranges of rank are identified in the Miocene coal. The first is coal having a vitrinite reflectance of between 0.28% and 0.55%. These coal were
mostly collected from the surface (outcrop) and shallow drilling, but includes samples from depths up to 1700 m in petroleum wells. The second group covers coal where the vitrinite reflectance ranges from 0.60% to 0.70%; the samples were taken from petroleum exploration wells below 2000 m depth.

The break in vitrinite reflectance between 0.55% and 0.60% in the histogram is due to a lack of coal seams from 1700 m to 2000 m depth, but the rank of coals if they existed is believed to be continuous. Consequently, the Miocene coal is all categorized brown to sub-bituminous coals with high volatile bituminous coals in some of cuttings samples from the deeper part of the Warukin Formation in BRK-1, BKO-1, and PRN-1 well sections.

Overall, these data suggest that increasing rank is closely related to increasing depth of burial (see also Chapter 5). No evidence was found to suggest that higher ranks, caused by contact metamorphism, as in the Bukit Asam coal and discussed by Daulay (1985), occur in the study area.

4.3.5. Fluorescence Colours of Macerals

Apart from reflected white light, fluorescence mode microscopy is essential to examine coal macerals. This is especially true for liptinite, oil and bitumens. Study of organic matter in coal and sedimentary rocks under fluorescence-mode has been of great fundamental and
practical interest during the past twenty years. Many pioneer workers have used this technique in petrographic studies (e.g. Gijzel, 1967; Ottenjann et al., 1975; Teichmuller and Wolf, 1977; Robert, 1979, 1980, 1981; Teichmuller and Durand, 1983; Diessel, 1985 and Bertrand et al., 1985). Recent studies on the fluorescence properties of vitrinite have been carried out by Wolf et al. (1983) and Lin et al. (1987).

Present studies on samples of coal and sedimentary rocks in southeastern Kalimantan reveal that most liptinite macerals show very strong to weak fluorescence with a variety of colours (Table 4.2). Some of the vitrinite, in particular detrovitrinite, shows fluorescence at low rank. Fluorescence is less intense for the other vitrinite sub-macerals. Inertinite exhibits no or very weak fluorescence. Natural solid oil and bituminous matter ("migrabitumen", see Section 4.4) also show intense auto-fluorescence.

Sporinite shows yellow to orange fluorescence with strong intensity in the Dahor and Warukin Formations, but becomes yellow to orange and dull orange of moderate fluorescence intensity in the Berau and Tanjung Formations. Cutinite dominantly shows strong to moderate fluorescence intensity of yellow to orange and dull orange colours in the Dahor and Warukin Formations, while in the Tanjung Formation this liptinite generally shows orange to dull orange fluorescence of moderate to weak intensity.

Resinite, which is reported to be derived from resin bodies of balsams, latexes, fats and waxes (Teichmuller,
1982), mostly has moderate yellow to orange fluorescence intensities in the Dahor Formation, but has moderate to weak fluorescence intensities in the Warukin and Tanjung Formations. The fluorescence colours of resinite characteristically shows strong variations from yellow, orange to dull orange even in a single sample. Because of this extreme variation, Teichmuller and Durand (1983) suggested that this maceral should not be used for rank estimation in place of vitrinite reflectance or other rank parameters.

In the Dahor Formation suberinite shows fluorescence ranging from weak yellowish orange (rare) to dull orange (major). Dominantly weak to very weak suberinite fluorescence, orange to dull orange in colour, occurs in the Warukin and Tanjung Formations. A marked change in the fluorescence colours and intensities of suberinite occurs at about 0.60% vitrinite reflectance.

Fluorinite, is dominantly associated with coal and is characterized by an intense green to greenish yellow and bright yellow fluorescence in the Dahor and Warukin Formations. The intensity of the fluorescence colours reduces with a red shift to be dominantly yellow in the Tanjung Formation. Robert (1981) believed that under the effects of thermal alteration, the majority of fluorinite disappears as they are converted into hydrocarbons.

Exsudatinite is generally characterized by strong fluorescence of bright yellow and yellow to orange colour in the Dahor and Warukin Formations, and in some samples from the Tanjung Formation. More detailed features of
exsudatinite are discussed in a later section.

Liptodetrinite typically shows wide variations in fluorescence colours because it is derived from fragments and degraded remains of sporinite, cutinite, resinite, alginite and suberinite (Teichmuller and Ottenjann, 1977; Teichmuller, 1982; Stach, 1982; and Standard Association of Australia 2856, 1986). The fluorescence colours are bright yellow, yellow, bright orange, orange to dull orange in all stratigraphic units. Telalginite (Botryococcus sp.), occurring in the Warukin and Tanjung Formations shows strong to very strong fluorescence which is bright yellow, yellow or bright orange in colour (Plates 2c-d, 2i and 3i). Due to its intense fluorescence and morphology, the alginite is clearly distinguishable from other liptinite macerals. The fluorescence of Botryococcus-related telalginite is still visible at ranks up to 1.2% vitrinite reflectance (Kantsler, pers. comm., 1984).

Phytoplankton are rare to sparse in the Warukin, Berai and the Tanjung Formations. In general, they represent remnants of dinoflagellate cysts or acritarchs. Fluorescence intensity also changes with rank, i.e. bright yellow to bright orange in the Warukin and Berai Formations, and yellow to orange in the Tanjung Formation. Cook (1982) reported that a rapid change of fluorescence intensity does occur for phytoplankton over the rank range of 0.7% to 1.2% vitrinite reflectance.

Most of the detrovitrinite in the samples studied show weak to very weak fluorescence, but fluorescence was rarely noted from the telovitrinite and gelovitrinite. The
fluorescence is generally dull orange to dull brown. Vitrinite fluorescence has been discussed by Teichmuller (1974, 1982) and Teichmuller and Durand (1983). The chemistry of vitrinite fluorescence was discussed by Lin et al. (1986, 1987). Diessel (1985) correlated the fluorescence properties of inertinite with reflectance and coking criteria.

Basically, vitrinite and inertinite have weak fluorescence since these macerals have a more prominent aromatic structure (Bertrand et al., 1985). Lin et al. (1986, 1987) outlined the quenching effects of these structures. Two types of vitrinite fluorescence have been recognized (Teichmuller and Durand, 1983). The first type is primary fluorescence of vitrinite which mainly occurs in the detrovitrinite groundmass for liptinite-bearing microlithotypes and in some of the precursors of telovitrinite (textinite) where the former cell wall was impregnated with cellulose, resin or other fluorescing constituents. This primary fluorescence decreases and is largely absent by the C-B boundary in sub-bituminous coals (0.45% vitrinite reflectance). The second type is secondary fluorescence which develops at the stage of high volatile bituminous A coal (Teichmuller and Durand, 1983: and Lin et al., 1987). Secondary fluorescence appears to be associated with the retention of bitumen-like substances within the vitrinite.

In the present study, secondary vitrinite fluorescence of the coal samples (Miocene and Eocene seams) is mostly visible up to 0.60% vitrinite reflectance. The secondary
fluorescence of the vitrinite decreases at a vitrinite reflectance of greater than 0.60%. The presence of fluorescence in vitrinite macerals seen in this study is probably closely related to the early phase of hydrocarbon generation, with the hydrocarbons being produced from the vitrinite itself and from some, but probably not all, liptinite macerals. This suggestion is supported by some evidence relating to the occurrence of migrabitumen and other natural solid oils in coal samples.

4.4. MIGRABITUMEN AND OIL SUBSTANCES

The name "migrabitumen" is adopted from the terminology of Jacob (1989) which was confirmed by a vote of Commission II organic petrologists at the I.C.C.P. 1990 meeting in Wollongong. Migrabitumen is a term used to describe all natural hydrocarbon-related substances which are secondary materials generated from fossil organic matter during diagenesis and catagenesis (Hunt, 1979). Cook (1982) added that bitumens are also formed from the degradation of natural crude oils by processes of microbial attack, inspissation or water-washing.

Many workers have studied bitumens using organic petrology and organic geochemistry techniques in order to understand the origin and occurrence of migrabitumen. These have included studies on exsudatinite, natural bitumens, fluorinitite and terpinite (e.g. Pottonie, 1950; Jacob, 1967, 1983, 1989; Hunt, 1979; Teichmuller, 1974, 1982, 1985, 1989;
Cook and Struckmeyer, 1986; and Kim and Cook, 1988a, b).

It is difficult to distinguish and separate the term exsudatinite from migrabitumen as they both relate to coal under microscopic examination. Exsudatinite was accepted by many organic petrologists as a liptinite maceral even though its origin was regarded to be secondary and it typically occurs as veins and filling cracks, cavities and cell lumens (Plates 2e, 3a, 3g, 4a, 4f-g and 4i).

Migrabitumen is defined I.C.C.P. (1990 Annual Meeting) as all natural solid bitumen occurring in sedimentary rocks, but excluding exsudatinite in coal and including oil-like substances expelled from macerals. In this study, however, exsudatinite is included as migrabitumen. Hence, the exsudatinite is added to migrabitumen when reporting the abundance of migrabitumen in the samples. This was done because no or little distinction between their optical features and fluorescence intensities could be made and the mode of occurrence of exsudatinite shows transitions to the typical modes for migrabitumen.

Approximately 40% of all samples analysed using organic petrological methods contain migrabitumens as defined above. Sixty percent of the samples containing migrabitumen are the Miocene or Eocene coals. The average abundance of migrabitumen within the dom of the Dahor Formation is approximately 0.24% (sparse) by volume. In the Warukin Formation migrabitumen within the dom comprises up to 0.80% (common; Plate 4c), it is rare (0.1%) in the Berai Formation, while the dom of the Tanjung Formation contains migrabitumen with an average value of approximately 0.32%
(sparse; Plate 4e).

In the coal samples the amount of migrabitumen is much higher than in dom. The Miocene coal contains migrabitumen ranging from 0% to 8.3%, with an average value of 2% (Plates 2e, 4a), while in the Eocene coal it ranges from 0% to 10%, with an average value of 1%. Greater abundance of liptinite macerals are not generally associated with measured migrabitumen content. For example, a sample of the Miocene coal (22300) contains 8.3% migrabitumen, but the liptinite content is only 3.5% by volume. In contrast, some samples (22664, 22730 and 2HPY) contain almost equal amounts of liptinite and migrabitumen. Consequently, migrabitumens can be associated with either liptinite or vitrinite-rich coal (Plates 2e, 4a). It can be argued that liptinite, on a volume basis source a higher proportion of migrabitumen, since this maceral is largely composed of resistant aliphatic constituents (Saxby and Shibaoka, 1986). However, the main association of exsudatinite is with telovitrinite, but this may reflect physical rather than chemical properties. Vitrinite, due to microbial processes, may contain both lignin-derived (aromatic) and minor amounts of lipid-derived (aliphatic) material which differentiates it from the original plant material (Saxby, 1978). According to Saxby and Shibaoka (1986), various oil-sized molecules may have formed by cracking C-C bonds which then become trapped in the coal structure. Gas or condensate-sized molecules can be produced by intensive cracking.

The average abundance of migrabitumen in each stratigraphic unit and the coals is presented in Fig. 4.14.
Its form and occurrence suggests that most previous models for generation and migration of hydrocarbons within coal require modification.

Migrabitumen itself is generally irregular in shape and features, but spherical, aggregate or individual balls, cauliflower-like shapes are present. Cracks and single or multiple fractures commonly occur in the migrabitumen and, commonly, oil-like liquid flows out from these fractures. Under reflected white light observation, migrabitumen is commonly transparent, although much of it is brownish grey in the higher rank samples.

The intensity and colours of fluorescence (Table 4.3) are very strong green and greenish yellow to yellow for migrabitumen occurring in the Dahor and Warukin Formations, and strong bright yellow to orange in the Berai and Tanjung Formations.

Oil cuts (Plate 4i) are common and closely associated with vitrite and clarite microlithotypes in the Miocene and Eocene coal but are very rare within dom. Discrete oil cuts are usually associated with telovitrinite and to some extent they are also found in other types of vitrinite. However, diffuse fluorescence associated with a greenish yellow haze, is often observed from desmocollinite.

Oil drops are abundant in the Dahor, Warukin and Tanjung Formations (Plate 4a and h), but rare from the Berai Formation. These substances are observed to be scattered in both clastic-dominated source rocks and coal and are also found in the resin mounted blocks as medium- to well-rounded globules ranging from 1 um to a maximum of 10 um in size.
Fluorescence is bright green to greenish yellow or bright yellow to orange. The oil drops in the mounting resin partly represent free oil and partly represent oil drops expelled during sample preparation.

Dead oil is also prominent in some samples from the Warukin, Berai and Tanjung Formations (Plate 4d). These materials exhibit bright yellow to orange fluorescence. In the Warukin and Tanjung Formations, the dead oil always occurs disseminated within pore spaces in the matrix of siltstone and sandstone, or lining quartz grains. Dead oil is rare to sparse in the Berai Formation, where it is usually found as impregnating material within micropores and moldic pores of micritic carbonate.

Migrabitumen reflectance was measured from the clastic rocks and coals of the Warukin and Tanjung Formations. The range of migrabitumen reflectance in the Warukin Formation is between 0.04% and 0.12% (the average is 0.08%); in the Tanjung Formation it ranges from 0.03% to 0.18%, where the average is approximately 0.09%. These data indicate that very little change in the migrabitumen reflectance values over the Warukin Formation to Tanjung Formation stratigraphic interval.

Several interrelationships between migrabitumen reflectance and vitrinite reflectance exist (Fig. 4.15). The migrabitumen reflectance rises slightly with increasing rank of coal (or dom). The fluorescence intensity of migrabitumen appears to become reduced with increasing rank as indicated by either the vitrinite or migrabitumen reflectance. Fluorescence disappears totally when the
bitumen reflectance is over 0.3% (Jacob, 1967, 1983 and 1989; and Robert, 1988). In reflected white light, the transparency of migrabitumen changes from slightly greyish to dull brown at the higher reflectances. As rank increases, the properties of migrabitumen tend towards those of vitrinite (Jacob, 1989).

Migrabitumen reflectance versus vitrinite reflectance of each sample, as plotted in Fig. 4.15, shows that, in general, migrabitumen has a lower reflectance than vitrinite. There is an indication that migrabitumen reflectance tends to increase at a greater rate beyond 0.50% vitrinite reflectance. Bitumen that occurs in samples where the vitrinite reflectance is above 0.50% is associated with polycondensed residues, probably formed from breakdown reactions which release lighter hydrocarbons (Robert, 1988). These residues are formed from the hardened or solidification of hydrocarbons which are either in situ or after secondary petroleum migration. Overall within the migrabitumen, a transition can be seen from a transparent, strongly fluorescent oil to forms with increased opacity and lower fluorescence intensity.

Classification of migrabitumen was made by Jacob (1989) based on its reflectance, intensity of fluorescence and microsolubility (and micro-flow point) as shown in Table 4.3. Based on reflectance values, all migrabitumen from southeastern Kalimantan may be categorized into "asphalt/asphaltite" classes. As can be seen in Fig. 4.16, they are closely comparable with some of the migrabitumens from other foreign countries plotted by Jacob (1989).
4.5. CLUSTER ANALYSES OF COAL PETROLOGICAL DATA

4.5.1. R-Mode

Studies were conducted using a software package modified after Davis (1973) by Dr B. G. Jones (pers. comm., 1990). R-mode analysis shows how the various organic components and mineral matter, together with vitrinite reflectance, can be distinguished and correlated. The results of R-mode cluster analysis of the data set (Miocene coal, lower and upper Eocene coal seams), using a Pearson product moment correlation coefficient, as a measure of similarity and the equally weighted pair-grouping method of clustering, are represented in the dendograms shown in Fig. 4.17 B (lower Eocene coal seam), Fig. 4.18B (upper Eocene coal seam) and Fig. 4.19B (Miocene coal).

The dendogram of lower Eocene coal seam (Fig. 4.17B) has the variables clustered into four groups, A,B,C and D, which have very low intergroup correlation coefficients (r), varying between -0.02 and 0.02. They are:

Cluster A - macrinite
Cluster B - detrovitrinite + sporinite + resinite + liptodetrinite + sclerotinite + inertodetrinite + gelovitrinite + migrabitumen + semifusinite + cutinite + suberinite + micrinite
Cluster C - telovitrinite + exsudatinite + fluorinite + alginate + bituminite + fusinite
Cluster D - vitrinite reflectance + mineral matter.

Cluster A includes a single variable, macrinite, which
is negatively correlated with cluster B. Cluster B consists of macerals having weak to moderate positive correlations ($r = 0.04$ to $0.59$) with each other. Migrabitumen shows weak correlation with semifusinite, and suberinite with micrinite. The strongest linkage among variables are detrovitrinite with sporinite (and to a lesser extent with resinite and liptodetrinite) and sclerotinite with inertodetrinite. The association of these macerals reflect assemblages of clarite microlithotypes in the samples examined.

Group C is characterized by very weak positive correlations ($r = 0$ to $0.20$). Only the correlation of exsudatinite and fluorinite with telovitrinite are significant, and it has been qualitatively observed that these two macerals most commonly occur within telovitrinite bands in the samples.

Cluster group D comprises the variables mineral matter and vitrinite reflectance that have a positive similarity coefficient of $0.40$. The correlation may result from type differences associated with the vitrinite present in shaly coal or could represent accelerated rates of coalification where clays are more abundant.

Data for the upper Eocene coal seam (Fig. 4.18B) is clearly divided into two major clusters A and B. As in the lower seam, the intergroup relationship has a very low similarity correlation coefficient ($r = -0.04$).

Cluster A - vitrinite reflectance + mineral matter +
alginate + bituminite + fusinite + telovitrinite
+ cutinite + micrinite

Cluster B - detrovitrinite + sporinite + resinite +
liptodetrinite + exsudatinite + migrabitumen +
gelovitrinite + sclerotinite + inertodetrinite +
fluorinite + semifusinite + suberinite +
macrinite

The variables in cluster A show no or very low positive inter-variable correlation coefficients (0 to 0.33). In this group, a significant relationship is found between vitrinite reflectance and mineral matter, and telovitrinite, cutinite and micrinite. In contrast, alginite, bituminite and fusinite form a poorly defined cluster because they represent very minor constituents in the coal.

Cluster B shows low to high similarity coefficients between variables (0.04 to 0.79). This cluster contains strongly linked variables, such as detrovitrinite, sporinite, resinite, liptodetrinite, exsudatinite and migrabitumen. Petrographically, this situation has some similarity to the dendrogram of the lower seam mentioned above. These macerals are certainly associated with clarite microlithotypes. Exsudatinite and migrabitumen variables form the strongest correlated cluster, indicating that these components seem to be genetically equivalent and closely related each other. The correlation of exsudatinite with migrabitumen has probably "pulled" exsudatinite out of the cluster containing telovitrinite. Inspection of the original correlation coefficient matrix shows a very low correlation coefficient of 0.07 for exsudatinite and
telovitrinite. A correlation is also found between sporinite and resinite macerals. Other variables, such as gelovitrinite, sclerotinite, inertodetrinite, fluorinite, semifusinite, suberinite and macrinite have weak positive correlations within the cluster, but the significance of these correlations is doubtful as most of the components are relatively minor.

The result of R-mode analyses for Miocene coal samples (Fig. 4.19B) indicates that two main cluster groups, A and B, are present. The groups have a negative intergroup correlation coefficient \( r = -0.05 \) and many of the within cluster correlations are weak.

Cluster A - vitrinite reflectance + exsudatinite + micrinite + semifusinite + inertodetrinite + fusinite + telovitrinite + macrinite + alginate + bituminite

Cluster B - dteovitrinite + sporinite + resinite + cutinite + liptodetrinite + fluorinite + migrabitumen + gelovitrinite + suberinite + sclerotinite + mineral matter

Cluster A has a wide range of similarity coefficients between 0 and 0.73. With the exception of sclerotinite, all the inertinite macerals are clustered in this group along with alginate, vitrinite reflectance, exsudatinite and telovitrinite. Alginate has only a weak correlation with other macerals.

The correlation coefficients in cluster B also range
widely between 0.04 and 0.60. This group is characterized by a grouping of liptinite macerals (except for alginate and bituminite) plus detrovitrinite, gelovitrinite and sclerotinite. The clustering in this group indicates that detrovitrinite and gelovitrinite partly form the groundmass for the liptinite macerals and are associated with migrabitumen. Gelovitrinite is closely paired with suberinite because of the botanical affinity of suberinite and corpovitrinite.

The results of the R-mode cluster analyses for the sets of data from Eocene and Miocene coal samples can be summarized as follows:

1. The results suggest that most of the inter-variable correlations for the samples analysed from both the Eocene and Miocene coals are not significant in terms of variation in the proportions of the three main maceral groups, vitrinite, liptinite and inertinite. This is largely related to the small range of variation in organic matter, climate, depositional environment and, therefore, organic facies during the Tertiary.

2. R-mode cluster analysis indicates that the distinction between telovitrinite, detrovitrinite and gelovitrinite throughout the rank range of the coal samples examined gives some discrimination in defining organic facies. However, detrovitrinite and gelovitrinite are always grouped together as they have similar abundance and similar associations with other variables in the data set.

3. The inertinite macerals tend to form a group with a
low level of organization, probably due to the small amounts of these macerals present.

4. Detrovitrinite, gelovitrinite and most liptinite macerals occur together in the clusters. From the structure of this grouping it can be seen that detrovitrinite and gelovitrinite are positively correlated with the proportion of liptinite, and with migrabitumen.

5. For the upper Eocene coal, migrabitumen is strongly correlated with exsudatinite. There may be a more general correlation of these secondary macerals but in terms of cluster analysis, clustering of exsudatinite with migrabitumen is disturbed for many samples by the strong correlation of exsudatinite with telovitrinite.

4.5.2. Q-mode

Like R-mode cluster analysis, Q-mode analysis can also be presented as a dendogram but the clustering reflects similarities (and dissimilarities) between samples. The results of these analyses are presented in Fig. 4.17A (lower Eocene coal seam), Fig. 4.18A (upper Eocene coal seam) and Fig. 4.19A (Miocene coal).

The Q-mode dendogram of petrological data from the lower coal seam of Eocene age (Fig. 4.17A) produces two major clusters, A and B based on cosine theta correlation coefficients, with a between group coefficient of -0.03.

Cluster A is divided into six sub-clusters (numbered from 1 to 6). Correlation between the sub-clusters is at
low levels of similarity but moderate to high correlation of samples occurs within each sub-cluster. In cluster A, sub-clusters 1 and 6 have low levels of similarity between coal rank and the proportion of macerals, especially the abundance of vitrinite and liptinite (slightly high) and mineral matter (low). Sub-clusters 2, 3, 4 and 5 are much more closely related. They have positive similarity coefficients ranging from 0.27 to 0.42. These clusters predominantly include samples containing slightly higher mineral matter and liptinite contents, but a low content of vitrinite macerals and they are low in ranks.

Cluster B consists of four well-defined sub-clusters numbered 1 to 4, where the intercluster correlation coefficients range from 0.25 to 0.03. Sub-cluster 1 is distinguished from the others in that it consists mainly of shaly coal with the mineral matter content ranging from 25% to 63%. In these samples the vitrinite reflectance is slightly higher than in samples within the other sub-clusters. Sub-clusters 2, 3 and 4 are generally characterized by high proportions of vitrinite and liptinite, but relatively low mineral matter content. These clusters represent samples having more clarite than vitrinite.

Q-mode analysis of the upper Eocene coal seam resulted in two major groups A and B having an intercluster similarity coefficient of -0.07 (Fig. 4.18A). Group A is divided into three well-defined sub-clusters. The similarity coefficient between the sub-clusters ranges from 0.01 to 0.1. Sub-cluster 1 shows high internal positive correlation of samples with similarity coefficients ranging
from 0.36 to 0.89. This cluster is separated from other clusters because the samples are mostly shaly coal having mineral matter contents of 23% to 62%. Vitrite contents are slightly lower than for samples in clusters 2 and 3, although liptinite contents are significantly higher. Clusters 2 and 3 have a low intercluster correlation but represent two groups with many similarities in maceral composition, rank, mineral matter and migrabitumen content.

Group B has two reasonably well-defined sub-clusters 1 and 2. Both sub-clusters are characterized by positive similarity coefficients between samples varying from 0.07 to 0.86. One striking difference between sub-clusters 1 and 2 is that the samples in sub-cluster 1 have vitrinite reflectance values (average 0.59%), vitrinite contents (average 73%), and mineral matter contents (average 8%) that are all higher, and liptinite contents (average 15.5%) that are lower, than in the samples forming sub-cluster 2 (average vitrinite reflectance 0.55%, average vitrinite content 69%, average liptinite content 19.6% and average mineral matter 6%). The inertinite content of both sub-clusters is similar (3%).

The Q-mode dendogram for Miocene coal is divided into two major clusters, A and B (Fig. 19A). Group A consists of 18 samples clustering together with positive similarity coefficients ranging between 0.03 and 0.74. Group B comprises 12 samples characterized by positive similarity coefficients ranging from 0.06 to 0.86.

The two clusters for the Miocene coal differ in a number of respects. Compared with those in cluster A,
samples in group B have a much higher content of vitrinite macerals (average 83%, cf. 68% in A) and a higher vitrinite reflectance (0.47%, cf 0.38% in A). Furthermore, the liptinite and mineral matter contents are higher in group B (average liptinite = 12.5% and average mineral matter = 6%; cf. in group A average liptinite = 8.2% and mineral matter = 4%). In group B, samples of shaly coal (22582, 22795 and 22666) contribute to the higher mineral matter content.

The results of Q-mode cluster analyses on the samples of the Eocene and Miocene coals can be summarized as follows:

1. Q-mode cluster analysis of all sample suites defines the discriminations among samples as represented by the various properties of the coal.
2. Most groups and subgroup clusters for the Eocene and Miocene coals appear to be related to each other since they have positive similarity coefficients. Overall, similarities and differences among clusters are due to variation in maceral composition, rank and mineral matter content.
3. It is probable that the maceral composition and mineral content differences correlate with the depositional environment. The relationship of vitrinite reflectance to the presence of shaly coal or liptinite indicates that it too is influenced by the depositional environment.
4.6. DISCUSSION

Summaries of maceral composition and liptinite fluorescence colour and intensity of dom and coal from the twelve petroleum exploration wells studied are given in Appendix 4.2. The composition of maceral groups in the Miocene and Eocene coal samples collected from shallow drilling is presented in Appendix 4.2.

The results of the present petrographic study show that the Tanjung, Warukin and Dahor Formations contain lithologies rich in dom and a number of coal seams. Laterally, abundance of dom in each formation does not seem to show much variation. However, coal content and variation in maceral group compositions are not consistent in all wells.

As can be seen in Figs 4.2-4.4 and 4.6-4.8, vitrinite forms the majority of the organic matter within stratigraphic units (Tanjung, Berai, Warukin and Dahor Formations) both in dom and in the coal. The second most abundant maceral group is liptinite within the Tanjung, Warukin and Dahor Formations. In the Berai Formation, inertinite appears to be the second most abundant maceral. In the Asem Asem Basin, however, the dom has a slightly higher inertinite content in the Berai and Warukin Formations than in the Barito Basin. The majority of organic matter types are of higher plant origin. Similar results were reported by Panggabean (1988, 1989) in an earlier preliminary report.

Telovitrinite is more prominent than dextrovitrinite and
gelovitrinite. Thin to thick telovitrinite bands (thickness ranging from 0.01 mm to 1.0 mm) are partly interbedded with detrovitrinite. Detrovitrinite predominantly occurs as a detrital groundmass while gelovitrinite is commonly found as inclusions within, or associated with, detrovitrinite and telovitrinite.

Gelification has been a very important precursor of the present vitrinite textures. Teichmuller (1982) suggested that gelification may be either biochemical or geochemical. Taylor et al. (1982) assumed that when the preservation of botanical structure is generally good, such coal has undergone minimal gelification. Moore and Ferm (1990) found that the Tertiary coal of southeastern Kalimantan contains well preserved plant structures, such as stems, roots and leaf tissues. Their microscopic observations revealed that variation in the level of preservation of plant structures and tissues during changes associated with the peat to coal transition results in the differences between non-banded and banded coal.

Liptinite macerals are the second most abundant maceral component in both the Miocene and Eocene coals. The most prominent liptinite macerals are sporinite, resinite and cutinite. Suberinite, fluorinite and exsudatinite are a less abundant group of liptinite macerals.

The telalginate is referable to Botryococcus sp., and occurs only in a few samples but is present in some samples from both the Miocene and Eocene coals. Botryococcus-related telalginate has also been noted by Daulay (1985) in the Ombilin coal and, in addition to the
occurrences noted in the present study, it is also known to occur in some coals from the Ketungau-Melawi Basins in West Kalimantan (Heryanto, pers. comm., 1990). Although Pediasstrum-related alginate was not seen to occur in the samples studied, its presence was noted in shales from some Indonesian Tertiary basins (Daulay and Cook, 1988).

The most common inertinite macerals are inertodetrinite, sclerotinite and sem fusinite; subordinate micrine and minor macrine are also present. Micrine occurs as very fine particles (less than 1 μm in diameter) which are commonly disseminated within vitrinite, and to a lesser extent, in liptinite macerals. Teichmuller (1974) and Teichmuller and Ottenjann (1977) considered micrine to be a secondary maceral derived from liptinite due to metamorphism at the high-volatile bituminous stage. They believed that its occurrence is related to petroleum generation from liptinite by disproportionation reactions. Shibaoka (1978, 1983) regarded porogeline as the main progenitor of cavity-filling micrine and considered it to be generated in response to an increase in rank.

Cook and Struckmeyer (1986) and Struckmeyer (1988) assumed that micrine forms as a degradation product associated with the generation of oil and related fluids from vitrinite, and also from some liptinite macerals. There is a possibility that the origin of some micrine in the Tertiary coal of southeastern Kalimantan is related to the early formation of abundant fluid oil-related substances noted within vitrinite and some liptinite.

Based on sedimentological features of the clastic rocks
associated with the coals, the Tertiary coal seams in southeastern Kalimantan were evidently deposited in low-lying swamps adjacent to a meandering river system which was part of a fluviatile dominated delta environment (see Chapter 3). From petrographic data, the maceral proportions in the coal samples suggest that they formed in wet forest swamps since the gelification index (GI) and tissue preservation index (TPI) defined by Diessel (1982, 1986) are relatively high. This supports the suggestion made by Mishra (1986), who compared the facies of some Indian, Canadian and New Zealand coals with a limited number of Indonesian Tertiary coals (Fig. 4.20), that the peat-forming facies was closely comparable with present-day peat deposits in Sarawak and Brunei (Anderson, 1964). He found the peat developed in areas of high rainfall is analogous to the raised swamps in regions with a temperate climate.

A comparison between the coal seams in the present study and other Indonesian coal deposits is based on the data from Daulay (1985; Fig. 4.21). In general, maceral group composition in the majority of Tertiary Indonesian coals shows very little variation so that the fields are largely superimposed on each other. They contain remarkably high vitrinite contents (70%-90%). However, coal from Bukit Asam (South Sumatera Basin) and East Kalimantan (Kutei Basin) contain slightly higher inertinite contents compared with other Indonesian coal. In addition, the Ombilin coal (West Sumatera) has a lower amount of liptinite macerals, while southeastern Kalimantan coal seams have significantly higher liptinite contents. Compared with overseas coal
deposits (cf. Smith, 1981; Daulay, 1985; Kim, 1987; and Mishra, 1986), Fig. 4.21 shows that the Tertiary Indonesian coals are very similar in composition to those of West Germany, Taiwan, New Zealand and Victoria, and to some South Korean coal deposits. They are, however, quite different from Indian, Turkish and Canadian coal deposits which have much higher inertinite contents. Depositional environment, climate and plant types are probably responsible for these differences in coal composition.

From previous discussion (Section 4.4), migrabitumen and other natural oil substances (oil cuts, oil droplets and dead oils) occur either associated with dom or coal throughout the stratigraphic units sampled. Petrographic data show that migrabitumen is more prominent especially in the Miocene coal than in the dom (Fig. 4.14).

Migrabitumen and exsudatinite are not easy to separate in most of coal samples studied, except where veins of exsudatinite occur in coal, or isolated masses of migrabitumen are associated with dom. Both migrabitumen and exsudatinite have similar properties in terms of reflectance, fluorescence intensity and colour. Morphological characteristics do not effect a complete separation.

Exsudatinite typically occurs as infillings of cracks, cavities and some cell lumens. It has been regarded as secondary solid bitumen derived from resinite (Teichmuller, 1974; and Stach et al., 1982). Cook and Struckmeyer (1986) and Struckmeyer (1988) suggested that the origin of exsudatinite/bitumen is more diverse than simply an exudate
from resinite.

Results of the present study indicate that most migrabitumen is not associated with any specific liptinite maceral or macerals, although some must originate from them. The dominance of migrabitumen occurrence within vitrinite (largely in telovitrinite and but also some in detrovitrinite) may be due to the greater frequency of cracks, especially cleat fractures, in vitrinite. Migrabitumen is rarely found in the open cell lumens of inertinite. Detailed observations of migrabitumen in many coal samples from the study area led to the following conclusions about migrabitumen occurrence (Fig. 4.22):

1. Migrabitumens are probably derived from liptinite assemblages as these components have higher H/C ratios than other macerals, but vitrinite macerals provide some contribution.

2. Liptinite macerals are more elastic than vitrinite and inertinite. Consequently, cracks and cleat fractures are less common within liptinite compared with other maceral groups.

3. Liptinite macerals tend to expel liquid hydrocarbons, which may favour effective migration out of liptinite itself. Conversely, vitrinite macerals, which have fractures and pores, have a higher absorption capacity. Therefore, liquid hydrocarbons which have been released by liptinite migrate out and are adsorbed by vitrinite but may also become reservoired in cleat fractures and cracks within vitrinite.

4. The processes above may have commenced at vitrinite
reflectances of about 0.4% and become less effective when the vitrinite reflectance exceeded 0.7%. According to Ting (1987) weakly anisotropic coal (low rank coal) contains more absorbed hydrocarbons than strongly anisotropic coal (high rank coal). The southeastern Kalimantan coal deposits are weakly anisotropic and contain considerable amounts of migrabitumen.

4.7. SUMMARY

Organic petrology reveals that vitrinite macerals are the dominant constituents of both dom and coal in the Tanjung, Warukin and Dahor Formations. Liptinite macerals are the second most abundant while inertinite is a minor component. However, inertinite macerals are more abundant in the marine sequences of the Berai Formation.

In general, the Eocene and Miocene coal deposits do not differ greatly in terms of maceral group composition. However, the Eocene coal seams contain slightly higher liptinite contents and are generally higher in rank than the Miocene coal. Vitrinite reflectance of the Eocene coal is 0.60% on average, whereas for the Miocene coal it is 0.47%.

Q-mode cluster analyses suggest that some lateral and vertical variations in coal seam compositions exist. The variations are largely associated with differences in vitrinite reflectance (generally related to type and environments of deposition rather than rank), mineral
mater, some maceral compositional features and migrabitumen content.

Migrabitumen is more prominent in the coal seams than in dom in both relative and absolute terms. Liptinite and vitrinite are the main source of migrabitumen. The occurrence of migrabitumen is assumed to be closely related to the adsorption capacity of vitrinite and the abundance of cleat fractures and cracks within vitrinite.
CHAPTER FIVE

SOURCE ROCK POTENTIAL, MATURITY AND HYDROCARBON GENERATION

5.1. INTRODUCTION

Reflected light microscope studies of organic matter in whole rock samples from the Tertiary sequences (Tanjung, Berai, Warukin and Dahor Formations) in both the Asem Asem and Barito Basins were used to identify and characterize the various maceral constituents. Their abundance and rank were used to determine source rock potential, the level of maturity and hydrocarbon generation characteristics. The assessment was based on the assumption that all macerals are capable of generating liquid hydrocarbons and gas. However, the degree of generation capacity may be different between the macerals.

Most organic matter in the Tertiary successions appears to be derived from higher plants; particularly that in the coal and shaly coal. Although dispersed organic matter (dom) contents in most of the clastic rocks (except for the carbonate rocks of the Berai Formation) are high, the majority of the organic matter occurs as beds of coal and shaly coal. The ratios of thickness between coal + shaly coal and clastic rocks are 4:100 in the Tanjung Formation, 6:100 in the Warukin Formation and 1:100 in the Dahor Formation. The Berai Formation does not contain coal and has a very low content of dom.
5.2. SOURCE ROCK POTENTIAL

Marine source rocks were effectively considered to be an essential precursor for oil for many years. Later, in the 1960's and 1970's terrestrially-derived organic matter was proposed as source rocks (e.g. Hedberg, 1968; Brooks, 1970; Philippi, 1974; and Durand and Oudin, 1979). In the early 1980's organic petrological and geochemical investigations indicated that coal seams played an essential component of liquid hydrocarbon source potential in many oilfields, especially in Australia and Southeast Asia (e.g. Smith, 1981; Thomas, 1982; Smith and Cook, 1984; Durand and Paratte, 1983; Tissot and Welte, 1984; Bertrand, 1984; Bertrand et al., 1985; Saxby and Shibaoka, 1986; Cook et al., 1985; Cook and Struckmeyer, 1986; Gordon, 1985; Cook, 1987; and Struckmeyer, 1988).

Smyth et al. (1984) developed a scoring system to rate prospects within the Birkhead Formation in the Eromanga Basin, Australia. The volume and composition of the three main maceral groups were used to calculate the scoring system developed by Struckmeyer (1988), from the system used by Smyth et al. (1984), for the assessment of hydrocarbon generating potential. The hydrocarbon generating potential score is calculated (using volume % of constituents in the sample) as follows:

\[ \text{Score} = \text{Liptinite} + 0.3 \times \text{Vitrinite} + 0.05 \times \text{Inertinite} \]

This formula was accepted for the present study since the
proportions of vitrinite, liptinite and inertinite in the southeastern Kalimantan samples are closely comparable with organic matter contents in the Otway Basin (Panggabean, 1986; Struckmeyer, 1988). The range of scores for the hydrocarbon generating potential terms used is given in Table 5.1.

The hydrocarbon generating potential score was employed to evaluate the various stratigraphic units examined in this study and the results are presented in Table 5.2. Calculated values of the score for individual samples from the Dahor Formation range from less than 0.1 to 8.0. Mean values for each of the various well sections range from 0.7 to 4.0. This indicates that the overall hydrocarbon generating potential of the formation is poor, although the best and most significant source rocks of the formation are present in the SMD-1 and BKO-1 well sections where mean values of 3.3 and 4.0 indicate fair source potential.

Hydrocarbon generation potential of dom in the underlying Warukin Formation is fair to very good with the mean scores ranging between 3.4 and 14.3 (Table 5.2). However, poor hydrocarbon generation potential occurs in this unit in MYA-1 well where the mean value for the only sample analysed is 0.6. Thirty Miocene coal samples from shallow drill cores of the Warukin Formation had a mean score of 52.2 which indicates excellent source potential. Overall, the Warukin Formation including coal seams is considered as having the best score potential for hydrocarbon generation.

Organic petrological data for some limestone samples
from the Berai Formation indicate that they contain no organic matter. Rare to sparse dom, consisting predominantly of inertinite, occurred only within associated calcareous siltstone and marl. Organic matter of marine origin comprising phytoplankton is rare. Hydrocarbon generation potential for the Berai Formation is poor with scores ranging from less than 0.1 to 0.3.

The dom from the Tanjung Formation has mean score values ranging between 4.3 and 6.3 throughout the well sections, which indicate that the source potential is fair to good. The mean score value calculated from 161 Eocene coal samples from the formation is 54.4 (excellent). Overall the Tanjung Formation, including coal, is considered to have a very good source potential, although the uppermost section is poor due to the existence of an organic-lean carbonate layer (see Chapter 3).

Struckmeyer (1988) compared the hydrocarbon generation potential scores to values of Rock Eval pyrolysis (S1 + S2) (Fig. 5.1). The quantity S1 is considered to represent the fraction of the original generating potential of organic matter which has been effectively transformed into hydrocarbons; S2 indicates fractions which have not yet been transformed into hydrocarbons (Espitalie et al., 1977; and Tissot and Welte, 1984). Based on the Rock-Eval pyrolysis value, Tissot and Welte (1984) defined the classification of the source rock potential as:
\[ S_1 + S_2 = < 2 \text{ kgt}^{-1} \] (poor oil source rock, source potential for gas)
\[ S_1 + S_2 = 2 - 6 \text{ kgt}^{-1} \] (moderate source rock)
\[ S_1 + S_2 = > 6 \text{ kgt}^{-1} \] (good source rock)

To estimate \( S_1 + S_2 \) values for all the southeastern Kalimantan samples in the Asem Asem and Barito Basins examined in this study, the means of all hydrocarbon generation potential scores in Table 5.2 were plotted on the best fit line of the diagram Fig. 5.1 from Struckmeyer (1988). This estimation shows that the \( S_1 + S_2 \) values of samples from southeastern Kalimantan are comparable to those for a number of samples of the Pretty Hill and Eumeralla Formations, Otway Basin, examined by Struckmeyer (1988). The Dahor Formation having score values of less than 5 (poor to fair hydrocarbon generation potential) shows estimated \( S_1 + S_2 \) values ranging from 0.4 kgt\(^{-1}\) to 4 kgt\(^{-1}\). Plotting scores for the Berai Formation results in estimated \( S_1 + S_2 \) values ranging from 0.1 kgt\(^{-1}\) to 0.5 kgt\(^{-1}\) for score values of less than 0.6. This formation represents a zone of poor hydrocarbon generation potential, although it may represent a significant reservoir for hydrocarbons in some locations. Samples from the Warukin Formation fall in a zone of hydrocarbon potential ranging from poor to very good as the values of scores varies between 0.4 and 19.0, and the estimated \( S_1 + S_2 \) ranges from 0.4 kgt\(^{-1}\) to 40 kgt\(^{-1}\). The Tanjung Formation is situated between the zone of fair and good hydrocarbon generating potential where the scores range from 4 to 6.3, and the estimated \( S_1 + S_2 \) values range from
4 kg t\(^{-1}\) to 9 kg t\(^{-1}\).

The Miocene and Eocene coal seams are all situated within the zone of excellent hydrocarbon generation potential. Consequently, both the Warukin and Tanjung Formations are considered to be the units having the best hydrocarbon generation potential. This hypothesis is supported by total organic carbon (TOC) values in Table 5.3 (Lemigas, 1983) for the Berai and Tanjung Formations. The average TOC from the Berai Formation is 0.41% indicating that the source rock potential is very poor (Cornford, 1986). Unlike the Berai Formation, the Tanjung Formation has an average TOC value of 0.82%. This value does not include coal samples. One coal sample from the Tanjung Formation has a TOC value of 40.83%. Thus, this formation is categorized as having a good source rock potential. Even though no TOC data is available for the Warukin Formation it can be assumed, based on petrographic data, to be similar to that of the Tanjung Formation.

5.3. ORGANIC MATURATION AND HYDROCARBON GENERATION

Assessment of vitrinite reflectance values and thermal gradients is essential and critical for evaluating the level of organic maturation and hydrocarbon generation. Thus, the maturity of organic matter in coal and sedimentary rocks is, in general, indicated by the level of coalification; a form of low grade metamorphism which is controlled by factors such as temperature, time and pressure. Generally both
coalification and hydrocarbon generation processes result from elevated temperatures acting on organic matter over geologic time (Cook, 1982).

Many authors have sought to establish the relationships between the maximum palaeotemperature, the length of time of exposure to elevated temperatures and vitrinite reflectance (e.g. Karweil, 1956; Vassoevich et al., 1970; Teichmuller, 1971; Lopatin, 1971; Hood and Castano, 1974; Mathews et al., 1975; Castano and Sparks, 1974; Dow, 1977; Bostick, 1973, 1979; Burne and Kantsler, 1977; Kantsler et al., 1978a,b; Kantsler and Cook, 1979; Cook and Kantsler, 1980; Smith, 1981; Waples, 1980; and Smith and Cook, 1980, 1984).

Although other rank parameters and indicators of maturity can be used, vitrinite reflectance is the most convenient, consistent, sensitive and widely accepted variable. It therefore forms the basis of the maturation evaluation in the present study.

5.3.1. Level of Maturation

The results of vitrinite reflectance measurements (Appendix 4.3) from twelve petroleum exploration wells show that the highest vitrinite reflectance level (0.85%) was found near the base of Tanjung Formation at 3834 m depth in SMD-1 well. The lowest value of 0.20% was recorded in the Dahor Formation and part of the Warukin Formation, at various shallow depths (from 0 to 210 m), in MRTP-1X, BKO-1, SMD-1, BRK-1, A1, A2, PB-1 and PB-2 wells.

Reflectance versus depth profiles plotted using
arithmetic scales (Figs 5.2-5.7 and 5.9), show significant linear or near-linear relationships in all well sections from the present surface down to approximately 3000 m depths. However, beyond that depth, the profiles of SMD-1 (Fig. 5.5) and BRK-1 (Fig. 5.4) wells show an inflection towards higher reflectance gradients in the lower section of the Warukin and Tanjung Formations, respectively, than in the upper sections of these formations. Higher vitrinite reflectance gradients result from a combination of high temperatures and/or temperature gradients associated with the proximity of basement (cf. Kantsler and Cook, 1979).

In general, reflectance gradients are approximately constant from the surface to the base of most wells (see Table 5.7). Small discontinuities in the reflectance profiles are found in A-1, A-2, BRK-1, BKO-1 and SMD-1 wells, between the Dahor Formation and the underlying Warukin Formation. They coincide perfectly with the presence of the unconformity plane (Chapter 2). The ranges of reflectance gradients at the 0.50% \( R_{v,\text{max}} \) level are low, typically ranging from 0.11%/km to 0.19%/km for all well sections over the depth range from 800 m to 2800 m. However, at similar vitrinite reflectance level (0.50% \( R_{v,\text{max}} \)), moderately low reflectance gradients (0.20%/km - 0.25%/km) are found in MYA-1, MRTP-1, BRK-1 and PB-2 sections. At the 0.70% \( R_{v,\text{max}} \) level, moderately high reflectance gradients (0.26%/km - 0.30%/km) occur at depths between 1000 m and 2500 m in A-1 well and beyond 3400 m depth in SMD-1 well.

Vitrinite reflectance gradients in southeastern
Kalimantan basins appear to be low compared with those in
the Sangata and Bunyu Island areas in the Kutei Basin
reported by Samuel (1980) and Fukasawa (1987). In the
latter areas, the reflectance gradients range from about
0.30%/km to 0.35%/km at the 0.50% \( R_{\text{v}}^{\text{max}} \) level, which are
comparable with the values at the 0.70% \( R_{\text{v}}^{\text{max}} \) level found in
the SMD-1 and A-1 sections.

Most vitrinite reflectance gradients from the present
data are low compared with the gradients of Australian
profiles reported by Kantsler et al. (1978a,b). They are,
however, similar to the reflectance gradients reported for a
number of sections of Late Cretaceous and Tertiary age in
the Gippsland (Smith and Cook (1984) and Otway Basins
(Panggabean, 1986; Struckmeyer, 1988) in Australia.

Figure 5.8 shows a plot of vitrinite reflectance versus
depth for all samples examined from both the Asem Asem and
Barito Basins. The envelope for all vitrinite reflectances
in Fig. 5.8 has a strong linear component and shows an
overall positive correlation between depth and rank. Rank
increases with depth in the southeastern Kalimantan basins
and the gradient appears to average about 0.13% \( R_{\text{v}}^{\text{max}}/\text{km}.\)
Figure 5.9 shows the trend lines of increasing maturity in
each well.

The oil generation zone or "oil window" is widely
accepted to lie between 0.50% and 1.35% \( R_{\text{v}}^{\text{max}} \) (Heroux et
al., 1979; Cook, 1982; Smith and Cook, 1984; Tissot and
Welte, 1984; and Cook, 1986). Hence, the profiles in
Figs 5.8-5.12 indicate that the oil generation zone has
generally been reached below 1600 m depth in the Asem Asem
and Barito Basins. The Tanjung Formation is generally mature in the Barito Basin (MRTP-1X, MYA-1 and SMD-1 wells; Fig. 5.10). A similar situation is also found in the southern part of the Asem Asem Basin (A-1 and probably A-2 wells) as illustrated in Fig. 5.10. However, the sequence is early mature in the Tanjung Formation in the northern Asem Asem Basin (PB-1 and probably PB-2 and JGRU-1; Fig. 5.12).

The Berai Formation is marginally mature to mature in the MRTP-1X, MYA-1, SMD-1 wells and parts of the BRK-1, DS-2, A-2 and PB-1 wells. The Berai Formation is also immature in MRTP-1X, SMD-1, MYA-1, BRK-1, PB-1, PB-2 and DS-2 wells where intersected but is probably late mature or overmature for oil generation in areas where a thick section of the overlying Warukin Formation is present.

The lower Warukin Formation is mid and possibly late mature for oil generation in the Barito Basin and the southern part of Asem Asem Basin (BKO-1, SMD-1, BRK-1, PRN-2 and A-1; Figs 5.10 and 5.11). The marginally mature zone occurs in the middle and upper parts of the Warukin Formation in the MRTP-1X, BKO-1, SMD-1, BRK-1, PRN-2, A1 and A2 wells, whereas the middle and upper parts of the Warukin Formation are immature throughout the well sections in the northern part of Asem Asem Basin (PB-1 and PB-2; Fig. 5.12) and in uppermost sections of A-1 and A-2 wells (southern part of the Asem Asem Basin) and MRTP-1X, PRN-2, BS-1 and DS-1 wells (Barito Basin).

The uppermost Warukin Formation and the Dahor Formation are immature for hydrocarbon generation. The significant
variation in depth for given reflectance levels and gradients in the various well locations examined (Figs 5.11 and 5.12) indicates considerable differences in the maturation patterns throughout the basins. Laterally, variation of maturation patterns is also evident in line sections, such as Figs 5.10 and 5.13. The latter figure shows contour patterns for depths equivalent to the 0.6% reflectance level ($R_{\text{vmax}}$). The contour patterns are closely related to the major structural features of the Barito and Asem Asem Basins. The contours indicate that depths to given reflectance levels are shallower on the flanks of the Meratus Range which consists of pre-Tertiary basement rocks. The greatest depths to the 0.6% $R_{\text{vmax}}$ reflectance level (over 2000 m) are situated in the southern and eastern parts of the Asem Asem Basin and the western and northern parts of the Barito Basin (near the Tanjung area).

Isoreflectance surfaces in the Barito Basin (Fig. 5.10) indicate that two major events have occurred in terms of the relationship between coalification and tectonism (based on Teichmuller, 1968; and Teichmuller and Teichmuller, 1982). They can broadly be placed in the pre-tectonic and post-tectonic coalification categories.

Post-tectonic coalification is most evident in the Dahor Formation sections where the isoreflectance surfaces appear to be concordant with the major stratigraphic units. This suggests that coalification in this unit is related to the present basin configuration, and major tectonic deformation has not occurred during or after coalification.

In contrast, syntectonic (or pre- + post-orogenic)
coalification has occurred within the Tanjung, Berai and Warukin Formations, as the isoreflectance surfaces are mostly oblique to the major stratigraphic boundaries. Therefore, the coalification may have started before folding commenced and been completed towards the end of the folding events. Uplift has then caused these coalification patterns to be "frozen" imprinted on the sequences.

Figures 5.11 and 5.12 show the isoreflectance surfaces in the southern and northern Asem Asem Basin respectively. The contour patterns appear to be closely similar in both sections. The isoreflectance pattern in the Dahor Formation is also very similar to that in the Barito Basin (post-tectonic coalification). Iso-rank surfaces are semi-oblique to oblique to the major stratigraphic boundaries within the Warukin, Berai and Tanjung Formations, indicating synorogenic coalification or a combination effect of pre-orogenic and post-orogenic coalification. Therefore, coalification in the southeastern Kalimantan basins both pre- and post-dates the Meratus Orogeny. The relative importance of each component varies systematically with stratigraphic position (pre-orogenic coalification is more important for the older units) and with geographic location (pre-orogenic coalification is more important close to the axis of the Meratus uplift; A.C. Cook, pers. comm., 1990).
5.3.2. **Microscopic Features indicating Hydrocarbon Generation**

Of the three main maceral groups, liptinite is considered to be most significant producer of hydrocarbons per unit volume (Smith and Cook, 1980; Cook, 1982; Smyth *et al.*, 1984; Smith and Cook, 1984; Cook and Struckmeyer, 1986; Saxby and Shibaoka, 1986; and Struckmeyer, 1988). However, vitrinite-rich source rocks, including sequences with coal seams, are thought to be producers of both gas and some oil (Smyth, 1983; Smith and Cook, 1984; Cook and Struckmeyer, 1986; and Saxby and Shibaoka, 1986).

Microscopic features, such as migrabitumen, oil droplets and oil cuts, oil haze, dead oil and micrinite, indicate that oil generation has taken place in both dom and coal from southeastern Kalimantan (Table 5.4). The data show that all the above petrographic features occur over the range of vitrinite reflectance between 0.30% and 0.85% for most samples from the Warukin and Tanjung Formations.

As mentioned in Chapter 4, both dom and coal in stratigraphic units from southeastern Kalimantan are dominated by vitrinite, followed by liptinite, but inertinite is generally only a minor component. The approximate range of vitrinite reflectance over which liquid hydrocarbons are generated by various macerals was discussed by Smith and Cook (1984; Fig. 5.15). Cook (1986) has suggested reflectance ranges for oil generation from the various macerals based on his work in the Eromanga Basin and these are given in Table 5.5.
The assessment of oil generation by various macerals in the southeastern Kalimantan basins was based on the suggestions given by Cook (1982), Smith and Cook (1984) and Cook (1986). These previous authors concluded that telovitrinite and detrovitrinite, followed by suberinite and resinite, begin to generate oil at a rank of about 0.40%–0.45% $R_v^{\text{max}}$, and that the main oil generation phase of these macerals ranges from 0.50% to 1.0% $R_v^{\text{max}}$ (see Table 5.5). The peak for oil generation from sporinite, cutinite and alginite macerals lies between 0.70% and 0.90% $R_v^{\text{max}}$. According to Cook (1986), exsudatinite is commonly developed in coal with reflectance values as low as 0.40% $R_v^{\text{max}}$. Over this rank range liptodetrinite also generates liquid hydrocarbons.

The release of liquid hydrocarbons in the southeast Kalimantan basins at a rank as low as 0.30% $R_v^{\text{max}}$ does not fit most commonly accepted theories, although Teichmuller (1974) did suggest a threshold of 0.30% in some of her earlier work on oil generation. Alternatively, oil and migrabitumen which are associated with dom at low rank may possibly be explained by migration from the deeper parts of the succession which have a much higher maturity. However, organic petrology in this study does suggest the occurrence of migrabitumen, oil cuts, oil drops, oil haze and fluorinite, which are more typically associated with coal and shaly coal in southeastern Kalimantan, to be of in situ origin or may be derived from local migration within the coal itself, as mentioned in Chapter 4.

Struckmeyer (1988) concluded that the peak of oil
generation from telovitrinite, detrovitrinite, suberinite and resinite is reached over the range 0.50% to 0.80% $R_v$ max, while other macerals, such as sporinite, cutinite and alginite, yield maximum oil between about 0.70% to 0.90%. Inertinite releases hydrocarbons (particularly gas) at ranks ranging from 0.20% to 0.50% $R_v$ max (Smith and Cook, 1984). Furthermore resinite-rich source rocks generate liquid hydrocarbons at a rank between 0.40% and 0.60% (Snowdon and Powell, 1982). Thus the rank values of the previous studies are nearly equal to the general peak of hydrocarbon generation defined in Fig. 5.14.

5.4. THERMAL AND BURIAL HISTORY

Increases in rank are associated with increasing temperatures at depth and the dependence of rank gradient on geothermal gradient has been extensively documented for numerous boreholes (e.g. Castano and Sparks, 1974; Kantsler et al., 1978; Bostick, 1979; and Teichmuller and Teichmuller, 1982). The increase in rank with depth is often referred to as "Hilt's Law" (Hilt, 1873). As hydrocarbon generation is dependent on temperature, estimation of palaeotemperature and thermal history from the coalification pattern may provide an indicator of the extent and timing of oil generation (see Section 5.4.2 below).
5.4.1 Geothermal Gradient

The present distribution of subsurface temperatures in the southeastern Kalimantan basins is derived from downhole temperature data based on logging runs. From the available borehole temperature data, geothermal gradients for the twelve wells may be calculated assuming a linear relationship between temperature and depth. In the absence of sufficient data on elapsed time, the formation temperatures have been corrected for cooling by circulation of drilling muds. A factor of 10% was added to the downhole logged temperature as suggested by Harper (1971), Thomas (1979) and Kantsler and Cook (1979).

Geothermal gradients calculated in this study were derived from the formula: \( \frac{dT}{dx} = \frac{(T - T_0)}{x} \), where \( T \) is the borehole temperature, \( T_0 \) is the surface temperature, and \( x \) is well depth at which the temperature \( (T) \) was measured. In this calculation, the mean annual surface temperature (onshore) is about 26°C (cf. Sikumbang, 1986) for southeastern Kalimantan. For the wells located offshore (A-1, A2, PB-2) the surface temperature is assumed to be close to that for the onshore area as the depth of the seafloor is less than 40 m.

The present geothermal gradients calculated for the twelve well sections studied are given in Table 5.6. Additional geothermal gradient data for other wells situated in southeastern Kalimantan were obtained from Aadland and Phoa (1981). The geothermal gradients range from 20°C/km to 55°C/km, and the average is approximately 33°C/km. The data
indicate that significantly higher geothermal gradients (28°C/km - 55°C/km) occur in the northern part of the Asem Asem Basin (south-southwest of Balikpapan), in the Tanjung area (27°C/km - 44°C/km) and the area west of Banjarmasin (35°C/km - 38°C/km). Low to moderate geothermal gradients are situated on the northwestern flank of the Meratus Range and in the southern part of the Asem Asem Basin (20°C/km - 30°C/km). The highest value of the present geothermal gradient is probably related to the Meratus uplift events.

Compared with the Tarakan Basin (see Fig.1.2), the average thermal gradient in the southeastern Kalimantan basins is much lower. Samuel (1980) noted the average geothermal gradient from Bunyu Island is 43°C/km. In the Attaka oilfield (offshore Kutei Basin) it is also low (about 20°C/km; Schwarts et al., 1973). Thamrin et al. (1980, 1981, 1982) reported temperature gradients from the North Sumatera Basin (average 41.4°C/km), Central Sumatera Basin (average 67°C/km), South Sumatera Basin (average 52.6°C/km) and Northwest Java Basin (average 41.4°C/km). The highest values are found in the Central Sumatera Basin. Reminton and Pranyoto (1985) pointed out that geothermal gradients in the Rengasdengklok and Arjawanungun areas of the Northwest Java Basin range from 44.4°C/km to 49.1°C/km and they increase southwards in the direction in which the Tertiary sequence thickens.
5.4.2. Palaeotemperature

The thermal history of selected formations in the southeastern Kalimantan basins is summarized in Table 5.6. All palaeotemperature values were obtained from the calculation of theoretical mathematic models developed by Kantsler et al. (1978a,b) based on the Karweil and Bostick nomogram (Fig. 5.16). The method is based on calculation of palaeotemperatures from measured values of vitrinite reflectance and the age (Ma) estimated using biostratigraphic correlation of the units.

In order to establish the relative palaeothermal history of a formation, Smith (1981) and Smith and Cook (1984) suggested testing isothermal and gradthermal models against present temperature. $T_{iso}$ (isothermal) values were determined from vitrinite reflectance data (using Scale-H on Fig. 5.16). $T_{grad}$ (gradthermal) was obtained from the $T_{iso}$ value multiplied by a conversion factor, i.e. $(T_{iso} - 10^°C) \times 1.6 + 10^°C$ (Cook, 1982; and Kantsler, 1985). The gradthermal model is a test which assumes that the sequences underwent continuous burial with temperature rising at a steady rate up to a present day maximum. $T_{iso}$ provides the temperature required to generate the vitrinite reflectance values over the whole period of coalification since deposition of the unit. In other words the sedimentary sequences would have achieved this temperature very early in the burial history. According to Smith (1981) and Smith and Cook (1984) a quantitative estimation of the timing of thermal events can be obtained by calculating the following
ratio:

\[ \text{Grad:Iso} = \frac{(T_{\text{pres}} - T_{\text{iso}})}{(T_{\text{grad}} - T_{\text{iso}})} \]

If the ratio \((\text{Grad:Iso}) < 1\), the present geothermal gradient is higher than in the past and the formation history approaches the gradthermal model. Conversely, if \((\text{Grad:Iso}) < 1\), the present geothermal gradient is lower than in the past and the formation history approaches the isothermal model. If the ratio is negative \((\text{Grad:Iso}) < 0\), the present temperature is lower than the isothermal temperature; that is, the isothermal palaeotemperature was significantly higher than the present temperature.

The results of model temperature calculations from the twelve well sections in the southeastern Kalimantan basins are presented in Table 5.7. Overall, \(\text{Grad:Iso}\) ranges from \(-1.04\) to \(+0.75\) and data from most of the wells (with the exception of MRTP-1X and SMD-1 wells at depths 2847 m, 3374 m, 3566 m and 3774 m where \(\%R_v\) ranges from 0.61\% to 0.83\%) indicate that \(T_{\text{pres}} < T_{\text{grad}}\). This evidence suggests that the present formation temperatures are significantly lower than those in the past. This assumption is in contrast with the results for a number of Australian sedimentary basins, such as the Perth and Carnarvon Basins (Cook and Kantsler, 1980) where the gradthermal temperatures are consistently below the present well temperatures by a considerable margin. Nevertheless, the gradthermal model in this study is comparable with some results for the gradthermal model obtained by Panggabean (1986) and Struckmeyer (1988) for the Otway Basin, Victoria, Australia.
Figure 5.17 shows a plot of the relationship between $T_{\text{grad\,thermal}}$ and $T_{\text{present}}$ for samples from the southeastern Kalimantan basins and other Indonesian Tertiary Basins (South Sumatera, West Sumatera, East Kalimantan and West Java) calculated by Daulay (1985). With the exception of the West Java Basin, the majority of results for the Indonesian Tertiary basins, including the Asem Asem and Barito Basins, are spread out below the tie line ($T_{\text{pres}} = T_{\text{grad}}$), but the data show a distinct trend to greater deviation from the tie line with increasing rank. Overall, the model and palaeothermolecal calculations indicate that relatively rapid, early coalification for the sections of Eocene age occurred over most of the southeastern Kalimantan basins. A second more rapid phase of coalification then affected the lower part of the Miocene succession. A late Miocene/Pliocene history (probably post-Meratus uplift) of constant or falling temperature resulted in a lowered thermal drive on maturation and migration. The basins studied are dominated by senescent thermal regimes.

5.4.3. Timing of Hydrocarbon Generation using Lopatin's Method

Attempts were made to assess the timing of hydrocarbon generation in the southeastern Kalimantan basins using the method of Lopatin (1971), as modified by Waples (1980, 1985). The model used assumes that the rate of organic maturation increases by a factor ($r$) which is close to a value of 2 for every $10^\circ\text{C}$ rise in temperature. The
temperature factor \( r \) at \( 10^\circ \text{C} \) temperature intervals is then formulated as \( r = 2^n \) where \( n \) is an index value used by Waples (1985). The product of time factor \( (dt) \) for any temperature interval and appropriated 'r' factor was defined by Lopatin (1971) as the Time - Temperature Index. The time temperature integral (TTI) represents the maturity of a rock unit for a given period in the "r" temperature interval and is expressed as follows:

\[
\text{TTI} = \sum_{n=\text{min}}^{n=\text{max}} (dt_n) (2^n),
\]

where \( n_{\text{max}} \) and \( n_{\text{min}} \) are the highest and lowest values of the temperature intervals encountered. Lopatin's model includes a construction of the subsidence curves for each rock unit within a well section. The value of TTI is obtained by knowing the grid of subsurface temperatures for every depth throughout the burial history using the present day geothermal gradient. The results show a band approximating the movement of the oil generation zone with time. The relationship between TTI values and measured vitrinite reflectance data provide significant information concerning the burial history and timing of organic maturity (Table 5.8).

Burial history models for six selected wells (MRTP-1X, SMD-1, BKO-1, BRK-1, A-1 and PB-1) from the Barito and Asem Asem Basins were constructed by simple backstripping techniques.

Corrections for sediment compaction during burial history are disregarded in this model. However, the break
in the succession, or an unconformity, occurring between the Warukin and Dahor Formations, which is also indicated by an offset in the reflectance profile, was included in the subsidence curve. The amount of sediment cover removed from the sequence was estimated from the reflectance profiles using the method suggested by Dow (1977). The loss of cover between the Warukin and Dahor Formations was estimated from linear extrapolation of the vitrinite reflectance profile, plotted on a semilog scale, to the 0.20% reflectance intercept. The result indicates that the average thickness of cover lost at the Dahor/Warukin unconformity was 1315 m, but for the offshore wells was approximately 400 m.

The results of maturation modelling and burial history for the six representative wells are given in Figs 5.18 (MRTP-1X well), 5.19 (SMD-1 well), 5.20 (A-1 well), 5.21 (PB-1 well), 5.22 (BKO-1 well) and 5.23 (BRK-1 well).

For MRTP-1X, SMD-1, BKO-1 and BRK-1 subsidence curves show that burial during Early-Middle Eocene was probably slow to moderate and mostly continuous. Rapid burial commenced in the Oligocene and the peak rate for this event was about the early Middle Miocene when the Warukin Formation was accumulating. During this major phase of subsidence, the Tanjung and Berai Formations and part of the basal Warukin Formation entered the zone of oil generation. A vitrinite reflectance of 0.50% or TTI=3 is considered to represent the initiation of oil generation in this study. A vitrinite reflectance of 0.60% or TTI=10 was reached in MRTP-1X, SMD-1, BKO-1 and BRK-1 wells prior to rapid burial.
During this period, at the locations of MRTP-1X and BKO-1, the Tanjung Formation reached the onset of oil generation and the event was rapidly followed by the entry of the lower part of the Warukin Formation into the oil window.

The maturation history of SMD-1 differs in that the Warukin Formation is not shown as entering the oil window. However, there is a possibility that the base of the formation entered the oil generation zone (probably in late Warukin times) since the palaeothermal model indicates that the $T_{\text{grad}}$ value is greater than $T_{\text{pres}}$. The measured $R_v^{\text{max}}$ of 0.60% near the base of the Warukin Formation indicates that using the present geothermal gradient underestimates maturity levels, thus indicating a higher temperature early in the history of the sequence. Thus at the end of a rapid burial phase (early Late Miocene) a period of uplift and erosion, related to the Meratus uplift event took place throughout both basins. The uplift and erosion was followed by a second phase of moderate-rate subsidence and burial as the uppermost unit (Dahor Formation) was deposited. This last event probably coincided with a reduction of the temperature gradient as heat flow into the basin waned.

When Lopatin's model is applied to the A-1 and PB-1 wells it indicates similar burial histories to those in SMD-1, MRTP-IX, BKO-1 and BRK-1. However, the deepest burial reached by the lowermost sequence (Tanjung Formation) is only 2600 m and, modeling with the present geothermal gradient, the onset of oil generation at TTI=3 and a vitrinite reflectance of 0.50% was only achieved in the Tanjung Formation. The model also indicates that the onset
of oil maturity probably commenced in the early Late Miocene at about the time of uplift associated with the Meratus event. The onset of oil generation in these wells is later than in the Barito Basin (MRTP-1X, SMD-1, BKO-1 and BRK-1). In the Tanjung Formation, the maximum calculated vitrinite reflectance is 0.60%, which is equal to a TTI of 10. The TTI adequately models measured reflectances for PB-1, but underestimates those for the A-1 well.

5.5. DISCUSSION

The results of organic petrological studies on the clastic and carbonate rocks, coal and shaly coal indicate that, in general, the Tanjung and Warukin Formations have better source potential for liquid hydrocarbons than the Berai and Dahor Formations. This suggestion is also supported by the TOC values reported by Lemigas (1983) as mentioned in Section 5.2.

Vitrinite is the dominant maceral in both the coal and dom, while liptinite is the second most abundant maceral; inertinite is a minor component. Most of these macerals are derived from terrestrial plants and most of the organic matter occurs as coal and shaly coal.

Coal-bearing strata of the Tanjung and Warukin Formations are considered to have good source potential for oil. This is supported microscopically by the presence of significant amounts of migrabitumen and other oil related substances within the coal and shaly coal samples. These
features, observed during microscopic analysis, indicate that coal is an active generator of liquid hydrocarbons (e.g. Cook and Struckmeyer, 1986; Cook, 1987; and Struckmeyer, 1988).

Based on organic petrology and geochemistry, Saxby and Shibaoka (1986) demonstrated oil yields from coal for slow pyrolysis under geological conditions (Fig. 5.23). They suggested a ratio of 40:5:1 for the maximum specific yield of oil which could be released from liptinite, vitrinite and inertinite. As vitrinite and liptinite are the main component macerals of the Eocene and Miocene coal seams, the coal can be considered to have released significant amounts of oil capable of migrating into reservoir rocks.

Vitrinite reflectance data show that the oil generation zone is generally reached below 1600 m depth. Thus the top of the oil window occurs in the middle and lower section of the Berai Formation (Asem Asem Basin) or the Warukin Formation (Barito Basin). The Tanjung Formation is within the oil window in all sections studied. The highest level of maturity (0.75%–0.85% $R_v$ max) is evident in the lowermost section (between 3400 m and 3900 m depth) of the Tanjung Formation in the SMD-1 and MRTP-IX wells, Barito Basin. In the Asem Asem Basin the value of 0.60%–0.70% $R_v$ max represents the highest level of maturity; again occurring within the Tanjung Formation.

The gradothermal model used to study timing of thermal events indicates that the present temperatures in the basin are generally lower than those in the past. Therefore, the present geothermal gradient (average 33°C/km) is probably
lower than that operative during the main period of coalification which was probably during the Middle Miocene. The model indicates that relatively rapid coalification may have occurred during the Miocene in the basins studied.

Subsidence curves show that rapid burial commenced in the Oligocene and continued until the early Middle Miocene. The Lopatin model indicates that the Tanjung and Berai Formations, and the lowermost section of the Warukin Formation, entered the zone of oil generation during the Miocene. The subsequent period of uplift and erosion (Meratus uplift) was associated with sufficient cooling to prevent further significant increases in maturation even during the deposition of the Dahor Formation.

5.6. SUMMARY

Two major source rock sequences are present in southeastern Kalimantan. They are the Tanjung and Warukin Formations and both units consist of coal measure sequences. The Berai Formation is considered to have a less significant source potential because the organic matter content of the unit is too low.

The onset of oil generation occurs below 1600 m throughout the basin. The base of the Tanjung Formation appears to have entered the oil window zone during the Miocene. In the Barito Basin, the lower part of the Warukin Formation is also within the oil window. Rapid coalification of the lower part of the sequence was caused
by the rapid deposition of the Warukin Formation. After Warukin deposition a history of falling temperatures developed due to the Meratus Uplift.
CHAPTER SIX

ORGANIC GEOCHEMISTRY

6.1. INTRODUCTION

Organic geochemistry is the study of the organic matter in sedimentary rocks and the hydrocarbon compounds present in crude oils. Two crude oil samples (HPX-1 and HPX-2) from depths of 2100 m and 3200 m from the Barito Basin (well name is not specified in this study due to confidential data) were analysed by column chromatography, gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS). Gas chromatography (GC), with its associated separation methods, gives the best method for resolving complex mixtures of crude oils and source rock extracts (Blumer, 1975) whereas gas chromatography-mass spectrometry provides structural information on the components of complex organic mixtures, especially the class of compounds known as biological markers (biomarkers). The major classes of biomarkers used in petroleum exploration are the branched and cyclic hydrocarbons (Philp, 1985).

Summons et al. (1987) and Summons and Powell (1987) described some conditions for GC and GC-MS analyses of the saturated hydrocarbons. Similar procedures were used to analysed the aromatic hydrocarbons. The samples, in hexane
solvent, were injected on-column at 60°C and heated to 300°C at 4°C/minute for GC or 3°C/minute for GC-MS. The gas chromatograph was equipped with a 50 m x 0.2 mm ID WCOT fused silica cross-linked methylsilicon capillary column (Hewlett Packard ULTRA-1).

Hydrogen with a linear flow rate of 30 cm/s was used as the carrier gas. For GC-MS, analyses of the saturated hydrocarbons the metastable reaction monitoring method (MRM) of 25 diagnostic parent-daughter relationships was employed. The compounds analysed were the series of C_{26-30} desmethyl-, C_{28-30} methyl-, and C_{29-31} dimethyl-steranes and rearranged steranes, C_{27-34} triterpanes and C_{28-32} methylhopanes. Components in the aromatic fraction were detected using selected ion monitoring (SIM) of 25 diagnostic ions for mono-, di-, and triaromatic steranes, monoaromatic hopanes, dimethyl- and trimethyl-naphthanes, phenanthrene and methyl-phenanthrenes. The analyses were carried out by T.G. Powell and R.E. Summons of the Bureau of Mineral Resources, Canberra, on samples provided by the author.

6.2. THE RESULTS OF ANALYSES

Gross compositional data from liquid chromatography of the whole oils are given in Table 6.1. Extractable organic matter (EOM) from HPX-1 was 210.1 mg, while HPX-2 is much lower, 6.2 mg. When the latter sample was extracted by sonication of the dried residue, the result increased to
289.1 mg. The asphaltene content for sample HPX-2 is nil, but a significant quantity was found in sample HPX-1 (33.3 mg).

6.2.1. Gas Chromatography (GC).

The gas chromatogram (GC) traces for the n-alkane fraction of the saturated hydrocarbons are shown in Figs 6.1 and 6.2. The oils show a slight odd to even predominance, especially in the region $C_{23}$ to $C_{27}$ and they have a high wax content with n-alkanes greater than $C_{22}$ (C. Boreham, J. Hope and R. Summons, pers. comm., 1990). The samples contain $C_{15}-C_{16}$ and $C_{18}-C_{20}$ acyclic isoprenoids in relatively high abundance.

Table 6.1 gives compositional data for some n-alkanes and isoprenoids from gas chromatograms of saturated hydrocarbons in the samples analysed. The values of the pristane (Pr) to phytane (Ph) ratio range from 2.66 to 5.89 with an average value of 4.3. The values of Pr/$n-C_{17}$ are greater than 1 (ranges from 1.60 to 1.29; mean=1.45). These values, particularly the Pr/Ph ratio indicate that the oils have a non-marine source and were probably derived from terrestrial land plants. Compared with samples from Miocene petroleum reservoirs in the Northwest Java Basin (T. Ratkolo, pers. comm., 1990) the Pr/$n-C_{17}$ and Pr/Ph values are, however, much lower in the Kalimantan samples. Higher values for these parameters were also found in Bekapai and Handil oils from the Mahakam Delta, East Kalimantan (Combaz and Matharel, 1978).
6.2.2. **Gas Chromatography-Mass Spectrometry (GC-MS)**

The selected ion monitoring (SIM) traces of the saturated hydrocarbon fractions shows the presence of hopanes and steranes which are below the concentration limits for accurate identification. However, analysis of the samples indicated relatively abundant dimethyl- and trimethylnaphthalenes, phenanthrene and methylphenanthrene. The methylphenanthrene index (MPI) of Radke and Welte (1983) can be obtained from the relative intensity mass to charge ratios (m/z) and it ranges from 178 to 192. The MPI value has been converted to a calculated vitrinite reflectance ($VR_{\text{calc.}}$) using the formula of Boreham et al. (1988). Table 6.3 represents the average maturity level at which each oil has been generated, or the maturation level of the oil including overprinting resulting from alteration in the reservoir. The oil sample HPX-1 is less mature ($VR_{\text{calc.}} = 0.65\%$) than HPX-2 which has a $VR_{\text{calc.}}$ of 0.82%. These values correspond to measured $R_{\text{v, max}}$ data, close to the source of the samples, of 0.62% and 0.83% respectively. These data indicate that little vertical migration has occurred for these two oil samples.

Alexander et al. (1988) showed that enrichment of source-specific 1-methylphenanthrene and 1,2,5-trimethylnaphthalene can be used to define oil families of related origin and geological age in the Eromanga and Cooper Basins, Australia. Figure 6.3 is a plot of 1-/9-methylphenanthrene vs 1,2,5-/1,3,6-trimethylnaphthalene, both variables being on log scales. The two oil samples
(HPX-1 and HPX-2) plot in different fields. These results suggest some difference in source for the two oil samples. The source of the HPX-1 oil is from a younger than the source for the HPX-2 oil. The HPX-1 oil was probably derived from the middle of the Warukin Formation. The HPX-2 oil was certainly derived from lower in the sequence, but may have come from the basal part of the Warukin formation which, on the basis of evidence from the Kutei Basin, may show more marine influence. It is possible that a contribution from the deeper Eocene Tanjung Formation is also present. However, the general characteristics of the n-alkanes provide a better match with the Miocene suite of oils than with oils from the Tanjung Formation (A.C. Cook, pers. comm., 1990).

6.2.3. Saturated Hydrocarbons

A. Pentacyclic triterpanoids

The metastable reaction monitoring (MRM) traces for the molecular ion of m/z (M+ –> m/z 191 reactions provide three main series of compounds (Fig. 6.5 for HPX-1; and Figs 6.9 and 6.10 for HPX-2).

The dominant middle eluting series contains the ubiquitous pseudohomologous series of C_{27}, C_{29+} pentacyclic triterpanes which are considered to be derived from the membranes of bacteria and cyanobacteria. The C_{27} member is 17α(H)-trishopane (Tm) and is the first member of the homologous series of 17α(H), 21β(H)-hopanes extending up to
C₃₄, and probably higher. From and above C₃₁ these extended members can appear as 22S and 22R epimers and for the hopanes appear as resolved doublets. The 22S configuration corresponds to the more stable geologically-derived stereochemistry and an equilibrium value of 60% 22S is reached at the early stage of oil generation (Seifert and Moldovan, 1978).

The later eluting series corresponds to 17β(H), 21α(H)-moretanes. The stereochemistry is of intermediate thermodynamic stability between the ββ biological configuration and the most stable αβ configuration. Mackenzie (1984) reviewed conversion pathways from the biological configuration. The absence of the ββ configuration in the analysed oil samples is in accordance with their total disappearance before the onset of oil generation. As can be seen in Table 6.4 (column 4), the proportion of moretane to hopane for both Kalimantan oils is less than 10%. This is considered to be an equilibrium value (Mackenzie, 1984), and is consistent with an oil released within the main phase of oil generation. The extended members of C₃₁ hopane, the 22S and 22R epimers, are not resolved although doublets occur for the higher homologues.

The earliest eluting series of hopanes appears to commence with 18α(H)-22,29,30-trisnor-neohopane (Ts). Ts is less abundant than Tm in both samples analysed. Similar results were obtained for oils from the Northwest Java Basin (T. Ratkolo, pers. comm., 1990). Conversion of Tm to Ts can occur with equilibrium being reached at peak oil generation.
(Seifert and Moldowan, 1978). However, the Tm:Ts ratio is also affected by organic matter type. Summons et al. (1988) identified biomarkers of Walcott Member, Arizona, containing higher homologues of the neohopanes, commencing with $C_{29}$, tentatively identified as $18\alpha(H)$, $21\beta(H)$-30-norneohopane, and continues up to the $C_{34}$ member. The extended members $\geq C_{31}$ again occur as doublets, possibly 22S and 22R epimers.

The $C_{28}$ compound and 29,30-bisnorhopanes are other triterpenoids identified by Summons and Powell (1987) together with the almost co-eluting $C_{30}$ isomers of oleanane $18\alpha(H)$ and $18\beta(H)$ were recorded by Riva et al. (1988).

Methylhopanes, detected from the $M^+ \rightarrow m/z$ 205 transitions, are in relatively low abundances (up to 6%) compared with the corresponding desmethyl counterparts (Table 6.4, column 7 and Fig. 6.8). The stereochemistry corresponds to $2\alpha$-methyl, $17\alpha(H)$, $21\beta(H)$ with subordinate amounts of $3\beta$-methyl, $17\alpha(H)$ and $21\beta(H)$ (Summons and Jahnke, 1989).

B. Steranes

Steranes and methylsteranes are traced from the $M^+ \rightarrow m/z$ 217 to $M^+ \rightarrow m/z$ 231 reactions (Figs 6.9, 6.10 and 6.11). The oil samples contain $C_{27}$-$C_{29}$ steranes but the most notable absences are $C_{30}$ desmethylsteranes and $2\alpha$-methyl, $3\beta$-methyl and $4\alpha$-methylsteranes. Furthermore, in the oil sample HPX-1, 20S+20R 5α(H), 13β(H), 17α(H) and 5α(H), 13α(H), 17β(H) diasteranes are more abundant than the 20S+20R 5α(H), 14α(H), 17α(H) and 5α(H), 14β(H), 17α(H)
steranes while in the oil sample HPX-2 the reverse holds (see Table 6.4, column 6).

Figure 6.4 is a ternary diagram plotting the abundance of 5α(H), 17α(H), 21α(H)-20R steranes (Shi et al., 1982) in samples from southeastern Kalimantan and the Northwest Java Basin. The diagrams show that the C$_{27}$ homologue becomes a progressively less dominant partner in the order NWJ-1 $\rightarrow$ HPX-2 $\rightarrow$ HPX-1, and for NWJ-2 and NWJ-3; the C$_{29}$ member is the major homologue.

In general, samples HPX-1, HPX-2, NWJ-2 and NWJ-3 are enriched in the C$_{29}$ component. Boreham and Powell (1987) interpreted such properties as indicating terrestrial organic matter provided the greater contribution.

6.3. DISCUSSION

The maturity parameter for the oil samples (Table 6.4, column 3) was derived from the ratio of 22S to 22αβ-C$_{32}$ hopane (57.6%) which is close to the equilibrium value of 60%. With increasing thermal stress, the initial biological ααα-20R configuration converts to the ααα-20S and αβα-20S+R sterane epimers. At the onset of oil generation about 30% 20S isomer is present while an equilibrium value of 50-60% 20S occurs at peak oil generation (Mackenzie, 1984). The ratio of 20S to 20R ααα-C$_{29}$ steranes is also close to equilibrium values (ranges from 52.0% to 63.0%; mean=57.5%). The scatter around the equilibrium value is more pronounced for the sterane ratio which decreases to lower values for the more mature oil sample.
The proportion of moretane (Table 5, column 4) in sample HPX-2 is 8%, while in HPX-1 it is 9%. Nevertheless, the moretane ratio of <10% of the hopanes indicates that the oils are mature.

Once oil generation has taken place the maturity parameters which continue to change (and which can be observed with GC-MS analyses) are MPI (and hence $V_R^{\text{calc.}}$) and Tm/TS (Tables 6.2 and 6.3). The ratio Tm/TS in some cases gives a better indication of maturation but this ratio can also be influenced by source factors, for instance the presence of other neohopanes. Therefore, Tm/TS and MPI do not represent an absolute maturation parameter, but rather are useful relative indicators (C. Boreham, J. Hope, and R. Summons, pers. comm., 1989).

Slight source influence on the MPI does not appear to have masked the true ordering for the HPX-1 and HPX-2 oils. However, an overall, examination of above the maturity sensitivity parameters suggest that the HPX-1 oil is less mature than the HPX-2 oil. The MPI value for HPX-1 corresponds approximately with the measured vitrinite reflectance data from the middle of the Warukin Formation where the $R_v^{\text{max}}$ range is from 0.56% to 0.67% (average = 0.62%). The calculated vitrinite reflectance (MPI and $V_R^{\text{exMPI}}$; see Table 6.3) for HPX-2 is close to the measured vitrinite reflectance values for the lower section of the Warukin Formation.

Huang and Meinschein (1979) and Boreham and Powell (1987) suggested that the relative abundance of $C_{27}:C_{28}:C_{29}$ steranes can provide information regarding the type
characteristics of the source of the oils. Land plant input is usually inferred from a dominance of the C29 sterane. However, algae possess a wide range of desmethyl sterols (C_{26}-C_{29}) and also may provide oils with a major C_{29} component. The nearly equal amounts of C_{27} and C_{29} steranes in HPX-2 and NWJ-1 oils (Fig. 5.4) suggest that sterols from a variety of sources have contributed to the oils. Although rare Botryococcus-related telalginite and some phytoplankton were found to be present in some coal and dom samples in both the Warukin and Tanjung Formations in the Barito Basin (see Chapter 4), higher land plants are thought to have been the significant source for the oils. This is indicated by a number of features including the relatively high concentration of resin-derived oleanane also the oils contain diterpenoids which are derived from a wide range of higher plant compounds, especially resins such as in the Barito Basin; these samples are also reliable indicators of a terrestrial input (Snowdon, 1980). Moreover, enhanced levels of 1-methylphenanthrene and 1,2,5-trimethylphenanthrene compared with the non-specific isomers (see Fig. 6.3) infer an input from a conifer Araucariacean flora. This is especially the case for the HPX-1 oil.

Many workers have discussed the source of oil from the Mahakam Delta sediments, Kutei Basin, Tarakan Basin, Northwest Java Basin and South Sumatera Basin, and these oils are generally stated to be derived from terrestrial land plants (Combaz and Matharel, 1978; Durand and Oudin, 1979; Schoell et al., 1983, 1985; Oudin and Picard, 1982;
Gordon, 1985; Horsfield et al., 1987; and Robinson, 1987). Robinson (1987) pointed out that the organic facies and original higher plant input is similar in the fluvio-deltaic oils from the South Sumatera, Kutei and Tarakan Basins because a comparison of triterpane and sterane distributions shows little variation. Talang Akar coal and shale were the major sources of the oil in the South Sumatera and Northwest Java Basins, while Sihapas coal has also generated oil in Central Sumatera and the Malacca Strait (Gordon, 1985; and Robinson, 1987).

In the eastern Indonesia basins, marine source rocks may have sourced oil in the Salawati Basin, Irian Jaya, and eastern Sulawesi (Phoa and Samuel, 1986; and Robinson, 1987). David (1990) suggested that oils in eastern Sulawesi were derived from the Early Miocene lower platform limestone sequence which contains coal and a mangrove flora. In the Bula Basin, Seram Island, Jurassic-Late Triassic marine carbonate and shale were assumed, by O'Sullivan et al. (1985), to be a source of oil reservoird in the Pleistocene and Triassic sequences. However, in the Bintuni Basin, Irian Jaya, the pre-Tertiary successions (in particular the terrestrial units containing coal of Permian and Jurassic ages) were suspected as the source of the Wiriaigor oil by Robinson (1987).

A terrestrial source for both oil samples from the southeastern Kalimantan basins in this study is further supported by the high Pr/Ph ratio and the n-alkane distributions in the C_{12+} fraction, where an odd/even preference is present in the wax region (>n-C_{22} in the odd
homologs). The larger amounts of $C_{30}$ hopane compared with the $C_{29}$ homologue (see Table 6.4) are consistent with non-carbonate-rich source rocks, as is the higher abundance of diasteranes compared with steranes. In the latter case, generation of diasteranes from rearrangements of steranes during early diagenesis is believed to be catalysed by the acidic sites on clay minerals. The absence of the specific marine marker, $C_{30}$ desmethylsterane, confirms a marine influence is not a contributor to the depositional environment of the source rock (Moldowan et al., 1985). The abundance of the hopanes relative to steranes (Table 6.4, column 11) and the occurrence of minor methylhopanes indicate a significant and variable bacterial contribution. Hopanes in sedimentary rocks are known to be derived from functionalized hopanoids in bacteria, in which hopanoids and hopane polyols, having an additional methyl substitution at C-2 or C-3 in ring-A, have been recognized in several classes of bacteria (for example methylatrophs and cyanobacteria). Price et al. (1987) observed that methylhopanes are commonly very abundant in carbonate sediments (they form up to 20% of the hopane analogue according to Summons and Jahnke, 1989) even though they are not diagnostic of this lithology.

For HPX-1 and HPX-2 the relative abundance of methylhopanes (4-6%, Table 6.4, column 7) is within the general range (1-10%) that is not indicative of any specific environment. The high abundance of 29, 30-bisnorhopane (up to 30% of the major $C_{30}$ hopane; Table 6.4, column 9), in the oil samples indicates that $C_{30}$-norhopanes are present.
According to Price et al. (1987), C$_{30}$-norphopanes are indicative, but not diagnostic, of carbonate in the source lithology. Thus it must be assumed that the abundance of methylhopanes and bisnorhopane are interesting observations but their abundance has no clear-cut explanation (C. Boreham, J. Hope and R. Summons, pers. comm., 1989).

In the samples for this study 2-, 3- or 4-methylsteranes are not present. The presence of oleanane is an indicator of a source sequence of Tertiary age, similar in organic facies to the sequences in which the reservoirs occur, and there are no unequivocal indicators of a marine contribution.

6.4. SUMMARY

The two oils have many similarities but, both in terms of bulk composition and biomarker distribution, they can readily be distinguished from one another. The oils were produced within the early to middle phase of oil generation. Sample HPX-1 appears to be less mature than the HPX-2 oil. This conclusion is supported by a number of maturity parameters, including the ratio of 22S to 22Rαβ-C$_{32}$ hopane (close to the equilibrium value of 60%) and the MPI. The ratio of 20S to 20Rααα-C$_{29}$ sterane is also within the equilibrium range (52-63%).

The ratio of moretane to hopane (<0.1) indicates that the oils are relatively mature. Odd/even preference in the waxy range of n-alkanes demonstrates that the oils are not
highly mature.

Terrestrial higher plants have been the main source for the oils. This is indicated by the relatively high concentration of resin-derived oleanane, the high Pr/Ph ratio, the Pr/n-C_{17} ratio, and the n-alkane distribution in the C_{12+} fraction.

The organic petrology results given in Chapters 4 and 5 suggest that the Tanjung and Warukin Formations are the main units with hydrocarbon generation potential. Both rock units include coal and shaly coal. The maceral types and abundance and the vitrinite reflectance values of the two formations suggest that oils could have been generated in the Warukin and Tanjung Formations.

The maturation levels for the HPX-1 and HPX-2 oils correspond approximately with those of the surrounding beds and therefore a Warukin source is inferred for both oils. Tanjung Formation oils have a different alkane profile to the HPX-1 and HPX-2 oils although their biomarkers have not been described. If the HPX-2 oil was derived from the Tanjung Formation it would be expected to show highly mature characteristics unless it was emplaced within the reservoir soon after deposition of the lower part of the Warukin Formation. In addition to a source from dispersed organic matter of terrestrial origin, coal may have also been an important source for oils in the southeastern Kalimantan basins as the oils are similar to terrestrially-derived ones described by Gordon (1985) from the Arjuna Sub-basin.
CHAPTER SEVEN

POTENTIAL PETROLEUM RESERVOIR ROCKS

7.1. INTRODUCTION

The potential for Tertiary petroleum reservoir rocks in southeastern Kalimantan basins has not been published by many authors, especially regarding the Asem Asem Basin. The major hydrocarbon accumulations found to date have been from the Tanjung and Warukin Formations in the Tanjung, Kambiti, South Warukin and East Tapian oil fields in the Barito Basin. The Berai Formation, which is composed mainly of carbonate, has produced only small amounts of oil and gas.

Reservoir rocks in the Tanjung and Warukin Formations are comprised mainly of shaly sandstone, sandstone and conglomerate forming distributary channel and distributary mouth bar deposits in a fluvio-deltaic sequence (Siregar and Sunaryo, 1980; and Kusuma and Nafi, 1986). The oil and gas were generally trapped in anticlinal structures, but stratigraphic traps are probably also present (Siregar and Sunaryo, 1980). The oils are predominantly paraffinic, although asphaltic oils are present in small quantities (Weeda, 1958; Siregar and Sunaryo, 1980; Kusuma and Nafi, 1986). The API value of oils ranges from 28 (0.9004 g/cc) to 38 (0.8347 g/cc).
7.2. MICROSCOPIC FEATURES INDICATING DIAGENETIC REGIMES

The main fundamental properties of reservoir rocks are their porosity and permeability. North (1985) claimed that porosity and permeability are geometric properties possessed by a rock, but they are not necessarily genetic properties. Therefore, the lithologic character of the rock, especially its textural properties, is more important than its age.

The porosity and permeability of reservoir rocks are substantially affected by diagenetic processes—especially the presence of authigenic minerals filling primary and secondary pore spaces. Petrography of thin sections and scanning electron microscopy (SEM) were employed as the main basis for understanding aspects of diagenetic textural relationships between detrital and authigenic minerals in this study. In addition, X-ray diffraction techniques were used to supplement the identification of clay minerals in fine clastic rocks and in the sandstone matrix.

7.2.1. Petrography of Thin Section

A. Tanjung Formation

The results of the petrographic analysis (Section 3.4.1) indicate that sandstone in the Tanjung Formation is composed of detrital components consisting mainly of variable amounts of quartz, feldspar, rock fragments and other accessory minerals. Sand-sized or larger aggregates
of detrital clay minerals, called "rip-up" clasts or intraclasts, are also present and were derived from erosion of siltstone layers deposited simultaneously with the sand-size debris (Wilson and Pittman, 1977). Approximately 80% of the samples analysed are sublitharenite and the remainder are quartzarenite, litharenite or feldspathic litharenite according to the sandstone classification of Folk (1980). Photomicrographs of typical sandstone from the Tanjung Formation are given in Plates 5e-h and 6a-h.

In general, the sandstone is moderately to well compacted and shows typically immature to submature textures where the average clay matrix content ranges from 1% to 16%. The clay matrix consists of fine particles of quartz, feldspar, mica, kaolinite, smectite-chlorite and chlorite filling pores. Kaolinite, smectite-chlorite and chlorite clays occur partly as thin films lining quartz grains (see Plates 5g, 5h and 6c, 6d). The most common cement constituents found in the sandstone are carbonate and silica. Carbonate cements include micrite, microspar and spar calcite, but siderite and dolomite are also noted as minor components. Approximately 30% of the carbonate cement, especially calcite, occurred infilling primary pore spaces in the sandstone, whereas the remaining 70% of the carbonate cement, including siderite and dolomite, has replaced the original clay matrix (Plate 5c and f). Limonite and hematite filled some primary pores in the sandstone, and few iron oxide grains are occasionally present as sand sized particles associated with other framework grains. Silica cement is also important and
includes chalcedony, chert and quartz overgrowths. The authigenic chalcedony and chert cements fill secondary pores, some micropores and to a lesser extent fractures or cracks found in the sandstone (see Plate 5g and 5h). Some grains of quartz and feldspar are partially dissolved and altered. Dissolution of these grains created secondary porosity within the sandstone of the Tanjung Formation. Authigenic quartz overgrowths are clearly visible in many sandstone samples (Plates 5g, 5h and 6c, 6d). Some quartz overgrowths are coated by a thin film of clay minerals (see also Section 7.2.2).

B. Berai Formation

The results of petrographic analysis of thin sections from some samples show that the carbonate rock of this formation is composed of fossil fragments and quartz grains. These grains are mainly supported by muddy micrite matrix and microspar calcite cement but a small amount of spar calcite cement is also present. Secondary dolomite and siderite are rarely found in the samples examined.

Many framework grains, especially fossil fragments, have been dissolved and replaced by microspar calcite, and a some of the muddy micrite was recrystallized to spar calcite. Based on the pore-size classification of Choquette and Pray (1970), the samples of carbonate rock contain predominantly micropores (<0.0625 mm in diameter) and mesopores (0.0625-4.0 mm in diameter), whilst megapores are absent. Most samples examined show that primary pore spaces
have been destroyed by infilling with authigenic calcite cements, whereas solution-enlarged mold pores are not well developed. The micropores occurred predominantly in micritic cement and the mesopores are always associated with intraparticle, moldic and fenestral fabrics. Interconnected pore throats are not common in most of the analysed samples.

C. Warukin Formation

Framework grains in the Warukin Formation are composed mainly of quartz, feldspar, rock fragments and other accessory minerals. The sandstone consists largely of quartzarenite and sublitharenite with a few feldspathic litharenite and subarkose samples. Photomicrographs of typical sandstone from the Warukin Formation are presented in Plate 5c-d.

The sandstone typically has an immature texture and is moderately to well compacted. Primary pores are generally filled by clay size matrix comprising fine particles of quartz, feldspar, mica, kaolinite, smectite-chlorite and chlorite. Carbonate cements, including calcite, siderite and minor dolomite, are also noted to occupy some pores in the sandstone. Some detrital quartz and rock fragments are coated with a very thin layer of chlorite and kaolinite (see Plate 5a). Limonite and hematite are rarely found in the sandstone samples examined. As in the Tanjung Formation, some quartz and feldspar grains exhibit peripheral alteration and dissolution producing authigenic clay minerals and secondary pore spaces. Pore sizes range from
Silica cements, comprising chalcedony, chert and quartz overgrowths, are commonly found in the sandstone samples examined. These cements occupy both primary and secondary pore spaces but are rare filling cracks or fractures.

7.2.2 Scanning Electron Microscopy (SEM)

Preliminary applications of SEM in diagenetic studies were largely to determine pore throat geometry, quartz overgrowth morphology and authigenic clays (e.g. Weinbrandt and Pigg, 1969; Waugh, 1970; Pittman, 1972; Wilson and Pittman, 1977). The most significant feature of SEM is that it enables examination of very small-scale (micron size) textural relationships, pore-throat configurations, shape, size and orientation of pores, and other factors which affect the porosity and permeability of reservoir rocks.

The diagenetic features of 30 samples of cores from shallow drilling, and cuttings and side wall cores from petroleum exploration wells were studied (Table 7.1). The samples are comprised of quartzarenite, sublitharenite, sandy siltstone and coal. The texture and mineral identification is generally based on Scholle (1979) and Welton (1984).

A. Warukin Formation

The samples examined are predominantly fine- to medium-grained sublitharenite, collected from the A-1 and
BKO-1 wells at depth intervals from 1073 m to 3200 m. Scanning electron micrographs of representative samples are given in Plate 7a-i. In general, the samples studied are composed of subangular to subrounded framework grains of quartz, rock fragments and feldspar (Plate 7a, b and d). Contacts between grains are commonly tangential but rare contacts straight or sutured. SEM analysis revealed that some quartz particles have micro-fractures (Plate 7a, d) filled by authigenic quartz crystals and clay minerals. Some of rock fragments (Plate 7b) are partially dissolved creating pore spaces.

Many primary pore spaces in the sandstone and sandy siltstone are filled by various alloogenic (detrital) and authigenic clay minerals, carbonate, mica and silica. Clay minerals and carbonate are the most prominent matrix and cements, while mica and silica are only minor components.

Clay minerals consist mainly of kaolinite and smectite-illite. Kaolinite is the dominant clay mineral filling primary and secondary pore spaces. Two genetic types of kaolinite (allogenic and authigenic) were recognized in some sandstone samples examined from the Warukin Formation. Authigenic kaolinite is the most common clay component filling the primary and secondary pore spaces. It is more abundant than allogenic kaolinite. Face to face stacks of pseudohexagonal plates called "booklets" (Timur et al., 1971; Wilson and Pittman, 1977; Whitaker, 1978; and Welton, 1984) are the characteristic texture of all authigenic kaolinite observed in the sandstone samples. The allogenic kaolinite shows irregular shapes, is not
well-arranged and consists of various sized aggregate particles. This kaolinite was probably introduced during deposition (syndeposition) or during the early diagenesis or eodiagenesis regime (Schmidt and McDonald, 1979b; and Burley et al., 1987).

Sparse authigenic smectite-illite (mixed-layer clay) occurs as pore linings and subordinate pore fillings in some sandstone in the Warukin Formation (Plate 7h). Some pseudohexagonal plates of authigenic kaolinite overlie the smectite-illite. Some pore spaces are locally lined by mica or muscovite flakes (Plate 7g). The micas are slightly bent due to compaction. Chlorite clay minerals are sparse to common in several sandstone samples. This mineral is well developed as a pore lining and grain coating and occurs mainly with a honeycomb texture, but rare rosettes and cabbagehead structures are also present.

Carbonate cements consist of calcite, siderite and dolomite which are sparse to common in most samples analysed by SEM. Calcite is the most prominent carbonate cement commonly filling and lining pore spaces (Plates 7c and i). Some authigenic calcite crystals are well developed (Plate 7i) reducing the primary intergranular pore textures. Nevertheless, observation of these calcite crystals indicates that micropores within them are pronounced, consisting essentially of small open microthroats which have a maximum diameter of 10 µm (Plate 7c). According to Kieke and Hartman (1973), micropores between calcite crystal faces were formed by mobile water under-saturated with respect to CaCO₃. Dolomite and siderite, which are present
as a minor component locally replace authigenic calcite cement.

The size and shape of pores are an important description parameter in determining reservoir quality of sedimentary rocks. SEM analysis in the present study revealed the type and texture of pore spaces within sandstone samples from the Warukin Formation. The pore-size classification was adopted from Choquette and Pray (1970). The basic classification of pore-sizes are defined as: (a) micropores where pores are smaller than 0.0625 mm in diameter size; (b) mesopores where pores are 0.0625-4 mm in diameter size; and (c) megapores where pores larger than 4 mm in diameter size.

Results of the SEM study indicate that sandstone from the Warukin Formation have pores ranging in size from micropores to mesopores. Approximately 60% of the pore spaces are classed as micropores and about 40% are mesopores. The majority of mesopores occur in authigenic cements (intracement porosity) and few occur in the framework grains as micro-fractures. The pore size ranges from less than 1 um to 20 um. The presence of micropores is presumably associated with dissolution of authigenic cement, especially carbonate and subordinate other authigenic clay cements and silica. Moreover, the existence of micropores within the authigenic clay cements can be a result of the platelet arrangement of kaolinite and to a lesser extent smectite-illite.

Mesopores are predominantly found between framework particles (intergranular porosity) whereas a few of these
pores also occur within individual grains (intragranular porosity) and cement/matrix (intracement porosity). Mesopores have a diameter ranging from 60 μm to 300 μm in all samples examined. These pores are commonly interconnected, although some are disconnected due to later infilling by authigenic clay and carbonate cements. Less than 80% of the total amounts of mesopores in the sandstone is identified as primary porosity caused by incomplete pore fillings, whilst the remaining pores are secondary due to dissolution of framework particles and cements.

B. Tanjung Formation

Twenty five selected samples from the Tanjung Formation were examined using SEM. The samples were collected from cores of shallow bores, comprising fine to coarse-grained quartzarenite, sublitharenite and coal. The sandstone is generally moderately to well compacted, consisting predominantly of subangular to rounded rock fragments. Tangential contacts between grains are common, but rare to sparse straight and sutured grain contacts were also noted in some sandstone samples. Some representative photomicrographs from the SEM analysis are presented in Plates 8a-1 and 9a-1.

Results of the SEM analysis indicate that the main diagenetic features observed in all samples were the presence of authigenic clay minerals, carbonate, silica, quartz overgrowths and secondary pores.
Like sandstone samples from the Warukin Formation, the majority of primary pore spaces in samples examined from the Tanjung Formation were lined or filled largely by authigenic clays and carbonates. Authigenic clays consist predominantly face to face stacked of pseudo-hexagonal idiomorphic kaolinite (Plates 8b,c,d and 9b,g). Authigenic kaolinite in a vermicular habit (Plate 8c and 9c) is common in the sandstone and some pore-filling clots of kaolinite are associated with organic matter (Plate 9e). In some sandstone samples authigenic smectite-chlorite clays are well developed lining and filling pore spaces. Some of these authigenic clays occurred rimming the surface of quartz overgrowths (Plate 8i). This diagenetic feature suggests that authigenic smectite-chlorite formed after the overgrowths were precipitated. Detrital mica or muscovite are also present as a minor component in the pores (Plate 8g).

Calcite cement is only rare to sparse in most of the sandstone, but this cement is prominent in few samples (e.g. HP756) filling most of pore spaces (Plate 9h). Much of the calcite cement has probably been dissolved forming secondary pore spaces. Dolomite, exhibiting rhombohedral crystal form, is only present in small amounts filling pore spaces throughout the sandstone samples analysed (Plate 8h). Similarly, siderite is rare to sparse lining pore spaces, but is occasionally associated with calcite cement. Other cements include silica, consisting predominantly of quartz overgrowths and intergrowths (Plates 8i and 9f).
Other diagenetic features observed in sandstone samples from the Tanjung Formation are the presence of some detrital feldspar and rock fragments which show partially resorbed margins creating secondary pore spaces (Plate 91). Pore spaces are partly occupied by authigenic kaolinite and calcite. Pores within feldspar grains could result from dissolution or from later leaching of authigenic replacement carbonate (Heald and Larese, 1973).

Three selected coal samples (HP308, HP316, HP582) from the Tanjung Formation were examined using SEM. The only detrital phase detected was kaolinite clay, but kaolinite is also the most common mineral matter component occurring as a pore-filling within cell lumens in the macerals. Rare to sparse free mineral matter was often noted in the samples filling original micro-cracks and it has a maximum size of 2 um. Probably, these cracks were partially filled by migrabitumen or exsudatinite (see Section 4.4).

Both micro- and mesopores were recognized throughout the sandstone samples from the Tanjung Formation. The majority of pore features in the Tanjung Formation can be favourably compared with those in the Warukin Formation, where, throughout the samples, about 60% of pore spaces are micropores and the remainder are mesopores. However, compared with the Warukin Formation, sandstone in the Tanjung Formation has more prominent secondary pores than relict primary pores. Plates 8a and 9a show significant numbers of mesopores (intergranular pores) between the framework grains of medium-grained sublitharenite. The mesopores are partly interconnected, having a size ranging
from 20 um up to 500 um. Mesopores also occur within authigenic kaolinite clay and carbonate cements, but the sizes vary between 15 um and 50 um. Detailed examination indicated that approximately 80% of mesopores are secondary pores formed during diagenetic regimes due to dissolution of cements and grains, and incomplete replacement of cements (see Plates 8i and 9a,g-i). Primary pores (about 20% of total mesopores) are clearly defined as pore spaces resulting from incomplete pore filling with free cement or matrix constituents. These pores are probably an inherited from the original pore space at the time of early diagenesis.

Micropores are also well developed in the authigenic cements (intracement pores), especially within carbonate, kaolinite and secondary silica. However, the micropores, which are less abundant within smectite-chlorite cement, are evident in the photomicrographs (Plates 8f and 9d). The formation of cements, such as calcite, silica and to a lesser extent kaolinite and smectite-illite, is an important diagenetic process. In addition, spaces between kaolinite stacks and the intergrown arrangements of crystals may also contribute to the formation of micropores in all samples studied. Table 7.1 presents qualitative and semiquantitative results of the SEM analysis for samples examined from the Warukin and Tanjung Formations.
7.2.3. X-Ray Diffraction

Twenty one samples selected from the southeastern Kalimantan basins have been examined using X-ray diffraction methods in order to identify minerals and variations in clay mineral suites from the Dahor, Berai, Warukin and Tanjung Formations. The samples comprise claystone, siltstone, quartzarenite, sublitharenite and coal. Figures 7.1-7.3 show the major minerals in three representative samples.

From the diffractogram peaks of the non-oriented whole rock samples, semiquantitative abundance of mineralogical components for the non-clay and clay fractions were calculated following the method of Deere and Bayliss (1969), modified by Jones (1970). The formula applied in this calculation is:

\[
\% Q = \frac{Q_{101} \times 100}{Q_{101} + K_{001} + F_{040} + I_{001} + M_{006}}
\]

where:
- \(Q\) = quartz at 3.34 Å,
- \(K\) = kaolinite at 7.13 Å,
- \(F\) = feldspar at 3.2 Å,
- \(I\) = illite at 10.0 Å,
- \(M\) = muscovite at 4.96 Å.

The results of this mineralogical identification and semiquantitative abundance and are presented in Table 7.2.
A. Non-clay minerals

The major non-clay mineral constituent in the Warukin and Tanjung Formations is quartz which ranges in abundance from 5% to 42.1%, with an average of 28.4% (see Table 7.2). It includes chalcedony and chert. Quartz is generally identified from the essential peaks at 4.26\(\AA\), 3.34\(\AA\) and 2.46\(\AA\). Identified feldspar minerals include plagioclase, orthoclase and microcline. Plagioclase is more abundant than orthoclase and microcline. Eleven samples contain plagioclase and its abundance ranges from 2% to 14.2%, with an average value of 5.2%. This mineral is more prominent in the Tanjung Formation and only occurs as a trace constituent in the Warukin Formation. From the X-ray diffraction graphs, it was confirmed by the 6.42\(\AA\), 4.05\(\AA\) and 3.78\(\AA\) peaks. Orthoclase was only found in two samples from the Tanjung Formation and one from the Berai Formation (the latter is probably cavings of cuttings from the Warukin Formation) having an abundance ranging from 2.8% to 9%. Orthoclase is characterized by the presence of the peak at 3.785\(\AA\). Microcline was detected in three samples from the Warukin and Tanjung Formations, and was recognized from peaks at 3.383\(\AA\) and 3.25\(\AA\). The abundance of this mineral ranges from 1.6% to 2.9%.

About 70% of the analysed samples contain muscovite or micas with an average abundance of less than 3%. They were clearly identified by the presence of the 4.96\(\AA\) peak in all samples.

Magnetite, hematite, pyrite and ilmenite occur in some
samples from the Warukin, Berai and Tanjung Formations. Pyrite is more common than the other heavy minerals and it was characterized by the 2.7Å peak. The abundance of magnetite, hematite, ilmenite and pyrite is given in Table 7.2.

Identified carbonate minerals consist of calcite, dolomite, siderite and ankerite. Calcite and dolomite were recognized from samples of the Dahor, Warukin, Berai and Tanjung Formations. Calcite is the major component of the Berai samples since this formation was deposited in a shallow marine environment. Siderite and ankerite occur in samples of the Tanjung Formation. Probably calcite was partly syngenetic for the samples of the Dahor and Berai Formations, but it was dominantly an authigenic mineral in the Tanjung and Warukin Formations. In addition, siderite, dolomite and ankerite occur predominantly as authigenic constituents.

A zeolite mineral identified as natrolite was present in one sample from the Tanjung Formation. This mineral was confirmed by the 2.86Å peak. Natrolite probably formed as a diagenetic alteration product of volcanic rock fragments.

B. Clay Minerals

Clay minerals from the 22 samples studied (Table 7.2) range in abundance from 28% to 73%. They comprise kaolinite, smectite, illite, chlorite and mixed-layer clay minerals. Semiquantitative analysis indicates that kaolinite is generally more abundant (ranges from 2% to
35.6%) than other clay minerals. Kaolinite was identified from the peaks at 7.18Å and 3.56Å which were typically much sharper than peaks for the other clay minerals (Figs 7.1-7.3). The SEM analyses (section 7.2.2) gave evidence that in sandstone cements much of the kaolinite has well developed face-to-face stacked pseudohexagonal crystals indicating an authigenic origin. Most of the X-ray diffractograms show that the kaolinite peaks become lower after glycol treatment and they disappeared when heated to 450°C for one hour (Fig 7.1-7.3). This indicates that kaolinite is transformed into other constituents during heat treatment. Weaver (1989) demonstrated that kaolinite cements in sandstones can crystallize during both shallow and deep burial and, in turn, they can be transformed to chlorite or illite when the water chemistry changes from acid to alkine. He added that kaolinite presumably formed at a considerable depth in shale adjacent to coal or other organic-rich beds where appreciable CO₂ is generated from organic matter. A significant amount of kaolinite is present in the Eocene coal samples (2.3%-4.7%). Some quartz, chlorite and calcite were also detected as mineral matter compounds from the three coal samples analysed (Fig. 7.4).

Mixed-layer clay minerals are more abundant than illite, smectite and chlorite. Two major mixed-layer clays, comprising chlorite-smectite and illite-smectite, are common in the claystone, siltstone and some sandstone samples from the Dahor, Warukin, Berai and Tanjung Formations. Mixed-layer chlorite-smectite is more prominent than
illite-smectite throughout the samples analysed and it was identified by a 4.50Å reflection while illite-smectite was identified by the 5.01Å peak. Chlorite-smectite is the major, and is commonly the only, secondary clay in a thick section of Paleogene arkose in California (Helmold and Van de Kamp, 1984). According to Weaver (1989), chlorite-smectite occurs primarily as a grain coating and forms during early shallow burial, following the incipient dissolution of heavy minerals and feldspar. The proportion of smectite layers reduces with increasing depth where eventually it is completely converted to chlorite. Therefore, the chlorite minerals found in some samples from southeastern Kalimantan (range from 1% to 7.4%) were probably the result of chlorite-smectite conversion and to a lesser extent came from volcanic rock fragment alteration. Another possibility is that chlorite formed from kaolinite under geopressed conditions at more than 100°C (Keiser, 1984).

Other clay minerals are illite and smectite, having similar average proportions (9%) in some samples. Smectite was identified by a 3.02Å peak while illite was recognized by peaks at 3.88Å and 2.60Å. Smectite ranges in abundance from 2% to 27% whereas illite ranges from 2.4% to 18.8%.

7.3. POROSITY AND PERMEABILITY

The major basic properties of reservoir rocks are porosity and permeability. Porosity and permeability of successions in the southeastern Kalimantan basins were
assessed in thin section and by SEM methods and the results were compared with some measurement data from oil exploration well logs. The qualitative range of porosity and permeability values in this study was based on North (1985) modified from Levorsen (1967) (Table 7.3). Permeability can be visually determined from SEM with thin sections as suggested by Sneider et al. (1983).

Both primary and secondary porosity are present in the southeastern Kalimantan basins. The terms primary and secondary porosity used in this study were outlined by Choquette and Pray (1970), and later modified by Hoholick et al. (1984).

The uppermost succession (the Plio-Pleistocene Dahor Formation) in the southeastern Kalimantan basins has the highest porosity and permeability. Although no petrographic data was collected from this unit, other porosity data which is available in well logs show that the formation has major primary porosity ranging from 30% to 35% (Fig. 7.5). Visual observations of some cuttings samples and the few outcrops in the field indicated that, in general, sandstone and some conglomerate in this formation are very loose and friable. The Dahor Formation is not considered as a potential reservoir rock since most of the succession has been exposed at the surface. Organic petrology data indicate that the fine-grained clastic sequences are all immature for hydrocarbon generation (average rank is less than 0.30%\(R_v\)max). The formation is too far above potential source rocks in the lower units for hydrocarbons to migrate and accumulate.
Thin section petrology and SEM studies of coarse clastic rocks revealed that the Warukin Formation contains good to very good reservoir rocks. In general, most of the sandstone exhibits abundant mesopores and micropores. Mesopores have a size range from 100 μm to 500 μm. Some sandstone samples have about 60% of the porosity as mesopores in the intergranular category. This represents primary porosity due to incomplete filling of original pores by cement. The porosity of sandstone samples dominated by mesopores is good to very good (range from 20% to 35%). SEM analysis shows that interconnected pore throats are common. Visual estimates of permeability (Sneider et al., 1983) in these rocks with mesopores indicates a good to very good permeability (>100 md). Pore-filling cements and matrix reduced the porosity of some sandstone in the Warukin Formation. In this case, dissolution and incomplete authigenic cement replacement formed micropores having a size of less than 60 μm which are categorized as intracement porosity. SEM analyses have shown that micropores also occur within the arrangement of authigenic crystals of kaolinite and some calcite. However, smectite-illite and chlorite, which occur in some sandstone samples, may have reduced porosity. The bound water of these authigenic clays will further reduce the permeability and give rise to very high irreducible water saturations (Wilson and Pittman, 1977; Almon, 1981; and Mathisen, 1984). Other types of porosity in sandstone from the Warukin Formation include microfractures occurring within the framework grains; but
they are only a minor constituent. All these micropores provide a maximum 10% porosity.

Several limestone samples from the Berai Formation indicate that they have low porosity and permeability. Lemiges (1983) reported that the Berai Formation has a low porosity in southeastern Kalimantan. Locally and sporadically, some of the patch reefs in the Berai Formation in the Barito Basin and the southern part of the Asem Asem Basin have been considered to have good porosity (Pelton, 1974; and Bishop, 1980).

Mesopores and micropores are extensively developed in many sandstone samples in the Eocene Tanjung Formation. Mesopores ranging in size from 60 um up to 500 um are more prominent than micropores. Generally, mesopores occur as an integral part of intergranular porosity textures. Approximately 60% of the mesopores in this formation represent secondary porosity and the remaining 40% are relict intergranular primary porosity. Intergranular primary porosity was clearly visible by using SEM (Plates 8a and 9a) which showed interconnected pore throats and a range of porosity from 20% to 25%. The pores spaces are generally well preserved with incomplete cementation since early diagenesis. In contrast, the intergranular secondary porosity shows that whole pore spaces between grains have been formed due to dissolution of authigenic cement such as calcite, kaolinite and silica (Plate 9h).

Incomplete replacement of authigenic cements and dissolution of feldspar and other framework grains may also have contributed to secondary porosity (Plate 9i). This
intragranular secondary porosity provides up to 10%-20% of the total porosity.

Micropores are generally well developed within the matrix and authigenic minerals, such as kaolinite, calcite and silica, but lesser amounts are present in the smectite-chlorite and smectite-illite. These pores are dominated by secondary intracement porosity textures formed by dissolution of cements, leaching and the arrangement of authigenic kaolinite, calcite and silica crystals. It can be estimated that intracement porosity in most sandstone samples examined ranges from 10% to 15% of the total porosity. Overall, sandstone from the Tanjung Formation has an average porosity value of about 20%.

7.4. DIAGENETIC HISTORY

The realm of diagenesis was divided by Choquette and Pray (1970), Schmidt and McDonald (1979a,b) and Burley et al. (1987) into eodiagenesis (early), mesodiagenesis (middle) and telodiagenesis (late). Foscolos et al. (1976) and Surdam et al. (1989) noted the general relationships between inorganic and organic diagenesis.

During eodiagenesis pore water is lost from shales, little hydrocarbon generation occurs, and coals are lignitic or sub-bituminous. The mesodiagenetic regime corresponds to the main phase of oil generation, and coal becomes high-volatile to low-volatile bituminous in rank. During the late mesodiagenetic stage extensive cracking of the organic matter occurs and dry gas is the main hydrocarbon
product. Telodiagenesis represents near surface processes and hydrocarbons tend to become oxidised.

Porosity and diagenetic features in the present study indicate that eo- and mesodiagenetic processes were operative in the southeastern Kalimantan basins (Table 7.1 and Plates 8-9). The eodiagenetic regime is characterized by well preserved primary porosity and it is prominent in the Dahor Formation, common to abundant in the Warukin Formation and less prominent in the Berai and Tanjung Formations. Mesodiagenesis, characterized by decreasing primary porosity, and creation and reduction of secondary porosity, occurs prominently in the Eocene Tanjung and Oligo-Miocene Berai Formations, but it is less common in the Middle-Late Miocene Warukin Formation.

A general model for the diagenetic history in the southeastern Kalimantan basins given in Fig. 7.5. It was constructed on the basis of data from thin section, SEM, XRD, organic petrology and well logs used in the present study. This model shows the time of occurrence and relative intensity of diagenetic features and events in the Tanjung, Berai and Warukin Formations in relation to the stages of diagenesis. The model is also matched with the porosity path and burial history derived from Lopatin's model as discussed in Section 5.4.

The earliest stages of the eodiagenetic regime were indicated by initial pore-filling and pore-lining by alloegenic and partly authigenic clay and calcite constituents. Pyrite and iron oxides are commonly associated with some alloegenic clays and calcite.
Therefore, these constituents were also formed during early diagenesis. Pyrite was probably associated with the transition from aerobic to anaerobic decay of organic matter. The allogenic clay minerals were deposited by infiltration from suspension, as flocules or as a result of bioturbation (Wilson and Pittman, 1977) which also increases packing.

Coalification commenced with the biochemical stage where the rank ranges from about 0.20% to 0.30% \( R_{\text{V}} \text{max} \). The origins of early calcite and other carbonate components in sandstone from the Warukin and Tanjung Formations are probably from dissolution of shell material, erosion of carbonate rocks and direct precipitation within the environment of deposition (e.g. Schmidt and McDonald, 1979b; and Blatt, 1979). Conditions promoting dissolution depend on the chemistry of downward moving meteoric waters. Carbon dioxide formed by degeneration of fatty coal and esters of organic matter may have also increased the solubility of shell material. Such conditions indicate that chemical diagenesis also began shortly after deposition and has affected the diagenetic events and sequence in the sandstone.

Compaction is the main mechanical diagenetic event, and it probably began in the middle eodiagenetic regime when the burial of sediments became slightly more intense. The final stages of the eodiagenetic regime were characterized by pore filling with some authigenic kaolinite but under conditions less intense than those required for the development of
authigenic illite, smectite, chlorite and mixed-layer clay minerals. Quartz grains appear to be partially dissolved at the point of grain contact due to the increasing burial and geopressure which increase quartz solubility at these points. The dissolved silica was subsequently reprecipitated as overgrowths on the surfaces of detrital quartz grains.

The early mesodiagenetic regime in the southeastern Kalimantan basins is shown largely by the more extensive formation of authigenic minerals, and the sediments appear to be gradually removed from the influence of depositional pore waters during deeper burial. Authigenic kaolinite is abundant throughout the sublitharenite and quartzarenite in the Warukin and Tanjung Formations, but minor amounts are also present in the Berai Formation. These clays were characterized by well developed of kaolinite crystals defined by face-to-face pseudohexagonal stack and booklet textures with some vermicular forms (see Plates 7-9). In addition, quartz overgrowths and some intragrowths of silica cement have reduced the abundance of kaolinite.

The middle to late mesodiagenetic history was indicated by other diagenetic events and features, such as the formation of authigenic chlorite, smectite, illite and mixed-layer clay minerals, authigenic carbonate cements, dissolution of feldspar and rock fragment grains, secondary porosity and hydrocarbon generation and migration.

The formation of authigenic chlorite, smectite, illite and mixed-layer clays is assumed to be contemporaneous, but
some illite, chlorite and smectite might have been formed slightly earlier than the mixed-layer clay minerals. Some of these clay minerals occur in voids between detrital grains and the relatively large crystals of authigenic kaolinite. This suggests that they probably developed later than the kaolinite. Many chlorite, smectite and mixed-layer clay minerals occur as a thin dust coating some parts of the surface of the quartz overgrowths (e.g. Plate 8i). This feature clearly indicates that these authigenic clays were formed after the quartz overgrowths. Keiser (1984) suggested two stages for the formation of chlorite. The first is that chlorite can be derived from smectite but it can also be derived from kaolinite when the latter is subjected to geopressed conditions at greater than $100^\circ$C. Further, Siebert et al. (1984) and Weaver (1989) demonstrated a general process that involves the reaction of feldspar with smectite to form illite and chlorite. The micaceous habit and various sizes of illite crystals in some sandstone from the Warukin and Tanjung Formations suggest that they were derived from detrital mica or muscovite (Sarkisyan, 1972; and Wilson and Pittman, 1977). In the case of the authigenic clays in the Warukin and Tanjung Formations, several origins may be suggested. The first is that the chlorite is frequently associated with volcanic fragments suggesting that it may have been derived by alteration of mafic minerals contained in the volcanic fragments. The second is the chlorite may have been formed at the expense both kaolinite and smectite. Finally, all authigenic clays (chlorite, smectite, illite and mixed-layer
clays minerals) in the Warukin and Tanjung Formations probably resulted from complex chemical reactions which transformed parent materials such as matrix, feldspar and volcanic rock fragments.

The zeolite natrolite was detected by X-ray diffraction analysis in one sublitharenite from the Tanjung Formation. This mineral may have been produced contemporaneously with chlorite and it appears to have been derived from the partial alteration of plagioclase (Surdam and Boles, 1979; and Mathisen, 1984).

Dissolution of unstable grains such as feldspar and rock fragments was initiated in the later stage of eodiagenesis, and become more prominent during the mesodiagenetic regime. This event provided space for the late carbonate cements and created secondary porosity in the coarse clastic rocks in the Warukin and Tanjung Formations, but it appears to be least intense in some of the carbonate rocks in the Berau Formation. The carbonate cements comprise predominantly calcite, siderite and dolomite which were presumably formed during mesodiagenetic carbonization reactions (Schmidt and McDonald, 1979b; and Surdam and Boles, 1979). Moreover, the formation of calcite is a common diagenetic reaction in feldspar and volcaniclastic sediments (Galloway, 1974; and Siebert et al., 1984). Siderite and dolomite formation requires the presence of Fe$^{2+}$ and Mg$^{2+}$ cations which were possibly derived from the mafic minerals in the volcanic rock fragments.

Some silica was dissolved and reprecipitated during mesodiagenesis partially as chalcedonic or chert cements in
the sandstone. In the Berai Formation, dissolution of carbonate was probably not really prominent, but recrystallization of calcite to form microspar and spar cement took place in some pore spaces.

Coalification continued during mesodiagenesis and the increase in rank coincided with the increasing depth of burial. The onset of oil generation occurs where $R_{\text{v,max}}$ is 0.50% and the Time-Temperature Index (TTI) value is 3 (Fig. 7.5). Consequently, hydrocarbon generation and initial migration may have occurred during this stage.

Because neoformation of authigenic carbonate and clay refilled the secondary pore spaces, reduced secondary porosity may have existed in some sandstone in the Tanjung Formation, but neoformation does not seem to be very prominent within the Warukin Formation.

7.5. DISCUSSION

Broadly speaking, the diagenetic history outlined above demonstrates a generalized transformation of the original framework grains, matrix and cements that promoted early loss of primary porosity and subsequent generation of secondary porosity and authigenic clay minerals. Depth of burial, temperature and overburden pressure are three main factors controlling diagenetic reactions (Galloway, 1974). Maxwell (1964) suggested that the geothermal gradient and residence time at depth are factors of first-order importance in the pressure solution process and composition of pore fluids.
The present study and others (e.g. Stephenson, 1977) indicate that basinal and tectonic history contribute significantly to the course of diagenesis. All diagenetic features possessed by many of the samples examined using thin section, SEM and X-ray diffraction indicate that the Tanjung, Berai and Warukin Formations in the southeastern Kalimantan basins have been influenced remarkably by the two main regimes of diagenesis i.e. eodiagenesis and mesodiagenesis (Fig. 7.5). The eodiagenetic regime is generally characterized by decreasing primary porosity, pore filling by alloogenetic and authigenic kaolinite and some authigenic precipitation of pyrite, hematite and carbonate cements. During this stage the major controlling factors include the chemistry of interstitial water and the effect of organisms, especially bacteria. Mechanical compaction also influenced this regime. Hurst and Irwin (1982) concluded that the environment of deposition tends to create a broad division of diagenetic modifications in sandstone sequences.

Early stage coalification of dispersed organic matter and coal probably commenced in the eodiagenetic regime where biochemical processes were the main controlling factor. In general, vitrinite reflectivity of organic matter found in dispersed organic matter and coal in Tanjung, Warukin and Berai Formations corresponds to the textural stage of eodiagenesis through to mesodiagenesis. This is partly due to the fact that both the organic and inorganic diagenetic reactions are mainly controlled by temperature and residence time. However, the reaction of organic matter to
temperature rise is much more sensitive and rapid than those of inorganic minerals and the incremental course of changes is more easily detected.

During the events of late eodiagenesis through mesodiagenesis, the formation of authigenic clays and other minerals was accompanied by dissolution and the enhancement of secondary porosity throughout the sandstone in the Tanjung and Warukin Formations. However, this situation is slightly different within the dominantly carbonate rocks from the Berai Formation. Dissolution of calcite was probably more significant than other diagenetic features, although a few authigenic clay minerals, dolomite and siderite are present.

All authigenic clays occurring in sandstone from the Warukin and Tanjung Formations are probably the result of chemically complex reactions changing the parent constituents through dissolution, alteration and precipitation. The peak of the mesodiagenetic regime probably corresponds with the commencement of the Meratus uplift as represented in the burial and diagenetic history given in Fig. 7.5.

The present study shows that porosity of the sandstone decreases with increasing depth of burial in the southeastern Kalimantan basins. This coincides with an increase in the development of diagenetic features (Figs 7.5 and 7.6). The average porosity gradient in the southeastern Kalimantan basins is approximately 7% per 500 m from the surface to a depth of 3800 m. Rocks in the Dahor Formation have well preserved primary porosity and show the highest
porosity values ranging from 31% to 37%. The Warukin Formation has a good to very good porosity (10%-35%). In general, the porosity decreases in the Berau (10%-15%) and Tanjung Formations (6%-20%; Fig. 7.6). The reduction of general porosity with increasing depth is probably closely related to reduced primary intergranular pore textures, which is partly modified by the effects of secondary porosity during the mesodiagenetic regime.

The relationship between porosity and permeability (Fig. 7.7) in the southeastern Kalimantan basins shows a clear positive correlation (R=0.94). This indicates that the decrease in porosity with depth is significantly followed by a reduction in permeability throughout the rock units. The controlling factors affecting permeability are grain size, sorting, shape, roundness, packing and pore throat features. In addition, burial and length of burial time have been responsible for changes in porosity and permeability because of their effects on diagenesis.

A plot of the abundance of cement and matrix against porosity (Fig. 7.8) shows a low correlation coefficient (R=0.26) indicating that there is no significant relationship between porosity and amount of cement and matrix in sandstone from the Tanjung and Warukin Formations. Therefore, the enhancement and reduction of porosity do not depend on the abundance of cement/matrix but must be controlled by other parameters, such as pore size, grain shape and diagenetic event factors.

In the present study, an appraisal of reservoir quality was established based on porosity and permeability values
and the effects of precipitation and dissolution through the
diagenetic regimes. A number of potential reservoir rocks
having high porosity and permeability occur at various
stratigraphic levels in the southeastern Kalimantan basins
(Fig. 7.9). The Eocene Tanjung Formation has good potential
reservoir rocks which mostly occur within the sandstone
facies in the lower and upper sequences (see Chapter 3).
Their average porosity ranges from 6% to 20% (good) with
permeability values varying between 5 md to over 100 md
(good to very good).

Several cap rocks which directly overlie the sandstone
units include mudstone, claystone and shale. Because the
Tanjung Formation was folded and faulted during the Meratus
Orogeny, these structures are considered to be favourable
potential traps for hydrocarbons, although some
stratigraphic traps may also exist.

The dominant limestone rocks of the Berai Formation
provide poor to fair porosity (10-15%) but the equivalent
permeability is less than 15 md (poor to fair). Therefore,
the Berai Formation only provides a fair quality reservoir
rock. The possibility for traps is also structural, such as
folds and faults, with some marls and carbonate mudstone
providing good potential cap rocks.

The Warukin Formation has a higher reservoir quality
(i.e. good to very good) because it contains abundant
sandstone layers having a good to excellent porosity
(10-35%) and a high to very high permeability (>100 md).
This formation has better reservoir quality in terms of the
average porosity and permeability values than the Tanjung
Formation. This is because some of the primary porosity has significant numbers of mesopore throats that are still well preserved. Like the Tanjung and Berai Formations, the sedimentary sequences in the Warukin Formation have structures (folds and faults) which can be considered to represent potential traps. However, stratigraphic traps due to sand pinchouts and isolated destruction or truncation of sand bodies occur in the Warukin Formation and may have potential to accumulate hydrocarbons. Considerable numbers of potential cap rocks in the Warukin Formation occur adjacent to reservoir sandstone units. Therefore, sandstone layers may be expected to be hydrocarbon-bearing in suitable traps. Migration of hydrocarbon may have occurred during the mesodiagenetic regime or shortly after the hydrocarbons were generated from parent source rocks within the Tanjung and Warukin Formations. The Meratus uplift during the Late Miocene to Pliocene possibly promoted the migration of oil and gas into or within potential reservoir rocks in the Tanjung, Berai and Warukin Formations. The biomarker study (Chapter 6) of some oil samples from the Warukin Formation suggested that most of the oil accumulated in the sandstone layers was derived from adjacent source rocks, but that a small amount of oil may have been contributed from deeper source rocks, i.e. Tanjung Formation.
7.6. SUMMARY

Most of the sedimentary sequences (Tanjung, Berai and Warukin Formations) in the southeastern Kalimantan basins were affected by diagenetic reactions. Thin section, SEM and X-ray diffraction analyses revealed characteristic diagenetic features in the sandstone, carbonate and argillaceous rocks that indicate modification in the eodiagenetic and mesodiagenetic regimes.

In general, eodiagenesis is characterized by mechanical compaction, early coalification, pore filling and pore lining by allogenic and authigenic clays, early calcite, pyrite and iron oxide. Mesodiagenesis is indicated by the presence of significant amounts of authigenic clay minerals, especially kaolinite, chlorite, smectite, illite and mixed-layer clay minerals filling original and secondary pore spaces. Dissolution of cements and framework grains is the main factor to promote the formation of secondary porosity which is more prominent in the Tanjung Formation compared with other rock units. Quartz overgrowths are also common diagenetic features in the Tanjung and Warukin Formations. Microspar and spar calcite cements are the major diagenetic feature in the Berai Formation, but some authigenic kaolinite is also present as a minor component. Overall, the sandstone beds in both the Tanjung and Warukin Formations are potentially good reservoir rocks since the major hydrocarbon accumulations are believed to have migrated from mature source rocks in the Tanjung and Warukin
Formations. The Berai Formation is also marginally favourable as a reservoir rock for hydrocarbon accumulations in the southeastern Kalimantan basins.
CHAPTER EIGHT

SUMMARY AND CONCLUSIONS

GENERAL GEOLOGY

The Tertiary southeastern Kalimantan basins are underlain by ophiolite-derived metamorphic, igneous, volcanic and sedimentary rocks having an age range from Early to Late Cretaceous. The Asem Asem and Barito Basins formed by rifting of the eastern Sunda continental margin, with the resultant depressions being filled with a transgressive-regressive cycle of Tertiary sedimentary sequences comprising the Eocene Tanjung Formation, the Oligocene-Miocene Berai Formation and Middle-Late Miocene Warukin Formation. The latter unit is unconformably overlain by the Plio-Pleistocene Dahor Formation.

The major structural elements in the Asem Asem and Barito Basins are faults, folds and lineaments. Fault structures are typically normal or block faults and thrust faults, trending NE-SW or NW-SE, which are sub-parallel to the general trends of fold axes. Folds are also abundant in this area occurring within both the pre-Tertiary and Tertiary rocks. Most folds in the Tertiary rocks were probably influenced by the Late Neogene Meratus uplift.
SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENTS

In general, the Tanjung Formation shows two major cycles of deposition. The lower sequence comprises the lower sandstone, mudstone and lower coal facies. The upper sequence is composed of the upper sandstone, mudstone and upper coal facies overlain by limestone in the uppermost section. Textures, sedimentary structures and the geometry of the facies indicate that the lower sequence was probably deposited in a fluvial fill environment with meandering river systems. Palaeocurrent analyses indicate that the mean current direction of the river systems was towards the south. The upper sequence was dominated by distributary mouthbar and interdistributary facies of a lower delta plain environment. Deposition of the Tanjung Formation ended with a transgression that flooded the region and resulted in the deposition of shallow marine carbonate rocks.

Thin section petrography of sandstone from the Tanjung Formation reveals that quartzarenite and sublitharenite are the dominant lithologies, while litharenite and feldspathic litharenite are minor components. The sandstone was mainly derived from recycled orogen areas, presumably from the Kuching High, part of the Mangkalihat Ridge and the Sundaland continent or Schwaner Block.

Two different depositional environments for the Eocene coal seams are proposed in this study. The lower seams were probably deposited in low-lying backswamps adjacent to the meandering river systems whereas the upper seams are interpreted to have accumulated in low-lying swamps in a lower delta plain setting. Overall, Eocene coal in the
southeastern Kalimantan basins probably developed in raised swamp systems, which are common in tropical peat-forming areas and are comparable to modern peat formation in Sarawak.

The Berai Formation is composed mainly of carbonate facies. Petrographic results indicate that the carbonate rocks comprise wackestone, packstone and grainstone with minor mudstone. The formation was deposited in an open shallow marine environment.

The Warukin Formation is composed mainly of shale, coal and sandstone facies. The shale facies represents suspended-load channel deposits, and probably accumulated in a coastal plain-delta association. The sandstone facies consists predominantly of fine- to medium-grained sandstone interbedded with siltstone, shale, mudstone and coal. The sandstone comprises largely quartzarenite and sublitharenite with subordinate feldspathic litharenite and subarkose. The sandstone facies represents a series of coarsening-upward sequences showing the general characteristics of distributary mouth-bar deposits. Provenance of the Warukin Formation is probably similar to that for the Tanjung Formation, i.e. the Kuching High, Mangkalihat Ridge and Sundaland continent. Overall, the formation was deposited in a fluvio-deltaic environment.

The Dahor Formation is the youngest stratigraphic unit, composed of sandstone, gravel, sand, mudstone, claystone, marl and lignite. They were deposited in fluviatile to neritic environments.
R-mode cluster analysis of petrographic data from sandstone in the Tanjung Formation shows that some of the variables are positively linked together in meaningful groups. Significant close positive relationships are found for K-feldspar, volcanic rock fragments and plagioclase indicating that they are derived from a similar volcanic source area. Quartz grains show a strong correlation with grain shape, packing and compaction textures. Most of the samples are closely packed and well compacted since quartz is the major framework constituent. Other significant close relationships occur between mudclasts and clay matrix; quartz overgrowths and silica cement; and between porosity and pore size.

Q-mode cluster analysis for the Tanjung Formation grouped together those samples with similar mineralogical composition, texture, structure and provenance. For instance, an assemblage of medium- to coarse-grained quartzarenite and sublitharenite deposited in channel and pointbar settings have a significantly close relationship to be clustered together in a single group. A second group consists of fine-grained, moderately- to well-sorted and subrounded quartzarenite and sublitharenite samples that all show positive linkage. This cluster represents an assemblage which largely comprises interdistributary channel, bar or crevasse splay deposits.

R-mode cluster analysis of carbonate rocks from the Beral Formation exhibits significant relationships among most variables. For example, a close relationship is found between micrite and microsparite because these constituents
are always present in similar proportions in many of the carbonate samples studied. Other variables, such as grain size, clay and spar calcite cement are also closely associated and have high positive correlation coefficients.

Q-mode cluster analysis of the Berai Formation shows a well-defined cluster of samples having similar amounts of framework grains and similar textures. The group having the closest relationships includes the grainstone samples which are composed mainly of coarse-grained skeletal fossil material supported by muddy micrite, microspar and spar calcite cement.

The R-mode dendrogram for sandstone from the Warukin Formation shows groups having close positive relationships between variables, e.g. quartz, metaquartzite, siltstone rock fragments, silica cement, porosity and sorting are linked together in a single group. In this group, the quartz, metaquartzite and siltstone grains are the dominant components in the well-sorted samples that consequently have a higher porosity and more frequent sites for silica cement.

As in the Tanjung Formation, the Q-mode cluster analysis of sandstone from the Warukin Formation also shows groups of closely associated samples. For example, samples containing coarse- to medium-grained quartzarenite and sublitharenite are positively linked together and constitute a group of channel or pointbar deposits. Furthermore, samples composed of fine- to very fine-grained quartzarenite and sublitharenite are linked together representing an association of distributary channel deposits.
ORGANIC PETROLOGY

Results of the organic petrological study show that the Tanjung, Warukin and Dahor Formations contain lithologies rich in dispersed organic matter together with a number of coal seams. The carbonate Berai Formation contains only rare organic matter.

Vitrinite is the major maceral in dispersed organic matter (dom) within the Tanjung, Warukin and Dahor Formations, while liptinite is the second most abundant maceral group. Telovitrinite is more prominent than detrovitrinite and is found as dom throughout the units, forming stringers and thin bands. Detrovitrinite occurs as small phytoclasts and rarely as thin bands. Detrovitrinite is the most abundant vitrinite maceral found in the Berai Formation, although it is only a minor constituent compared to the inertinite and liptinite particles.

Liptinite within the Tanjung Formation, comprises mainly sporinite, resinite and cutinite with subordinate liptodetrinite. Dom in the Warukin Formation contains thin beds or lenses of liptinite which is largely composed of sporinite, resinite, cutinite and liptodetrinite, plus a small amount of suberinite, exsudatinite, fluorinite, telalginite and phytoplankton.

Inertinite consists of inertodetrinite, semifusinite, sclerotinite and micrinite throughout all the stratigraphic units studied.

The Eocene coal is typically vitrinite-rich with liptinite-poor vitrite being the major microlithotype. However, clarite is also abundant in several samples of
liptinite-rich coal, especially in the upper coal seam. Telovitrinite is a more prominent constituent than detrovitrinite or gelovitrinite throughout the Eocene coal seam sections. Liptinite in the Eocene coal comprises mainly sporinite, resinite and cutinite. Liptodetrinite, suberinite, fluorinite and exsudatinite occur as secondary liptinite macerals within the coal samples. Sparse Botryococcus-related telalginite is present in some samples. Inertinite consists of inertodetrinite, sclerotinite, micrinite and semifusinite; while macrinite is a very minor component in several samples.

Similar to the Eocene coal, the Miocene coal contains abundant vitrinite and liptinite. The amount of liptinite in the Miocene coal is less than in the Eocene coal, therefore, vitrinite is still the dominant microlithotype in the Miocene coal. Liptinite in the Miocene coal consists mainly of sporinite, cutinite and resinite while suberinite, liptodetrinite, fluorinite and exsudatinite are only present in small amounts. Botryococcus-related telalginite is also present but it is only sparse. Within the liptinite macerals, fluorinite, exsudatinite, telalginite and phytoplankton are generally characterized by highly intense fluorescence, i.e. green to greenish yellow and bright yellow to bright orange. Cutinite, sporinite and resinite show less intense fluorescence and are generally yellow to dull orange. Liptodetrinite commonly exhibits a wide variation in fluorescence colours from green and greenish yellow to dull orange. Fluorescence of suberinite is weak to very weak orange or dull orange. Many vitrinite macerals
have very weak dull yellow or dull orange fluorescence. Inertinite in the Miocene coal is predominantly sclerotinite, semifusinite and rare to sparse micrinite and macrinite.

The average abundance of mineral matter in the Eocene coal is higher than that found in the Miocene coal. Quartz, kaolinite, pyrite and carbonate are the main mineral matter components recorded from most coal samples. Minor chlorite is also present in some Eocene coal samples.

The Eocene coal ranges between sub-bituminous and high volatile bituminous rank, having mean vitrinite reflectance values ranging from 0.58% in the upper coal to 0.62% in the lower coal. The highest rank of over 0.80% \( R_v \)\text{max} for the Eocene coal occurred at a depth of 3700 m in SMD-1 well, Barito Basin.

The present study indicates that many clastic sedimentary rock and coal samples from the Tanjung and Warukin Formations contain abundant exsudatinite, bitumen and oil (oil droplets, oil cuts, oil haze and dead oil). Exsudatinite is included in the migrabitumen group because no, or very little, distinction can be made between exsudatinite and bitumen on the basis of optical properties. Hence, exsudatinite has been added to migrabitumen when reporting the abundance of migrabitumen contained in the coal samples.

R-mode cluster analysis of data from the Eocene and Miocene coal samples showed that inter-variable correlation was not significant in terms of variation in the contents of the three maceral groups: vitrinite, liptinite and
inertinite. This is most probably related to the small range of variation in origin, climate and depositional environment and, therefore, organic facies during the Tertiary. The analysis shows that in both Eocene and Miocene coals, the distinction between telovitrinite, detrovitrinite and gelovitrinite throughout the rank range provides discrimination in defining organic facies. For example, detrovitrinite and gelovitrinite are always clustered because they have similar abundance and associations with other variables. The inertinite macerals also tend to link together into a group showing a low level of organization and a low abundance.

Q-mode cluster analysis, using organic petrographic criteria from all analysed samples, discriminates between the samples based on the various properties of the coal. Similarities and differences among cluster groups for the Eocene and Miocene coals are clearly caused by maceral composition, rank and mineral matter content. For example, the samples containing higher vitrinite and liptinite contents but low mineral matter content cluster together and have moderate to high positive similarity coefficients. The cluster comprising predominantly samples of shaly coal also shows moderate to high positive similarity coefficients between samples in the group. Moreover, the samples having higher vitrinite reflectance values, and vitrinite and liptinite contents are linked together as a cluster with moderate positive similarity coefficients.
SOURCE ROCK AND HYDROCARBON GENERATION POTENTIAL

Organic petrology data show that the Tanjung and Warukin Formations have very good hydrocarbon generation potential. The Berai Formation has poor potential whereas the Dahor Formation has fair potential but is generally not thermally mature.

Apart from coal seams, the mudstone facies (including shale, claystone and siltstone) in the Warukin and Tanjung Formations contains the most abundant organic matter. This facies is significant since it is thick and widely distributed throughout the Barito and Asem Basins. Organic matter consists largely of vitrinite and liptinite which are predominantly derived from terrestrial higher plants. Therefore, the mudstone facies has the greatest potential as a source rock for the generation of oil and gas. This is confirmed by microscopic features, such as migrabitumen, oil droplets, oil cuts, oil haze and dead oil, which are significantly abundant in the mudstone facies of both the Tanjung and Warukin Formations. These features are also present in minor amounts in some samples from the Berai and Dahor Formations.

Vitrinite reflectance gradients in the southeastern Kalimantan basins are relatively low (average 0.13%/km) compared to those of the Kutei and Tarakan Basins. Nevertheless, vitrinite reflectance data from the southeastern Kalimantan basins have suggested that the oil generation zone has generally been reached below depths of 1600 m. Hence, the Tanjung Formation section is mature throughout most of both basins, although this unit is
marginally mature in the section penetrated in the northern Asem Asem Basin. Maturity is also attained in the deeper sections through the Berai Formation and the lower part of the Warukin Formation. The uppermost portion of the Warukin and all sections through the Dahor Formation are immature for oil generation.

The present geothermal gradient ranges from $20^\circ$C/km to $55^\circ$C/km, with an average of $33^\circ$C/km. Significantly higher gradients ($27^\circ$C/km - $55^\circ$C/km) occur in the Tanjung area, in the northern Barito Basin, and in the northern part of the Asem Asem Basin. Low to moderate ($20^\circ$C/km - $27^\circ$C/km) geothermal gradients are found on the northwestern flank of the Meratus High and in the southern part of the Asem Asem Basin.

The gradthermal model and palaeothermal calculations indicate that relatively rapid, early coalification of the Eocene units occurred over most of the southeastern Kalimantan basin area. A second more rapid phase of coalification has affected the lower section of the Miocene succession. During the Miocene and Pliocene (including the post-Meratus uplift), a constant or falling temperature resulted in a lowered thermal drive for maturation and migration. Overall, the palaeothermal model for the southeastern Kalimantan basins suggests that the present temperatures in the basins are generally lower than in the past.

The burial history in the Asem Asem and Barito Basins, derived from Lopatin's model, supports the above suggestions that the Tanjung and Berai Formations, and the lower part of
the Warukin Formation, entered the oil window zone in the Miocene. Subsequent to the Meratus uplift (Late Miocene–Pliocene) an erosional episode probably promoted a constant or falling temperature and resulted in a slight decrease in thermal drive on maturation for generating hydrocarbons.

Gas chromatography and gas chromatography–mass spectrometry analyses indicate that the oils in the Barito Basin were produced within the early to middle phase of oil generation. This result corresponds to measured vitrinite reflectance data within the lower and middle sections of the Warukin Formation. The organic petrology indicates that the Tanjung Formation may have contributed some oil to reservoir rocks within the Barito and Asem Asem Basins.

The pristane/phytane ratio demonstrated that the analysed oil was derived from terrestrial higher plant material. The results of maceral analyses confirmed that the majority of organic matter throughout the Tertiary sequences in the southeastern Kalimantan basins originated from terrestrial higher plants. The Eocene and Miocene coal seams probably also played an important role in oil generation in the southeastern Kalimantan basins.

**POTENTIAL PETROLEUM RESERVOIR ROCKS**

Petrography of thin sections, scanning electron microscopy and X-ray diffraction analyses were employed to assess the properties of potential reservoir rocks in this study. The results indicate that the porosity and permeability of suitable reservoir rocks in the Tanjung,
Berai and Warukin Formations have been strongly affected by diagenetic events, i.e. during the eodiagenetic and mesodiagenetic regimes.

The eodiagenetic regime is generally characterized by decreasing primary porosity because the pores are partially filled with allogenic detritus, authigenic clay minerals and early calcite cement. During the period of late eodiagenesis through mesodiagenesis, the formation of more significant amounts of authigenic clays occurred. This phase was accompanied by dissolution of early cement and some framework grains, which enhanced secondary porosity in sandstone units in the Tanjung and Warukin Formations. However, dissolution of calcite cement and some fossil fragments was probably more significant in the Berai Formation.

The average porosity gradient in the southeastern Kalimantan basins shows a decrease of 7% per 500 m from the surface to a depth of 3800 m. The Dahor Formation has a very high primary porosity (31%-37%). Sandstone in the Warukin Formation has a good to very good porosity (10%-35%) and a high to very high permeability ( >100 md). The carbonate rocks of the Berai Formation show poor to fair porosity (10%-15%) with a permeability of less than 15 md (poor to fair). Sandstone in the Tanjung Formation has a porosity ranging from 6% to 20% (good) with permeability values ranging from 5 md to over 100 md (good to very good). Overall, the sandstone beds in both the Tanjung and Warukin Formations are potentially good reservoir rocks throughout the southeastern Kalimantan basins. The Berai Formation is
marginally favourable as a reservoir rock for hydrocarbon accumulation.

In the Tanjung and Warukin Formations, several seal or cap rocks directly overlie the sandstone beds and consist of mudstone, claystone and shale. Some marl, carbonate mudstone and limestone beds provide good potential cap rocks for reservoir bodies in the Berai Formation.

Fold and fault structures are considered to be favourable potential traps for hydrocarbon accumulations in the Tanjung, Berai and Warukin Formations. However, some stratigraphic traps are also probably present as facies changes, sand pinchouts and isolated truncation of sand bodies.

Migration of hydrocarbons may have occurred during the mesodiagenetic regime or shortly after hydrocarbons were generated from parent source rocks within the Tanjung and Warukin Formations. The Meratus uplift probably promoted the capability for vertical and lateral secondary migration within or out from source rocks and into reservoir rocks in the southeastern Kalimantan basins.

The present study indicates that the southeastern Kalimantan basins are potential coal, oil and gas producing areas.

Both Eocene and Miocene coal seams are categorized as steaming coals which have potential for electricity power generators in terms of type, rank and mineral matter contents. They can also be used as active carbon.

The lower Eocene coal should have higher priority to be mined because the seam is generally thicker (average 5.1 m)
than the upper Eocene coal seam; the upper coal seam is composed of many layers ranging from 0.1 m to 2 m in thickness and it contains higher mineral matter.

Apart from the Sangsang and Satul mining areas near Kintap, which are currently mined by P.T. Arutmin, the eastern flank of the Senakin Peninsula is also potentially mineable where the structure will not cause exploitation problems. The thickness of cover for surface mining in the latter area is a of maximum 100 m. Other areas which show good potential for mining are north of the Kintap and Gunung Kukusan areas. The latter area is approximately 20 km southwest of Sarongga on the eastern flank of the Meratus Range. However these areas have been folded and faulted which may cause problems for mining exploitation. Small scale mining of the upper seam should also be undertaken by local public mining systems.

The Miocene coal is also mineable by surface mining methods. The thickness of coal varies from 1 to 40 m with an average of 8 m. The area recommended for mining is at Sarongga and Bunati, near Kintap, where the maximum cover is 50 m.

On the basis of the present study, the basins are also potential oil and gas producing areas. Onshore, it is recommended that oil exploration, with several drilling tests and seismic geophysical investigations, be continued in the eastern and southern parts of the Barito Basin. Additional drilling should also be undertaken to determine the maximum depth to basement rocks, where this is not known, as this will give critical data for more detailed
evaluation of source and reservoir rock potential which is predicted in the deeper parts of the Tanjung and Warukin Formations. Because drilling has been limited in the Asem Asem Basin, additional drilling is recommended in offshore areas, such as south of Pulau Laut and south of the A-1 and A-2 wells.

CONCLUSIONS

The conclusions reached in this study can be summarized as follows:

1. The Eocene Tanjung Formation was deposited in a meandering river system, comprising fluvial to lower delta plain regions, with a shallow marine system in the uppermost part of this formation. The Oligo-Miocene carbonate Bera Formation was deposited in an open reef shoal marine environment. The overlying Middle-Late Miocene Warukin Formation accumulated in a fluvo-deltaic environment. Unconformably over this unit, the Plio-Pleistocene Dahor Formation is deposited in fluviatile to shallow marine environments.

2. The Eocene coal, consisting of lower and upper seams, is widely distributed in the southeastern Kalimantan basins. The thickness of the lower coal seam averages 5.1 m, while the upper coal seam varies between 0.1 m to 2 m. Vitrinite is the major maceral group followed
by liptinite; only minor amounts of inertinite occur. These coals are of sub-bituminous to high volatile bituminous rank.

The Miocene coal is restricted to the eastern part of the Meratus Range area where its thickness is 8 m on average. The coal is of brown to sub-bituminous rank. Overall, the Eocene and Miocene coals were deposited in raised swamps similar to those prevailing during the accumulation of modern peat in Malaysia, Sarawak and Brunei.

The coal from southeastern Kalimantan can be utilized for electric power generation. However, more specific and detailed investigations of coal utilization for these coals are recommended before further economic development.

3. Vitrinite reflectance data suggest that the oil generation zone generally has been reached below 1600 m depth for all areas in the southeastern Kalimantan basins. Mature levels occur in most sections of the Tanjung Formation in the Barito and Asem Asem Basin. Although the Berai Formation contains little organic matter, vitrinite reflectance data indicate that this unit is also mature in the deeper part of the Barito Basin. Similarly, the deeper sections of the Warukin Formation are mature, but this unit is marginally mature in the middle sections and immature in the shallow sections. The Dahor Formation is immature throughout the basin. Coalification of the Eocene and
lower part of the Miocene succession was relatively rapid and occurred over most of southeastern Kalimantan early in its geological history.

4. The dom and coal are mostly derived from terrestrial higher plants. A biomarker study on oil samples also showed that terrestrial higher plants were the main source of the oils in the Miocene section, although they were produced only within the early to middle phase of oil generation.

5. In southeastern Kalimantan, sandstone in the Tanjung Formation has good reservoir potential in terms of porosity, permeability and diagenetic features. Carbonate rocks in the Berai Formation have fair or marginally favourable reservoir potential. A very good reservoir quality is also possessed by sandstone in the Warukin Formation but the Dahor Formation has a low potential for hydrocarbon accumulations. Mudstone facies, which are abundant in the Tanjung and Warukin Formations, are potential seals or cap rocks of the above reservoir rocks. In the Berai Formation, marl and carbonate mudstone are also good cap rocks. Structural traps are the most likely sites for oil and gas accumulation in the southeastern Kalimantan basins, although stratigraphic traps are almost certainly present in the Tanjung and Warukin sections.
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