# Source rock characterization and oil grouping in the NW Java, Central Java and NE Java Basins, Indonesia

#### **Ragil Pratiwi**

Indonesian Sedimentologist Forum (FOSI)

Corresponding author: ragilpratiwi@gmail.com

## ABSTRACT

This study reveals the detailed organic geochemistry from crude oils (acquired from wells and seepages) and rock extracts from NW Java and NE Java Basin that have been gathered and compiled from previous publications. The interpretation was conducted from geochemical data value and plot, GC-MS fingerprints, and agglomerative-hierarchical cluster analysis using the Euclidean algorithm. Various source rocks from those basins were deposited under fluvio-lacustrine to the marine environment. Six groups of crude oils are also distinguished. Groups 1, 2, and 6 are oils from deltaic source rocks, Groups 3 and 4 are oils from marine source rocks, and Group 5 is from lacustrine and/or fluvio-lacustrine source rocks. Groups 1, 2, and 6 could be distinguished from the pristane/phytane (Pr/Ph) ratio and  $C_{29}$  sterane composition, while Groups 3 and 4 differ from the distribution of  $C_{27}$  sterane. The schematic depositional environment of source rocks is also generated from this study and suggests that Group 5 is deposited during early syn-rift non-marine settings, while the remaining groups are deposited in the deltaic (Group 1,2 and 6) and marine settings (Groups 3 and 4). The main differences between those groups are including the distributions of  $C_{27}$ - $C_{28}$ - $C_{29}$  steranes.

*Keywords*: organic geochemistry, crude oil, oil seepage, rock extract, oil families, agglomerative hierarchical cluster analysis, Euclidean algorithm.

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## INTRODUCTION

A series of back-arc basins in Java within Sundaland (Figure 1) has been known for their prolific oil and gas accumulation. They lie from west to east, from NW Java Basin to NE Java Basin. These basins shared roughly similar tectonostratigraphic history during Cenozoic, which consists of Cretaceous-Early Paleogene? pre-rift, Late Eocene-Oligocene synrift, Early Miocene postrift, and Middle Miocene inversion (Satyana and Purwaningsih, 2003; Doust and Noble, 2008). These similarities caused the similar type and deposition of source rocks which were deposited during early and late synrift basin phases. However, the heterogeneities within individual source rocks might cause the different

compositions of crude oil and natural gas. This paper analyses the detailed organic geochemistry of crude oils from various basins in Java based on their composition and biomarker characteristics compiled from various publications.

## **PREVIOUS WORKS**

Previous works on oil-to-source rock correlation in several basins in Java mostly emphasized on conventional geochemical analysis from biomarker and isotope data with quantitative (geochemical bivariate plot) and qualitative (comparing fragmentogram peaks) methods (e.g. Satyana and Purwaningsih, 2003; Wiloso et al., 2008; Devi et al., 2018 in NE Java Basin; Subroto et al., 2008; Praptisih,



**Figure 1**. Back-arc basins in Java, Indonesia. The oil samples for this paper were taken from the NW Java Basin and NW Java Basin (green areas indicate producing basin), while the remaining basins are not studied. Some authors suggest that NW Java Basin is a bigger basin that contains several sub-basins including Sunda-Asri, Billiton, and Ardjuna. In this paper, the classification for the basin in Indonesia uses one from Doust and Noble (2008).

2018 in Central Java; Ponto et al., 1988; Rahmad (2016) in NW Java Basin]. However, hierarchical clustering analysis (HCA) is rarely performed since not all samples were analyzed using full range geochemistry analysis from bulk composition to stable carbon isotope. The other reason is that not all samples contain a similar biomarker, or the biomarker is coeluted and difficult to be calculated.

In NW Java, Napitupulu et al. (1997) differentiate three groups of oils from lacustrine, marine shales, and marine carbonate source rocks. In the eastern part of NW Java Basin (near Semarang, Central Java), oil seepage was studied by Praptisih (2018). In East Java, Devi et al. (2018) suggested one oil family from deltaic to marginal marine source rock in NE Java Basin. Satyana and Purwaningsih (2003)discuss the geochemistry of oils and extracts from East Java Basin from 100 wells and seeps (86 crude oils, 35 natural gases, and 57 rock samples from onshore and offshore areas). This study suggests that there are two "classes" of oils based various geochemistry on parameters and plots, however, the hierarchical cluster analysis has yet to be done (Satyana and Purwaningsih, 2003). The classification that they used was one from BP Research Center (1991, in Satvana and Purwaningsih, 2003) which enables oils to be put into one of five categories: A (marine nonclastic with mixed algal and bacterial input), B (marine clastic with mixed algal and bacterial input), C (lacustrine algae), D (high resin terrestrial) and E (low resin terrestrial), depending upon their bulk properties. Satyana and Purwaningsih (2003) classify oils in

East Java into two: Class D1 and Class D2.

Other work that incorporated HCA and principal component analysis (PCA) have been done by Sosrowidjojo (2011) Sunda-Asri the Basin and in Ramadhina et al. (2017) in the NE Java Basin. The HCA and PCA performed by Sosrowidjojo (2011) indicates that oils in the Sunda-Asri Basin can be classified into 6 clusters that reflect their different geographical locations and not due to differences in source rocks. These 6 clusters consist of North Oil Field (2 clusters), Central Oil Field (2 clusters) and South Oil Field (1 cluster) and 1 mixed oil group. In the NE Java Basin, Ramadhina et al. (2017) classify the crude oils from published data into 3 main groups that reflect their subtle differences in API gravity and "final" depositional environment, suggesting the initial source rocks are similar (of non-marine possibly origin) and then were transported and deposited on different places from terrigenous to transition and marine. Unlike the work done by Sosrowidjojo (2011) and Ramadhina et al. (2017), the current study attempts to do HCA on crude oils and source rocks from across several basins.

## DATA AND METHOD

Several publications from NW Java Basin and NE Java Basin (Figure 1) that contained geochemistry of crude oil, rock extract, and oil seepages were studied, analysed, and compiled to understand (1) source rock facies and depositional environment, (2) oil geochemistry from those basins, (3) classification and groups of oils based on their geochemistry parameters using hierarchical cluster analysis, and (4) schematic depositional environments of each group of source rock.

In this study, several biomarkers were analysed, including pristane and phytane (Pr/Ph),ratio n-alkanes distribution.  $C_{27}$ - $C_{28}$ - $C_{29}$ steranes ternary diagram, and fingerprint of selected steranes and terpanes. Table 1 explains those parameters and their interpretation. Each publication mentioned above has a different range of geochemistry analyses, however, most of them have at least one or two parameters (e.g., pristane and phytane ratio and  $C_{27}$ - $C_{28}$ - $C_{29}$ steranes distribution) that are of important source-related biomarker. Therefore, cluster analysis is also used to understand the similarity and/or opposition of each sample based on geochemistry characters and tectonostratigraphy.

## Hierarchical Clustering Analysis (HCA) for Oil Grouping

Cluster analysis is one of the common methods for geochemists to classify oils. Peters et al. (1999) used this method to classify crude oil from Eastern Indonesia, Sosrowidjojo (2011) in the Sunda-Asri Basin. and Ramadhina et al. (2017) in the NE Java Basin. In this paper, the geochemical data from various publications were subjected for oil-to-oil correlation. In addition to qualitative and quantitative geochemical analysis, HCA, a common method that have been widely used in many scientific applications (e.g., Gower et al., 1967), was also performed. The goal of HCA is not to

find a single partitioning of the data, but a hierarchy (generally represented by a tree) of partitions that may reveal interesting structures in the data at multiple levels of granularity (Balcan et al., 2014). The most widely used hierarchical methods are the bottomup or the agglomerative clustering technique; most of these techniques start with a separate cluster for each point and then progressively merge the two closest clusters until only a single cluster remains (Balcan et al., 2014). To calculate the distance (d) between two points (p and q), the Euclidean algorithm is utilized and shown in Equation 1:

$$d(p,q) = \sqrt{(p-q)^2}$$

(1)

Several samples are selected for the analysis which have at least six parameters, such as Pr/Ph, S%, C<sub>27</sub>and  $C_{28}-C_{29}$ steranes, oleanane /hopane ratio. Therefore, in this study, HCA was only performed for samples that have multiple geochemical parameters. Various limitations that include the number of geochemical parameters that are not available from all samples from published work, hydrocarbon alteration, and thermal maturation are not discussed in this paper. This study assumed that such factors will not greatly affect the results Finally, the of HCA. HCA was performed using XL Stats software with a high confident level.

| Geochemical<br>Parameters                                     | Analysis | Biomarker   | References   |  |  |
|---|----------|---|--|--|--|
| <i>n</i> -alkanes   | GC       | The distribution of n-alkanes are indicators for organic matter input, e.g., $nC_{27}$ , $nC_{29}$ , $nC_{31}$ are indicators of terrestrial origin.  | e.g., Tissot and<br>Welte (1984)                                       |  |  |
| Pr/Ph   | GC       | e.g., Hughes<br>(1984),<br>Palacas et al.<br>(1984)   |  |  |  |
| C <sub>27</sub> -C <sub>28</sub> -C <sub>29</sub><br>steranes | GC-MS    | The distribution of $C_{27}$ - $C_{28}$ - $C_{29}$ is a<br>source parameter that can be used to<br>differentiate depositional settings. The<br>principal use of the ternary diagrams<br>is to distinguish groups of crude oils<br>from different source rocks or different<br>organic facies of the same source rock. | e.g., Huang<br>and<br>Meinschein<br>(1979),<br>Peters et al.<br>(2004) |  |  |
| Oleanane  | GC-MS    | Oleanane is a biomarker characteristic<br>of GC-MS angiosperms (flowering<br>plants) found only in Cretaceous and<br>younger rocks and oils   | Peters et al.<br>(2004)  |  |  |
| Bicadinanes   | GC-MS    | Bicadinanes are derived from higher<br>plants and GC-MS used as an<br>indicator for terrestrial organic matter<br>input.  | e.g., Summons<br>and<br>Jahnke (1992)                                  |  |  |
| Carbon<br>Isotope of<br>Saturates<br>and<br>Aromatics         |          | Combination of stable carbon isotope<br>ratios of Saturates and Aromatics, a<br>sterane ternary Carbon Isotope<br>diagram, and other supporting data<br>was used to classify oil groups and<br>relate most of them to source rock<br>extracts.  | Grantham et<br>al. (1988)  |  |  |

**Table 1**. Selected geochemical parameters to understand the various depositional environment, redox conditions, organic matter input and to classify crude oils based on their genetic origins based on various authors.

# GEOLOGICAL SETTINGS AND TECTONOSTRATIGRAPHY

Java island of Indonesia is located in the SE part of Sundaland in which various back-arc basins lie, including NW Java Basin and NE Java Basin (Figure 1) studied in this paper. In nearly all the basins within Sundaland including Java and Sumatra, four stages of tectonostratigraphic evolution could be recognized (Doust and Noble, 2008):

1. Early Synrift (generally Eocene to Oligocene) corresponds with the period of rift graben formation and the following period of maximum subsidence,

- 2. Late Synrift (Late Oligocene to Early Miocene) corresponds with the period of waning subsidence in the graben when individual rift elements amalgamated to form extensive lowlands that filled with paralic sediments,
- 3. Early Postrift (typically Early to Middle Miocene) corresponds with a period of tectonic quiescence following marine transgression that covered the existing graben-horst topography,
- 4. Late Postrift (typically Middle Miocene to Pliocene) corresponds to periods of inversion and folding, during which regressive deltas were formed. Doust and Noble (2008) described the stratigraphy of



*Figure 2*. Stratigraphic sections of several Indonesian basins from Sumatra including North, Central, and South Sumatra Basins, and Java including Sunda-Asri, NW Java, and NE Java basins. The sequences in those basins are divided into four sections: Early and Late Synrift, Early and Late Postrift (Doust and Noble, 2008).

Sumatra and Java, suggesting rifting stage during Eocene and terminated in Oligocene, followed by post-rift since Miocene (Figure 2).

The four stages of tectonostratigraphic evolution their and relations to petroleum system elements are summarised in Table 2. To summarise, Eocene Oligocene the to fluviolacustrine to paralic/deltaic shales synrift are the main source rocks in Java Basins, including Banuwati (Sunda Asri Basin), Talangakar (NW Java Basin), and Ngimbang formations (NE Java Basin). Howes and Trisnawijaya (1995) also suggest other source rocks from Cenozoic sequences in the NW Java Basin. Reservoirs vary from Oligocene to Miocene syn- and postrifts sediments, including Baturaja, Talangakar, and Kujung formations.

## GEOCHEMISTRY OF SOURCE ROCK FROM JAVA

The geochemistry cross plot of stable carbon isotopes from saturates fraction versus Pr/Ph (Figure 3) distinguished three different groups of source rocks namely Banuwati, Talangakar, and Ngimbang formations from Sunda-Asri, NW Java, and NE Java basins, respectively (Figure 3). On the sterane plot, all samples have a predominance of C<sub>29</sub> steranes suggesting input from terrestrial higher plant organic matter (Figure 4, Table 3; Huang and Meinschein, 1979).



**Figure 3**. Cross plot between carbon isotope of saturates and pristane/phytane (Pr/Ph) ratio that suggests different characters of source rocks. In Sunda-Asri and NW Java basins, Banuwati and Jatibarang/TAF source rocks could be distinguished. Banuwati source rock tends to have higher Pr/Ph and lower carbon isotope of saturates. In East Java Basin, all potential source rocks tend to have similarities, however, Ngimbang Formation could be distinguished from the lower carbon isotope of saturates. Sunda-Asri and NW Java data are from Bishop (2000) and Rahmad (2016), and NE Java data are from Satyana and Purwaningsih (2003) and Devi et al. (2018).

|                | Tectonostra  | Proven  |   |   |   |
|----------------|--|---|---|---|---|
| Basin          | Early<br>Synrift   | Late Synrift  | Early Post<br>rift  | Late Post rift  | Petroleum<br>System   |
| Sunda<br>-Asri | Oligocene<br>fluvio-<br>lacustrine<br>Banuwati<br>(SR)   | Oligo-Miocene<br>fluvio-deltaic<br>Talangakar<br>and Baturaja<br>carbonates (R)                               | Middle<br>Miocene<br>transgressive<br>marine<br>shales of<br>Airbenakat<br>(C)  | Miocene –<br>Quaternary<br>regressive &<br>deltaic<br>sediments of<br>Cisubuh   | Banuwati-<br>Talangakar (!)   |
| NW<br>Java     | Late Eocene<br>– Early<br>Oligocene<br>lacustrine<br>Jatibarang<br>and deltaic<br>Talangakar<br>(SR)     | Oligo-Miocene<br>transgressive<br>fluvio-deltaic<br>to shallow<br>marine<br>Talangakar<br>and Baturaja<br>(R) | Early –<br>Middle<br>Miocene<br>regressive &<br>deltaic clastic<br>of Cibulakan<br>(R), (C)                             | Late Miocene<br>to Quaternary<br>platform<br>carbonates<br>and regressive<br>clastic of the<br>Parigi and<br>Cisubuh                                | Talangakar-<br>Cibulakan (!)  |
| NE<br>Java     | Late Eocene<br>to Early<br>Oligocene<br>lacustrine to<br>paralic<br>sediment of<br>Ngimbang<br>(SR), (R) | Late Oligocene<br>to Early<br>Miocene<br>marine<br>carbonates of<br>the Kujung<br>and Prupuh<br>(R)           | Early to Late<br>Miocene<br>carbonate<br>platforms of<br>Tuban,<br>Wonocolo<br>shales and<br>Ngrayong<br>sands (R), (C) | Late Miocene<br>to Quaternary<br>marine clays,<br>volcaniclastics,<br>carbonates<br>and sands<br>from shallow<br>to deeper<br>water<br>environments | Ngimbang-<br>Ngrayong (.),<br>Ngimbang-<br>Ngimbang (!),<br>Ngimbang-<br>Kujung (!),<br>Cenozoic-<br>Miocene (.),<br>Cenozoic-<br>Pliocene (!)<br>(Howes and<br>Trisnawijaya,<br>1995). |

**Table 2**. Tectonostratigraphy and its relation to petroleum system elements in several basins within Java (Doust and Noble, 2008). The symbols SR, R, and C are for source rock, reservoir, and caprock or seal, respectively.

| Rock Extracts  | δ <sup>13</sup> C<br>Saturates<br>(‰) | Pr/Ph | C <sub>27</sub><br>steranes<br>(%) | C <sub>28</sub><br>steranes<br>(%) | C <sub>29</sub><br>steranes<br>(%) | Authors                         |
|----------------|---------------------------------------|-------|------------------------------------|------------------------------------|------------------------------------|---------------------------------|
| Jatibarang/TAF | -29.70                                | 5.40  | 25.00                              | 25.00                              | 50.00                              | Bishop (2000), Rahmad (2016)    |
| Jatibarang/TAF | -29.50                                | 6.10  | 31.00                              | 22.00                              | 47.00                              | Bishop (2000)                   |
| Kujung         | -28.00                                | 1.56  | 34.00                              | 36.00                              | 30.00                              | Devi, et al. (2018)             |
| Kujung         | -25.68                                | 2.90  | 25.00                              | 29.00                              | 46.00                              | Satyana and Purwaningsih (2003) |
| Ngimbang       | -26.77                                | 1.80  | 34.00                              | 21.00                              | 45.00                              | Devi, <i>et al.</i> (2018)      |
| Ngimbang       | -27.40                                | 2.07  | 29.00                              | 29.00                              | 42.00                              | Devi, <i>et al.</i> (2018)      |
| Ngimbang       | -28.10                                | 3.44  | 30.00                              | 20.00                              | 50.00                              | Devi, et al. (2018)             |
| Ngimbang       | -27.10                                | 2.30  | 30.00                              | 25.00                              | 45.00                              | Devi, et al. (2018)             |
| Tuban          | -25.54                                | 5.40  | 5.00                               | 39.00                              | 56.00                              | Satyana and Purwaningsih (2003) |

**Table 3**. Source rock extracts from NW Java Basin and NE Java have a significant amount of  $C_{29}$  steranes, an indicator of the higher plant from the terrestrial origin. The high Pr/Ph ratio (more than 1) indicates sub-oxic to oxic conditions. Two samples from Kujung and Ngimbang (Devi et al., 2018) and one from Tuban (Satyana and Purwaningsih, 2003) have higher  $C_{27}$  and  $C_{28}$  steranes indicating a predominance of marine and lacustrine organic matter, respectively.



**Figure 4**. The distribution of  $C_{27}$ - $C_{28}$ - $C_{29}$  steranes is presented in the ternary diagram. All samples indicate the same location with a significant number of  $C_{29}$  steranes. Huang and Meinschein (1979) studied the importance of steranes as indicators for the depositional environment, where a high abundance of  $C_{27}$ ,  $C_{28}$ , and  $C_{29}$  steranes suggest marine, lacustrine and terrestrial environments respectively. NW Java data are from Bishop (2000) and Rahmad (2016), and NE Java data are from Satyana and Purwaningsih (2003) and Devi et al. (2018).

| Group | Classification  | Dissimilarity with other<br>groups   | Pristane/<br>Phytane | s            | C <sub>27</sub> steranes<br>(%) | C <sub>28</sub> steranes<br>(%) | C <sub>29</sub> steranes<br>(%) | Oleanane /<br>Hopane | Oils                               |
|-------|---|--|----------------------|--------------|---------------------------------|---------------------------------|---------------------------------|----------------------|------------------------------------|
| 1     | Deltaic-sourced oil   | Higher in C <sub>29</sub> steranes than<br>Group 2   | 3.95 - 9.81          | 0.07 - 0.35  | 11 - 17                         | 21 - 28                         | 55 - 63                         | 0.12 - 0.51          | NE Java Basin                      |
| 2     | Deltaic-sourced oil   | Lower in C <sub>29</sub> steranes<br>compared to Group 1   | 2.40 - 7.72          | 0.00 - 0.68  | 16 - 24                         | 26 - 32                         | 45 - 55                         | 0.04 - 2.19          | Mostly NE Java<br>Basin            |
| 3     | Marine-sourced oil  | C <sub>27</sub> > C <sub>28</sub> > C <sub>29</sub> .<br>C <sub>27</sub> is a biomarker from<br>marine plankton or algae | 4.10 - 13.77         | 0.07 - 0.43  | 40 - 48                         | 25 - 33                         | 18 - 28                         | 0.22 - 0.43          | NW Java Basin and<br>NE Java Basin |
| 4     | Marine-sourced oil  | $C_{\rm 29}$ Steranes is the lowest compared to $C_{\rm 28}$ and $C_{\rm 27}$  | 3.95 - 9.75          | 0.00 - 0.25  | 38 - 47                         | 38 - 46                         | 6 - 18                          | 0.36 - 0.76          | Mostly NW Java<br>Basin            |
| 5     | Lacustrine or Fluvio-<br>lacustrine-sourced oil                           | $C_{28} > C_{29} > C_{27}$ .<br>$C_{28}$ is an indicator for<br>lacustrine oils  | 0.00 - 11.70         | 0.09 - 0.42  | 23 - 34                         | 42 - 49                         | 19 - 28                         | 0.10 - 0.46          | NW Java Basin and<br>NE Java Basin |
| 6     | Deltaic-sourced oil,<br>potentially from coal<br>or carbonaceous<br>shale | Higher in Pr/Ph compared<br>to Group 1 and 2   | 3.82 - 16.25         | 00.00 - 1.19 | 22 - 36                         | 29 - 37                         | 31 - 41                         | 0.00 - 0.37          | NW Java Basin                      |

**Table 4**. Six groups of oils are observed in this study. Groups 1, 2, and 6 are crude oils from deltaic source rocks, Groups 3 and 4 are crude oils from marine source rocks, and Groups 5 are crude oils from lacustrine and fluvio-lacustrine source rocks. Pr/Ph ratio, S (sulfur, wt%),  $C_{27}$ - $C_{28}$ - $C_{29}$  steranes (%), and oleanane/hopane are the parameters for conducting the HCA analysis in this study.

The Banuwati Formation is an excellent deep lacustrine Type I source rock in the Sunda-Asri Basins, with TOC of up to 8 wt% and a hydrogen index (HI) of up to 650 mg HC/g TOC (Doust and Noble, 2008; Ralanarko et al., 2020). In the Ardjuna sub-basin (NW Java Basin), the Talangakar Formation is known as the source rocks, with TOC of 40-70 wt% in coals and 0.59 wt% in the shales and HI of 200-400 mg HC/gTOC (Ponto et al., 1988), indicating that the source rock is oil- and gas-prone (Bishop, 2000). Noble et al. (1991) distinguished three facies of Talangakar Formation, which are delta plain (coal facies), delta plain (shale marine-influenced facies). and interdistributary bay. Delta plain coals have higher TOC and HI of 62.7-72.2 wt% and 348-406 mg HC/g TOC, respectively. Napitupulu et al. (1997) observed the occurrence of Botryococcane in the oils from NW Java

Basin that indicate they were derived from lacustrine source rocks. In NE Java, Ngimbang Formation has TOC from 0.79-40.15 wt% and HI from 107-282 mg HC/g TOC (Devi et al., 2018).

# OIL FAMILIES IN THE NW JAVA AND NE JAVA BASINS

Oil grouping in NW Java and NE Java basins is conducted using hierarchical cluster analysis where the main parameters are sulphur content, Pr/Phratio, oleanane/hopane ratio, and distribution of  $C_{27}-C_{28}-C_{29}$  steranes (Tables 4 and 5). Other geochemistry plots are also used to understand the correlation between each group.

Based on those methods, six oil groups in NW Java and NE Java basins are classified (Table 4) and presented in a dendrogram (Figure 5).

| Group<br>Interpretation | Oil / Seepage       | S    | Pr / Ph | Oleanane<br>/Hopanes | C <sub>27</sub> steranes<br>(%) | C <sub>28</sub> steranes<br>(%) | C <sub>29</sub> steranes<br>(%) |
|-------------------------|---------------------|------|---------|----------------------|---------------------------------|---------------------------------|---------------------------------|
|                         | Kawengan            | 0.25 | 5.30    | 0.50                 | 14.00                           | 28.00                           | 58.00                           |
|                         | Nglobo              | 0.07 | 5.60    | 0.60                 | 17.00                           | 25.00                           | 58.00                           |
|                         | Wonocolo            | 0.13 | 4.70    | 0.50                 | 14.00                           | 28.00                           | 58.00                           |
|                         | Kertageneh          | 0.13 | 5.00    | 0.51                 | 16.00                           | 21.00                           | 63.00                           |
|                         | Lerpak              | 0.10 | 5.00    | 0.38                 | 16.00                           | 25.00                           | 59.00                           |
| Group 1                 | poleng(JS 20-4)     | 0.10 | 6.15    | 0.29                 | 16.00                           | 27.00                           | 57.00                           |
| Group 1                 | JS 1-1              | 0.17 | 5.80    | 0.29                 | 11.00                           | 26.00                           | 63.00                           |
|                         | JS 2-1              | 0.34 | 6.21    | 0.13                 | 16.00                           | 26.00                           | 59.00                           |
|                         | JS 14A              | 0.20 | 9.81    | 0.21                 | 11.00                           | 26.00                           | 59.00                           |
|                         | JS 19-1             | 0.25 | 6.65    | 0.12                 | 16.00                           | 26.00                           | 59.00                           |
|                         | JS 20-4 (Poleng)    | 0.14 | 3.95    | 0.31                 | 16.00                           | 27.00                           | 57.00                           |
|                         | Poleng A-3          | 0.14 | 5.28    | 0.29                 | 17.00                           | 28.00                           | 55.00                           |
|                         | NWJ-21              | 0.00 | 2.40    | 0.15                 | 24.85                           | 29.58                           | 45.57                           |
|                         | Banyuasin           | 0.28 | 5.00    | 1.88                 | 19.00                           | 28.00                           | 53.00                           |
|                         | Semanggi            | 0.15 | 5.90    | 0.62                 | 19.00                           | 26.00                           | 55.00                           |
|                         | Lidah               | 0.05 | 5.00    | 0.59                 | 21.00                           | 29.00                           | 50.00                           |
|                         | Gegunung            | 0.07 | 5.60    | 0.62                 | 20.00                           | 29.00                           | 51.00                           |
| Group 2                 | Kuti                | 0.13 | 5.00    | 2.19                 | 17.00                           | 32.00                           | 51.00                           |
|                         | Arosbaya            | 0.13 | 3.50    | 0.36                 | 23.00                           | 26.00                           | 51.00                           |
|                         | KE 6-3              | 0.38 | 2.69    | 0.95                 | 16.00                           | 31.00                           | 53.00                           |
|                         | L 46-1(SE Kangean)  | 0.68 | 4.19    | 0.04                 | 23.00                           | 29.00                           | 48.00                           |
|                         | L 46-1 (SE Kangean) | 0.68 | 4.19    | 0.04                 | 23.00                           | 29.00                           | 48.00                           |
|                         | L 46-2 (SE Kangean) | 0.09 | 7.72    | 0.09                 | 18.00                           | 32.00                           | 50.00                           |
|                         | NWJ-2               | 0.43 | 4.10    | 0.22                 | 48.19                           | 25.71                           | 26.10                           |
|                         | NWJ-7               | 0.07 | 9.65    | 0.43                 | 40.92                           | 30.63                           | 28.45                           |
| Group 3                 | NWJ-8               | 0.15 | 13.77   | 0.30                 | 41.25                           | 31.09                           | 27.66                           |
|                         | NWJ-13              | 0.08 | 11.56   | 0.29                 | 43.50                           | 32.91                           | 23.59                           |
|                         | NWJ-19              | 0.12 | 9.03    | 0.37                 | 47.90                           | 33.32                           | 18.78                           |
|                         | Suci-B              | 0.00 | 3.94    | 0.00                 | 47.10                           | 46.20                           | 6.70                            |
|                         | NWJ-10              | 0.24 | 5.28    | 0.40                 | 38.41                           | 42.79                           | 18.80                           |
| Group 4                 | NWJ-12              | 0.20 | 6.54    | 0.44                 | 42.89                           | 38.30                           | 18.81                           |
| Group 4                 | NWJ-14              | 0.25 | 5.12    | 0.76                 | 38.94                           | 43.98                           | 17.08                           |
|                         | NWJ-16              | 0.08 | 9.75    | 0.36                 | 42.73                           | 40.87                           | 16.40                           |
|                         | NWJ-18              | 0.05 | 7.54    | 0.45                 | 43.65                           | 45.45                           | 10.90                           |
|                         | Sekarkorong         | 0.19 | 11.70   | 0.10                 | 31.00                           | 44.00                           | 38.00                           |
|                         | NWJ-3               | 1.14 | 9.63    | 0.43                 | 23.47                           | 48.78                           | 27.75                           |
| Group 5                 | NWJ-5               | 0.16 | 7.62    | 0.30                 | 25.47                           | 44.02                           | 30.51                           |
|                         | NWJ-9               | 0.13 | 6.07    | 0.39                 | 31.94                           | 45.80                           | 22.26                           |
|                         | NWJ-11              | 0.42 | 0.00    | 0.46                 | 31.11                           | 49.75                           | 19.14                           |
|                         | NWJ-20              | 0.09 | 7.74    | 0.41                 | 34.57                           | 42.86                           | 22.57                           |
|                         | Mudi-1              | 0.36 | 3.54    | 0.00                 | 33.90                           | 34.70                           | 31.50                           |
|                         | KE 9                | 0.32 | 3.82    | 0.15                 | 22.00                           | 37.00                           | 41.00                           |
|                         | JS 44-A1            | 0.70 | 5.15    | 0.28                 | 26.00                           | 34.00                           | 41.00                           |
|                         | NWJ-1               | 1.19 | 4.88    | 0.05                 | 34.20                           | 34.65                           | 31.15                           |
| Group 6                 | NWJ-4               | 0.11 | 7.68    | 0.39                 | 24.66                           | 34.37                           | 40.97                           |
|                         | NWJ-6               | 0.00 | 8.12    | 0.24                 | 27.21                           | 34.89                           | 37.90                           |
|                         | NWJ-15              | 0.02 | 14.40   | 0.26                 | 36.01                           | 29.48                           | 34.51                           |
|                         | NWJ-17              | 0.02 | 16.25   | 0.37                 | 31.76                           | 32.65                           | 35.59                           |
|                         | INVVJ-22            | 0.08 | 1.11    | 0.31                 | 34.11                           | 34.74                           | 31.15                           |

**Table 5**. This study distinguished six groups of oils. Oil geochemistry in this study is compiled from NW Java Basin (Napitupulu et al., 1997) and NW Java Basin (Satyana and Purwaningsih, 2003).



**Figure 5**. The dendrogram resulted from HCA from oils from Java, including NW Java and NE Java Basins, where six groups were distinguished. Group 1, 2, and 6 are from marine-sourced oils, Group 3 and 4 are from marine-sourced oils, and Group 5 is from lacustrine-sourced oils. Group 1, 2, and 6 can be distinguished from the number of pristane/phytane (Pr/Ph) ratio and C<sub>29 sterane</sub>, while Group 3 and 4 differ based on the distribution of C<sub>27</sub> sterane.

Most oil groups show significant numbers of Pr/Ph ratio (higher than 1, see Table 4) and predominance of  $C_{29}$ sterane indicating that these crude oils were derived from source rock which was deposited under suboxic-oxic with predominance input from terrestrial organic matter. The crude oils also contain oleanane, a biomarker from angiosperm which is an indicator from Cretaceous and younger (Peters et al., 2004).

Group 1 and 2 are crude oils derived from deltaic shale facies, where the main difference is the distribution of  $C_{29}$  steranes and Pr/Ph ratio. Group 3 and 4 are crude oils derived from a marine shale source rock based on the distribution of  $C_{27}$  sterane (Huang and Meinschein, 1979; Figure 6 and Table 4) that ranges from 40-48% and 38-47%, respectively. Group 5 is oil from the lacustrine and fluvio-lacustrine source rocks based on the high distribution of C<sub>28</sub> sterane (Huang and Meinschein, 1979; Figure 6 and Table 4) that ranges from 42-49% (Table 4). Group 6 has the same characteristics



Figure 6. Sterane distribution of six oil groups in Java, Indonesia indicating depositional environment from fluviolacustrine to shallow marine (after Huang and Meinschein, 1979). Oil grouping of Java Oils shows a good correlation with  $C_{27}$ - $C_{28}$ - $C_{29}$  steranes. One oil from Semarang, Central Java is obtained from Praptisih (2017) and categorised as Group 6 in this study. This sterane distribution is analyzed from various publications including NW Java Basin (Napitupulu et al., 1997) and NW Java Basin (Satyana and Purwaningsih, 2003).



Figure 7. The distribution of n-alkanes and isoprenoids that contains Botryococcane from NWJ oils (Napitupulu 1997). Botryococcane et al., is a biomarker derived from Botryococcus braunii, colonial Chlorophycean algae that only live in the lacustrine environment (Peters et al., 2004).

as Group 1 and 2 but has a higher Pr/Ph ratio (up to 16.25) indicating oils from coal measure source rocks, in which Wang et al. (2019) defined coal measure source rocks as those which include coal, carbonaceous shale, and grey shale.

## Lacustrine and Fluvio-Lacustrine Group

The crude oils from this group are characterized by the abundance of  $C_{28}$ steranes ( $C_{28}$ >  $C_{29}$ >  $C_{27}$  steranes) that are typical of lacustrine-sourced oils (McKirdy et al., 1984). The deltaic sourced oils tend to have a slight dominance of  $C_{29}$  over  $C_{28}$  and  $C_{27}$ steranes (Noble et al., 1991). Huang and Meinschein (1979) suggest that  $C_{28}$ sterane are derived from lacustrine algae. Only one group (Group 5) is lacustrine/fluviocategorised as lacustrine group. Group 5 consists of five oils from NW Java Basin and one oil from NE Java Basin (Sekarkorong oil). Oils from NWJ-3 and NWJ-5 also contain Botryococcane that is observed

the chromatogram (Figure on 7, 1997). Napitupulu et al., Botryococcane is a saturated, irregular isoprenoid biomarker produced by the lacustrine. colonial Chlorophycean algae Botryococcus braunii, an organism that thrives only in fresh/brackish water lacustrine environments (Peters et al., 2004). Botryococcane is also an age-related biomarker, indicating oil from Cenozoic (Peters et al., 2004). In the NE Java Basin, Botryococcane is not detected.

The gas chromatograph from NWJ oil from NW Java Basin (Figure 7) shows high concentration of  $nC_{21+}$  and peaks in  $nC_{29}$ ,  $nC_{31}$ ,  $nC_{33}$  alkanes. Group 5 also has relatively low sulphur, low oleanane/hopane, while the Pr/Pr ratios are varied from low to high indicating input from terrestrial organic matter in the fluvio-lacustrine settings (Table 4).

## **Deltaic-sourced Groups**

Group 1, 2, and 6 are crude oils from deltaic source rocks that typically have slight dominance of  $C_{29}$  over  $C_{28}$  and  $C_{27}$  steranes (Noble et al., 1991). Group 1



*Figure* 8. Partial m/z 217 fragmentogram from crude oil retrieved from NWJ-1 (Napitupulu, et al., 1997).



**Figure 9**. The distribution of n-alkanes and isoprenoids from KE-9 oil, NE Java (Satyana and Purwaningsih, 2003). Pristane (Pr) > phytane (Ph) indicate an oxic condition in the fluvio-deltaic environment (e.g., Peters et al., 2004).

and 2 consists mostly of oils from NE Java Basin while Group 6 consists of oils from NW Java Basin. These groups have a predominance of  $C_{29}$  over  $C_{28}$ and  $C_{27}$  steranes. The considerable dissimilarities between three groups are from the number of  $C_{29}$  sterane and Pr/Ph ratios. Group 1 is relatively high in C<sub>29</sub> sterane, Group 2 is less C<sub>29</sub> sterane, and Group 6 has the highest value of Pr/Ph. The steranes plot (Figure 6) shows that Group 1 has more terrestrial organic matter input from higher plants compared to Group 2 and 6, while Group 6 has more marine influence than Group 1 and 2 (Figure 2) that is indicated from high  $C_{27}$  sterane (Figure 8). One oil from the eastern part of NW Java Basin (oil seepage from Semarang) is categorised as Group 6 (Figure 6).

From Group 6, the gas chromatograph from KE-9 shows a high peak of pristane compared to phytane (Figure 9; Satyana and Purwaningsih, 2003). Compared to the chromatograph in the lacustrine and fluvio-lacustrine group, the deltaic group has a lower chain of n-alkanes, from  $nC_{9^+}$  and peaks in  $nC_{14}$  to  $nC_{16}$ .

From Group 6, NWJ-1, the partial m/z 217 fragmentogram (Figure 8) shows a  $C_{27} > C_{29} > C_{28}$  steranes and high  $C_{19}$  and  $C_{20}$  tricyclic terpanes (Figure 10). Some tricyclic terpanes are terrigenous indicators (Noble, 1986) including  $C_{19}$  and  $C_{20}$  tricyclic terpanes that are derived from vascular plants (Barnes and Barnes, 1983).

#### Marine-sourced Groups

Groups 3 and 4 are crude oils from marine source rocks as they differ from lacustrine and deltaic source rocks from their high distribution of  $C_{27}$ sterane (Table 4 and 5, Figure 5) and low molecular n-alkanes distribution (Figure 11). Groups 3 and 4 are similar in terms of the abundance of  $C_{27}$ sterane and typically have sterane distribution as follows:  $C_{27} > C_{28} > C_{29}$ steranes. Group 4 differs from Group 3 in its lack of  $C_{29}$  sterane (Table 4), indicating oils from marine source rocks.



**Figure 10**. Partial m/z 217 fragmentogram from crude oil retrieved from NWJ-1 (Napitupulu, et al., 1997).

Groups 3 and 4 are dominated by crude oils from NW Java Basin, although one oil from NE Java Basin, Suci-B oil is categorised into Group 4 as it differs from other oils from NE Java Basin. Suci-B has the lowest composition of  $C_{29}$  sterane (6.70) indicating a low influence of organic matter from terrestrial higher plants (based on Huang and Meinschein, 1979), and high in  $C_{27}$  and  $C_{29}$  steranes indicating an oil from the marine source rock.

Napitupulu et al. (1997) suggests that two oils, NWJ-1 and NWJ-2 are derived from marine source rocks from their low molecular weight n-alkanes ( $nC_{11}$  to  $nC_{17}$ , Figure 11), low diasterane /sterane ratio, hopane/sterane > 2,  $C_{23}$ tricyclic terpane higher than  $C_{24}$ tetracyclic terpane,  $C_{35}/C_{34}$ homohopane ratio > 1, a high homohopane index,  $C_{29}/C_{30}$  hopane > 1 and an intermediate to high sulphur



**Figure 11**. The n-alkanes and isoprenoids distribution from NWJ oil suggesting marine source rock (Napitupulu et al., 1997).

content. This study supports that NWJ-2 is from a marine source rock yet suggests that NWJ-1 is from deltaic source rock based on its sterane distribution (Figure 6), Pr/Ph ratio, and HCA analysis (Figure 5).

# INTERPRETATION OF SOURCE ROCK DEPOSITIONAL ENVIRONMENT BASED ON OIL GROUPING

During early rifting, the early synrift deposit of fluvio-deltaic rocks (Figure 12a) were deposited under terrestrial depositional environments. Several rock facies were deposited including an alluvial fan, braided fluvial channel, and lacustrine shales. The lacustrine shales are the main source rocks in this setting. This type of source rock generally types I oil-prone with high hydrogen index. In this study, Group 5 oils are derived from this lacustrine source rocks.

During late rifting, the depositional environment ranges from deltaic to marine settings, where the deltaic source rocks (Group 1, 2, 6) and marine source rocks (Group 3, 4) were deposited (Figure 12b). Group 1, 2, and 6 are generally from terrestrial organic matter where Group 6 is potentially high in carbonaceous and coaly material. Group 3 and 4 are oils from marine source rocks that are potentially generated from siliciclastic source rocks. During early postrift, deltaic and marine rocks are also potential source rocks (Figure 12c), especially in the NE Java Basin, however, the late postrift are generally non-source rock potential (Figure 12d).

#### RIFTING



**Figure 12**. The schematic depositional environment during rifting and post-rift where the source rocks are mainly deposited during syn-rift, both early (Group 5) and late (the remaining groups). The early post-rift sediments may also be potential source rocks mainly in NE Java Basin, while the late post-rift has no potential source rocks.

#### CONCLUSIONS

This study reveals different groups of potential source rocks in NW Java and NE Java basins based on various geochemical parameters including Pr/Ph and  $\delta^{13}$ C of saturate fraction (Figure 3). Banuwati Formation differs

from Talangakar Formation from its high  $\delta^{13}$ C of saturate. Oil extracts from Tuban Formation are relatively similar to Talangakar Formation based on its Pr/Ph and  $\delta^{13}$ C of saturate. Ngimbang and Kujung formations relatively have Pr/Ph less than 4 and  $\delta^{13}$ C of saturate less than -26‰ (Figure 3). The agglomerative-hierarchical cluster analysis using the Euclidean algorithm is utilised in this study to classify various oils NW Java and NE Java oils, where several geochemical parameters are performed such as sulfur content, Pr/Ph,  $C_{27}$ - $C_{28}$ - $C_{29}$  steranes, and oleanane/hopane. Six oil groups are determined from this analysis. Group 1, 2, and 6 are oils from deltaic source rocks, with a significant number of  $C_{29}$ sterane. These groups differ from each other in their  $C_{29}$ sterane concentration, where Group 1 has the highest C<sub>29</sub> steranes, followed by Group 2 and Group 6. Group 5 is oil from and/or fluvio-lacustrine lacustrine source rock where  $C_{28}$  steranes are more dominant than  $C_{27}$  and  $C_{29}$ steranes. Some crude oils from NW Java in this group (NWJ-3 and NWJ-5) also contain Botryococcane (Napitupulu et al., 1997), an isoprenoid biomarker formed from precursors in Botryococcus braunii that only live in fresh/brackish water lacustrine environment (Peters et al., 2004). Finally, Group 3 and 4 are oils from marine source rocks where they are dominated by oils from NW Java oils, and only one oil from NE Java (Suci-B) that has very low  $C_{29}$  steranes and high  $C_{27}$  steranes.

The schematic depositional environment of source rocks is also described in this study (Figure 10). Group 5 is deposited under a nonlacustrine marine early svnrift environment, while the remaining groups are deposited in the deltaic (Group 1, 2, and 6) and marine settings (Group 3 and 4). The main differences between those groups are including the distributions of C<sub>27</sub>-C<sub>28</sub>-C<sub>29</sub> steranes.

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