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A petrographic comparison of oil-generating coals from the tropics and non oil-generating coals from the arctic

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Abstract: This paper discusses the findings of a comparative study of microscopically recognisable oil-generative features observed in coals from two presently extreme climatic conditions: the arctic and the tropics. The samples investigated are from Spitsbergen, Svalbard and from Sarawak, Borneo. Both sets of coals are of Tertiary age and both were deposited in a lower coastal plain setting. The Palaeocene - Eocene coals of Spitsbergen were deposited in temperate to subarctic conditions while the Miocene coals of Sarawak were deposited in subtropical to tropical conditions. Features associated with oil-generation from the Sarawak coals include a widespread occurrence of exsudatinite veins and oil globules/haze. Hydrocarbon generation is often observed to be associated with the occurrence of a high abundance of framboidal pyrite. Coals from Spitsbergen, on the other hand, lack the oil generative features described above. Although the occurrence of oil-smears can be observed, they are not extensive and exsudatinite is rarely observed. To date, no significant oil accumulations of terrestrial origin have been discovered on or around the island of Spitsbergen. In contrast, offshore Sarawak is a prolific oil and gas producing province. Considering that the terrestrially-derived oils of the Balingian Province are sourced from stratigraphic equivalent sequences to the onshore coal-bearing sequences investigated here, it is clear that microscopical features are good indicators for the recognition of oil-prone coals.

Abstrak: Kertas kerja ini membincangkan suatu kajian perbandingan ciri-ciri mikroskopi kecenderungan penjanaan minyak yang boleh di kenali bagi arang batu dari kawasan tropik berbanding arang batu dari kawasan artik. Sampel-sampel yang dikaji adalah dari Spitsbergen, Svalbard dan dari Sarawak, Borneo. Kesemua arang batu ini berumur Tertiar dan dienapkan di persekitaran dataran pantai bawah. Arang batu dari Spitsbergen berumur Paleosen – Eosen dienapkan dalam iklim sederhana ke subartik, sementara arang batu Miosen dari Sarawak dienapkan dalam keadaan subtropik ke tropik. Ciri-ciri yang berasosiasi dengan penjanaan minyak bagi arang batu dari Sarawak termasuk kehadiran secara meluas telerang exsudatinit dan globul-globul minyak serta kabut hidrokarbon. Penjanaan hidrokarbon biasanya dilihat berasosiasi dengan pirit framboid yang banyak. Sebaliknya arang batu dari Spitsbergen kekurangan ciri-ciri tersebut, walaupun lumuran minyak didapati hadir, tetapi kewujudannya tidak meluas sementara exsudatinit pula jarang dilihat. Setakat ini tiada penemuan besar akumulasi hidrokarbon asalan terrestrial di daratan atau pun di sekeliling perairan Spitsbergen. Sebaliknya luar pantai Sarawak adalah kawasan yang kaya dengan minyak dan gas. Memandangkan minyak asalan terrestrial dari wilayah Balingian yang mana stratanya berkedudukan sama secara stratigrafi dengan kawasan kajian, oleh itu adalah jelas yang ciri-ciri mikroskopik yang dibincangkan di sini merupakan penunjuk yang baik untuk mengenal arang batu yang berkecenderungan menjana minyak.

INTRODUCTION

Spitsbergen is the largest island within the Svalbard archipelago, a group of islands in the northwest corner of the Barents Shelf of Europe between 74° and 81° north and 10° and 35° east (Figure 1). Norway obtained sovereignty of Svalbard under the Treaty of Paris in 1920. The islands are mountainous and are sharply indented by frozen or partly frozen fjords and valleys. Spitsbergen's climate is polar. More than 60 per cent of Svalbard is permanently covered by glaciers and inland ice. No trees presently grow on the island. Due to its high northerly latitude, the sun never rises above the horizon in winter, resulting in four months of darkness when temperatures may drop below –50°C. Conversely, in summer there are four months of unbroken daylight, with temperatures of up to 15°C.

In stark contrast, Sarawak, consisting of over 80 per cent tropical jungle, is hot and humid throughout the year with mean daily temperatures ranging from 23°C to 32°C. The climate remains fairly stable throughout the year except for monsoonal changes. Situated just above the equator (north of Kalimantan, Indonesia; Figure 2), Sarawak, Malaysia's largest state, houses one of the richest and most diverse ecosystems in the world. Swampy lowland (consisting largely of mangrove and peat swamp) along the coast rises to mountain tops of up to 1,200 m in the interior towards the east.

GEOLOGICAL BACKGROUND

Geologically, Spitsbergen possesses an almost continuous stratigraphical sequence from the Precambrian to Cenozoic, much of which can be seen in exposures. Fossiliferous strata are abundant. Svalbard is positioned on an elevated part of the submerged continental shelf of the Barents Sea, adjacent to the North American plate and separated by a passive plate margin (Harland, 1969; Eldholm and Sundvor, 1980). This setting is considered of special

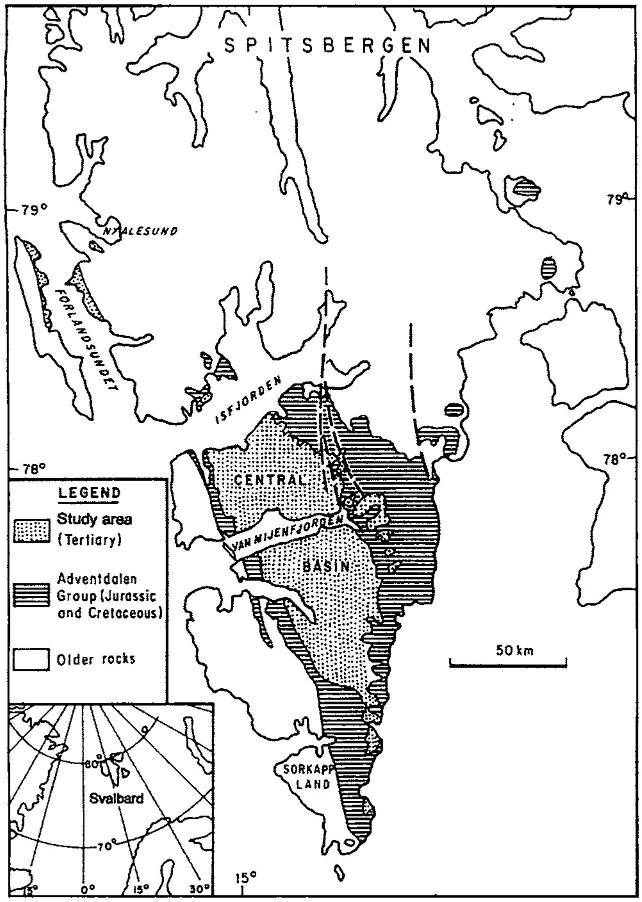

Figure 1. Location of the study area in Spitsbergen.

interest with respect to the search for petroleum and has triggered exploration activities by many international oil companies.

The Sarawak basin, occupying the southern margin of the South China Sea, forms part of the sedimentary basin of the Sunda shelf. The term Sundaland refers to the landmass of southeast Asia, including Sumatra, Java and Borneo, which stood above sea level during the Pleistocene epoch (Hutchison, 1996). The tectonic evolution of the South China Sea has had a major impact on the structural evolution of the Sarawak and other northern Borneo basins. The resulting development of petroleum provinces within the region is thoroughly discussed by Mazlan Hj. Madon (1999) and Tjia (2000).

PETROLEUM EXPLORATION ACTIVITIES

The Balingian Province is a proven hydrocarbon province in offshore Sarawak and has been actively explored since the early 1920s. Current oil production is from Upper Oligocene to Lower Miocene siliciclastic reservoirs in four main fields. The main source rocks were identified as coals of a lower coastal plain setting (Mazlan and Abolins, 1999). Based on geological evidence (e.g. Mohd Idrus and Redzuan, 1999) supported by the similarities in the biomarker distributions (Mazlan and Abolins, 1999; Wan Hasiah 1999), it is clear that the onshore Upper Oligocene to Lower Miocene Nyalau Formation coal-bearing

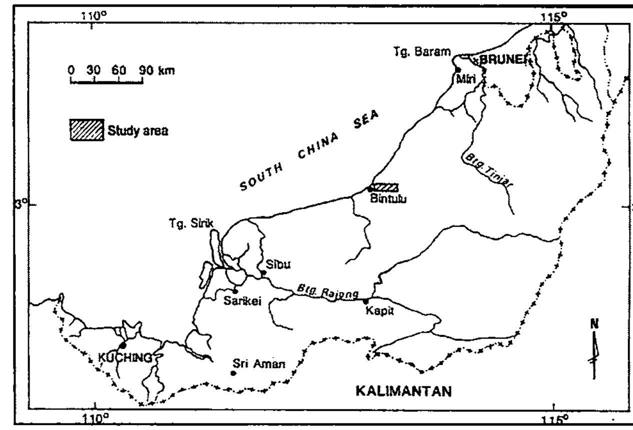

Figure 2. Location of the study area in Sarawak.

sequences are of stratigraphic equivalence to the offshore sequence of Cycles I and II. Therefore the coals described in this study should be similar to those that sourced the terrestrially-derived oils of the offshore Balingian Province. To date, however, no commercial oil accumulations have been found within the onshore Balingian Province.

Exploration work on and around the island of Spitsbergen has mainly been undertaken by oil companies from Norway, Sweden, the U.K. and by Russian groups. Since the burst of exploration activity during the 1970s, several wells have been drilled onshore in Spitsbergen. However, a major oil discovery is yet to be made. Based on a well drilled in 1988, hydrocarbon reserves of between 5 bcf and 5 tcf were estimated (Oil & Gas Journal, Nov. 23, 1992). Hydrocarbon discoveries made 7 years ago by Russian groups were only recently disclosed to Norwegian authorities and could spark new interest in oil and gas exploration on Svalbard (Norway Daily, Nov. 29, 1999).

COAL PALAEODEPOSITIONAL SETTING

The Paleocene-Eocene coal-bearing sequence was deposited contemporaneous with mountain building on Spitsbergen and prior to the early Oligocene rifting in the Norwegian-Greenland Sea (Eldholm *et al.*, 1984; Helland-Hansen, 1990). The Palaeogene (Palaeocene-Oligocene) was a time of rapid accumulation of terrigenous sediments in the large subsiding basin of central Spitsbergen (Steel and Worsley, 1984). The coals of Palaeocene age occur within the Firkanten Formation and those of the Eocene occur within the Aspelintoppen Formation. The coals are interbedded with sandstones and shales of fluvial-deltaic and shallow-marine deposits. Based on paleoclimatic indicators and probable palaeolatitudes proposed by Steel and Worsley (1984), these coals would have been deposited in temperate to subarctic conditions (Figure 3).

The Sarawak basin, made up of several onshore and offshore provinces (Tjia, 2000), developed in response to the uplift and erosion of the Rajang Fold-Thrust Belt which acted as the provenance of the Oligocene-Miocene sediments which subsequently accumulated in the Sarawak basin, including the offshore Balingian Province (Haile, 1969; Mazlan, 1999). In onshore Sarawak, the clastic sediments that constitute the Nyalau Formation investigated here consist of thin coals that rarely exceed 1 m in thickness, thin and thick sandstone beds, and subordinate shales. The coals of the Nyalau Formation around Bintulu area are mainly Miocene in age (Kho, 1968). The depositional facies of the Nyalau Formation was identified as representing shallow marine, tidal and coastal plain deposits (Liechti, 1960; Wolfenden, 1960; Bait and Asut, 1991).

Balingian Oils and coal extracts of the Nyalau Formation are characterised by the presence of higher plant derived biomarkers such as oleanane and bicadinanes (Mazlan and Abolins, 1999; Wan Hasiah, 1999). These terrestrial markers have been widely associated with triterpenoids of angiosperms origin and resin-derived compounds, respectively (e.g. Ekweozor and Udo, 1988; van Aarssen *et al.*, 1990, 1992). It is interesting to note that biomarker assemblages that commonly designate fluvio-deltaic facies (similar to that of Balingian Province's oil/coal extracts) have been associated with mangrove-derived precursor materials (e.g. Brown, 1989).

In the Sunda region during the Late Oligocene-Early Miocene times, the climates were substantially cooler than

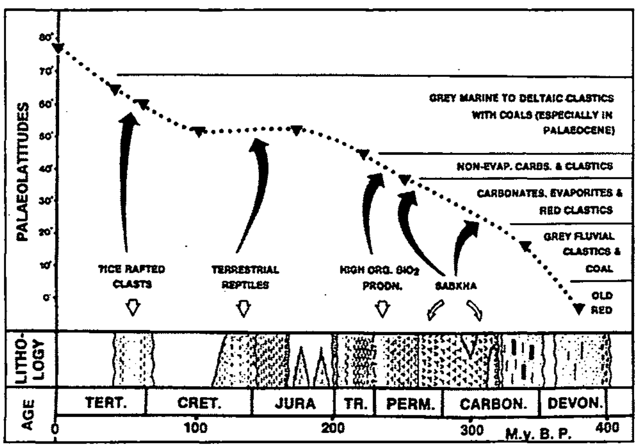

Figure 3. Spitsbergen's changing palaeolatitudes and palaeoclimatic indicators (after Steel and Worsley, 1984).

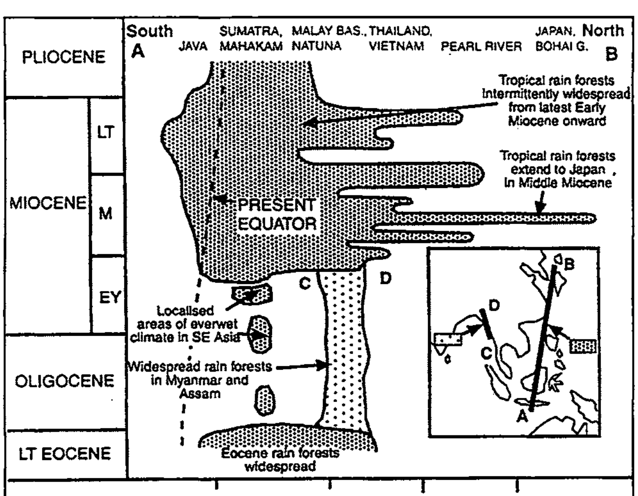

Figure 4. Distribution of tropical rain forest climates in SE Asia during the Tertiary (after Morley, 2000).

present-day climates of Southeast Asia (Morley, 2000), therefore tropical rain forests were not widespread (Figure 4). Based on the palynomorph assemblage presented by this author, the tropical rain forests were intermittently widespread by the latter part of the Early Miocene (about 20Ma).

METHODOLOGY

Microscopical studies were performed using a Leica photometry microscope under both normal reflected white light and blue light excitation. Maceral analysis was carried out (using 1000 point counts) on 30 samples. Vitrinite reflectance (%Ro) was carried out using a MPV SP photometer head with a 50x oil immersion objective. Vitrinite reflectance (VR) is a measure of the proportion of light reflected from the polished surface of a sample compared to that of a standard. Calibration is made using a leucosapphire standard of known reflectance. VR is a standard method for determining the thermal maturity (or rank) of coals and dispersed organic matter in sediments. The maturity is a measure of the degree of chemical and physical changes experienced by a coal with increasing depth of burial.

THERMAL MATURITY

Thermal maturity was determined on sixteen coal samples from Bintulu-Tatau area of Sarawak and fourteen samples from central Spitsbergen. Coals from the Bintulu-Tatau area range in rank between 0.45 and 0.70%. Coals from Spitsbergen range in rank between 0.43 to 0.85%. In terms of the traditional oil-window, these ranges would normally be within the immature to mid mature generation range.

MACERAL COMPOSITION

In both sets of coals (from Spitsbergen and from Sarawak) vitrinite is the most dominant maceral. The overall liptinite content is higher in the coals from Sarawak whereas the overall inertinite content is higher in the coals from Spitsbergen (Table 1). There are also distinct differences in the abundance and types of liptinite macerals present in these sets of coals. Resinite, suberinite, bituminite and exsudatinite are generally very common in the Sarawak coals but are low to virtually barren in the Spitsbergen coals. On the other hand, cutinite is low and sporinite is fairly common in both sets of coals.

The difference in the maceral assemblages, especially the contrasting liptinite contents, among these coals is the most significant factors in determining whether they possess oil-generating potential or not. The oil-generating potential possessed by the Sarawak coals is believed to be attributed to the high abundance of the maceral suberinite and bituminite (which subsequently forms exsudatinite veins or dispersed hydrocarbons in the form or oil haze/globules

Table 1. A summary of maceral composition (% by volume)

Samples	cutinite	liptodetrinite	resinite	sporinite	suberinite/ bituminite	exsudatinite liptinite	Total vitrinite	Total inertinite	Total matter	mineral
Sarawak	1-2	2-4	1-20	2-7	4-14	4-15	12-36	40-78	3-9	3-19
Spitsbergen	0-2	0-3	0-4	2-12	0-3	0-3	2-22	44-88	2-32	0-29

as described below) and, to a lesser degree, the maceral resinite.

OIL GENERATIVE FEATURES

A number of petrographic features indicative of oil generation in coals from Sarawak and Kalimantan have been described in earlier studies (e.g. Wan Hasiah, 1997a, 1997b; Cook and Struckmeyer, 1986). The most distinctive feature associated with oil-generation from the coals of the tropics investigated here is the occurrence of extensive exsudatinite veins. These veins form an interconnecting network of hydrocarbon pathways that pervade the coal fabric, subsequently brecciating the coals (Figures 5a and 5b). Saturation of the predominantly vitrinitic fabric by the expelled hydrocarbons causes it to fluoresce vaguely. Hydrocarbon generation can also be recognised from the common occurrence of oil globules or oil haze (Figure 6b) associated with the precursor liptinitic material, in particular suberinite and bituminite. The maceral bituminite in the Sarawak coals has been recognised to have originated from the suberinite maceral (Wan Hasiah, 2000). Coals of Spitsbergen, on the other hand, are lacking in suberinite and are virtually barren in bituminite and exsudatinite (Wan Hasiah, 1994; Table 1).

In the Sarawak coals, it is observed that towards the end of hydrocarbon generation, the fluorescence intensity decreases gradually, corresponding to diminishing generative capacity. At this stage, the oil generative precursor material and the exsudatinite veins are commonly observed to leave behind a micrinitic residual product or highly reflecting veins. Phlobaphinite, a type of corpocollinite, shows a relatively higher reflectance compared to the surrounding vitrinite matrix (Figure 5a).

One other distinctive petrographic feature recognised in this study is the intimate association of framboidal pyrite with oil-prone material, particularly suberinite/bituminite and exsudatinite. The presence of framboidal pyrite is apparent from the beginning to the end of hydrocarbon generation. Framboid density is highest within coal fabric strongly saturated with bitumen (hydrocarbon) and is commonly observed to be associated with disintegrated suberinite (derived from the break down of suberinite subsequent to hydrocarbon generation). In coals of relatively higher maturity, framboid remnants are frequently filled with yellow fluorescing hydrocarbon material. Framboidal pyrite is not common in the Spitsbergen coals but when present does not appear to be associated with hydrocarbon generation.

The occurrence of framboidal pyrite in sediments is often attributed to a marine incursion or regarded to be indicative of reducing depositional conditions. However, framboidal pyrite is known to be widespread in sediments of all ages and in various depositional environments, and is even observed in non-sedimentary rocks e.g. in lavas (Love and Amstutz, 1966; Rickard, 1970). In the coals currently studied, the framboidal pyrite seems to be derived by processes involving the replacement or infilling of organic (hydrocarbon) globules and gaseous vacuoles (Figures 6a and 6b). The spheroidicity is believed to be exclusively pseudomorphic after an organic spherule, in this case, gas

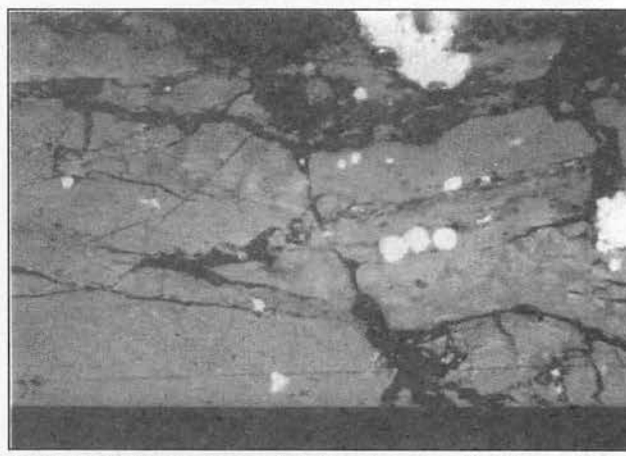

Figure 5a. Dark brown exsudatinite veins pervading the coal fabric forming an interconnecting network of hydrocarbon pathways. Occurring in close association with the exsudatinite are suberinite, phlobaphinite (which shows a relatively higher reflectance compared to other surrounding vitrinite) and framboidal pyrite; reflected light, field width = 0. 25 mm.

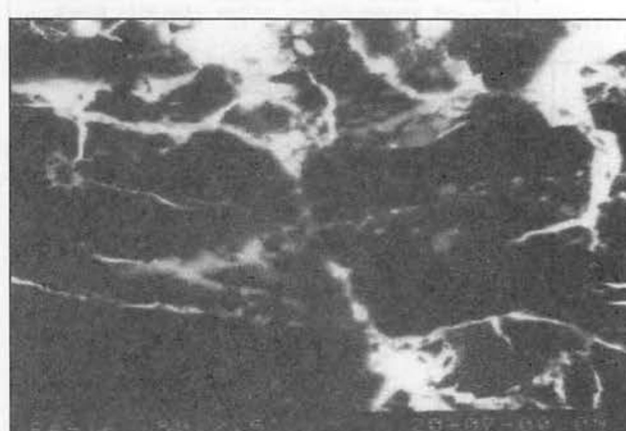

Figure 5b. The pervading exsudatinite veins showing intense yellow fluorescence under blue light excitation (same view as Figure 5a).

bubbles or oil globules. Such an origin for spheroidal framboids has previously been suggested by Rickard (1970).

INFLUENCE OF FLORA/MACERAL COMPOSITION

Spitsbergen coals were deposited in temperate to subarctic conditions (Figure 3) as suggested by the abundance of conifers and the lack of any warm climate pollen (Kellog, 1975). Besides the gymnosperms, arctic tundra plants such as mosses, lichens, low shrubs and sedges would most likely be significant organic matter contributors that formed these coals. Present day harsh arctic conditions are unfavorable for tree growth and therefore accumulation of peat is negligible. There has therefore been a considerable deterioration in climatic conditions on Spitsbergen since deposition of the early Tertiary coals. This could be a consequence of a northward drift of Svalbard subsequent to the opening of the Greenland-Norwegian Sea.

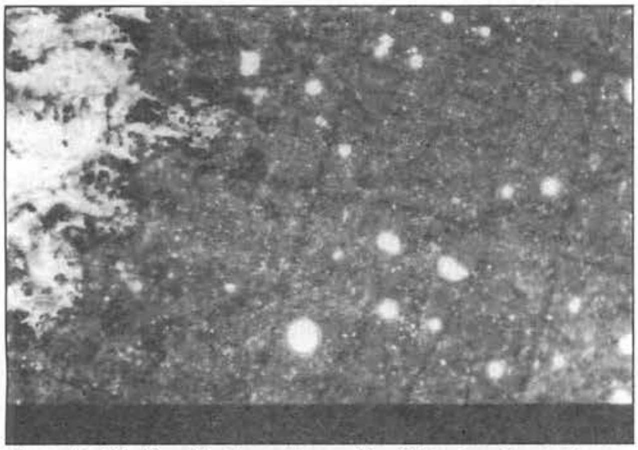

Figure 6a. Highly reflecting spheres of variable sizes in very low reflecting bituminite matrix. The infilling of these spherules appear to be an emulsion of hydrocarbon-volatile matters. Pyritisation of these organic globules may form framboidal pyrite; reflected light, field width = 0.65 mm.

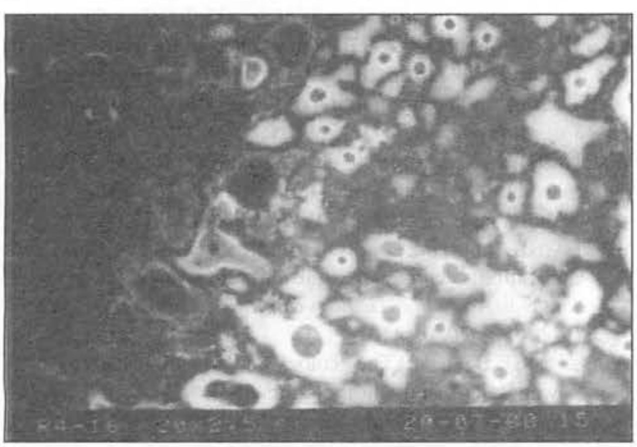

Figure 6b. Occurrence of greenish-yellow fluorescing oil globules and hydrocarbon haze surrounding the organic spherules (same view as Figure 6a); blue light excitation, field width = 0.65 mm.

According to Morley (2000), conifer pollen and temperate angiosperm species were the characteristic palynomorph assemblage during Oligocene and earliest Miocene times in the SE Asia region. By the latter part of the Early Miocene (about 20Ma) the tropical rain forests, which include mangroves (e.g. Rhizophoraceae), were intermittently widespread within the North Borneo region. This would suggest the plant constituents that formed the coal seams of the Nyalau Formation investigated here were subsequently accumulated during this late Early Miocene time.

As depositional environments within lower coastal plain setting were common for both sets of coals discussed here, it is apparent that floral types had a significant control over the oil-generative potential of the deposited coals. The occurrence of angiosperms, including mangroves, of relatively cooler (subtropical) to tropical conditions appear to be more oil-prone compared to the gymnosperm of the temperate to subarctic climates. Thus, this study has also shown that in regions where depositional setting are rather similar, it is the predominant of the coal-forming floral assemblage that controls the oil generative potential of coals. However, considering that flora, depositional environment and climatic conditions are strongly interrelated, due consideration should be given to all factors (including eustacy and tectonics) in assessing the likely generation potential of coals.

CONCLUSIONS

Oil-generative features in coals can easily be identified microscopically under normal reflected white light and blue light excitation. Such features have been discussed here for coals from the tropics of onshore Sarawak. Extensive development of an exsudatinite crack network that is capable of brecciating the coal fabric is the most dominant feature. Other oil generative features commonly associated with hydrocarbon generation include the widespread occurrence of oil globules, oil haze and framboidal pyrite. Such features (although non-quantitative) are important indicators and contributors to commercial oil accumulation in the oil fields of offshore Sarawak. In contrast, all of these oil-generative features are lacking in the coals from the arctic of Spitsbergen, and therefore these coals are regarded as not possessing sufficient oil generative capacity to give rise to commercial hydrocarbon accumulation. To date, no oil accumulation of terrestrial origin occurs on or around the island of Spitsbergen.

Based on the maceral assemblages and their association with the generative features observed, the macerals suberinite and bituminite, the latter predominantly derived from the former, are the most oil-prone macerals in the Sarawak coals. Thus, the lack of oil-generative capacity of the Spitsbergen coals is most likely attributed to the virtual absence or low abundance of these macerals. Since the oil-prone coals seem strongly influenced by the dominance of angiosperm floral of Tertiary age, the oil-prone macerals (suberinite/bituminite) would therefore likely to have originated mainly from the angiosperm/mangrove species of plants. This is very much in agreement with the findings based on organic geochemical parameters, particularly biomarkers, thus emphasizing the importance of petrographic features described in this study.

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