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The petroleum potential of Tertiary coals from Western Indonesia: Relationship to mire type and sequence stratigraphic setting

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Abstract

More than 500 deltaic sediments from 14 basins in Western Indonesia were subjected to detailed geochemical, petrographic and palynological analysis. The resultant data represent each of the main peat-forming tectonostratigraphic episodes (Paleogene syn-rift transgressive, Paleogene–Neogene post-rift transgressive and Neogene syn-tectonic regressive) of the Indonesian Tertiary. The coals are hydrogen-rich, with average hydrogen index (HI) of 250–300 and atomic H/C ratios of 1.0–1.3 where immature. Paleogene coals from syn-rift transgressive systems tracts are more hydrogen-rich than Neogene coals from syn-tectonic regressive systems tracts, and upon pyrolysis, yield lower gas/oil ratios, implying they are more oil-prone. Pliocene coals from a strongly regressive sequence in the Sumatran fore-arc are very hydrogen-poor with average HI of 138. Indonesian coals display a systematic increase in HI with increasing rank, peaking at a Tmax of c. 430 °C, suggesting that Rock-Eval pyrolysis underestimates petroleum potential in low rank coals. The increase in HI is accompanied by a decrease in S1/TOC ratio and the disappearance of suberinite and resinite, reflecting the assimilation of these macerals into the coal matrix with increasing diagenesis. Petrographic analyses reveal a very poor correlation between liptinite content and HI. The term Detrovitrinite Index (DI) is coined to describe the ratio of detrovitrinite/total vitrinite. A better relationship between HI and DI suggests that vitrinite type is a more important control on petroleum potential than liptinite content.

The coals are classified into four sub-types (I–IV) on the basis of their pyrolysis potential and petrographic composition. Sub-types I, II and III are low ash coals and are likely to have been deposited in raised mires. Sub-type I is hydrogen-rich and primarily represents Middle to Late Miocene coals, deposited in a regressive megasequence. Sub-type II coals are hydrogen-poor and occur in multiple tectonostratigraphic settings. Sub-type III consists of very hydrogen-poor Pliocene coals from the rapidly subsiding West Sumatran fore-arc. Sub-type IV is hydrogen-rich, and consists of high ash Eocene coals, deposited in submerged mires in a transgressive, syn-rift setting.

A close relationship between HI and tissue preservation index (TPI) suggests that the degree of degradation of the peat is an important factor in determining petroleum potential. Highly degraded peats result in hydrogen-rich coals with a higher proportion of vitrinite of detrital or allochthonous origin. The degree of degradation is most likely related to the amount of time the peat spends within the zone of influence of the water table, and is unlikely to be directly related to tectonostratigraphic setting.

Keywords: Indonesia; Tertiary; Coal; Source rock; Rock-Eval; Vitrinite; Depositional environment

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1. Introduction

A number of important reviews have been published over the past few decades that highlight significant oil potential in deltaic settings, particularly in Late Mesozoic and Tertiary coals (Durand and Paratte, 1983; Cook and Struckmeyer, 1986; Hunt, 1991; Boreham and Powell, 1993; Fleet and Scott, 1994; Isaksen et al., 1998; Wilkins and George, 2002). Indeed, approximately 36% of Indonesia's petroleum has been attributed to Tertiary fluvio-deltaic source rocks, with a further 5% assigned to lacustrine-deltaic sources (Howes and Tisnawijaya, 1995). The most important of these resources are found in the highly petroliferous Kutei Basin petroleum province in Southeast Kalimantan, the South Sumatra Basin, and the Ardjuna Basin of Northwest Java. Commercial or sub-commercial quantities of oil attributed to coal have been described from the Barito Basin in Southeast Kalimantan (Kusuma and Darin, 1989; Rotinsulu et al., 1993) and the East Java Sea (Phillips et al., 1991), and oil seeps have been typed to Paleogene coals in Western Sulawesi (Coffield et al., 1993). The nature of Kutei Basin source rocks has been described by many authors (e.g. Combaz and de Matharel, 1978; Boudou et al., 1984; Hoffman et al., 1984; Monthioux et al., 1985, 1986; Dunham et al., 2000; Peters et al., 2000) and Talang Akar Formation source rocks from the Ardjuna Basin were characterized by Gordon (1985), Horsfield et al. (1988), Noble et al. (1991), Sukamto et al. (1995) and Noble et al. (1997). Accounts of the petroleum potential of deltaic source rocks from other parts of Indonesia are less common, and restricted to a few key papers (Central Sumatra — Macgregor and Mackenzie, 1986; Longley et al., 1990; South Sumatra — Teerman and Hwang, 1989; Kamal, 2000; Barito Basin — Kusuma and Darin, 1989; West Sulawesi — Coffield et al., 1993; Wilson et al., 1998; Natuna Sea — Michael and Adrian, 1996; East Java Sea — Phillips et al., 1991; Pepper and Matthews, 2000).

Establishing a link between petroleum potential and the peat-forming environment is critical to developing a predictive model of the source potential of coals in the subsurface. Although some parameters such as ash and

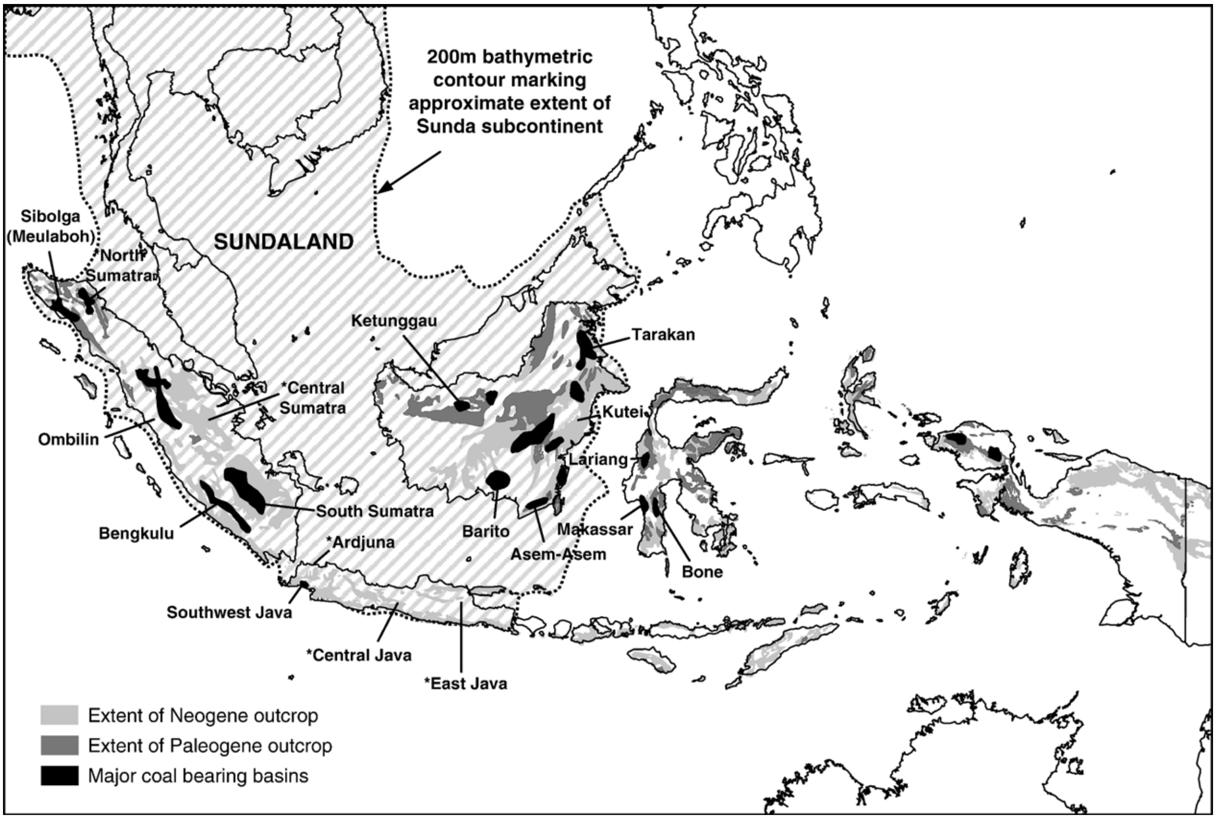

Fig. 1. Map of Indonesia showing extent of Sunda subcontinent, major coal deposits, Tertiary surface geology, and approximate sample localities (basins marked * not sampled in this study; major coal-bearing basins after Hutton et al., 1994; surface geology modified after U.S. Geological Survey, 1999).

sulphur content have direct implications with respect to depositional environment, on the whole this is a difficult undertaking, and previous authors have found little or no relationship between peat type and tectonostratigraphic setting (Moore and Shearer, 2003). The purpose of our study was firstly to define the petroleum potential and petrographic composition of a representative selection of coals from Tertiary basins throughout Indonesia, secondly, to divide these coals into different sub-types based on their pyrolysis potential and petrographic character, and thirdly to discuss the processes responsible for differentiating these sub-types.

2. Tectonostratigraphic setting of Tertiary Indonesian coals

Much of the western part of the Indonesian subcontinent known as Sundaland is presently submerged, but due to sea level fluctuation and tectonic uplift, the position of the coastline has changed throughout the Tertiary, with frequent potential for the deposition of deltaic sequences (Moss and Wilson, 1998). Economic coal deposits are mainly restricted to the major basins of Sumatra and Eastern Kalimantan, but rift deposits containing thin coal seams occur in Western Sulawesi and Southwest Java (Fig. 1). Maximum peat deposition occurred during warm and wet periods – the most favourable climatic conditions for peat swamp development – and the thickest coals are attributed to high stand (HST) and transgressive (TST) systems tracts, where preservation potential was at an optimum. The Eocene was a period with little or no glaciation, warm wet climate and high sea level (Sloan et al., 1992; Zachos et al., 1993, 2001). At this time the Earth was extensively vegetated by tropical and subtropical rainforests up to 30°N, and by the Middle Eocene, peat swamps were widespread globally (Wolfe, 1985). Major cooling associated with glaciation began towards the end of the Eocene (Aubry, 1992; Zachos et al., 2001), resulting in a hiatus in peat formation in the Early Oligocene (Fig. 2). Chattian to Aquitanian peats developed during another global temperature maximum (Morley and Flenley, 1987), and Middle Miocene peats correspond with high stand conditions, and a maximum

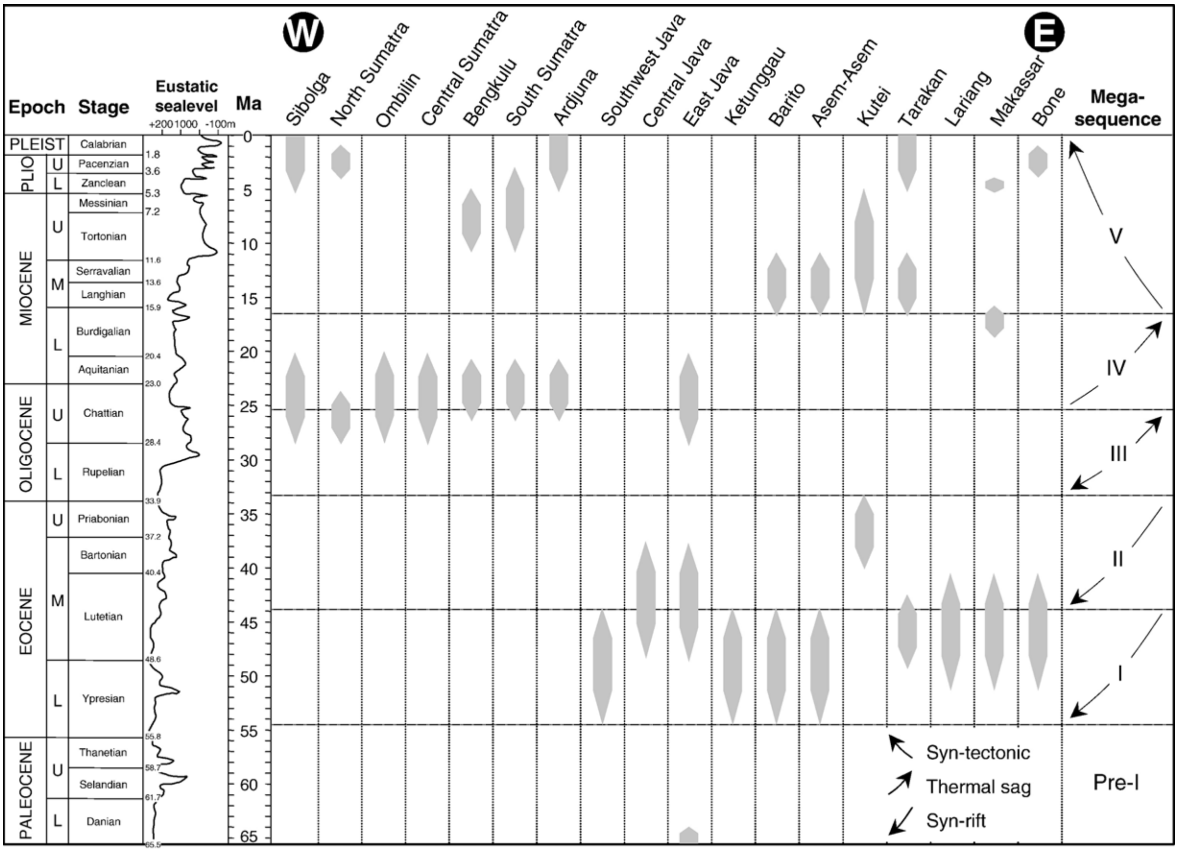

Fig. 2. Main periods of peat development in Indonesian basins (see Fig. 1 for locations) (U = Upper, M = Middle, L = Lower; time scale after Gradstein et al., 2004; eustatic sealevel after Haq et al., 1987; megasequences and tectonic stages after Longley, 1997 and Wornardt, 1999).

palaeo-temperature at around 15 Ma (Flower and Kennett, 1994; Morley, 1998). During the Late Miocene, climatic cooling led to progressive glaciation at the poles (Zachos et al., 2001), and a fall in eustatic sea level (Haq et al., 1987). Sundaland experienced regional regression and Late Miocene peats were restricted to the subsiding depocentres of South Sumatra and East Kalimantan. Extensive peat development recommenced with the Early Pliocene global warming event at circa 5 Ma (Zubakov and Borzenkova, 1988), and peat swamps are currently widespread throughout the Indonesian archipelago (Whitten et al., 1987), though it is questionable how many are actively being preserved.

There were three major episodes of peat formation within the Tertiary of Indonesia, related to the tectonic stages or megasequences of Longley (1997). Recalibrated megasequences using recent dating of significant bounding surfaces (Noon et al., 2003) are shown in Fig. 2. The first episode occurred during Early to Middle Eocene rifting in Java, Kalimantan and Sulawesi. According to Longley (1997), Western Indonesia experienced two phases of early Tertiary rifting (I, II in Fig. 2), though differences in the age of Eocene coals are potentially an artifact of equivocal dating, rather than the result of different rifting events. A second episode of peat formation, associated with thermal subsidence and transgression, began in the Late Oligocene in Sumatra and Java (III–IV in Fig. 2). The third episode is marked by the development of major prograding deltas along the eastern margin of Borneo during the Middle Miocene global high stand. These deltas extended over the whole region by Late Miocene to Pleistocene times (V in Fig. 2).

The stratigraphic setting of Western Indonesian coal-bearing sequences, including many of the formations

Table 1
Geographic distribution, age and rank of samples

Province	Basin	Type of sample site	Formation	Age	Rank	Number of samples		
						Claystone (<5% TOC)	Claystone (5–40% TOC)	Coal (>40% TOC)
Sumatra								
North	Sibolga	Open cast	Tutut	Pliocene	Lignite	2	17	62
			Sibolga	Oligo–Mio	Sub-bit/high vol		2	44
Central	Ombilin	Underground	Sawahlunto	Oligo–Mio	Sub-bit/high vol	1	3	23
			Sangkarewang	?Eo–Oligo	Sub-bit		2	
West	Bengkulu	Open cast	Unnamed	Oligo–Mio	Lignite/sub-bit		3	10
South	South Sumatra	Open cast	Muara Enim (A Mbr)	Late Mio	Sub-bit		1	36
			Muara Enim	Late Mio	Lignite/sub-bit	1	4	74
					Semi-anthracite			5
			Air Benakat	Mid–Late Mio	Sub-bit			1
	Sunda (onshore)	Outcrop	Talang Akar	Oligo–Mio	High vol	1		3
Kalimantan								
Central	Ketunggau	Outcrop	Kantu	Eocene	Sub-bit/high vol		2	4
			Ketunggau	Eocene	Sub-bit/med vol			32
Northeast	Tarakan	Open cast	Lati	Late Mio	High vol			3
Southeast	Kutei	Underground	Balikpapan Grp	Mid–Late Mio	Sub-bit		4	27
			Kamboja	Mid–Late Mio	Sub-bit		1	9
			Prangat	Mid–Late Mio	Sub-bit		3	2
	Barito	Open cast	Warukin	Mid Mio	Sub-bit/med vol			9
	Asem-Asem	Open cast	Warukin	Mid Mio	Lignite/sub-bit			14
			Tanjung	Eocene	Sub-bit	3	5	40
Sulawesi								
West	Lariang	Outcrop	Unassigned	Eocene	Sub-bit/med vol		2	5
	Makassar	Outcrop	Tonasa	Oligo	Lignite/sub-bit		1	
			Malawa	Eocene	Sub-bit/low vol	1	4	10
			Toraja	Eocene	Sub-bit/high vol			2
	Bone (onshore)	Outcrop	Walanae	Pliocene?	Lignite/sub-bit		1	2
			Bua Kayu	Late Mio	Sub-bit/high vol		2	
			Toraja	Eocene	Sub-bit		4	10
Java								
West	SW Java	Outcrop	Bayah	Eocene	Sub-bit/high vol			5
Total						9	61	432

sampled in this study, is described in some detail by Friedrich et al. (1999). Paleogene coals were formed in transgressive settings in low lying (rheotrophic) mires. They tend to contain higher ash and higher sulphur, and are more laterally continuous, but thinner than coals of Neogene age. Neogene coals were deposited in a regressive, and often tectonically active setting, in raised (ombrotrophic) mires, analogous to the modern domed peats of Northwest Borneo (Anderson, 1964; Anderson and Muller, 1975). They are less laterally continuous, but form very low ash, low sulphur seams, in some instances over 30 m thick.

3. Samples analysed in this study

We studied a suite of over 500 coaly terrigenous sediments from 14 basins in Western Indonesia (Table 1), using a range of geochemical, petrological and palynological techniques. This paper focuses on the results of coal (>40% TOC) analyses, which comprise about 85% of the data set, though elemental ratios of all samples are included in Fig. 3. Pre-Tertiary coals are known from Eastern Indonesia, but our samples were restricted to the Tertiary basins of Sundaland: primarily Sumatra, Kalimantan and Western Sulawesi. The majority was obtained from open cast pits, though samples were also available from underground collieries in the Ombilin (PT Bukit Asam) and Kutei (PT Kitadin) Basins. Coals from the onshore Sunda, Southwest Java, Ketunggau, Lariang, Makassar and Bone Basins were obtained from outcrop as they are not currently mined. Notable exclusions

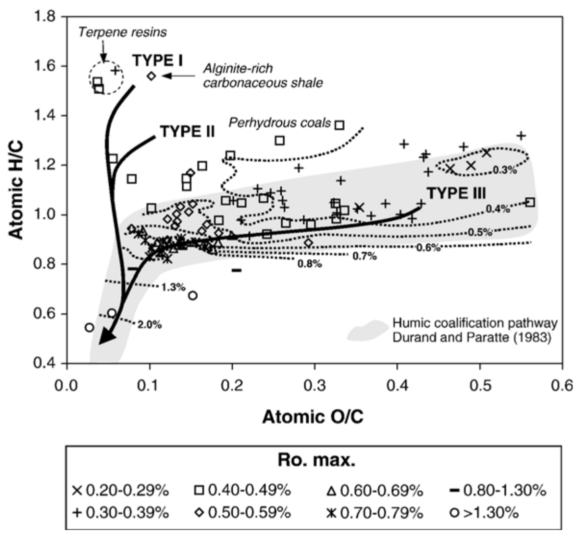

Fig. 3. Van Krevelen diagram showing atomic ratios from elemental analysis (data contoured by vitrinite reflectance maturity — 0.1% contour interval from 0.3% to 0.8% Rm., then 1.3% and 2.0% Rm.).

are Oligocene Talang Akar Formation coals from the Ardjuna Basin, Northwest Java, and Eocene Ngimbang Formation coals from the East Java Basin, which neither outcrop, nor are mined. A detailed discussion of the provenance and geological association of samples is beyond the scope of this paper, but is documented in an earlier unpublished work (Core Laboratories, 1993). Approximate localities relative to major coal basins (Hutton et al., 1994) and areas of Palaeogene and Neogene outcrop (U.S. Geological Survey, 1999) are indicated in Fig. 1.

Eocene sections were sampled from Central and Southeast Kalimantan, three basins in Western Sulawesi, and one location in Southwest Java. Oligocene–Early Miocene sequences were sampled from the Ombilin and Sibolga Basins in Central and West Sumatra. A large number of Middle to Late Miocene samples were available from open cast sites in East Kalimantan and South Sumatra. Of the South Sumatran examples, coals were sampled from the top of the Middle to Late Miocene Air Benakat Formation, from the Late Miocene Muara Enim Formation, and from the A Member of the Muara Enim Formation (Hutchison, 1996). Four pure or nearly pure Middle to Late Miocene resin samples were isolated from coals from the South Sumatra, Kutei and Asem-Asem Basins. Pliocene coals were sampled from the Meulaboh region of the Sibolga fore-arc in Northwest Sumatra, and the onshore Bone Basin in Western Sulawesi.

Coals are notoriously heterogeneous and ideally, samples for chemical and petrographic analyses are collected by coring or channel cut (Stanton, 1989). This allows a representative sample of a seam to be collected and analysed. Moore (1990) noted that representative petrographic compositions of coals can be obtained on fewer samples if they are prepared in an uncrushed, polished and etched block form. Unfortunately our sample set contains neither channel nor core samples, and petrographic analyses were performed on crushed particles embedded in resin. Alternative means were therefore necessary to obtain a representative composition from each locality (see Section 5).

4. Weathering and oxidation

Samples collected at outcrop are potentially affected by weathering and/or subaerial oxidation. Taylor et al. (1998) (Ch. 9 and references therein) note that weathering of coal results in a gradual loss of hydrogen from aliphatic bonds, increase in oxygen and decrease in fixed carbon content, as well as a loss of thermoplastic properties, representing a continuous loss of volatile components. Strong natural oxidation (weathering) may be observed by a decrease in the reflectance of vitrinite grain boundaries, but subtle oxidation is difficult to detect without performing comparative studies on fresh and oxidized coals under blue light. The complex methodology required to determine the degree of subaerial oxidation meant we were unable to quantify the effects of weathering or long term storage on these coals. However all samples petrographically analysed were examined for evidence of weathering and if evidence for weathering was found, the sample was rejected.

5. Analytical program

All samples were subjected to total organic carbon (TOC) screening by LECO and bulk pyrolysis by Rock-Eval 5. Approximately one third of samples were subjected to pyrolysis-gas chromatography (Py-GC) using a Pyroprobe 1000 pyrolyser, interfaced with a Varian Series 3400 gas chromatograph. Pyrolysis analyses were performed at Core Lab's facilities in Jakarta. Elemental (CHON, dry mineral matter free) analyses were performed on about one in five samples, by Huffman Laboratories, Colorado. Mean maximum vitrinite reflectance and maceral typing analyses (by point counting, approximately 500 counts each) were performed on approximately three-quarters of the samples by Keiraville Konsultants Pty (New South Wales).

We attempted to alleviate the effect of random heterogeneity by basing many of our observations on average seam properties. Only true coals were included in this exercise. Excluded were carbonaceous clastics (TOC < 40%), thermally altered coals, and pure or nearly pure resinites from the Asem-Asem, Kutei and South Sumatra Basins. The minimum number of coals used to derive average properties was nine. No numerical analysis was performed to determine whether this number yielded statistically significant average compositions, although it is three times the number used by Moore (1990) and Moore et al. (2000) to obtain a representative analysis. This reduced the usable sample set to about 60% of the database, encompassing 12 basins. Syn-rift coals from three basins in Western Sulawesi (Bone, Lariang and Makassar) were treated as a single entity on account of their identical age and tectonic setting.

6. Results

6.1. Elemental composition

Fig. 3 plots atomic hydrogen/carbon (H/C) versus oxygen/carbon (O/C) ratios from elemental analyses (dmmf) on a van Krevelen diagram (Tissot and Welte, 1984). Most samples fall within Durand and Paratte's (1983) humic coalification pathway, derived from the elemental analyses of a large number of coals. Substantial decrease in O/C occurs before H/C begins to decrease appreciably, resulting in a sharp downward deflection of the maturation path above 0.8% Rm (mean, maximum vitrinite reflectance). This is characteristic of Type III kerogens and reflects elimination of oxygen as carbon dioxide from low rank coal. Loss of hydrogen is as great between lignite and high volatile bituminous rank coal (c. 0.3–0.8% Rm) as throughout the whole of the conventional "oil window" (0.8–1.3% Rm). Atomic H/C ratios decrease from 1.0–1.3 in low rank samples to 0.7–0.8 at the base of the oil window (c.

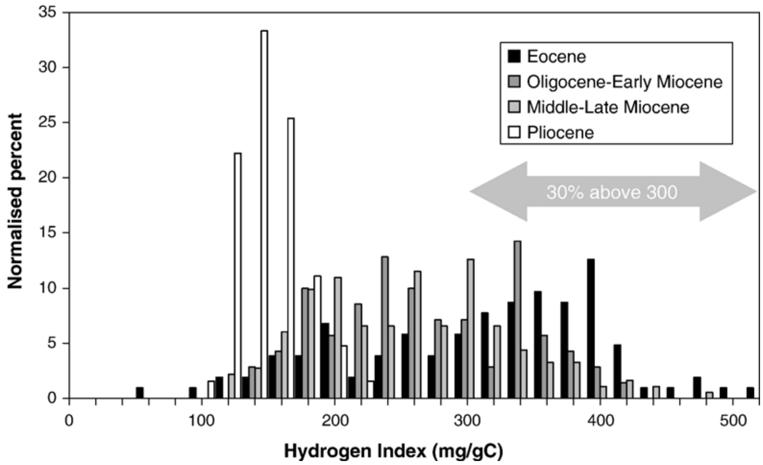

Fig. 4. Normalised percent histogram of hydrogen index by age (coals).

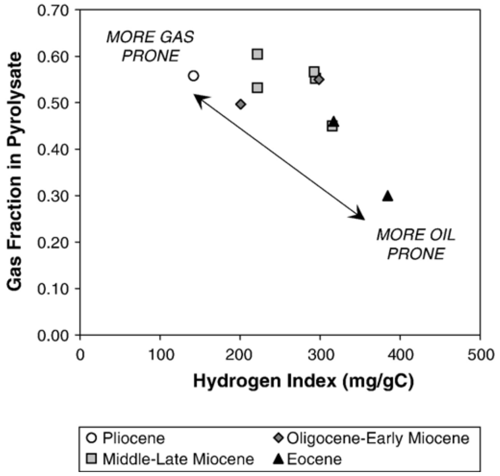

Fig. 5. Average gas fraction in pyrolysate versus hydrogen index (coals).

1.3% Rm). Some low rank hydrogen-rich coals may contain perhydrous vitrinite, though the presence of resinite or alginite may also cause significant elevation in H/C. Terpene resins from Middle to Late Miocene coals of the Warukin Formation (Asem-Asem Basin) and the Balikpapan Group (Kutei Basin), and alginite-rich lacustrine shale from the Eocene Sangkarewang Formation of Central Sumatra (Ombilin Basin) yield extremely high H/C ratios of 1.5–1.6.

6.2. Bulk pyrolysis and pyrolysis-gas chromatography

TOC and Rock-Eval analyses reveal that coals of different age have markedly different pyrolysis potential. Fig. 4 is a histogram showing the distribution of hydrogen index (HI) by age, normalised to the number of coals in each age group. Pliocene coals from West Sumatra are hydrogen-poor with low average HI of 138. Oligocene to Early Miocene and Middle to Late Miocene coals are richer, with average HI of 259 and 263 respectively, and Eocene coals are the most hydrogen-rich, with average HI of 302. About 30% of our sample set (uncorrected for sampling bias) yielded hydrogen indices above 300, suggesting a substantial proportion of Indonesian coals have moderate to significant potential to generate and expel liquids.

Pyrolysis-gas chromatography (Py-GC) was performed on 113 coals and 3 Miocene resins. This method allows us to determine the identity and distribution of compounds in the Rock-Eval S2 fraction, and the proportion of gaseous versus oil range products (Larter and Douglas, 1980, 1982; Mukhopadhyay et al., 1985; Mukhopadhyay, 1989; Horsfield, 1989, 1990). Py-GC confirmed the majority of Indonesian coals are capable of generating waxy paraffinic oil. In contrast, the principal thermal breakdown products of Miocene resinites are bicyclic sesquiterpenoids. This is characteristic of Class II resins composed of a polycadinene biopolymer (Grantham and Douglas, 1980; Van Aarssen et al., 1990; Anderson et al., 1992; Anderson and Crelling, 1995) and derived from Dammar-type precursors. Dammar resins are attributed to members of the Dipterocarpacae, which proliferated in Southeast Asia in post-Eocene times (Maury-Lechon and Curtet, 1998), and were an important component of Neogene peat-forming palaeofloras. Rock-Eval HI may overestimate petroleum potential where substantial resinite is present (Horsfield et al., 1988; Katz et al., 1991). Fig. 5 demonstrates that the majority of coals yield similar average gas fractions of 0.5–0.6 in their pyrolysates, despite significant variation in HI, suggesting Rock-Eval parameters are not closely linked to oil potential in Tertiary coals.

Sykes (2001) observed a systematic increase in HI in New Zealand Taranaki Basin coals with increasing maturity, to a Suggate rank of 11–12.5 (c. 0.65–0.85% Ro) (Suggate, 2000, 2002). This was taken to indicate that Rock-Eval underestimates HI in low rank coals. A similar increase is observed in our data set, with peak HI occurring at a Tmax of about 430 °C (c. 0.6% Ro; Fig. 6). This suggests Rock-Eval pyrolysis may underestimate the petroleum potential of low rank Indonesian coals by up to 100 mg/g C, though evidence presented below suggests the low potential of Pliocene coals may to some extent be real. At the same time the bitumen index (BI = S1 / TOC * 100) decreases by almost an order of magnitude (Fig. 6). It is unlikely that the decrease in bitumen content reflects early petroleum

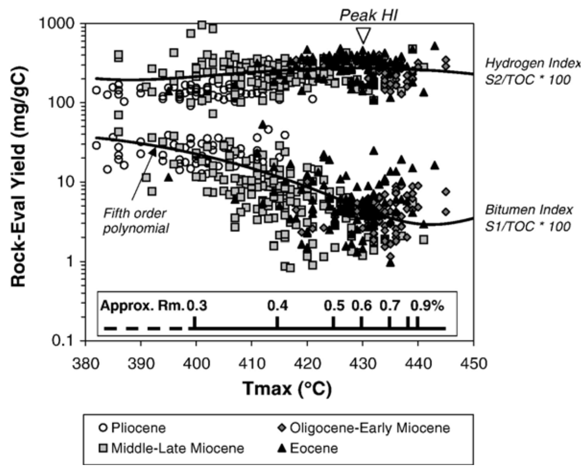

Fig. 6. Rock-Eval S1 and S2 yields versus Tmax (coals).

expulsion. In fact, the inverse relationship between S1/TOC and S2/TOC suggests that labile components are progressively transformed into a kerogen-like polymer, or otherwise locked into the coal matrix during diagenesis.

There are several possible reasons for the increase in HI. If one compares the magnitude of change in median S1/C and S2/C, it seems that only a small proportion of the increase – about 30 mg/g C, or 30% – can be attributed to the transformation of labile material into kerogen. A recognised limitation of the Rock-Eval process is that HI in organically lean samples may be suppressed by the catalytic effect of clay minerals on the kinetics of kerogen breakdown (Katz, 1983; Espitalié et al., 1984). Langford and Blanc-Valleron (1990) attributed positive intersections of the *x*-axis of a plot of S2 yield versus TOC, to mineral matrix effects. Matrix-induced suppression may hardly be invoked in coals, however, where detrital mineral matter is typically less than 10%. Another possibility is that the continuous increase in HI with increasing maturity is an effect of compaction and elimination of non-hydrocarbons. Durand and Paratte (1983) proposed that loss of oxygenated components as CO_2 during pyrolysis of low maturity coals is the cause of HI suppression. As the Rock-Eval FID does not measure CO_2, S2 yield is lower, relative to TOC. With increasing rank, less CO_2, and more hydrocarbons are evolved, resulting in an apparent increase in HI. A third possibility is that part of the increase is real. A linear relationship between HI and TOC is often observed in suites of similar kerogen type, which is commonly attributed to increasing preservation of organic matter. The higher HI in Palaeogene coals may therefore be the result of differences in palaeoflora and/or preservation within different tectonic settings and peat-forming environments.

6.3. Maturity

Tmax is available for all samples. This can be used as a rank indicator, though for a given maturity it varies significantly according to kerogen type, as it is sensitive to differences in the kinetic behaviour of different macerals (Snowdon, 1995). Vitrinite reflectance is more satisfactory, though many authors have pointed out the difficulty in using this as a rank parameter for hydrogen-rich coals, due to suppression in the presence of liptinite (particularly alginite, bituminite, or resinite), or the presence of different vitrinite types with inherently different reflectance. Recently, Suggate (2000, 2002) proposed a rank parameter (Rank(S_r)) based on volatile matter content and calorific value, or atomic ratios (dmmf) to overcome such variation. This proved difficult to implement here, as no proximate analyses were performed, and only a small proportion of our samples was subjected to elemental analysis. Despite its limitations, vitrinite reflectance therefore remains our maturity parameter of choice.

Most coals in our sample set are of lignite to high volatile bituminous rank, with very few reaching a high volatile bituminous A stage of maturity (>0.75% Rm; Fig. 7). Rank variations conform to those described by Hutton et al. (1994) and Daulay and Cook (2000). Maturities generally reflect their age, but Oligocene coals from Sumatra are exceptionally mature, more so than Eocene coals from Kalimantan, due to tectonic uplift and/or higher regional heat flow in a back-arc setting. A few coals with high vitrinite reflectance are altered by contact metamorphism. These include semi-anthracites from the Muara Enim Formation in South Sumatra, with Rm of 2.2–2.5%, medium volatile bituminous coals from Eocene and Late Miocene

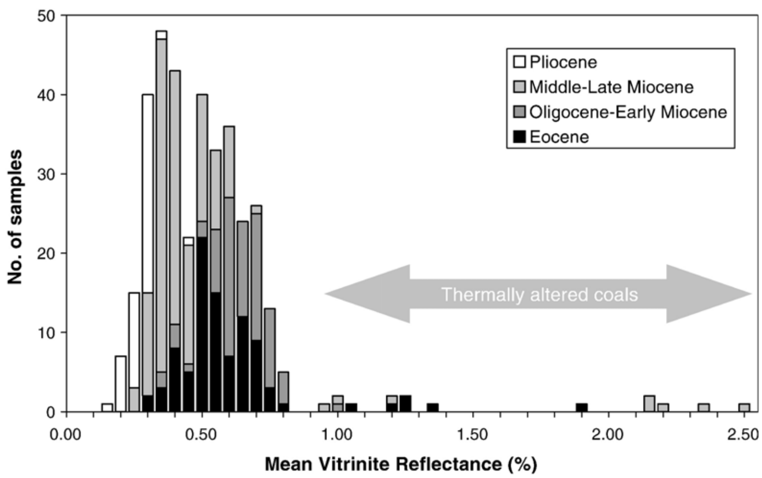

Fig. 7. Frequency histogram of vitrinite reflectance by age (coals).

formations of Southeast Kalimantan and Western Sulawesi, with Rm of 0.8–1.4% and one higher rank high, volatile bituminous example from the Bengkulu Basin of West Sumatra, with Rm of 1.0%.

6.4. Organic petrography

6.4.1. Distribution of major maceral classes

Coal maceral distribution and mineral content were determined by point counting polished blocks. One of the limitations of our analyses is that macroscopic textures such as bright and dull banding were not recorded. Moore and Ferm (1988) suggested that differences between banded and non-banded coal from the Eocene of Southeast Kalimantan reflects the level of preservation of plant parts and tissues. They also noted the inadequacy of petrography methods in differentiating coals that are megascopically distinct in the field, and that petrographic analyses of crushed samples tend to overstate the proportion of matrix material, relative to intact blocks of coal.

In contrast to claims by Thompson et al. (1985), and despite their hydrogen-rich character, Indonesian coals are generally poor in liptinite, with a modal content of 8% (Fig. 8). Inertinite is scarce with mode of about 2% (Fig. 8), demonstrating a lack of forest fires and/or oxidation of the peat by subaerial exposure, or submersion by oxygenated flood waters. Hutton et al. (1994) note that some Miocene coals from the Mahakam region have anomalously high inertinite content (18–31%), though no such examples occur in our data set. A similar proportion of inertinitic material occurring above the water table in the Palangkaraya peat deposit of Central Kalimantan, is attributed to fungal oxidation in response to a lower than normal or fluctuating water table (Moore et al., 1996). The majority of coals contain very little mineral matter, with a mode of about 5% (Fig. 8), indicating that raised (meso- or ombrotrophic) mires were more common than submerged (rheotrophic) mires. Pyrite and carbonate minerals are rare, and consistent with limited post-depositional marine influence.

Pyrite and total mineral matter are typically elevated in Eocene syn-rift coals from the Asem-Asem, Makassar, Lariang and Bone Basins. Abundant pyrite is probably related to infusion of sulphate-bearing waters from an overlying marine transgression, whereas the higher ash content in these coals is related to a higher water table. Thicker, lower ash coals occur in Miocene–Pliocene sequences, resulting from ombrotrophic mires that were raised above the level of annual floods (Friedrich et al., 1999).

6.4.2. Liptinite content

On the whole, liptinite macerals are more abundant in the Eocene coals than in their Neogene counterparts. Eocene coals are also more hydrogen-rich, though generally there is little relationship between liptinite and HI, even allowing for sample heterogeneity by averaging data from multiple analyses (Table 2). The

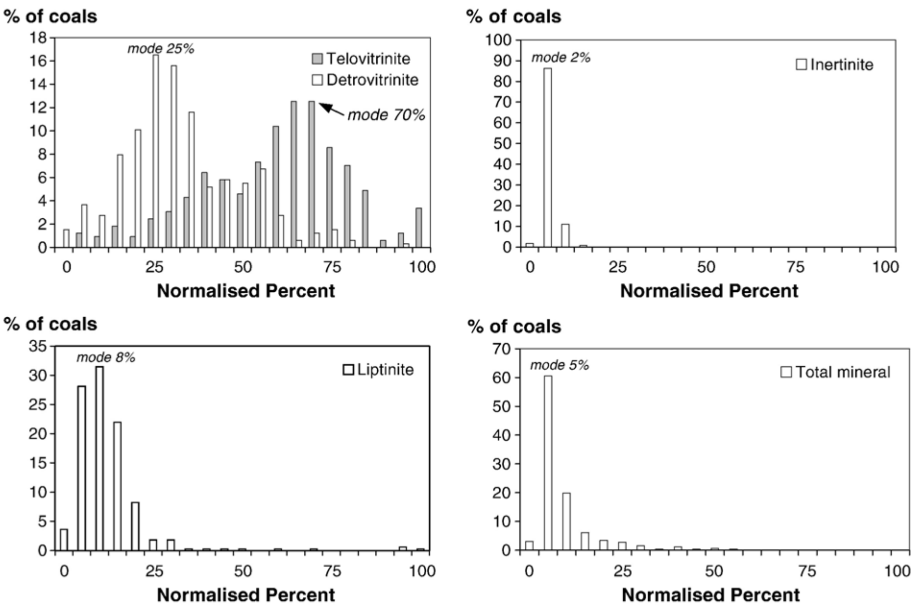

Fig. 8. Histograms of normalised vitrinite, liptinite, inertinite and total mineral matter as a percentage of all analysed coals.

Table 2
Average parameters for coals subjected to statistical analysis (av = average; DI = Detrovitrinite Index; see text for definition)

Basin	Formation	Age	No. of coals	TOC_{av} (%)	HI_{av} (mg HC/g C)	Gas $fraction_{av}$	$Tmax_{av}$ (°C)	Rm_{av} (%)	$Lipt_{av}$ (%)	$Mineral_{av}$ (%)	DI_{av}
Sibolga	Tutut	Pliocene	63	48.1	138	0.56	401	0.33	10.4	6.4	0.30
Bengkulu	Unnamed	Late Mio	9	58.4	312	0.55	426	0.50	12.2	4.5	0.42
South Sumatra	Muara Enim	Late Mio	74	57.7	203	0.53	415	0.44	9.5	5.3	0.38
South Sumatra	Muara Enim (A Mbr)	Late Mio	34	58.7	278	0.45	416	0.40	6.9	3.0	0.46
Kutei	Balikpapan Grp	M–Late Mio	36	62.9	284	0.57	413	0.50	10.9	4.1	0.42
Asem-Asem/Barito	Warukin	M. Mio	21	54.1	262	0.60	415	0.43	11.0	5.9	0.38
Ombilin	Sawahlunto	Oligo–Mio	23	64.8	318	0.55	432	0.64	4.2	3.3	0.40
Sibolga	Palaeogene	Oligo–Mio	44	59.5	223	0.50	436	0.70	3.9	6.1	0.22
Asem-Asem	Tanjung	Eocene	40	65.3	365	0.30	426	0.54	12.2	14.0	0.43
Ketunggau	Ketunggau/Kantu	Eocene	32	55.9	224	0.56	427	0.63	5.5	6.1	0.32
W. Sulawesi	Palaeogene	Eocene	15	57.6	304	0.46	423	0.49	13.2	17.8	0.45

Oligocene–Early Miocene and Middle to Late Miocene coals have similar hydrogen indices, but average liptinite contents tend to be much lower in the Oligocene–Early Miocene coals. The Pliocene coals have comparable liptinite contents to those of the Middle to Late Miocene coals, yet have much lower hydrogen indices.

The dominant liptinite species are resinite and suberinite, and the thermal behaviour of these macerals is thought to play an important role in the petroleum generative behaviour of coals (Horsfield et al., 1988; Noble et al., 1991; Hutton et al., 1994). Khorasani (1987) observed high Rock-Eval S1 and total solvent extract (TSE) yields in immature, mid-Jurassic coals of the Walloon coal measures, Surat Basin, Australia, and a strong positive correlation between suberinite/terpene resinite content and S1/TOC ratios. In the present data set, suberinite + resinite concentrations (normalised to total maceral content) display a broadly positive correlation with bitumen index (BI; Fig. 9). Most of this correlation lies with resinite alone. There is a discernible relationship between BI and maturity of the coals, which differs from conventional clastic source rocks. In clastics, BI remains constant at low maturity, then increases and decreases in response to petroleum generation and expulsion (Tissot and Welte, 1984). In this data set BI displays a general decrease from the lignite to high volatile bituminous stage (Fig. 10). This is most likely due to increasing polymerisation or adsorption of labile macerals into the coal matrix with increasing rank. Mature coals at 0.7–0.8% Rm appear to have higher bitumen yields than immature samples, suggesting there is an increase in bitumen content in response to petroleum generation, though there are very few samples above 0.75% Rm in our data set to illustrate this trend.

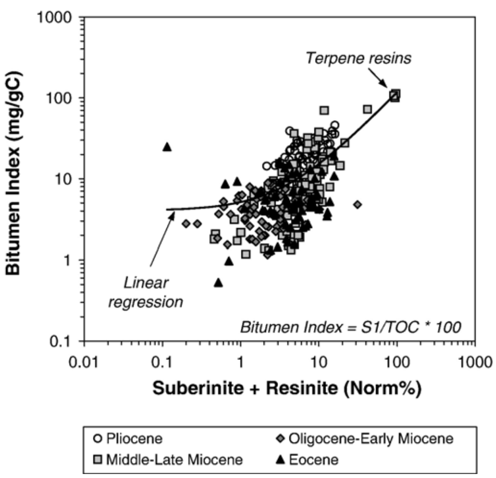

Fig. 9. Bitumen index (S1/TOC × 100) versus normalised percentage of suberinite and resinite (coals).

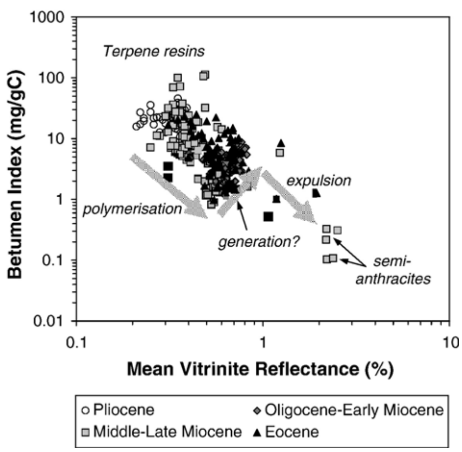

Fig. 10. Bitumen index (S1/TOC × 100) versus mean vitrinite reflectance (coals).

Early generation from resinite and suberinite is supported by two observations. Firstly, the abundance of these macerals displays an inverse relationship with maturity decreasing by almost an order of magnitude between about 0.2% and 0.9% Rm. (Fig. 11). Secondly, there is evidence from fluorescence emission spectra that different liptinite macerals generate petroleum at different times (Khorasani and Murchison, 1988). With increasing maturity, residual carbon in kerogen becomes increasingly aromatic due to progressive removal of saturated structures and loss of alkyl substituents from aromatic nuclei (Vandenbroucke, 2003). This results in a progressive change in emission spectra towards the red end of the spectrum, termed red shift. Khorasani and Murchison (1988) considered the timing of this change to indicate the order of generation in individual liptinite macerals. By this measure, terpene resinites generate early, by about 0.55% Ro, and suberinite, a maceral derived from cork tissue, abundant in many Miocene coals, generates even earlier, by about 0.35% Ro. Cutinites and sporinite also generate comparatively early (0.55–0.60% Ro), whereas aliphatic macerals such as alginite and lipid resinite generate later, at c. 0.7% and 0.8% Ro respectively. The difference in timing of generation from different liptinite species may be a critical factor in determining whether coals will be efficient expellers of oil (Wilkins and George, 2002).

6.4.3. Vitrinite type

Two types of vitrinite were differentiated by point counts. Telovitrinite is defined within the ICCP System 1994 (ICCP, 1998) as a form of vitrinite with preserved botanical structure, derived largely from parenchymatous and woody tissues of root, stem, bark and leaves of herbaceous and arborescent plants. Detrovitrinite is described as finely comminuted plant remains, either isolated or cemented by amorphous vitrinitic matter, and derived by strong chemical decay and/or mechanical attrition. Telovitrinite dominates most of the coals with a mode at about 70%. Detrovitrinite is subordinate, with a mode at 25%. We define the term Detrovitrinite Index (DI), as the ratio of detrovitrinite to total vitrinite. When average HI is plotted against average DI (to mitigate variation due to heterogeneity) for each formation, a positive relationship emerges (Fig. 12). Detrovitrinite appears to correlate with petroleum potential to a much greater degree than the abundance of liptinite macerals. A similar relationship was observed by Petersen and Rosenberg (2000) for Middle Jurassic coals of the Danish North Sea, suggesting this is an important, but poorly documented mechanism influencing the petroleum potential of coals. Understanding the environmental factors controlling DI may therefore be critical to establishing the distribution of oil-prone coals in the subsurface.

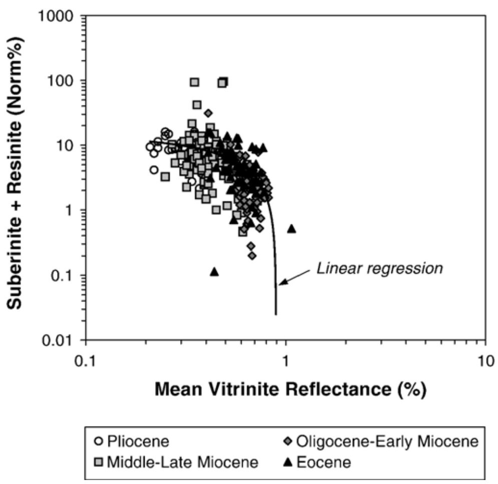

Fig. 11. Suberinite and resinite content (normalised to whole kerogen) versus mean vitrinite reflectance (coals).

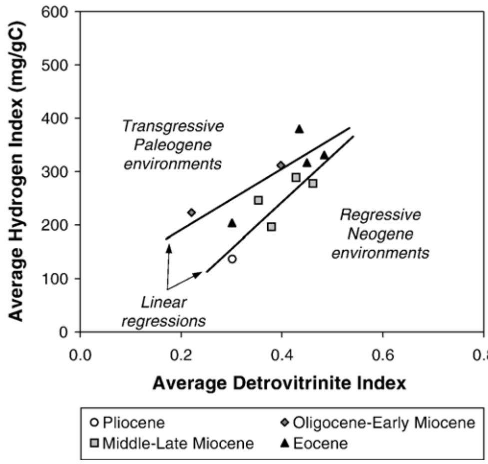

Fig. 12. Average hydrogen index versus average detrovitrinite index by age (coals).

7. Statistical analysis: definition of coal sub-types

Using statistical means, we classified the Indonesian coals into a number of sub-types with distinct physicochemical characteristics. For the purposes of including a sample in our analysis, we used 40% TOC as a convenient chemical definition of coal. This excluded a number of lignite grade, low ash coals with TOC as low as 35%, but included several higher rank coals with relatively high mineral contents.

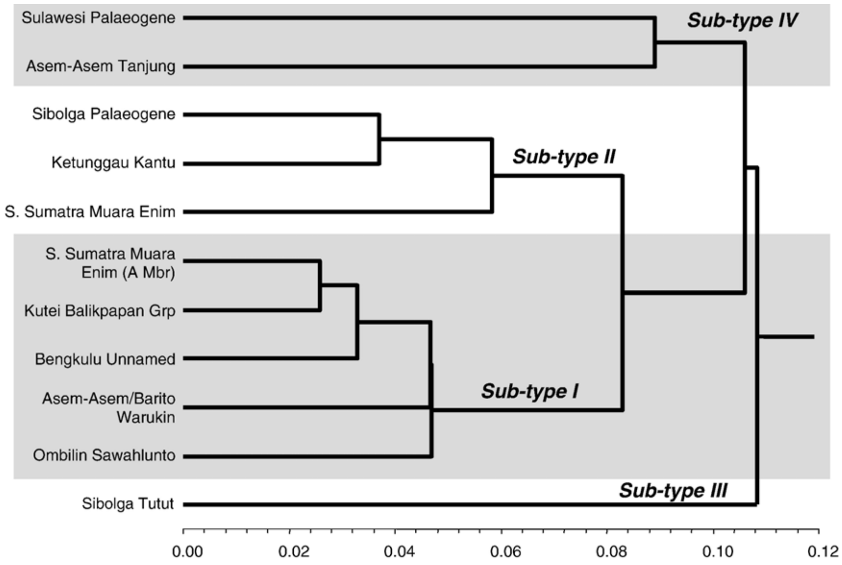

Fig. 13. Dendrogram from cluster analysis showing coal sub-types I–IV.

Few causal relationships exist between the optical and chemical properties of our coals. This is partly a function of heterogeneity, and arises due to the small sample sizes used in geochemical analyses, and the fact that each analysis was performed on a different sub-sample. The result of any single analysis lies on a distribution of possible results whose standard deviation is proportional to the heterogeneity of the sample. The range of uncertainty inherent in individual analyses is to some degree addressed when multiple values from a single seam are averaged using the method described in Section 5. The proximity of the value obtained to the true average (i.e. the precision) is then related to the number of available analyses, and the standard deviation of the population. Seams with heterogeneous chemistry or maceral content, and limited sample numbers are expected to yield less precise average properties than seams of homogeneous composition.

A total of 22 (1 chemical and 21 microscopically derived) parameters were selected to characterize the data set. Average HI, DI, the percentage of each liptinite (cutinite, liptodetrinite, resinite, sporinite, suberinite, bituminite, alginite, fluorinite), inertinite (semifusinite, macrinite, inertodetrinite, micrinite, sclerotinite) and vitrinite type (detrovitrinite and telovitrinite) normalised to total kerogen, pyrite plus iron oxide content, total mineral matter, and bulk maceral classes (vitrinite, inertinite, exinite) were calculated for each seam. These parameters were subjected to cluster analysis (nearest neighbour and Euclidean distance similarity method) using StatistiXL 1.4 with Microsoft Excel 2000.

Four sub-types are defined from Fig. 13 and summarised in Table 3. The primary distinguishing factor was HI, followed by liptinite content, then DI.

Table 3
Geographic distribution, age and tectonic setting of coal sub-types I–IV (see Fig. 1 for basin locations)

Coal sub-type	Basin	Formation	Age	Tectonic setting
I	Asem-Asem/Barito	Warukin	Middle Miocene	Regressive, syn-tectonic
I	Bengkulu	Unnamed	Late Miocene	Regressive, syn-tectonic
I	Kutei	Balikpapan Group	Mid–Late Miocene	Regressive, syn-tectonic
I	South Sumatra	Muara Enim (A Mbr)	Late Miocene	Regressive, syn-tectonic
I	Ombilin	Sawahlunto	Late Oligocene–Early Miocene	Transgressive, post-rift
II	South Sumatra	Muara Enim	Late Miocene	Regressive, syn-tectonic
II	Ketunggau	Ketunggau/Kantu	Eocene	Transgressive, syn-rift
II	Sibolga	Unassigned	Late Oligocene–Early Miocene	Transgressive, post-rift
III	Sibolga	Tutut	Plio-Pleistocene	Regressive, fore-arc
IV	Asem-Asem	Tanjung	Eocene	Transgressive, syn-rift
IV	Western Sulawesi	Palaeogene	Eocene	Transgressive, syn-rift

Mineral matter proved valuable only in distinguishing sub-type IV, and inertinite played virtually no role in differentiating coal sub-types.

Sub-type I and sub-type IV have high average HI and DI, and on the basis of hydrogen index, are likely to be the most oil-prone. On the basis of the gas fraction in pyrolysates, sub-type IV remains the most oil-prone (Fig. 5), and there is little to choose between sub-type I, II or III. Sub-type II is differentiated from sub-type III primarily on the basis of HI, with relatively minor differences in liptinite and inertinite contents. Sub-type I is primarily associated with regressive Neogene sequences. Sub-type II occurs in depositional settings of all ages and tectonostratigraphic associations. Sub-type III is represented by Pliocene coals from the West Sumatran fore-arc, whereas sub-type IV is represented by Eocene syn-rift deposits on either side of the Makassar Strait (Table 3).

Sub-type I tends to have low liptinite and mineral contents, whereas sub-type IV has high liptinite and mineral contents, including abundant pyrite, which may be an indication of marine influence. Friedrich et al. (1999) observed that the basal coal seam within the T2 Member of the Tanjung Formation, Asem-Asem Basin, is immediately overlain by a marine transgression, and an increase in sulphur content, mainly due to pyrite, is observed towards the top of the seam. Attrital bands are common within sub-type IV, and frequently contain a distinctive maceral assemblage of micrinite, bituminite and alginite, dominated by telalginite (Botryococcus) colonies. This is consistent with deposition in water-logged or wholly submerged conditions.

8. Discussion

8.1. Relationship between peat formation, preservation, petrographic composition and petroleum potential

Fundamental differences in methods of sampling and analysis of peat and coal mean few studies can be used to directly compare their lithotypes. It is difficult therefore, to establish a link between characteristics of the peat forming environment, and the physicochemical properties of coals. Some authors have attempted to overcome this by modifying the procedure for petrographic analysis of coals (Moore and Ferm, 1988), and by characterizing peat cores using parameters that can more adequately be compared with coals (e.g. grain size analysis, ash and sulphur content — Moore and Hilbert, 1992; Esterle and Ferm, 1994). Moore et al. (2000) explored how different coal textures are formed in the peat and examined the relationship between texture and key coal properties. Using a similar approach, Moore and Shearer (2003) found no relationship between peat type, depositional environment, climate or tectonic setting, and they concluded that using organic petrography to interpret mire type is unproductive.

The domed peat bogs of the Southeast Asian archipelago have frequently been used as precursor analogues for coal, as they are both humic, and contain very low ash and sulphur, in accordance with most commercial coal seams (McCabe, 1987). Major characteristics of these mires are that they are raised above the surface of the surrounding flood plain (Anderson, 1964), and frequently display floral zonation which is reflected in the palynomorph content of the resulting coals (Anderson and Muller, 1975; Cameron et al., 1989; Moore and Hilbert, 1992; Esterle and Ferm, 1994). McCabe (1987) produced a series of schematic diagrams to illustrate stages in the development of these mires. The cycle typically begins on an alluvial plain incised by drainage channels. The development of ephemeral lakes leads to the deposition of floating mires and clay-rich gyttja. These are gradually replaced by telmatic peats, and a low lying or rheotrophic mire develops. Rheotrophic mires have yet to develop any relief and are frequently flooded, with sediment washed in from adjacent regions. The resultant peats are mineralic, and support a diverse floral community. If the mire fails to develop any further, the result will be a thin, high ash, sapropelic coal or carbonaceous shale. Continued peat growth may result in the development of a raised or mesotrophic mire. Slight topographic elevation can dramatically reduce the ash content of the peat, due to sediment bypass and clay flocculation around the margins of the deposit (Esterle and Ferm, 1994). Ultimately a fully ombrotrophic, domed mire develops, in which the water table is fed by rainfall alone. These mires often have poorly drained, slightly concave upper surfaces, promoting acidic, water logged conditions in the centre of the dome. Loss of the nutrients provided by periodic flooding results in a restricted and stunted flora, and slower growth of the peat leads to a greater degree of humification. The prevailing floras are rich in cellulosic components which degrade more readily, and the centre of the deposit becomes densinite-rich, whereas the base and margins are richer in other huminites.

Zonation of the peat body is preserved to some extent within the resulting coal, and manifests as differences in both macro- and microlithotype. Moore and Hilbert (1992) showed that the Teluk Keramat peat dome in NW Kalimantan consists of several megascopic peat types — fine hemic peat in the centre, sapric peat interbedded with fine hemic peat on the flanks, and coarse hemic peat towards the base. The centre of the deposit is composed of fine hemic peat right to the base, suggesting even at an early stage of formation the mire is most heavily degraded in the middle, where it is most protected from the influence of flood waters. Esterle and Ferm (1994) observed that domed peats in the Baram delta region of Borneo are similarly structured. The most highly degraded sapric peat is interlayered with locally granular fine hemic peat on the steep flank and at the base of the deposit. This is overlain by successive layers of hemic, coarse hemic and fibric peat. The hemic peat is proposed to be a product of pole forest and the transition community into the open bog plain. The uppermost fibric zone forms from the root systems of shrubs and trees in the acidic, nutrient starved centre of the dome.

Moore and Ferm (1988) noted that the highest concentration of wood and bark tissue tends to occur at the edge and base of peat bodies, and therefore changes in the abundance of plant parts and tissues within a coal bed may be used to indicate its position within the mire. Moore et al. (2000) further demonstrated this structural zonation in New Zealand coals, where the highest proportion of vitrain bands occurred at the top, bottom and edges of seams, and the centre is characterized by a higher proportion of amorphous matrix.

Differences in ash content, petrographic composition and petroleum potential of the various sub-types of Indonesian coals likewise suggests they were deposited in different mire types, or at different stages in the development of a mire. Low ash contents suggest that sub-type I, II and III coals were deposited primarily in meso-ombrotrophic mires, whereas high ash contents suggest that sub-type IV coals were deposited in rheotrophic mires. The rapidly subsiding syn-rift setting of Eocene Sub-type IV coals may well have resulted in frequent flooding and submersion that hindered vertical growth of the peat, while promoting extensive microbial degradation and liptinite enhancement.

Diessel (1982, 1986, 1992) developed two indices to assist in classification of peat-forming environments. The Gelification Index (GI) is essentially the ratio of huminite to inertinite, whereas the Tissue Preservation Index (TPI) is the ratio of tissue-derived structured over unstructured macerals. The resultant classification scheme was developed from Australian Gondwanan coals, and it may be unsuited to classifying Tertiary tropical coals (Amijaya and Littke, 2005). Indeed, GI is invariably high in Indonesian coals due to the low inertinite content. TPI is redefined in this study as the ratio of (telovitrinite + semifusinite)/(detrovitrinite + macrinite + inertodetrinite). Average TPI and GI of each seam studied place them within Diessel's telmatic (terrestrial) rather than limnic peat zone. Average TPI ranges from 1.47 to 3.92, and as such, even our most hydrogen-rich, sapropelic syn-rift coals lie within Moore and Shearer's (2003) wood dominated, fibric peat or vitrain macrolithotype. We conclude that our TPI is perhaps significantly higher than TPI *sensu* Diessel (1982, 1986, 1992).

A number of factors operate on TPI, including the type of flora, degree of humification, and subsidence rate relative to the water table. Low TPI values are characteristic of peats formed from herbaceous flora, or those which have undergone extensive huminite degradation. If we compare average TPI with average HI for each formation, we see an excellent relationship (Fig. 14). Clearly the degree of degradation of the peat, as reflected by TPI, is inextricably linked to petroleum potential. Eocene coals from sub-type IV and Miocene coals from sub-type I display the highest HI values and the lowest degree of tissue preservation. Sub-type II coals and one coal attributed to sub-type I (Warukin coals from the Asem-Asem/Barito Basins) display lower HI and higher TPI values. Pliocene coals from the Sibolga Basin (sub-type III) display the lowest HI and among the highest TPI of all. This is evidence that the low HI of these fore-arc coals may not be entirely an artifact of Rock-Eval analysis (cf. discussion in Section 6.2).

The two most hydrogen-rich coal sub-types (I and IV) were respectively formed in ombrotrophic and rheotrophic mires. There is little to differentiate sub-types II and III coals from sub-type I, other than hydrogen index and detrovitrinite index. The most likely cause of variation in petroleum potential is therefore likely to be a difference in the degree of degradation of the peat. Clymo (1984) observed that the greatest

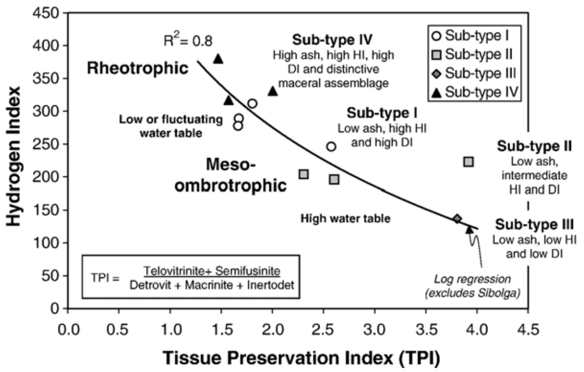

Fig. 14. Relationship between coal sub-types, hydrogen index and tissue preservation index (after Diessel, 1992).

amount of degradation occurs within the aerobic zone above the water table (acrotelm). Plant material falling on the surface of the peat and passing through the acrotelm is highly susceptible to degradation by microbial and fungal decay. This led Moore et al. (2000) to conclude that coals may be derived largely from root material that penetrates the anaerobic layer (catotelm) of the peat.

Moore and Shearer (2003) argue that coal type is more closely related to the degree of degradation of the peat than other factors such as climate, depositional environment or tectonic setting. Where water tables are high, the peat body will contain a thin acrotelm and on the whole, will be well preserved. Where the water table is low or frequently fluctuating, plant matter will experience a longer residence time in the acrotelm, resulting in more intense degradation of the peat. Highly degraded or sapric peat, rich in liptinite and detrovitrinite, is comparable to the durain coal macrolithotype of Stach et al. (1982). Less degraded hemic peat is equated to the clarain macrolithotype, whereas the best preserved fibric peat type is comparable to the telovitrinite-rich vitrain macrolithotype of Stach et al. (1982). Telovitrinite-rich sub-type II and III coals, with elevated TPI, are likely to have formed under conditions of retarded humification, where the water table was consistently high, resulting in a higher degree of preservation of the original plant material. Sub-type III (Pliocene) coals display very low hydrogen indices as a combination of the above, and the effect of HI suppression at very low maturity (as described in Section 6.2).

9. Conclusions

Indonesian Tertiary coals display a remarkable range of petroleum potential. The most hydrogen-rich, and by implication, the most oil-prone, are high ash, liptinitic Eocene coals deposited in submerged mires in a transgressive, syn-rift setting. Equally hydrogen-rich, though yielding more gas-rich pyrolysates, are low ash Oligocene–Early Miocene and Middle–Late Miocene coals deposited in raised mires in a regressive, syntectonic setting. Hydrogen-poor, low ash coals from similar raised mire settings are common, and are differentiated primarily on the basis of hydrogen index (HI) and a new parameter describing the type of matrix (detrovitrinite/total vitrinite). We propose this parameter be called Detrovitrinite Index (DI).

There is a clear link between HI and DI, indicating that the petroleum potential of Indonesian Tertiary coals is more sensitive to vitrinite type than liptinite content. The type of vitrinite that dominates is related to the degree of preservation of the peat precursor. A link between HI and tissue preservation index (TPI) has also been demonstrated, such that the greater the degree of peat degradation, the greater the petroleum potential of the coal. Peat degradation is controlled by the position of the water table relative to the surface of the peat, and is unlikely to be significantly influenced by climate, depositional environment or tectonostratigraphic setting.

Although it may not be possible to use the petroleum potential and petrographic character of coals to infer their mode of deposition, we have demonstrated at least four sub-types within Indonesian Tertiary coals. The ability to differentiate sub-types of coal using readily available parameters (Rock-Eval hydrogen index, petrographic composition), and link these to processes within the peat-forming environment is a major step towards being able to predict the distribution of oil-prone coals in the sub-surface.

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