Jurnal Geologi Indonesia, Vol.4 No. 1 Maret 2009: 43-55

An appraisal for the petroleum source rocks on oil seep and rock samples of the Tertiary Seblat and Lemau Formations, Bengkulu Basin

Hermes Panggabean and R. Heryanto

Geological Survey Institute, Geological Agency, Jl. Diponegoro 57, Bandung

Abstract

The Tertiary Bengkulu Basin is known as a typical fore-arc basin, situated in southwest Sumatera. The basin initiated during Eocene-Oligocene times, accumulates the Lahat equivalent formation. The formation is is unconformably overlain by the Oligocene-Miocene Hulusimpang Formation consisting of volcanic rocks. It is then succeeded by siliciclastics and minor carbonates of the Early-Middle Miocene of Seblat Formation. Unconformably overlying the Seblat is siliciclastics of the Middle-Late Miocene Lemau Formation, then overlain by the Late Mio-Pliocene Simpangaur Formation. The basin succession is terminated by the sequence of volcanic rocks named as the Bintunan or Ranau Formation.

Geochemistry analyses (i.e. TOC, Rock-Eval and Gas Chromatography-Mass Spectrometry) conducted on selected outcrop and sub-crop samples, and one oil seep sample collected during field work, have given an appraisal to identify the nature of petroleum source rocks within the basin. The result of organic geochemistry and also organic petrology analyses indicates that potential source rocks may occurred in the stratigraphic succession of the basin. The Lahat equivalent formation, Seblat, and Lemau Formations may play an important role to generate oil within the Bengkulu Basin.

Keywords: Source rock, oil seep, oil generation, Lemau Formation, Seblat Formation, Bengkulu Basin

Sari

Cekungan Tersier Bengkulu dikenal sebagai suatu tipe cekungan busur-muka, yang terletak di barat daya Sumatera. Cekungan ini terbentuk sejak umur Eosen-Oligosen dengan diendapkannya Formasi setara Lahat, yang ditindih secara tidak selaras oleh batuan vulkanik Oligosen-Miosen Formasi Hulusimpang. Kemudian dilanjutkan oleh silisiklastika dan sedikit karbonat Miosen Awal-Tengah Formasi Seblat. Tidak selaras di atas Formasi Seblat adalah silisiklastika Miosen Tengah-Akhir Formasi Lemau, yang selanjutnya ditindih oleh Formasi Simpangaur berumur Miosen Akhir-Pliosen. Runtunan pengendapan di cekungan ini diakhiri oleh batuan vulkanik Formasi Bintunan/Ranau.

Analisis geokimia (seperti TOC, Rock-Eval, dan Gas Kromatografi-Mass Spektrometri) yang dilakukan pada percontoh singkapan dan sub-singkapan terpilih, dan percontoh rembesan minyak yang didapatkan selama melakukan pekerjaan lapangan, telah memberikan penilaian dan identifikasi potensi sumber batuan pembawa minyak di dalam cekungan. Hasil analisis kimia organik dan petrologi organik mengungkapkan bahwa potensi batuan sumber pembawa minyak diduga terdapat di runtunan stratigrafi cekungan. Formasi setara Lahat, Formasi Seblat, dan Formasi Lemau mungkin berperan penting untuk menghasilkan minyak di dalam Cekungan Bengkulu.

Kata kunci: *Batuan sumber, rembesan minyak, pembentukan minyak, Formasi Lemau, Formasi Seblat, Cekungan Bengkulu*

Introduction

The Tertiary Bengkulu Basin is a typical fore-arc basin, situated in southwest Sumatera Island. Most of the covered basin area belongs to the Bengkulu Province, administratively (Figure 1). The Bengkulu Basin is bounded by the Barisan Magmatic Zone to the northeast and Mentawai Ridge to the southwest. It is filled by the Eocene to Pleistocene volcanic, siliciclastic, and minor carbonate rocks.

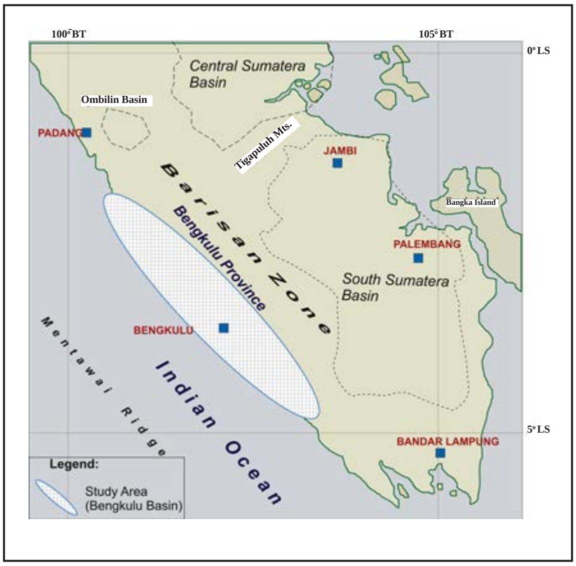

Figure 1. Locality map of the study area, showing the Bengkulu Basin.

Fieldwork activity taking place in 2005 and 2006, was intended to collect field data including outcrop and sub-crop rock samples, sedimentology, and stratigraphy. Observations were carried out in the Seblat and Lemau Formations outcropping in many rivers, tributary and also road cut, and some in coal mining areas. The outcrop was also observed in the northern part of the South Bengkulu Regency (upstream of the Manna and Kedurang Rivers).

The major aim of study is to determine and offer a possible appraisal for petroleum source rock potential in relating to one of the hydrocarbon systems in the Bengkulu Basin. All selected outcrop and sub-crop samples and oil seep have been collected during a fieldwork for laboratory analysis purposes, such as organic petrology and organic geochemistry.

Metodology

The research method comprises two types, these are fieldwork and laboratory analysis. The fieldwork consists of stratigraphy measurement along the rivers, creeks or tributaries, and also several mining areas where the outcrops or sub-crops are available for conducting observations. A total of thirty two fresh rock samples are collected, and also one oil sample collected that is derived from oil seep point in Padangcapo, Sukaraja Sub-Regency that are all for laboratory analysis. Organic petrology was also conducted for maceral analysis, including vitrinite reflectance measurements. Additionally, organic geochemistry analyses, such as TOC (Total Organic Carbon), Rock-Eval Pyrolysis, and gas chromatography-mass spectrometry were applied to determine both characters and fingerprint (biomarker) of oil seepage and source rock samples. All analyses for organic geochemistry on rock and oil seep samples were carried out in PPTMG-Lemigas, Jakarta.

Geological Setting

The geological map of the Bengkulu Quadrangle made by Gafoer *et al.* (1992) is shown in Figure 2, whereas the stratigraphic column cited from Yulihanto *et al.* (1995) is presented in Figure 3. The stratigraphy of the Bengkulu Fore-Arc Basin can be divided into offshore and onshore areas. The Eocene-Oligocene equivalent Lahat, recognized from seismic interpretation and well descriptions, occurs in the offshore Bengkulu area. This formation has not been recognized in the onshore area so far (Yulihanto *et al.*, 1995; Guntoro and Djajadiharja, 2005).

The oldest Tertiary rock in onshore area is the Oligocene-Miocene Hulusimpang Formation consisting of lava, volcanic breccia, and tuffs. It is overlain by intercalations of mudstone, calcareous mudstone, and sandstone with interbedded limestone and conglomerate of the Early–Middle Miocene Seblat Formation.

The Middle-Late Miocene Lemau Formation (mudstone, calcareous mudstone, coal seams, sandstone, and conglomerate) unconformably overlies the Seblat Formation. The Lemau Formation in turn, is conformably overlain by the Mio-Pliocene

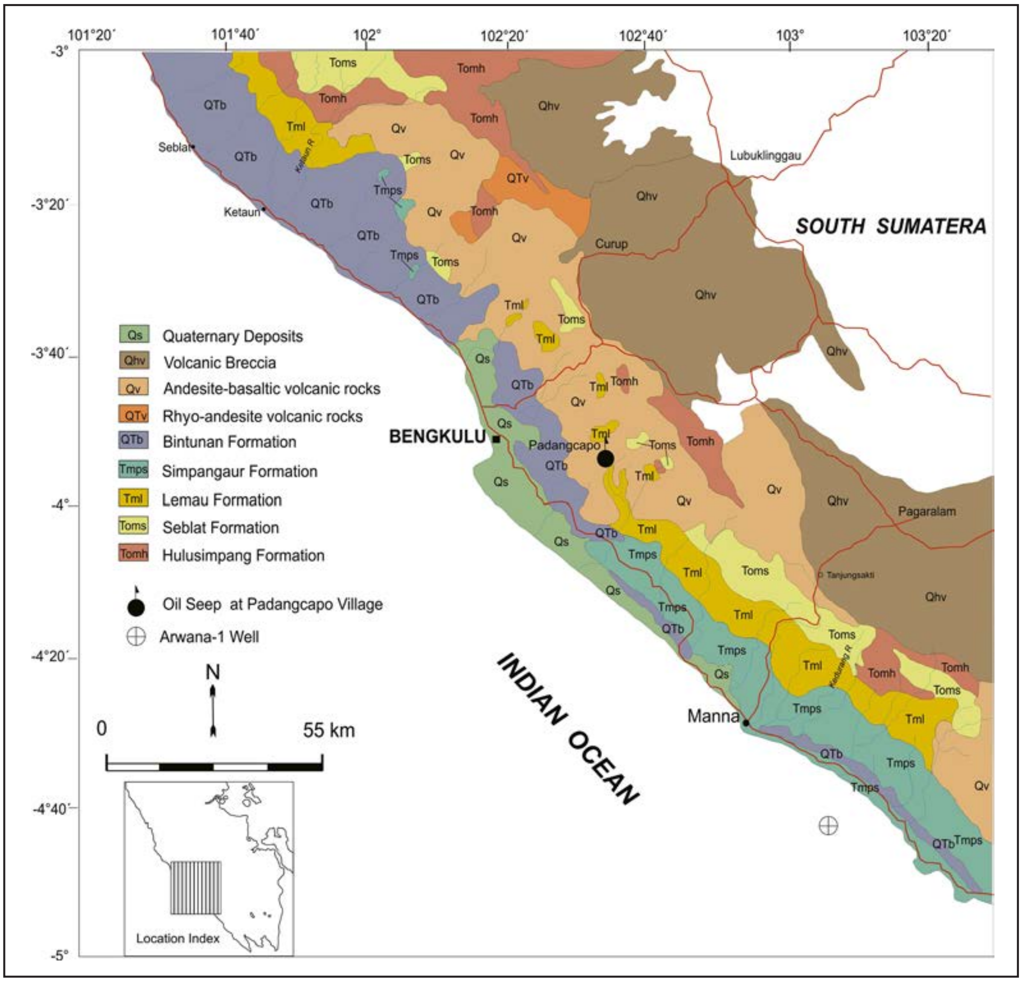

Figure 2. Geological map of the Bengkulu Basin (simplified from Gafoer *et al.*, 1992 and Amin *et al.*, 1994) showing the distribution of Seblat and Lemau Formations, and also the location of oil seep.

Simpangaur Formation which comprise conglomeratic sandstone, sandstone, and mudstone containing mollusc shells. Finally, the basin fill ended with the deposition of tuff, tufaceous mudstone, and polymict conglomerate of the Plio-Pleistocene Bintunan Formation correlated to the Volcanic Ranau Formation (Amin *et al.*, 1994).

Furthermore, the most specific stratigraphic unit (Seblat and Lemau Formations) will be briefly described below as those rock units are considered to be the most important role for petroleum source rock in the Tertiary Bengkulu Basin.

Seblat Formation

The Seblat Formation well outcrops in the road to Tanjungsakti, where the lower section of the formation is dominated by claystone and mudstone, grey to blackish colour, thick bedded to massive, partly shows a parallel lamination containing organic matter or carbonaceous rock (Figure 4a). A coarse to conglomeratic sandstone succession, well bedded (25-150 cm) is found in the lower part of this section. Most of the conglomerate fragments consist of volcanic rocks having a diameter of 0.2 to 5 cm long, subangular to subrounded shape, and poorly sorted. The matrix comprises tuffaceous sands.

The upper part of the formation is preceded by a series of clastic limestone which consists of calcilutite, and then folowed by an intercalation (10-30 cm) of calcilutite and fine- to coarse-grained calcarenite. This unit is overlain by a well-bedded (30-150 cm), medium- to coarse-grained calcareous sandstone,

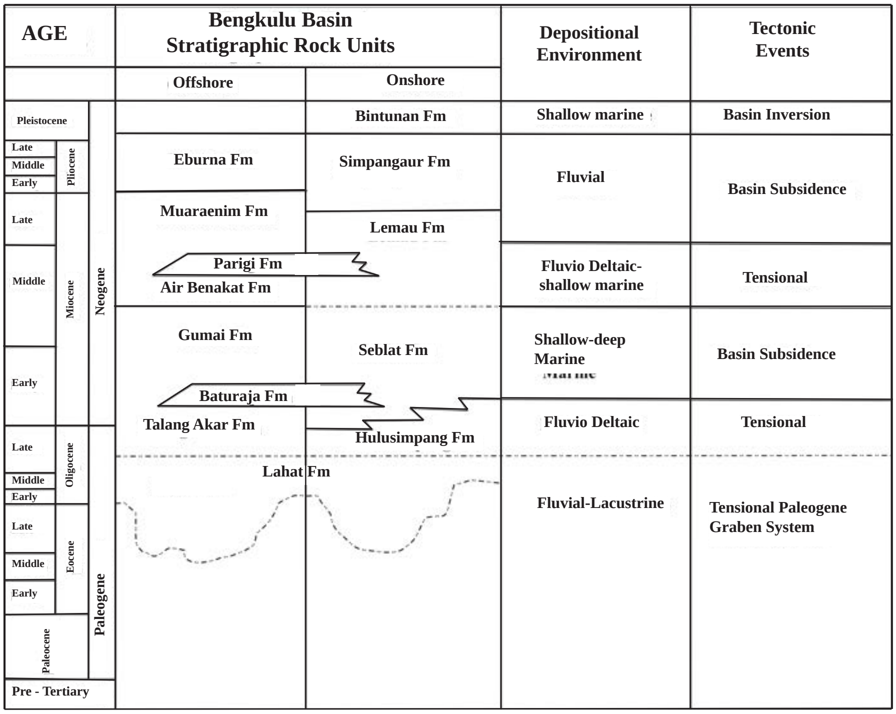

Figure 3. Stratigraphic column of the Bengkulu Basin (modified from Gafoer *et al.*, 1992; Amin *et al.*, 1994; and Yulihanto *et al.*, 1995).

compact, showing some sedimentary structures such as parallel beds and graded beds. Subsequently, it is folowed by intercalations (10 - 30 cm) of calcareous mudstone and fine- to coarse-grained calcareous sandstone, having a minor sedimentary structure of parallel laminations. The limestone series is overlain by intercalations (5 - 25 cm) of mudstone, tuffaceous mudstone, and fine-grained tufaceous sandstone, also showing parallel laminations.

Based on the nanno fosil assemblage (*Sphenolithus heteromorphus, S. belemnos, S. moriformis, Helicosphaera carteri, Discoaster deflandrei, D. drugii , Coccolithus miopelagicus, Cyclicargolithus floridanus,* and *Calcidiscus macintyrei*), the age of the formation is suggested to be Early Miocene or NN3 zone. The formation has been confirmed to be deposited in a shallow marine environment (Heryanto, 2006a).

Lemau Formation

The Lemau Formation comprises claystone, calcareous claystone, coal seam, sandstone, and conglomerate. A series of the Lemau Formation in the Sebayur area (Ketahun) was observed on sub-crop or core samples of several shallow drillings conducted by private coal company in this area. Generally, the Lemau Formation can be divided into two parts of successions. The lower part is dominated by sandstone, whilst the upper part is dominantly composed of carbonaceous mudstone that is interbedded with coal seams (Figure 4b) and also claystone intercalated with fine- to medium-grained sandstone as found in the Kedurang River (Figure 4c). In some places, in the uppermost section of this formation is also recognized interbedded volcanics and sandy mudstone being rich in mollusca shells (Heryanto, 2005, 2006b).

Based on the nanno planktonic fossil analysis, the Lemau Formation is Middle Miocene in age, and it was deposited in a shallow marine environment. Additionally, the palinology analysis on the Lemau Formation resulted in Middle to Late Miocene age, shows a mangrove to fresh water depositional environment. According to Heryanto (2005), the appropriate age for the Lemau Formation is presumed to be Middle to Late Miocene, and the formation was deposited in a shallow marine to transition environment.

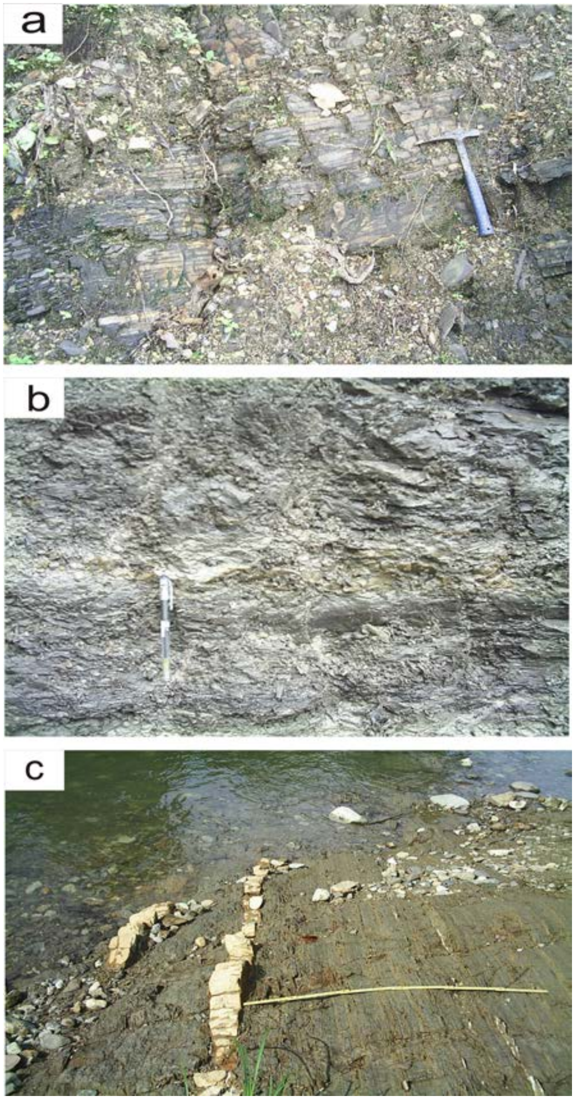

Figure 4. Photographs of outcrop of: a) carbonaceous mudstone of the Seblat Formation in the road to Tanjung sakti; considered as a petroleum source rock; b) carbonaceous mudstone within the Lemau Formation in PT Danau Mas Hitam Coal Mine area that is also considered as a candidate for petroleum source rock; c) the Lemau Formation in the Kedurang River consisting of well bedded claystone intercalated by fine-to medium-grained sandstone; the claystone my also be considered as petroleum source rock;

An Appraisal on the Result of Analysis to the Petroleum Source Rocks

To find out the potential of petroleum source rock within the basin, TOC (total organic carbon) analysis, Rock-Eval pyrolysis, organic petrology, and organic geochemistry (Gas Chromatography- Mass Spectrography) were conducted. These analyses were carried out on fine-grained clastics, such as shale, claystone, and mudstone samples, whereas petrographic analysis is not only carried out on shale and mudstone, but also on coal samples. The oil seep (SY-47) collected from Padangcapo (Figure 5) is also analyzed by the Gas Chromatography-Mass Spectrography mode. The oil indicates a moderately biodegraded type.

Figure 5. Photograph of an oil seepage at location of 05 SY 47 in Padang capo, Sukaraja Sub-Regency (see Figure 2); this oil seep sample is analyzed for main reference discussion in this paper.

Organic petrology or optical method was a good tool for determining maceral analysis and vitrinite reflectance measurement (Cook, 1982; Tissot and Welte,1984). Total organic carbon (TOC) analysis is a basic parameter and useful measurements related to quantity of organic matter within the source rocks (Peters, 1986; Bordenave, 1993). The result of TOC measurements, Rock-Eval pyrolysis (Table 1), Gas Chromatography-Mass Spectrometry including biomarker, organic petrology together with maceral analysis and vitrinite reflectance measurements will be described and discussed below.

Organic Geochemistry

Laboratory works were mainly done for the organic geochemistry, total organic carbon (TOC) analysis, and Rock-Eval pyrolysis on the total of thirty two rock samples from the Seblat and Lemau Formations (Table 1). Those samples were examined to provide a useful and valuable information on generation potential (ultimate hydrocarbon yield) and expected hydrocarbon product (gas and/or

Table 1. Results of TOC and Pyrolysis Rock-Eval Analyses for some Outcrop and Sub-crop Samples of the Seblat and Lemau Formations

No.	Samples No.	Lithology	Formation	TOC (%)	S_1 kg/ton	S_2 kg/ton	PY kg/ton	PI	T_{max} (°C)	HI
1.	05RH11	Claystone	Seblat	1.37	0.45	3.89	4.34	0.10	440	284
2.	05RH17	Claystone	Seblat	1.37	0.45	3.89	4.34	0.10	440	284
3.	05RH20B	Shale	Seblat	1.54	1.04	0.79	1.83	0.57	453	51
4.	05RH27	Claystone	Seblat	1.16	0.55	1.15	1.70	0.32	452	99
5.	05RH30	Claystone	Seblat	1.40	0.44	1.86	2.30	0.19	455	133
6.	05RH32	Claystone	Seblat	0.22	0.13	0.35	0.48	0.27	447	159
7.	05RH34	Claystone	Seblat	1.22	0.75	1.53	2.28	0.33	418	126
8.	05RH37	Claystone	Seblat	1.24	0.27	3.09	3.36	0.08	439	250
9	05RH74D	Claystone	Seblat	3.85	0.32	4.57	4.89	0.07	416	119
10	05RH50D	Claystone	Lemau	8.68	0.50	14.77	15.27	0.03	426	170
11	05RH50G	Claystone	Lemau	1.55	0.21	2.47	2.68	0.08	440	159
12	05RH50H	Claystone	Lemau	9.57	1.05	23.64	24.69	0.04	433	247
13	05RH50J	Claystone	Lemau	6.09	0.66	21.44	22.10	0.03	443	352
14.	05RH51A	Claystone	Lemau	3.53	0.08	0.10	0.18	0.44	570	3
15	05RH51D	Shale	Lemau	1.05	0.03	0.04	0.07	0.43	577	4
16	05RH52A	Coaly shale	Lemau	3.15	0.06	0.11	0.17	0.35	572	3
17	05RH53C	Claystone	Lemau	11.53	0.95	20.12	21.07	0.05	453	174
18	05RH54B	Claystone	Lemau	0.65	0.11	0.12	0.23	0.48	510	19
19	05RH60C	Claystone	Lemau	3.01	0.62	9.16	9.78	0.06	427	304
20	05RH65	Shale	Lemau	0.85	0.02	0.74	0.76	0.03	435	87
21.	05RH71A	Coaly shale	Lemau	14.71	3.62	113.68	117.30	0.03	426	773
22	05RH73B	Shale, carbonaceous	Lemau	8.59	0.75	60.36	61.11	0.001	426	703
23.	05RH75A	Shale, carbonaceous	Lemau	5.39	0.40	29.62	30.02	0.01	434	550
24.	05RH81	Shale, carbonaceous	Lemau	8.65	0.64	48.96	49.60	0.01	427	566
25.	05RH84	Shaly coal	Lemau	9.81	0.88	55.68	56.56	0.02	426	568
26.	05RH85D	Coaly shale	Lemau	27.09	1.04	187.84	188.88	0.001	426	693
27.	05RH85I	Shale, carbonaceous	Lemau	4.45	0.17	15.08	15.25	0.001	430	339
28.	05RH87B	Claystone	Lemau	2.73	0.00	4.23	4.23	0.00	435	155
29.	05RH101D	Shaly coal	Lemau	23.58	0.24	84.24	84.48	0.00	421	357
30.	05RH102C	Claystone	Lemau	0.72	0.03	1.16	1.19	0.03	502	161
31.	05RH104B	Shale, carbonaceous	Lemau	2.62	0.17	10.46	10.63	0.02	435	399
32.	05RH107B	Claystone	Lemau	0.64	0.01	0.47	0.48	0.02	569	74

EXPLANATIONS:
TOC : Total organic carbon
S_1 : Quantity of free hydrocarbon
S_2 : Quantity of hydrocarbon from kerogen
PY : Total hydrocarbon ($S_1 + S_2$)
PI : Production Index $= S_1 / (S_1 + S_2)$
T_{max} : Maximum Temperature (°C) for hydrocarbon formation from kerogen
HI : Hydrogen Index

oil). In addition, the Rock-Eval pyrolysis, with its limitations, facilitates the character type of organic matter and the general nature of the hydrocarbon products (e.g. oil vs. gas) which will be generated upon a thermal maturation (Espitalie *et al.*, 1977; Katz, 1983). Source rocks are fine-grained sedimentary rocks (such as shale, carbonaceous mudstone, and claystone) containing considerable volumes of usually autochthonous dispersed organic matter or kerogen from which significant amounts of oil may be extracted by pyrolysis.

The TOC and Rock-Eval pyrolysis results in that ten samples (05RH53C, 05RH50J, 05RH50H, 05RH75A, 05RH81, 05RH84, 05RH101D, 05RH73B, 05RH71A, and 05RH85D) of thirty two rock samples have been defined in according to Tissot and Welte (1984), Peters (1986), and Bordenave (1993) as an excellent potential (PY: 21 -189 kg/ton rock and TOC: 4.5 - 23.6 %), and four samples (05RH60C, 05RH104B, 05RH85I, and 05RH50D) yielded a good potential (PY: 9.8 - 15.3 kg/ton rock and TOC: 2.6 - 8.7 %). All of the above samples are from the Middle-Late Miocene Lemau Formation. The next eight samples (05RH30, 05RH50G, 05RH37, 05RH87B, 05RH34, 05RH11, 05RH17, and 05RH74D) are categorized as a fair value (PY: 2.3 - 4.9 kg/ton rock and TOC: 2.4 - 3.8 %). Two of those samples are also from the Lemau Formation and the other six samples are from the Early-Middle Miocene Seblat Formation. The rest eight samples fall into a poor source rock category. In order to illustrate the relative hydrocarbon potential, data for all thirty two samples are plotted in Figures 6a and 6b, which show an oil and oil - gas prone zones

The Hydrogen Index (HI) versus maximum temperature (T_{max}) diagram shows maturation levels of the source rock to be immature to early mature (Figure 7). The diagram also indicates that three samples from the Lemau formation contain Type I kerogen, thirteen samples from the Lemau and five from the Seblat Formations contain Type II kerogen, and two samples from the Lemau and four from the Seblat Formations have Type III kerogen. The plotting diagram shows that five samples could not be readily categorized.

One source rock sample from the Lemau Formation (05RH101D) and one oil seep sample have been analyzed for gas chromatography, and their results are mentioned in Table 2 and Figure 8a. Gas chromatography and biomarker distributions for source rock samples from the Lemau Formation (Figure 8a) indicates a terrestrial organic matter origin. It is characterized by the occurrence of high bicadinanes, having low oleananes as well as relatively high oxic environment (Pr/Ph > 3). The thermal maturity of the sample indicates a low maturity level as shown by high 22R homohopane and high odd over even carbon number (CPI >1) as defined by Tissot and Welte (1984), Moldowan *et al.* (1985); Philp (1985); and Fildani *et al*. (2005).

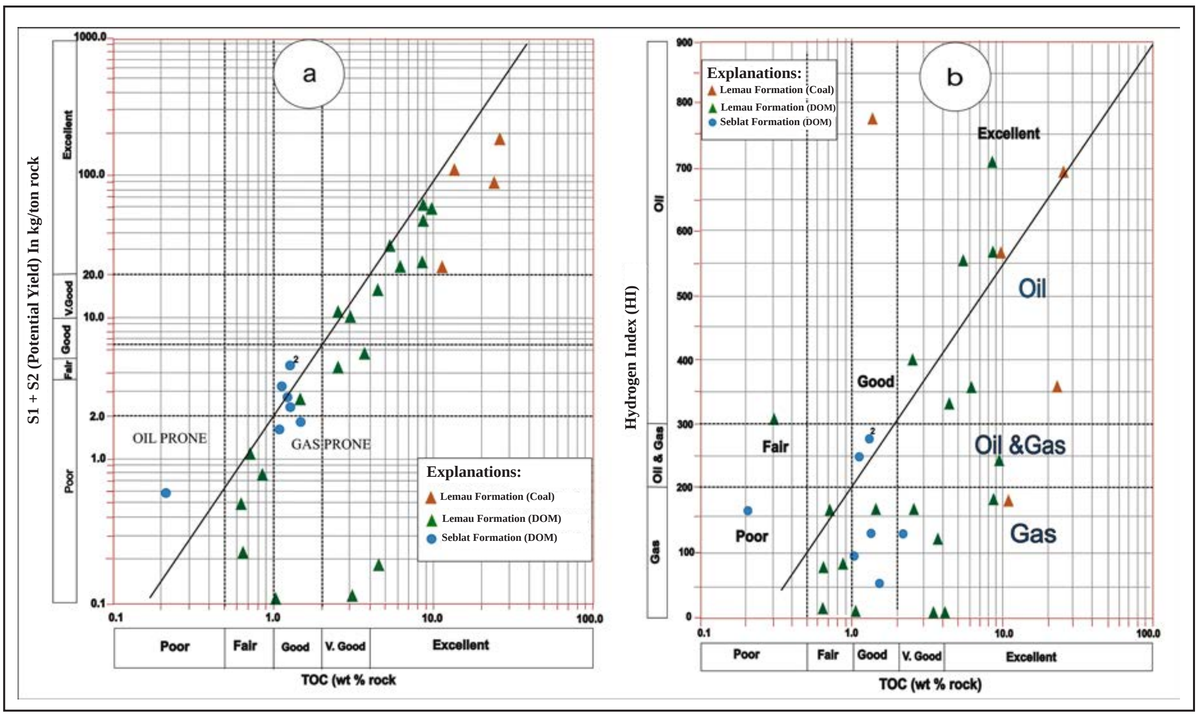

Figure 6. Diagrams showing a) Plotting TOC versus potential yield (PY) for all source rock samples of the Seblat and Lemau Formations indicating that the Lemau has a very good to excellent source rock potential, whilst the Seblat ranges from poor to good; b)Ploting TOC versus Hydrogen Index (HI), Indicating that the source rock samples of the Lemau Formation range from fair to excellent for "oil, and oil &gas", whilst the source rock samples for the Seblat Formation range from poor to good for "gas, and oil & gas only".

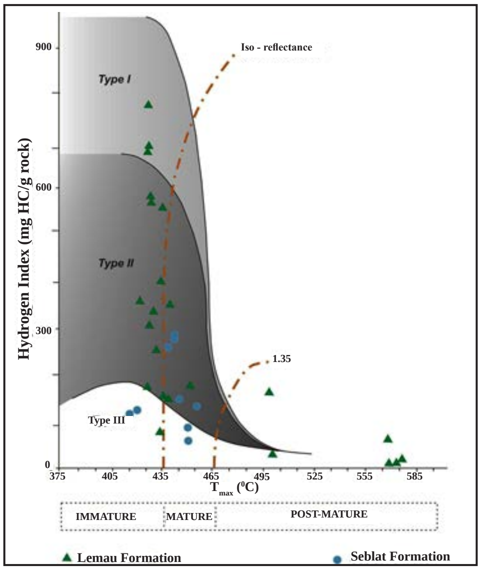

Figure 7. Plot of whole rock T_{max} versus Hydrogen Index (HI), showing that the kerogen types and hydrocarbon maturation for the Seblat and Lemau Formations.

The result of gas chromatography and mass-spectrometry analysis on one oil seep sample (Figure 8b), shows that the oil is typically a moderate biodegraded type. The oil was originated from a mature source rock, that is inferred to be derived from organic matter of terrestrial high plants as characterized by the presence of bicadinanes, oleananes and taraxastanes (Moldowan *et al.*, 1985; Philp, 1985).

Maceral Type

The maceral type within the Seblat and Lemau Formations is recognized by using optical method of organic petrology. The main advantages are to discriminate and locate organic matter of different types of macerals (Cook, 1982; Tissot and Welte, 1984). The dispersed organic matter (dom) found within the carbonaceous mudstones, shale, and claystones of the Seblat and Lemau Formations respectively are presented in Table 3.

Table 2. Correlation of the Result of Organic Geochemistry Analyses between Oil Seep and Source Rock Sample

			Source Rock (05RH101D)	Remarks	Oil Seep (SY-47)	Remarks
		CPI	1.23	Low maturity; Marine deltaic	ND	-
Saturates	GC	Pr/Ph	3.85	Higher plant; deltaic environment. Low to moderate oxygenated bottom water column env.	ND	-
Saturates	Sterane	Dia/Ste	0.11	Low maturity; marine deltaic environment.	1.39	Early mature; marine clay rich condition oil
Saturates	Sterane	20S/20R	0.35	Immature	0.78	Mature, oil window
Saturates	Sterane, % ββ	C_{27}	ND	-	ND	-
Saturates	Sterane, % ββ	C_{28}	ND	-	ND	-
Saturates	Sterane, % ββ	C_{29}	ND	-	ND	-
Saturates	Tricyclic Terpanes	Ste./Hop.	0.93	Marine deltaic shale	0.69	Oil was derived from marine shale
Saturates	Tricyclic Terpanes	C_{19}/C_{23}	1.65		8.27	
Saturates	Tricyclic Terpanes	$C_{24}Te/C_{26}$	2.13	Marine deltaic environment.	0.92	Oil was derived from a marine source rock
Saturates	Tricyclic Terpanes	$C_{28}Te/C_{25}$	0.53	Marine deltaic environment.	2.40	Lacustrine Marine shale sourced oil
Saturates	Tricyclic Terpanes	Tri./Hop.	0.03	Immature	0.57	Early mature
Saturates	Tricyclic Terpanes	Ts/(Ts+Tm)	0.76	Immature	0.40	Oil was derived from a mature source rock
Saturates	Tricyclic Terpanes	C_{29}/C_{30}	0.93	Higher plant organics; deltaic environment.	0.69	Marine
Saturates	Tricyclic Terpanes	22S/22R	0.42	Immature	0.61	Early mature
Saturates	Pentacyclic Triterpanes	Mor./Hop.	0.04	Immature	0.31	Early mature
Saturates	Pentacyclic Triterpanes	Ol./Hop.	0.04	Higher plant organics	1.14	
Saturates	Pentacyclic Triterpanes	Gam. (%)	ND	-	ND	-
Saturates	Pentacyclic Triterpanes	C_{35} (%)	ND	-	ND	Oil was derived from a higher plant organics
Saturates	Pentacyclic Triterpanes	ββ (%)	ND	-	ND	-
Saturates	Pentacyclic Triterpanes	BMI	1.63	Immature	2.44	Early mature

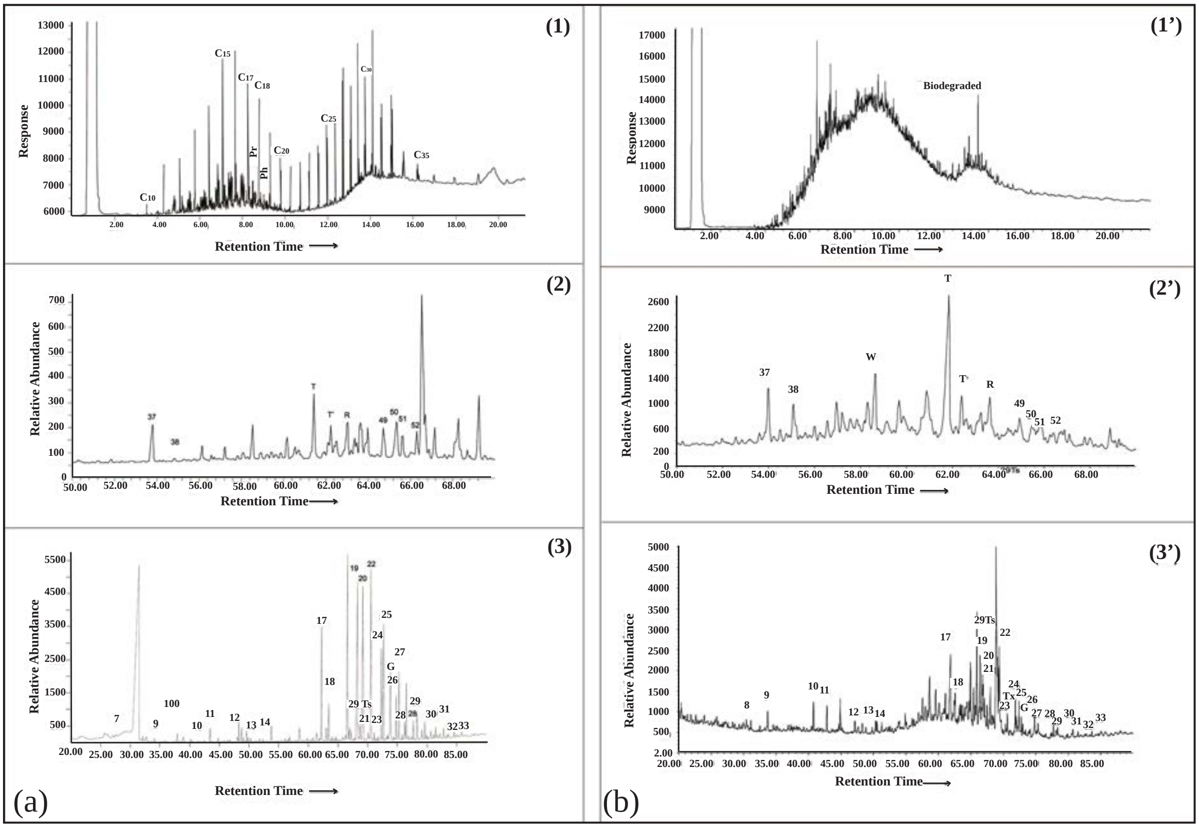

Figure 8. a) Gas chromatography analysis of a rock sample from the Lemau Formation (05RH101D), showing (1) Gas Chromatography-Mass Spectrometry analysis; (2) Saturate Biomarkers m/z 217 Steranes; (3) m/z 191 Triterpanes; b) Oil seep sample (SY-47), showing (1') Gas Chromatography-Mass Spectrometry analysis where the oil appears to have been biodegraded; (2') Saturate Biomarkers m/z 217 Steranes; (3') m/z 191 Triterpanes.

Table 3. Maceral Analyses of Dispersed Organic Matter (d.o.m) of the Seblat and Lemau Formations

Maceral	Seblat Fm.	Lemau Fm.
Vitrinite	1 - 2 %	0.9 - 14.4 %
Exinite	0.1- 6 %	0.2 - 9 %
Telalginite	0 - 1 %	0 - 2 %
Lamalginite	0 - 1 %	0 - 2 %
Resinite	0 - 2 %	0.2 - 3 %
Sporinite	0 - 0.1 %	0 - 2 %
Bituminite	0 - 2 %	0 - 1 %
Cutinite	0 - 1 %	0 - 1 %
Liptodetrinite	0 - 2 %	0 - 2 %
Inertinite	0 - 1 %	0 - 2 %
Vitrinite Reflectance (%Rv_{max})	0.54 - 0.58 (n=2) Average = 0.56	0.39 - 0.55 (n=3) Average = 0.40

Maceral analysis, carried out by organic petrographic techniques, examined the dispersed organic matter (dom) isolated from shale and mudstones samples of the Lemau and Seblat Formations. Maceral from coal sample of the Lemau Formation was also examined. The dom of the Seblat Formation consists of exinite (0.1 - 6 %), vitrinite (1 - 2 %), and inertinite (0 - 1 %) maceral group. The exinite group comprises alginites, such as telalginite and lamalginite. Resinite (0 - 2 %), sporinite (0 - 0.1 %), bituminite (0 - 2 %), cutinite (0 - 1 %), and liptodetrinite (0 - 2 %) are also present.

The dom of the Lemau Formation comprises vitrinite (0.9 - 14.4 %), exinite (0.2 - 9 %) and inertinite (0 - 2 %) maceral group. The exinite group is composed of alginite (1 - 4 %), resinite (0.2 - 3 %), sporinite (0 - 2 %), bituminite (0 - 1 %), cutinite (0 - 1 %), and liptodetrinite (0 - 2 %). The alginite maceral type is present as telalginite (0 - 2 %) and lamalginite (0 - 2 %).

Thus, the maceral type of dom of the Seblat Formation is predominantly vitrinite and exinite with rare inertinite. Its characters and maceral composition indicate that the dom was probably derived from terrestrially origin (Cook, 1982;

Tissot and Welte, 1984) with a small amounts of brackish organic inputs indicated by the presence of telalginite sub-macerals (0 - 1 %). Almost similar to the Seblat Formation, the maceral type within the Lemau Formation comprises largely vitrinite with minor exinite and rare inertinite. Vitrinite maceral within the Lemau Formation is more abundant compared to those the Seblat Formation. Accordingly, the dom characteristics of the Lemau Formation are also almost similar to those the Seblat Formation, i.e. terrestrially origin with also an influence of few brackish organics of typically telalginite sub-maceral (0 - 2 %) (Table 3).

Maturity Indicators

A normal vitrinite reflectance value on fine-grained clastics in the Lemau Formation (i.e. those unaffected by igneous intrusions), such as carbonaceous mudstone, shale claystone, and coal ranges from 0.39 % to 0.55 %, with an average of 0.40 %. Consequently, the source rock maturation of these samples (Lemau Formation) is defined as an immature to early mature level (Cook, 1982; Tissot and Welte, 1984; Bordenave, 1993). This vitrinite reflectance value designates that the sediment successions of the Lemau Formation have ever been buried at a depth of about 2500 m where the paleotemperature has reached 80^o C (Kantsler *et al.*, 1978; Burley *et al.*, 1987).

The vitrinite reflectance (%Rv_{max}) in the dom of the Seblat Formation was difficult to be determined (Table 3), even though the reflectance of a small amounts of fine-grained vitrinite has successfully been measured. The vitrinite reflectance value within the dom of the Seblat Formation ranges from 0.54 % to 0.58 % (see Table 3) having an average value of 0.56 %. Thus, it can be deduced that the thermal maturation level of petroleum source rocks of the Seblat Formation may be defined as an early mature category (Cook, 1982; Tissot and Welte, 1984; Bordenave, 1993).

The T_{max} value obtained from pyrolysis mode represents that the Seblat Formation has a maturity level from early mature to mature (416° C to 455° C) as shown in Table 1 and Figure 7. The Lemau Formation has T_{max} value ranging from 421° C to 577° C. It means that the petroleum source rock has a level of maturity from immature to post mature. However, the high value of T_{max} on the Lemau Formation (>450° C) might has been affected by a thermal intrusion of igneous rocks.

The parameter of organic geochemistry (see Table 2) for one sample of the Lemau Formation shows that the petroleum source rock has an immature level (Herroux *et al.*, 1979; Tissot and Welte, 1984; Peters, 1986). The result of analysis on the oil seep sample shows that the level of maturity is mostly early mature to mature. Accordingly, based on organic geochemistry parameter, the Lemau Formation does not appear to correspond with the oil seep

Oil Seep to Source Rock Correlation: Discussions

The important matter of oil source in the petroleum source rocks is the exinite maceral group with some additional vitrinite fragments (dom), showing a general fluorescent colour that ranges from greenish yellow to yellow and also brownish yellow or orange. The exinite content in the Lemau Formation has a positive corelation with the pyrolyses yield (PY). This condition indicates that the Lemau Formation has an excellent potential of petroleum source rock, even though that the parameter of maturity does not support for generating oil level (see Figures 6a, 6b, and 7).

T_{max} values, ranging from 421° C to 577° C, show that the maturity level is situated between immature to early mature stage (Figure 7). This condition is also supported by the vitrinite reflectance showing values from 0.39 % to 0.55 % (early mature level). However, the average value of vitrinite reflectance (see Table 3) is 0.40 % (immature). The thermal maturity of the sample is also supported by the gas chromatography and biomarker analyses which indicate a low maturity stage as shown by high 22R homohopane and carbon number (CPI >1). The diagenesis level of the sediments varies from Late Eodiagenesis to Early Mesodiagenesis, which is equal to the immature to early mature stage (Cook, 1982). This condition indicates a burial depth of about 2500 m depth where the paleotemperature reached 80^o C (Kantsler *et al.*, 1978; Burley *et al.*, 1987).

According to Guntoro and Djajadiharja (2005), oil shows in Arwana-1 well (offshore) were encountered in thin volcanoclastics of Early Miocene to Early Oligocene age, and also in a dolomitic interval equivalent to the Baturaja Formation at a depth of 2988 - 3092 m. The oil shows in Arwana-1 were not derived from the Lemau source rock, but more probably from the Seblat Formation one. However, it is possible its presence was contributed from an oldest source rock-bearing formation, that is a unit which is equivalent to the Lahat Formation.

Biomarker analysis (GC-MS mass spectrogram) of a selected sample extracts of one source rock from the surface sample of the Lemau Formation (05RH101D) of the Bengkulu Basin is compared to the oil seep sample (SY-47) in an attempt to establish oil seep – source rock correlation (Table 2).

Figure 9a shows plotting diagram between oleanane/C_{30}hopane ratio and Ts/(Ts+Tm)ratio adopted from Fildani *et al*. (2005) clearly indicates that the influence organic facies change (marine versus terrestrial) is not supported by positive correlations between source rock sample and oil seep sample. A correlation between oleanane/C_{30}hopane ratio and diasterane/sterane ratio on both source rock and oil seep samples (Figure 9b) does not appear to be matched each other. It means that the oil seep has not been generated from that source rock (Lemau Formation). A similar suggestion is also obtained from other biomarker parameters (see Table 2), indicating that the oil seep characters do not correspond to the source rock sample.

Triangular diagram of chemical gross composition (Figure 10) shows that the oil seep has been moderately biodegraded. Nevertheless, the oil seep indicates to be typically situated within a mature pathway. The source rock sample (05RH101D) does not match with the oil seep sample. Hence, it could be confirmed that the source rock of the Lemau Formation was not a generative source rock within the Bengkulu Basin. The oil seep might have not been generated from the oldest rock that is the Lemau Formation, but it is most possibly the Seblat Formation or the Lahat equivalent Formation.

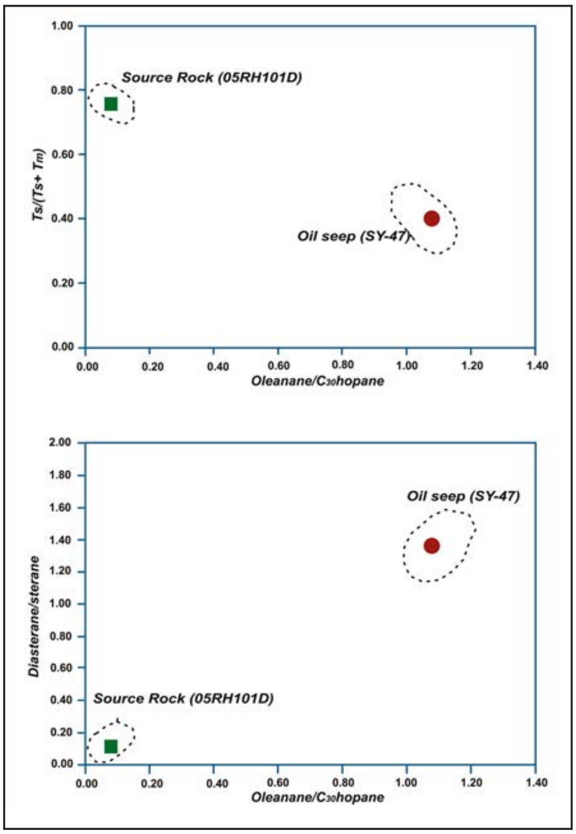

Figure 9. Source rock-oil seep correlation using parameters of: (a) oleanane/C_{30}hopane versus Ts/Ts+Tm) ratios, and (b) oleanane/C_{30}hopane versus diasterane/sterane ratios; the result indicates that the oil seep does not appear to perfectly matching with the source rock sample.

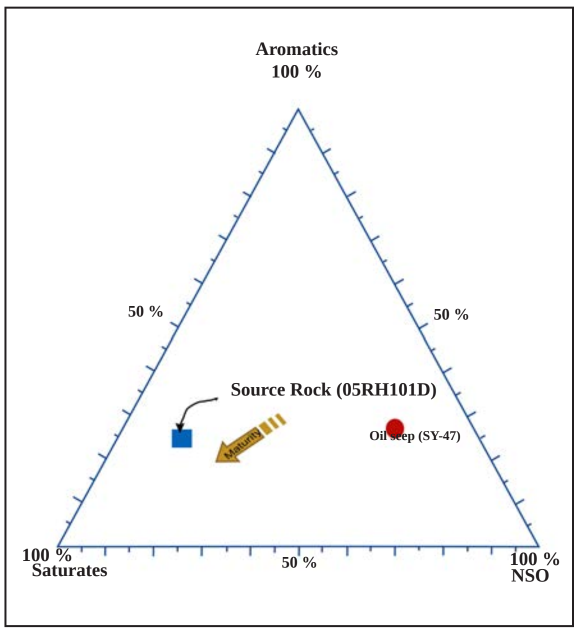

Figure 10. Triangular diagram of chemical gross composition for oil seep sample and source rock extracted (outcrop) reflecting that the oil does not appear to match with the source rock (Lemau Formation).

Conclusions

- Source rocks of the Lemau Formation include samples having a good to excellent potential, whereas those of the Seblat Formation have a poor to good potential. These samples appear to be oil and mixing oil-gas prone.
- The maturation level of most of samples analyzed for the Lemau Formation having kerogen of Type I, II, and III are immature to early mature. The vitrinite reflectance ranging from 0.39 up to 0.55 % indicates a burial depth of about 2500 m in depth and paleotemperature of 80^{o} C.
- The Seblat Formation mostly indicates a mature source rock type, while the organic content consists of Types II and I kerogen, and dominant vitrinite, with some exinite, and rare inertinite maceral. The vitrinite reflectance ranges from 0.54 % to 0.58 %.
- Rock-Eval and biomarker data of oil seep and Lemau source rock samples indicate that both materials contain organic matter input from a terrestrial to a few brackish environment. Although the oil seep was derived from a mature source rock, the Lemau samples are still of low maturity. The biomarker analysis also indicates that the oil seep sample does not correlate with the source rock sample of the Lemau Formation. Thus, the oil seep is most probably derived from the oldest rock units, i.e. the Seblat Formation or other rock units, such as the Lahat equivalent Formation.

Acknowledgments—The authors wish to thank the Head of Geological Survey Institute and also the Programme Coordinator for Basin Dynamics who give a permission to publish this paper. The authors also would like to thank all colleagues for helpful suggestions and discussions.

References

Amin, T.C., Kusnama, Rustandi, E., and Gafoer, S., 1994. *Geological Map of Manna and Enggano Sheets, Sumatera, Scale 1 : 250.000*. Geological Research and Development Centre, Bandung.

Bordenave, M.L., 1993. *Applied Petroleum Geochemistry*. Editions Technip, 27 Rue Ginoux 75737, Paris, cedex 15, 524pp.

Burley, S.D., Kantorowicz, J.D., and Waugh, B., 1987. Clastic Diagenesis. In: Beaumont E.A. and Foster, N.H. (comps.), *Reservoirs II, sandstone*, Treatise of Petroleum Geology Reprint Series No 4, *American Association of Petroleum Geologists*, p. 408-445.

Cook, A.C., 1982. *The origin and petrology of organic matter in coals, oil shales and petroleum source-rocks*. Geology Department, The University of Wollongong, 106pp.

Espitalie, J., Laporte, J.L., Madec, M., Marquis, F., Leplat, P., Paulet, J., and Boutefeu, A., 1977. Methode rapide de caracterisation des roches meres, de leur potentiel petrolier et de leur degre d'evolution. *Revue Institut Francais Petrole*, 32 (1), p.23-40.

Fildani, A., Hanson, A.D, Chen, Z., Moldowan, J.M., Graham, S.A., and Arriola, P.R., 2005. Geochemical characteristics of oil and source rocks and implications for petroleum systems, Talara basin, northwest Peru. *American Association of Petroleum Geologists Bulletin*, 89 (11), p.1519-1545.

Gafoer, S., Amin, T.C., and Pardede, R., 1992. *Geologi Lembar Bengkulu, Sumatera, Sekala 1:250.000*. Pusat Penelitian dan Pengembangan Geologi, Bandung.

Guntoro, A. and Djajadiharja Y.S., 2005. Tectonic Scenario of the Sumatra Fore-Arc Basin in Relation To the Formation of Petroleum Systems. *International Conference on Geology, Geotechnology and Mineral Resources of Indochina* (GEOINDO 2005) 28-30 November 2005, Khon Kaen, Thailand.

Heroux, Y., Chagnon, A., and Bertrand, R., 1979. Compilation and Correlation of Major Thermal Maturation Indicators. *American Association of Petroleum Geologists Bulletin*, 63(12), p. 2128-2144.

Heryanto, R., 2005. Laporan Penelitian Sumber Daya Hidrokarbon di Cekungan Bengkulu, Bengkulu. Pusat Penelitian dan Pengembangan Geologi, Balitbang ESDM, (Laporan Internal).

Heryanto, R., 2006a. Karakteristik Formasi Seblat di Daerah Bengkulu Selatan. *Jurnal Sumber Daya Geologi*, XVI (3), p.179-195.

Heryanto, R., 2006b. Provenance batupasir Formasi Lemau di Cekungan Bengkulu, *Seminar Nasional Geologi Indonesia :"Dinamika dan Produknya"*. Pusat Survey Geologi, Bandung, 5-6 Desember 2006.

Kantsler, A.J., Cook, A.C., and Smith, G.C., 1978. Rank variation, calculated paleotemperatures in understanding oil, gas occurrence. *Oil and Gas Journal*, 20, p.196-205.

Katz, B.J., 1983. Limitations of 'Rock-Eval' pyrolysis for typing organic matter. *Organic Geochemistry*, 4, p.195-199.

Moldowan, J.M., Seifert, W.G., and Gallegos, E.J., 1985. Relationship between Petroleum Composition and Depositional Environment of Petroleum Source Rocks. *American Association of Petroleum Geologists Bulletin*, 69(8), p.1255-1268.

Peters, K.E., 1986. Guidelines for Evaluating Petroleum Source Rock Using Programmed Pyrolysis. *American Association of Petroleum Geologists Bulletin*, 70(3), p. 318-329.

Philp, R.P., 1985. Biological markers in fossil fuel production. In: Beaumont, E.A and Foster, N.H (Eds.), *Geochemistry.*

Treatise of Petroleum Geology, Reprint Series No. 8., American Assocociation of Petroleum Geologists, Tulsa, Oklahoma 74101, U.S.A., p. 337-390.

Tissot, B. and Welte, D.H., 1984. *Petroleum formation and occurrence*. Springer-Verlag, Berlin-Heidelberg-New York-London-Paris-Tokyo. 2nd ed., 699pp

Yulihanto,B., Situmorang, B., Nurdjajadi, A., and Sain, B. 1995. Structural Analysis of the onshore Bengkulu Forearc Basin and Its Implication for Future Hydrocarbon Exploration activity. *Proceedings 24th Indonesian Petroleum Association, Annual Convention, p.85-96.*

Naskah diterima : 23 Juli 2008
Revisi terakhir : 26 Februari 2009