Eocene Coals of the Barito Basin, Southeast Kalimantan : Sequence Stratigraphic Framework and Potential for Sources of Oil

Awang H. Satyana [1)]
Margaretha Eka M.P. [2)]
Moh. Imron [3)]

[1)] Exploration Pertamina MPS, [2)] Institute Technology of Bandung
[3)] Exploration Pertamina Upstream

Abstract

Significant coal seams intercalate the middle Eocene siliciclastic series of the Lower Tanjung Formation of the Barito Basin, Southeast Kalimantan. The formation can be identified as composed of the seven sequences representing synrift and postrift sediments. The coals occur in the three sequences of the postrift phase with the most regional and the thickest coal seams distribute in the transition between the synrift and postrift phases. The coals were deposited within the environments from paralic to upper deltaic settings in various systems tracts including the late lowstand to early transgressive, late transgressive to early highstand, and early highstand to middle highstand.

Geochemical constraints are examined to see the possibility of the coals as sources for oil. The coals have excellent total organic carbon (TOC) of 44 – 73 %, very good hydrogen index (HI) from 285 – 567 mgHC/gTOC (averagely 425 mgHC/gTOC) and high elemental hydrogen to carbon ratio (H/C) of 0.87 to 1.18 concluding that the coals are liptinitic and can generate oil. These values are much higher than the cut off values established for coal to act as oil source (HI of 200 and H/C of 0.80). Geochemical correlation using carbon isotope and biomarker fingerprinting results in positive correlation meaning that the Tanjung coals have sourced the Tanjung oil. The coals may have substantial potential as sources of oil if the coals are volumetrically important.

Introduction

Coal is a readily combustible organoclastic sedimentary rock composed mainly of lithified plant remains and containing more than 50 % by weight of carbonaceous material and inherent moisture (Evans, 1997). Microscopic examination indicates that coal consists of particles and bands of different kinds of carbonaceous material (macerals) which differ from each other in their morphology, hardness, optical properties and chemical characteristics.

In mining point of view, coal has been the fuel of the world since the industrial revolution and now it still represents the world's biggest mined mineral tonnage. Over sixty countries produced more than 10,000 metric ton annually and about 90 % of coal production is still consumed in its country of origin (Evans, 1997). Demand is now increasingly determined by the rapidly expanding economies, particularly those of the Far East including Indonesia.

In petroleum point of view, to which this paper will contribute, coal has been understood as important source rocks of liquid and gaseous hydrocarbons (Thompson *et al.,* 1985; Cook and Struckmeyer, 1986; Hunt, 1996; Bohacs and Suter, 1997 and references therein) and also as substantial reservoirs of gas. Meissner (1984) *in* Hunt (1996) estimated that the Fruitland coals of the San Juan Basin of New Mexico and Colorado have acted as both gas sources and reservoirs. The coals generated 55 TCF of methane, of which 26 TCF is adsorbed by the coal. Therefore, predicting the occurrence, distribution, volume and characteristic of coals and coaly rocks is very important in many areas of current exploration and exploitation.

Kalimantan, Indonesia, to which the paper is based, is a land with its very famous coal deposits in the country. Coal mining has been started in this island since the Dutch times. The coals, mainly in the Kutei Basin, are also frequently concluded as the important source rocks in the basin (such as Thompson *et al*., 1985, Cook and Struckmeyer, 1986) contributing substantial oil and gas trapped in giant to supergiant fields of the Mahakam Delta.

This paper will examine the Eocene coals of the Barito Basin, once formed a counterpart to the Kutei Basin (Satyana *et al*., 1999). Sedimentologic and stratigraphic evaluation supports positive results on the distribution and geometry of the coals. Geochemical analyses even show that the Barito coals are richer in quality than those of the Miocene coals of the Kutei Basin as sources of liquid hydrocarbon. Accordingly, this paper addresses two main points : (1) to evaluate the distribution and geometry of the Eocene Barito coals within a sequence-stratigraphic framework and (2) to evaluate the geochemistry of the coals as sources for oil.

Geologic Setting and Petroleum System

The Eocene coals of the Barito Basin intercalate the siliciclastic series of the middle Eocene Lower Tanjung Formation. The geologic setting of the basin during the Paleogene is important to the occurrence and distribution of the coals, and the Neogene to Pleistocene setting is important to the preservation of the geometry of the coals and their capabilities to generate and expel hydrocarbons.

The Barito Basin is situated along the southeastern margin of the Schwaner Core in southeastern part of Kalimantan (*Figure 1*). The basin is defined by the Meratus Mountains to the east and separated from the Kutei Basin to the north by a flexure of the Adang Fault. The basin has a narrow opening to the south towards the Java Sea. The basin has a configuration of an asymmetric geometry with a foredeep in the eastern part of the basin and a platform at the western part approaching the Schwaner Core.

The Barito Basin commenced its development in the Late Cretaceous – Paleo/Eocene following a micro-continental collision between the Schwaner Core and the Paternoster micro-continent (Satyana *et al*., 1999). Paleogene extensional deformation occurred as tectonic consequence of the oblique convergence. This produced a series of NW-SE trending rifts. The rifts became accommodation spaces for synrift deposits of alluvial fan and lacustrine sediments of the middle Eocene Lower Tanjung Formation. As transgression proceeded, the rifts submerged and resulted in postrift deposits of widespread marine shales of the Upper Tanjung Formation. The important Eocene coals were deposited at the transition from the synrift phase to the postrift phase. Thinner coals were deposited during the later development of postrift phase.

During the Oligocene to early Miocene, the Barito Basin was in later sagging phase following a lithospheric thermal cooling. The basin regionally subsided and sea transgressed the whole basin resulting in widespread platform carbonate of the Berai Formation. During the later Miocene times, the sea regressed due to the uplift of the Schwaner Core and the Meratus Mountains. Eastwards-prograding deltaic sediments of the Warukin Formation were established. The rising Meratus Mountains contributed the sediments into the foredeep area. The uplift of the Meratus Mountains continued into the Pleistocene and resulted in molassic-deltaic sediments of the Pliocene Dahor Formation.

The structural development of the Barito Basin is a consequence of the two distinct, separate, regimes (Satyana *et al*., 1999). Firstly, an initial transtensional regime during which sinistral shear resulted in the formation of a series of NW-SE trending wrench-related rifts, and secondly, a subsequent transpressional regime involving convergent uplift has reactivated and inverted old tensile structures resulted in wrenching, faulting and folding. Presently, the structural grain of the basin is characterized by the concentration of structures in the north/northeastern part of the basin typified by the tight, parallel SSW-NNE trending folds bounded by high-angle easterly-dipping imbricate reverse faults towards the Meratus Mountains and involved the basement.

In the Barito Basin, hydrocarbons are trapped in five fields : the Tanjung, Kambitin, South Warukin, Central Warukin and East Tapian Fields. All of the fields occurred in faulted anticlines dipping to the east. The hydrocarbons are reservoired in the Lower Tanjung sands (middle Eocene) and in the Lower and Middle Warukin sands (middle Miocene). The Pre-Tertiary basement rocks and Berai carbonates also can act as reservoirs where they are fractured. The hydrocarbons were expected to be sourced from the Tanjung coals and carbonaceous shales, and from the Lower Warukin carbonaceous shales. The main kitchen is located in the foredeep area. Generation, migration and entrapment of the hydrocarbons has taken place since the middle early Miocene (20 Ma). The intra-formational shales mainly provide the sealing rocks.

Eocene Coal Depositional Sequences

To examine the occurrence, distribution, and geometry of the Eocene Barito coals, we first discuss the Eocene sedimentary setting of the Barito Basin which was prone to coal occurrence and deposition, we then focus on paralic setting – the most important coal-forming areas. We examine the effects of relative sea level on paralic setting and propose a model for the occurrence and disribution of the coals within depositional sequences. A study by Bohacs and Suter (1997) on coal sequence stratigraphy is referred as basis of classifying coal deposits according to their depositional sequences/ systems tracts.

The occurrence, distribution, and character of coals vary systematically as a function of the relative rates of peat production and accommodation change due to relative sea and ground water levels (Bohacs and Suter, 1997). Accommodation changes predictably throughout a depositional sequence; hence, the distribution of coals may be predicted within a sequence stratigraphic framework. The thickest, most isolated coals occur in upper lowstand and basal transgressive systems tracts; the most continuous coals are found in middle lowstand and middle highstand systems tracts; and minimal, very isolated coals are found in basal lowstand, middle transgressive, and upper highstand systems tracts (*Figure 2, Table 1*).

The middle Eocene Lower Tanjung Formation, into which the studied coals intercalate, has been studied (Pertamina and Trend Energy, 1988; Hartanto et al, 1993) to evaluate the remaining hydrocarbon potential of the Tanjung reservoirs. These studies have been re-examined using sequence stratigraphic method concentrating on interbedded coal deposits.

The Lower Tanjung Formation represents a general transgressive sequence containing rift-infill alluvial fan and lacustrine sediments of relatively coarse siliciclastics (conglomerate, pebbly sandstone) at the base, becoming progressively overlain by low energy, paralic to marine sediments of thinner bedded and finer grained siliciclastics (fine grained sandstone, siltstone and shale). Coals occur regionally in early postrift phase (*Figure 3*).

Representative sequence stratigraphic correlation showing the occurrences of the coals amid the siliciclastic series of the Lower Tanjung Formation is presented at *Figure 4*. The study shows that the Lower Tanjung Formation is composed of seven sequences (Sequence A – Sequence G). The configuration of the Paleogene horsts and grabens was reflected in topographic highs and lows which determined the characteristics and thicknesses of the Lower Tanjung Formation sediments. The Sequence A to Sequence C are rift-infill (synrift) sediments, whereas the Sequence D to Sequence G are postrift sediments. Coal deposits occur in Sequence D, Sequence E, and Sequence G.

The thickest and the most widely distributed Eocene coal occurs in the Sequence D representing the first postrift sediments which were not controlled by the pre-existing horst and graben topography. These coal seams form a distinct coal section which is useful as a widespread regional chronostratigraphic marker. Geochemical analyses indicate that the coals were deposited under anoxic conditions, from which it is inferred that their depositional setting was in stagnant water located in a lower floodplain or interdistributary setting. The coals are typically vitreous, non-argillaceous, black and fracture into splintery sub-conchoidal shards. The existence of seat-earths in some places indicates that the coals are autochthonous (Pertamina and Trend Energy, 1988). The individual coal seam is 2.0 – 4.0 meters thick making a total coal stack of around 15 meters thick. The coals occur within the late lowstand to early transgressive, middle transgressive, late transgressive to early highstand system tracts. The parasequence stacking are slightly retrogradational, progradational, to strongly aggradational. The coals were deposited as sediments of overbank flow or floodplain aggradation at environments of supralittoral, deltaic plain, and interdistributary. Regionally, the coals are continuous. As stated by Bohacs and Suter (1997), within a composite sequence, coals tend to be best developed in sequence sets with stacking that is aggradational to slightly retrogradational. These are the sequence sets wherein the rates of accommodation and peat production balance for the greatest amount of time.

Thinner and more isolated coals occur in the Sequence E with thickness of 0.5 – 1.0 meter. The coal seams make a total coal stack of 2.0 meters thick only. The coals were deposited as early, middle, to late highstand systems tracts making them as relatively thin and non-significant coals within lower deltaic plain. The parasequence stacking of the coals are generally retrogradational. The coals occur within dominating shale and silts of the Lower Tanjung Formation.

The uppermost coal seams of the Lower Tanjung Formation occur in the Sequence G. The coals are also thinner, some are isolated, and the thick shales and silts separate each coal seam. The coals are 0.5 to 2.0 meters thick. The coals occur within late lowstand to early transgressive, late transgressive, and middle highstand systems tracts deposited at lower deltaic plain. The coals of late lowstand to early transgressive systems tract are continuous and forming regional coal marker of "M1A". The M1A marker is everywhere recognizable. Sequence G sediments mark the closure of the Lower Tanjung Formation transgression, represented by inner to middle neritic muds and silts. The sediments were deposited in a low energy sub-wave base environment as recognized from their lateral and vertical homogeneity and their uniform thicknesses.

Eocene Barito Coals as Sources for Oil

The thickest Eocene coals in the Barito Basin, which occur in the Sequence D, were analyzed using well and outcrop samples. We examine the organic geochemical analyses of the coals (rock pyrolysis, maturation, elemental analysis, carbon isotope, gas chromatography, gas chromatography mass spectrometry). We then examine the geochemistry of existing oil in the Barito Basin to see the evidence of whether the coals have sourced the oil. Curry (1987) and Pertamina and Trend Energy (1988) provided geochemical analyses of the Barito Basin. Thickest coals typically correspond to best conditions for organic preservation, and commonly have enhanced petroleum source potential (Bohacs and Suter, 1997).

The possibility that coals may act as oil source rocks has been widely discussed (Roe and Polito, 1979; Durand and Oudin, 1979; Thomas, 1982; Durand and Paratte, 1983 *in* Thompson et al., 1985; Cook and Struckmeyer, 1986; Hunt, 1996). Hydrogen content of coals holds a key to this possibility. The effect of the increasing hydrogen index on oil generation from coal has been observed in the laboratory (Lewan 1990 *in* Hunt, 1996). The result is that the yield of high-wax oil rose with an increase in the hydrogen content of the coal. The hydrogen content was the only factor measured that showed a good correlation with the oil yield. The percentage of exinite and resinite in coals is plotted against the H/C (hydrogen/carbon) atomic ratio of the coals, which is a rough indicator of their hydrocarbon-generating capacity. Organic matter with an H/C ratio larger than about 0.8 definitely has some liquid-generating ability. Coals with more than about 10 – 15 % exinite plus resinite are capable of generating oil. Organic matter with hydrogen index (HI) values above 200 is usually considered capable of generating some liquid hydrocarbons. There is no doubt that hydrogen-rich coal and terrestrial kerogen can generate economic quantities of liquid petroleum. This has been recognized in the fields and in the laboratory experiments (Hunt, 1996).

Fluvio-deltaic coals and shale source rocks have generated large volumes of oil in Indonesia (Robinson, 1987). Coals usually contain 40.0 – 80.0 % total organic carbon (T.O.C.) with very high pyrolysis yields of 150 – 300 mg hydrocarbons/ gram rock. The shales and coals typically have pyrolysis HI in the 200 – 400 mg HC/g TOC range and kerogen elemental H/C ratios of 0.8 – 1.0.

Outcrop samples of the Eocene coals of the Barito Basin record T.O.C. values in the range from 44 to 73 % with pyrolysis HI from 285 to 567 mgHC/gTOC (average 425 mgHC/gTOC). Elemental composition of the coals also shows that they can generate oil. The van Krevelen elemental analysis of atomic H/C and oxygen/carbon (O/C) ratios of the coals shows that the Tanjung coals have a higher relative concentration of hydrogen (which determines the amount of oil generated) than normal type III kerogen (called as type III-H, hydrogen-rich vitrinite 2, or desmocollinite). The Tanjung outcrop coal is significantly richer in hydrogen (higher H/C ratio) than the other coals or kerogens. H/C ratio of Tanjung coals range from 0.87 – 1.18 and O/C of 0.06 – 0.16 causing the coals are within kerogen type II in van Krevelen diagram. The high values of both HI and H/C of the coals show the potential to generate oil.

Geochemical correlation to see whether the Eocene coals of the Barito Basin have sourced the existing oil is conducted using carbon isotope data and biomarkers (saturate and pyrolysis/asphaltene gas chromatography – GC and gas chromatography mass spectrometry – GCMS) (see *Figure 5* and *Table 2*). Existing Tanjung oil is typified by characteristic oil sourced by fluvio-deltaic coals and coaly shales. Oil formed from coals and coaly shales tend to have high ratios of pristane to phytane and of sterane to hopane, compared with marine-sourced oil. They also have relatively high concentrations of (1) C_{21}-C_{35} n-alkanes; (2) C_{29} steranes; (3) bicyclic sesquiterpanes; (4) tricyclic diterpanes; and (5) tetracyclic diterpanes and oleananes.

Carbon isotope ratios of the Tanjung oil are averagely –27.3 to –28.0 ‰, perfectly correlatable with carbon isotope ratios of Tanjung coal outcrop ranging from –27.4 to –28.7 ‰. Saturate and asphaltene GC scans also show that the Tanjung coals are typical of waxy oil prone organic matter, as evidenced by their high molecular weight alkane distribution. The asphaltene GC of Tanjung coal shows a perfect correlation with the asphaltene GC of oil of the Tanjung Field. Average pristane to phytane ratio of oil of the Tanjung Field is 8.03. Pristane to phytane ratio of the Tanjung coals (outcrop and well samples) are 10.51-15.67. Wax ratio (nC_{31} to nC_{19}) of Tanjung oil and Tanjung coal is 0.86 and 0.78, respectively. Oleanane to C_{30} hopane (m/z 191) ratio of the Tanjung oil and the Tanjung coals are 0.10-0.23 and 0.10-0.34, respectively. C_{29} sterane to C_{30} hopane ratio for the Tanjung oil and the Tanjung coals are 0.64-.0.86 and 0.59-0.85, respectively. Mass fragmentograms of triterpane (m/z 191) and sterane (m/z 217) of Tanjung coal show similar patterns to those of the Tanjung oil

Accordingly, based on the HI and H/C ratios, and positive correlation between the Tanjung coals and the Tanjung oil, it can be concluded that the Eocene Barito coals have sourced some of the Tanjung oil. Microscopic analysis of the Indonesian coals indicates that they contain desmocollinite or the hydrogen-rich vitrinite-2 (Cook and Struckmeyer, 1986; Hunt, 1996). Layers of liptinitic material are interspersed in vitrinite along with impregnations of bitumen and other fluorescent materials. The coals were estimated to contain 15 – 65 % liptinite. Liptinite contents above 15 % can generate and release waxy oil. A process of liptinite enrichment (Thompson *et al.,* 1985) is necessary in order for coal to become hydrogen-rich and oxygen-poor. Reworking of coastal plain peats to form drift deposits in tidal flat or lagoonal environments along the coastal margin is one mechanism by which this can occur. Such processes are observed in present day Indonesian deltas and are considered to be responsible for the formation of coaly oil source rocks of the Indonesian basins.

The Eocene Barito coals are even richer in HI than that of the coals of the Kutei, Northwest Java, and Sunda basins which have HI ranges from 250-450 mg HC/gTOC. However, the Eocene Barito coals are much thinner than the cumulative thickness of the Miocene Kutei coals which is totally 175 meters thick (Thompson *et al.,* 1985).

Conclusions

Several coal seams intercalate the siliciclastic series of the middle Eocene Lower Tanjung Formation of the Barito Basin which can be divided into seven sequences including synrift and postrift sediments. The coals occurred in the three sequences of the postrift phase deposited within paralic to upper deltaic setting. The thickest coal seams (cumulative 15 meters thick) occur in a transition between synrift and postrift phases. The coals were deposited in various systems tracts including the late lowstand to early transgressive, late transgressive to early highstand, and early to middle highstand.

The Eocene coals of the Barito Basin have excellent total organic carbon (TOC) of 44 – 73 %, very good hydrogen index (285 – 567 mgHC/gTOC, averagely 425 mgHC/gTOC) and high ratio of elemental hydrogen/carbon (H/C) of 0.87-1.18 which both indicate much higher values than those of the cut off values established for coal to act as source of oil (HI of 200 and H/C of 0.8 – Hunt, 1996). Therefore, the Eocene Barito coals can generate oil and may have good – excellent potential if the coals are volumetrically important. Geochemical correlation using carbon isotope and biomarkers result in positive correlation meaning that the Eocene Barito coals have sourced the existing Tanjung oil.

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Table 1 Sequence stratigraphic distribution of paralic coaly rocks (modified after Bohacs and Suter, 1997)

No.	Systems Tract	Parasequence Stacking	Coastal Plain Sedimentation	Coaly Rock Thickness	Coaly Rock Geometry	Organic Preservation
1	Late highstand, lowstand fan, early lowstand wedge	Strongly progradational, bypass and erosional truncation	Amalgamated channels, subaerial exposure	No significant coals (≤ 0.5 m)	Restricted, isolated	Minimal
2	Middle to late lowstand wedge	Moderately aggradational	Valley fill, low to moderate overbank flow	Relatively thin to moderately thick (1-3 m)	Widespread, continuous (100s of km^2)	Moderately good
3	Late lowstand to early transgressive	Strongly aggradational to moderately retro-gradational	Frequent overbank flow, floodplain aggradation	Thick to very thick (≥ 3 m)	Relatively scattered	Good to excellent
4	Middle transgressive	Strongly retro-gradational	Frequent overbank flow, ponding, some erosion by retreating shoreface	Relatively thin (≤ 1 m)	Restricted, scattered	Moderate to poor, potentially high sulfur content
5	Late transgressive to early highstand	Slightly retro-gradational to strongly aggradational	Frequent overbank flow, floodplain aggradation	Thick to very thick (≥ 3 m)	Relatively restricted, relatively isolated to isolated (≤ 100 km^2)	Good to excellent
6	Early to middle highstand	Aggradational	Moderate overbank flow, floodplain aggradation, soil formation	Relatively thin to moderately thick (1-3 m)	Widespread, continuous (100+ km^2)	Moderately good

Table 2 Oil to Source Correlation Parameters

Sample	Pristane to Phytane	Oleanane to C_{30} hopane	C_{29} sterane to C_{30} hopane	Wax ratio (nC_{31}/nC_{19})	Carbon Isotope Ratio (‰)
Tanjung Coal	10.5-15.6	0.10-0.34	0.59-0.85	0.78	- 27.4 to - 28.7
Tanjung Oil	8.0	0.10-0.23	0.64-0.86	0.86	- 27.3 to - 28.0

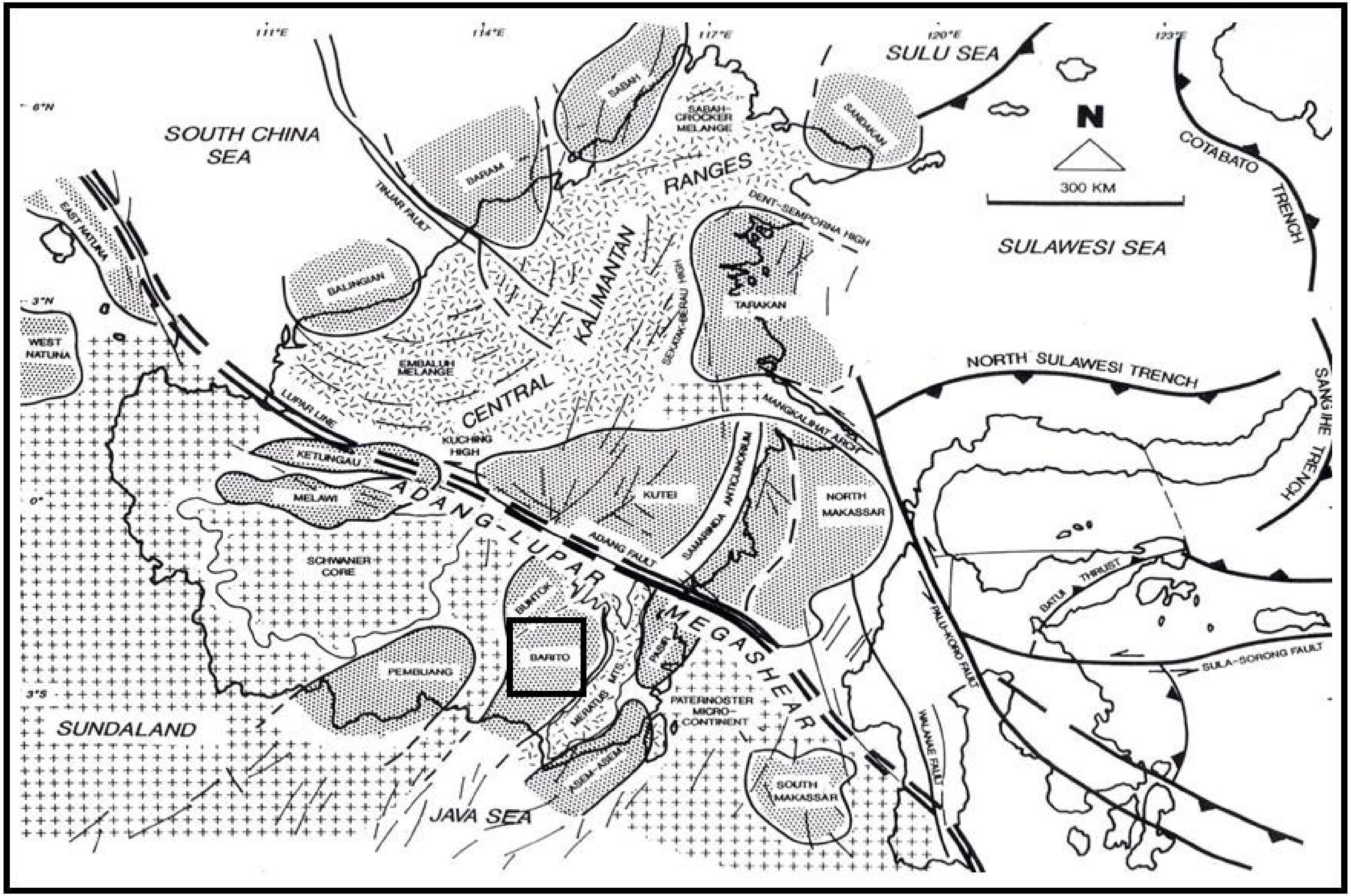

Figure 1 Location of study area (Barito Basin) within regional geologic setting of Kalimantan.

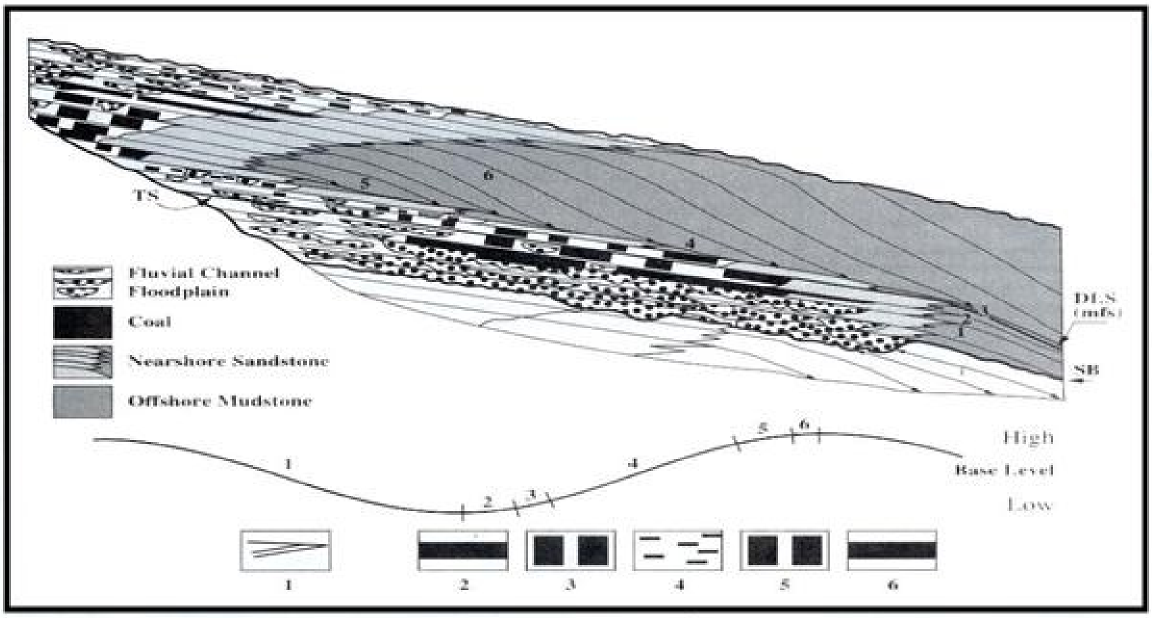

Figure 2 Occurrence and distribution of paralic coals within a depositional sequence. See Table 1 for explanation of coal systems no. 1 to no. 6 (Bohacs and Suter, 1997).

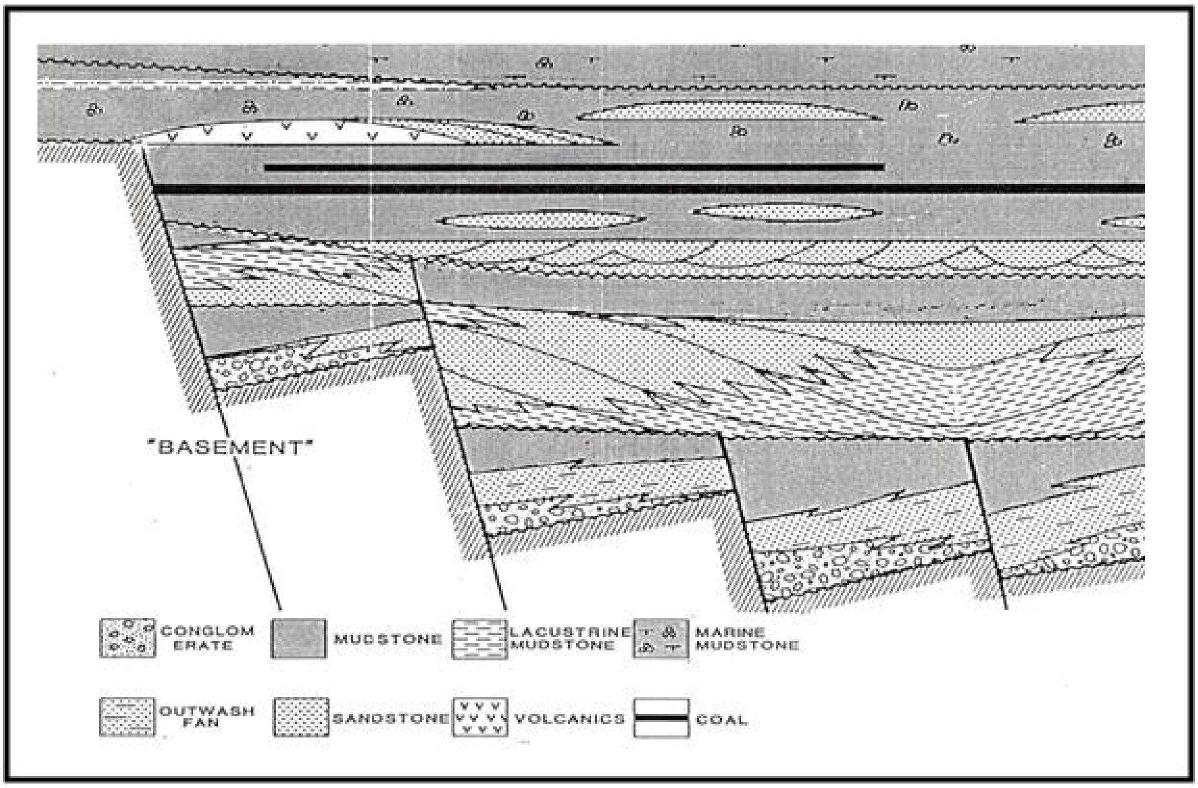

Figure 3 Coal deposition within siliciclastic series of the Lower Tanjung Formation. The coals mainly occur at the transition between synrift and postrift phases (modified from Pertamina and Trend Energy, 1988).

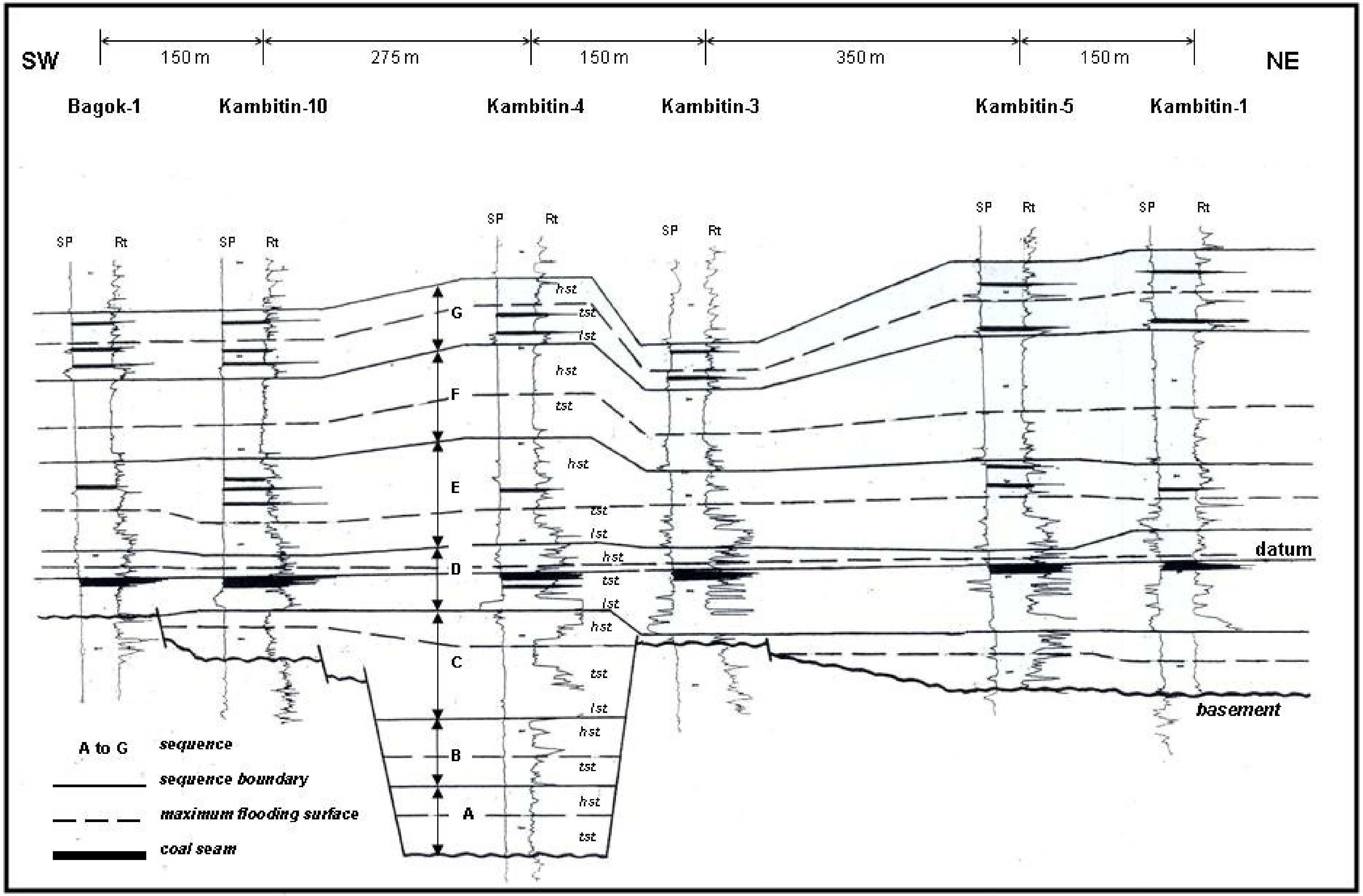

Figure 4 Representative section through Barito rifted structure showing the distribution of coal seams within sequence stratigraphic setting of the Lower Tanjung Formation.

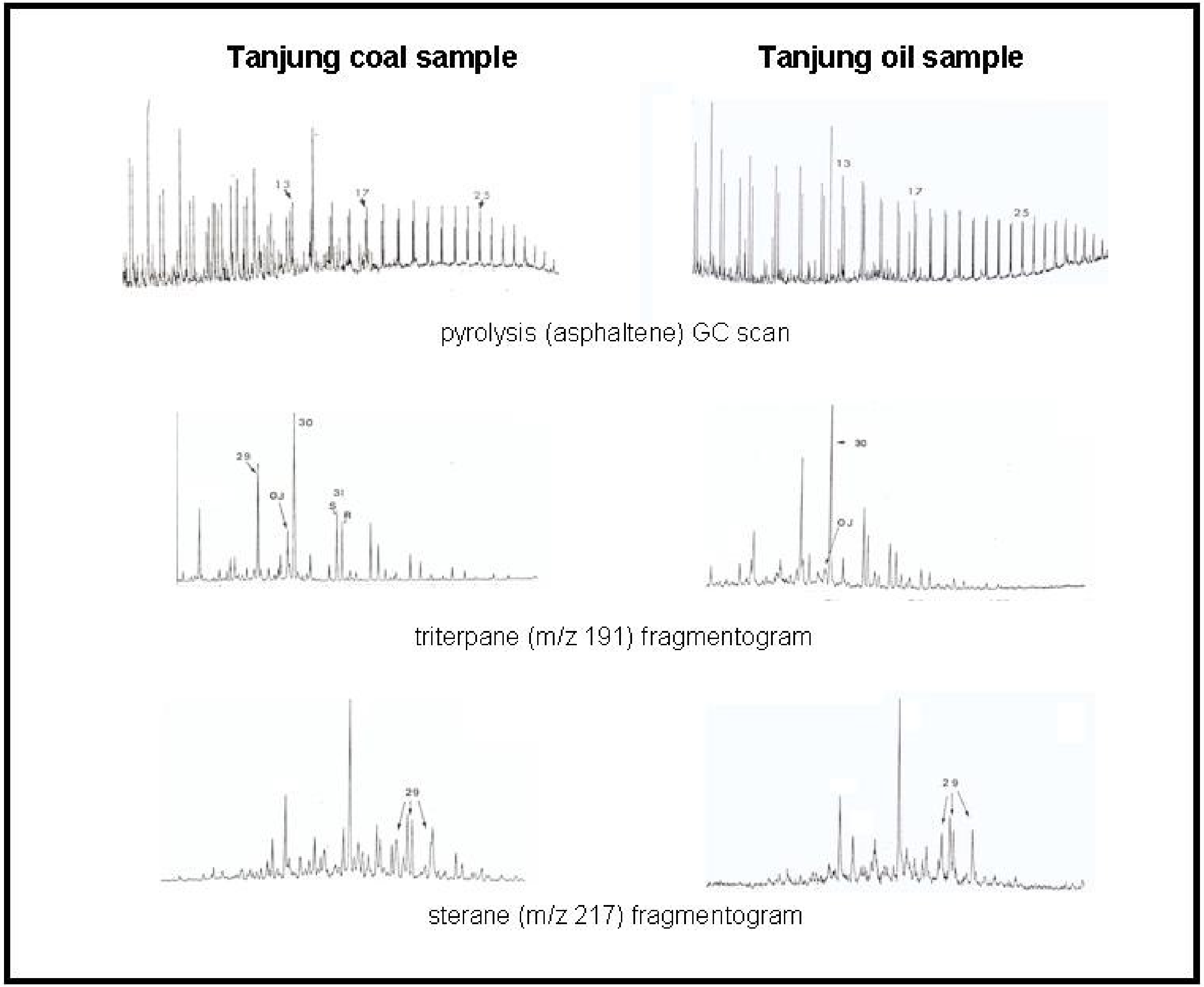

Figure 5 Correlation of Tanjung coal to Tanjung oil samples showing a positive correlation.