Source rocks study and thermal modelling in Salawati basin, West Papua

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Abstract. Hydrocarbon in Salawati Basin is generated from Tertiary and Pre-Tertiary source rock. Several source rocks studies have been conducted, such as in Sirga, Kais and Klasafet Formation. Lack of knowledge in characteristics and thermal modelling source rock in Sirga and Pre-Faumai Formation, also curiosity to observe basin reverse polarity occurrence is intriguing to be researched further. The purposes of this research are to know: a.) Sirga and Pre-Faumai Formation source rock characteristics to generate hydrocarbon in Salawati Basin; b.) Maturity values based on %Ro, Tmax and 1D basin modelling. Research methodology was carried out using petroleum geochemistry analysis, including: TOC, Rock Eval Pyrolysis, kerogen typing, vitrinite reflectance from 9 cutting samples. Based on TOC parameter, organic-rich materials in both formations show good to very good quantity. On the other hand, PY parameter shows fair to good potency quality as source rock to generate hydrocarbon. Kerogen type composition dominated NFA which indicates oxidizing marine or lacustrine depositional environment. Sirga and Pre-Faumai Formation show low level maturity based on %Ro and Tmax. On the contrary, based on 1D basin modelling maturity of the source rock on Warir-1X well and WIR-1A (outside research area) show higher level maturity (early to mid-mature) since Middle Pliocene and progressed into late maturity stage on oil generation since Early Pleistocene. Basin polarity reversal occurred since Pliocene and changed basin configuration i.e. depocenter from southern area becoming on northern area. Sirga and the Pre-Faumai Formation are believed to be the two formations as hydrocarbon generating source rocks in the Salawati Basin based on geochemical characteristics analysis. Maturity based on % Ro shows the level of immature to peak mature.

1. Introduction
Salawati Basin is Tertiary basin that has 0.5 BBO oil reserves and 0.1 TCFG gas reserves (Figure 1). Hydrocarbon in Salawati Basin is generated from Tertiary and Pre-Tertiary source rocks. Several source rocks have been studied, such as in Klasaman, Kais and Klasafet Formation, but there are still a little who conduct research on the Sirga and Pre-Faumai Formations as hydrocarbon generating source rocks.

Until now, the one, which was classified as oil source rock in Salawati Basin is Klasafet Formation’s mudstone, and was deposited in inner neritic environment in Middle Miocene age. Another part was
from Kais Formation’s Limestone, particularly the one, which contains coal in limestone, presumably a source rock of Early Miocene age [1].

One of the last studies, signs of oil and gas were also found in Late Oligocene Sirga Formation’s sandstone in SF-1X exploration well drilled in 2007. Besides, oil in Pre-Kais’ sandstone was also found in SAR-1x well (2008), this become new evidence to support Sirga Formation as alternative source rock in Salawati Basin to generate oil which is trapped in Sirga Formation’s sandstone and Lower Kais Formation’s limestone (intra-kais) [1].

![Image of Oil and Gas Fields of Indonesia]

**Figure 1.** Salawati Basin location, which is encountered 61 findings [2].

Lack of knowledge on Sirga and Pre-Faumai Formation characteristic and thermal modelling data, as well as curiosity on observing basin reverse polarity based on hydrocarbon geochemistry data, is an intriguing object to be researched further. Analyzed samples obtained from several wells, which has not or lack of analysis data, furthermore, will add knowledge in new petroleum system in exploration activities in west Papua region.

The purposes of this research are to know: a.) Sirga and Pre-Faumai Formation source rock characteristics to generate hydrocarbon in Salawati Basin; b.) Maturity values based on %Rc, T_max and 1D basin modelling.

1.1. Stratigraphy

The following in Figure 2 is the Salawati Basin stratigraphy and formations discussed only related to research study:

Waripi Formation (Paleocene; 66.5-54 Ma), was particularly composed by Dolomitic Carbonate and Quartz Sandstone. The formation was deposited in Paleocene-Eocene shallow marine. Above this formation, deposited conformably Faumai Formation. Composed of thick-bedded limestone (15 meter), and is high abundant of foraminifera fossil, silty limestone, and bedded quartz sandstone with thickness up to 5 meters. Formation thickness approximately 500 meters.
Figure 2. Salawati Basin stratigraphy, West Papua and geochemistry analysis target [3].

Sirga Formation (Oligocene; 36-25.2 Ma) was deposited conformably above Faumai Formation. This formation was affected by regression phase in Middle Oligocene, which resulted large terrain formation. Transgression occurred in Late Oligocene has role in sedimentary rock depositional process, in form of: sandstone, siltstone, calcareous shale, as well as a few of limestone from Kemum High in the north.

1.2. Structural geology

According to Satyana, Salawati Basin is fore-arc basin, and it was located in front of Australia continent fragment, where on the north bounded by Left-lateral Sorong Fault [2]. Sorong Fault is strongly regarded as control geology of Salawati Basin since Mio-Pliocene, including:

- Southward basin sedimentation path reverses polarity since Paleozoic until Late Miocene, turned to northward since Mio-Pliocene.
- Klasaman Formation sedimentation in Pliocene.
- Generation and migration of hydrocarbon.

Sorong Fault bounded Salawati Basin on the north and west, furthermore Sorong Fault strongly affected the petroleum system and geology of Salawati Basin, from Miocene to Pliocene. Sorong Fault turned basin polarity from Southward basin sedimentation before Pliocene, turned to northward sedimentation (Figure 3). Basin subsidence on the north provided petroleum generation from main source rock, which is Miocene carbonate and shale (Kais-Klasafet Formation).

Basin depocenter is where sedimentation occurred, on the other hand basin platform is sedimentary provenance. In petroleum system, depocenter commonly act as mature kitchen where is hydrocarbon generated. Furthermore, hydrocarbon migrates toward up dip from depocenter to platform.

Schematic sections show Salawati Basin evolution on the west and east. The important pattern shows basin has depocenter on the southern part during Paleozoic to Late Miocene, showed by southward thickening on all Late Miocene to older layers. In Early Pliocene, Sorong Fault started to control the basin, depocenter direction started turn to north. In Plio-Pleistocene, basin has similar configuration like at the present with depocenter configuration on the north and became active ‘kitchen’. Oil has been produced from ‘kitchen’ since Middle Pliocene and migrated to Southward up dip, filled faulted-reefs and carbonates in Kais Formation. On eastern part of basin, slight differences on the evolution since
Late Pliocene. On the northeastern of basin, uplifted by Sorong tectonics. On the other hand, western part of it, encountered the subsidence.

Figure 3. West and East Salawati Basin evolutions. Changed on basin path occurred on the west, east, and middle of basin which encountered subsidence’s as a respond of uplifting on the North and South during Miocene-Early Pliocene [2].

2. Research methodology
Research method is by using petroleum geochemistry analysis, and it was done analysis including: TOC (Total Organic Carbon), REP (Rock EvalPyrolisis), kerogen typing, vitrinite reflectance (%R_o) from 9 cutting source rock samples obtained from 3 wells, which are: AM-01, AM-02andAM-03.

Petroleum geochemistry analysis is done to evaluate potency or to know characteristics and source rock maturity, among them are: (1) to determine quality level stated in TOC (total organic carbon); (2) which continues to determine the level of quantity, such as kerogen typing, rock-evilpyrolisis, composed of: S_1 (free hydrocarbon), S_2 (pyrolisable hydrocarbon), PY (Potential Yield) or THGP = S_1 + S_2, PI (Production Index) = S_1/(S_1 + S_2), HI (hydrogen index), OI (oxygen index)

Maturity from: T_{max}dan R_o

The study was conducted in the Salawati Basin. Data that has been used belong to Pertamina EP asset V (Salawati area), it covers: 1.) primary data, in the form of cuttings samples of Sirga and Pre-Faumai formations (Pre-Tertiary?). 2.) Secondary data, in the form of well and geochemical reports.

3. Result and discussions
Laboratory observation result on analysed sample showed in the following table:
3.1. Source rock quality and quantity

Sirga and Pre-Faumai Formation have 3 wells that show the values:

- TOC on Sirga Formation ranges from 0.26% to 2.79%, and shows poor to excellent potency quality. Where as in Pre-Faumai Formation TOC ranges approximately from 1.33%-2.04% that dominantly show good potency as source rock in generating hydrocarbon.
- PY parameter or THGP on Sirga Formation is about 0.27 mg/g rock -11.03 mg/g rock, and show poor to excellent potency. Where a son Pre-Faumai Formation the PY or THGP is about 0.96 mg/g rock -10.66 mg/g rock, and shows fair to good potency quantity as source rock in generation hydrocarbon.

3.2. Source rock maturity

3.2.1. $T_{\text{max}}$ pyrolysis parameter: Based on $T_{\text{max}}$ maturity, it was known that HI against $T_{\text{max}}$ plot in Sirga Formation shows value of approximately range 413°C-452°C. It indicates that most of the samples are immature to peak mature ($T_{\text{max}}$ 435°C-445°C) conditions.

### Table 1. Result of Rock Eval Pyrolysis (REP) and VR (%Rv) Analysis from Laboratory Observation.

| Well      | Sample Depth | Lithology | TOC (wt.%) | mg/g rock | $T_{\text{max}}$ (°C) | Potential Yield (S+S2) | HI | VR (%Rv) |
|-----------|--------------|-----------|------------|-----------|------------------------|-------------------------|----|----------|
| Formasi Sirga |              |           |            | S1        | S2         |                        |    |          |
| AM-01  | 1564 - 1566 m | White to medium grey calc-Sls-Sls | 0.26 | 0.06 | 0.21 | 0.24 | 419 | 0.27 | 81 | 92 | 0.42 |
| AM-01  | 1576 - 1578 m | Grayish brown to dark grey Sls – Clyst | 0.27 | 0.05 | 0.26 | 0.25 | 413 | 0.31 | 96 | 93 | 0.45 |
| AM-02  | 1386 - 1388 m | dkgv, frm, cal, Clyst | 0.97 | 0.11 | 1.12 | 0.46 | 449 | 1.23 | 169 | 47 | 0.56 |
| AM-02  | 1400 - 1402 m | dkgv, frm, cal, Clyst | 1.48 | 0.31 | 3.68 | 0.36 | 452 | 3.99 | 182 | 24 | 0.58 |
| AM-02  | 1416 - 1418 m | dkgv, frm, coally, cal, Clyst | 2.79 | 0.67 | 10.36 | 0.45 | 445 | 11.03 | 180 | 16 | 0.60 |
| AM-03  | 12177 feet   | dkgv, frm, cal, Clyst | 1.53 | 0.40 | 6.97 | 0.45 | 448 | 7.37 | 302 | 35 | 0.64 |
| AM-03  | 12380 feet   | dkgv, frm, cal, Clyst | 1.68 | 0.61 | 5.82 | 0.36 | 452 | 6.43 | 298 | 24 | 0.66 |
| Pre-Faumai |            |           |            |           |           |                        |    |          |
| AM-01  | 2022 - 2024 m | dkgv, frm, non cal, Clyst | 1.49 | 0.03 | 0.61 | 0.51 | 447 | 1.12 | 218 | 34 | 0.63 |
| AM-01  | 2024 - 2026 m | dkgv, frm, non cal, Clyst | 1.33 | 0.05 | 0.53 | 0.43 | 445 | 0.96 | 204 | 32 | 0.64 |
| AM-03  | 13460 feet   | dkgv, frm, cal, Clyst | 1.97 | 0.54 | 9.95 | 0.32 | 456 | 10.49 | 314 | 25 | 0.63 |
| AM-03  | 13585 feet   | dkgv, frm, coally, cal, Clyst | 2.04 | 0.54 | 10.12 | 0.42 | 459 | 10.66 | 324 | 25 | 0.69 |

3.2. Source rock maturity

3.2.1. $T_{\text{max}}$ pyrolysis parameter: Based on $T_{\text{max}}$ maturity, it was known that HI against $T_{\text{max}}$ plot in Sirga Formation shows value of approximately range 413°C-452°C. It indicates that most of the samples are immature to peak mature ($T_{\text{max}}$ 435°C-445°C) conditions.

### Table 2. Kerogen composition analysis.

| Well      | Sample Depth | Amorphinite (Type I-III/IV) | Exinite (Type I/II) | OPK (%) | Vitrinite Type III (%) | Semi Fusinite Type IV (%) | Inertinite Type IV (%) |
|-----------|--------------|------------------------------|---------------------|---------|------------------------|--------------------------|------------------------|
| Formasi Sirga |              | NFA (%) | F.A (%) | A (%) | C (%) | S (%) | R (%) | SB (%) | L (%) |         |         |         |
| AM-01  | 1564 - 1566 m | 70 | 20 | 10 |         |         |         |         |         |         |
| AM-01  | 1576 - 1578 m | 75 | 2 | 13 |         |         |         |         |         |         |
| AM-02  | 1386 - 1388 m | 87.5 | 1 | 7 | 9 | 7 |         |         |         |         |
| AM-02  | 1400 - 1402 m | 89.2 | 1 | 5 | 2 | 1 |         |         |         |         |
| AM-02  | 1416 - 1418 m | 83.5 | 5 | 5 | 5 | 5 |         |         |         |         |
| AM-03  | 12177 feet   | 89 | 1 | 8 |         |         |         |         |         |         |
| AM-03  | 12380 feet   | 88.5 | 1 | 10 |         |         |         |         |         |         |
| Pre-Faumai Formation |              |         |         |         |         |         |         |         |         |         |
| AM-01  | 2022 - 2024 m | 65.5 | 0.5 | 20 | 8 | 3.5 |         |         |         |         |
| AM-01  | 2024 - 2026 m | 74 | 1 | 20 |         |         |         |         |         |         |
| AM-03  | 13460 feet   | 93.5 | 1 | 5 |         |         |         |         |         |         |
| AM-03  | 13585 feet   | 92 | 8 |         |         |         |         |         |         |         |

information: NFA = non-fluorescent amorphous, F.A = fluorescing amorphous, A = alginite, S = sporinite, R = rounded C = cutinite

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3.2.2. *Parameter pirolisis* $T_{\text{max}}$: All samples of maturity levels in Pre-Faumai Formation show values approximately 445°-459°C, and it indicates peak mature on maturity level ($T_{\text{max}}$ 445°-450°C).

3.2.3. Vitrinite reflectance or $\%R_o$ Parameter: Maturity data is based on microscope observation, and the result of vitrinite analyses in 3 wells show values of $\%R_o$ as follows (Table 3):

- In Sirga Formation are about 0.39% - 0.66%, and it suggests immature to early mature maturity level ($\%R_o$ 0.20% - 0.60%),
- Pre-Faumai Formation is about $\%R_o$ 0.50% - 0.69%, and it suggests as maturity level is *early mature* ($\%R_o$ 0.60% - 0.65%).

3.2.4. Kerogen type: Visual description is carried out by counting maceral presence quantity contained in sample, afterward plotted on ternary diagram. The result was showed on the following figure (Figure 4):

- Sirga Formation is dominated by NFA 70%-92.5%; another composition is vitrinite (type III) and inertinite (type IV) 5% - 30%; and OPK (oil prone kerogen) 0.5%-2.5%, as well as exinite 1%-6% which show kerogen dominantly NFA (type III). The formation was deposited in oxidizing marine or lacustrine environment, and if kerogen has reached maturity, the tendency is to produce gas (gas prone).

### Table 3. Vitrinite reflectance ($VR/R_o$) observations result.

| Well         | Samples Depth | Plug Type | Mean $R_o$ (%) |
|--------------|---------------|-----------|----------------|
| FormasiSirga |               |           |                |
| AM-01        | 1366 - 2022 m | C         | 0.39           |
| AM-01        | 1958 - 2022 m | C         | 0.46           |
| AM-02        | 1386 - 1388 m | C         | 0.56           |
| AM-02        | 1400 - 1402 m | C         | 0.58           |
| AM-02        | 1416 - 1418 m | C         | 0.60           |
| AM-03        | 12177 feet    | C         | 0.64           |
| AM-03        | 12380 feet    | C         | 0.66           |
| Pre-Faumai Formation | | | |
| AM-01        | 2022 - 2060 m | C         | 0.50           |
| AM-01        | 2022 - 2024 m | C         | 0.63           |
| AM-01        | 2024 - 2026 m | C         | 0.64           |
| AM-03        | 13460 feet    | C         | 0.63           |
| AM-03        | 13585 feet    | C         | 0.69           |

*Information: sample type: cuttings (C)*

![Figure 4. Ternary diagram plot based on vitrinite, inertinite, liptinite and NFA.](image-url)
Pre-Faumai Formation dominated by NFA 65.5%–94.5%; another composition is vitrinite (type III) and inertinite (type IV) 5%–38%; and OPK (oil prone kerogen) 0.5%–1.5%, as well as exinite 1%–2% show kerogen dominantly NFA (type III). The formation was deposited in oxidizing marine or lacustrine, and if the kerogen has reached maturity, the tendency is to produce gas (gas prone).

Based on result of REP, according to Peter and Cassa, there is a relation between kerogen type and hydrogen index (HI) value [5]. Kerogen type from Sirga Formation cutting samples, based on HI values approximately, range between 81–302, furthermore included into type III, although mostly are type II/II_I mixture. Kerogen type from Pre-Faumai cutting samples based on HI values is about 204–314, thus it is a mixture of type II/III.

3.3. Thermal modelling
Thermal modelling is history-development modelling in the past in a sedimentary basin as a result of upward heat flow from base of basin and rock thermal conductivity from each layer.

Thermal maturity data based on 1D basin modelling on Warir-1X well at ± 12.600 feet depth in Sele Strait and WIR-1A at ± 15.800 feet in northern Salawati show source rock maturity evolution occurrence in Lower Klasaman Formation, Klasafet, and Kais. Those formations are Late Miocene-Pliocene; however, they show higher thermal maturity, which is early to mid-mature maturity levels in Middle Pliocene, and late maturity level on oil generation that have reached since Early Pleistocene. In northern Salawati, all events occurred slower, Kais and Klasafet Formation’s source rocks formed wet gas generation since Late Pliocene, and formed dry gas in depocenter kitchen [6].

3.4. Discussions
As a result of Geochemistry analysis study, it is believed that oil and gas forming have occurred in Salawati Basin. Result of this research, mainly focused on Sirga and the Pre-Faumai Formation, suggest that the two formations are hydrocarbon generating source rocks in the Salawati Basin. Organic-rich materials data in Sirga Formation is about 1.48%–2.79%, on the other hand, Pre-Faumai Formation ranges from 1.33% to 2.04%. It as indicates good-very good TOC quantity as hydrocarbon producer source rock.

Sirga Formation PY data shows poor to excellent potency quality. On the other hand, Pre-Faumai shows fair to good potency quality that indicates most of the samples are highly potential to generate hydrocarbon (generation hydrocarbon source potential). Based on Sirga Formation and Pre-Faumai quantity and quality, both source rocks are believed to have ‘potential’ as hydrocarbon producer rocks.

Both source rock characteristic data show differences from those on AM-01 well geochemistry report showing low TOC and PY values [4]. High TOC and PY values on analysed wells probably affected coal presences and its color is dark grey on samples.

Thermal maturity determination as observed in those 3 wells based on %R_o parameter, in Sirga Formation has maturity level between immature to early mature. On the other hand, Pre-Faumai Formation has early mature maturity level. Based on T_max parameter, Sirga Formation shows immature to peak mature conditions. On the other hand, Pre-Faumai Formation shows peak mature maturity level.

Thermal maturity data was obtained from 1D basin modelling on Warir-1X and WIR-1A wells located outside research area. Both wells are the deepest at research area of about 12.600 feet depth (Warir-1X well) and 15.800 feet (WIR-1A well). Thermal modeling show maturity evolution in Lower Klasaman, Klasafet, and Kais Formation’s source rocks that have reached early to mid-mature and occurred in Middle Pliocene [2].
In AM-01 well is generating of hydrocarbons (temperature 90° - 95° C) is estimated to occur in the oldest formation. Estimated of critical moment occurs at 9.8 Ma (Late Miocene) in the depth of 1960 meters. Early mature were reached by the Pre-Faumai Formation which occurred during the Late Miocene (2.9 Ma) at a depth of 1880 meters (Figure 5). At present-day, the Pre-Faumai Formation is in the early mature, which has a value of VR of 0.55% - 0.60% R₀, whereas in younger formations, it can be categorized as immature (value of VR ≤ 0.55% R₀). Maturity in this well shows immature.

It assured the occurrence of basin reverse polarities, showed by Sirga Formation and Pre-Faumai Formation, which are has older age (Palocene-Oligocene), although it shows low maturity. On the other hand, Lower Klasaman Formation, Klasafet Formation, and Kais Formation, having younger age, but they show higher maturity levels. It shows that Salawati Basin has reached thermal maturity, particularly on younger age formation (Late Miocene-Pliocene). Basin reverse polarity occurrence from Southward basin orientation before Pliocene, changed to northward and acted as basin depocenter also effected thermal maturity enhancement on source rock in Salawati Basin. In depocenter Petroleum system, it is common to become as mature kitchen where hydrocarbon is produced. Besides, the lowering on northern part of the basin, became petroleum generation trigger from Miocene source rock in Kais–Klasafet–Lower Klasaman Formation [2].

Based on Satyana data (Warir-1X and WIR-1A wells) it is believed that there has been a basin reversal polarity, but according to the results of thermal modeling studies it doesn’t indicate this. It may be necessary to study some thermal modeling to convince the opinion of reversal of depositional polarity.

Kerogen type samples from 3 wells have been analysed on Sirga Formation and compositions show NFA dominated 65.5%-94.5%; other compositions are vitrinite (type III) in minor abundance and inertinite (type IV), as well as liptinite, also in Pre-Faumai Formation that shows NFA compositions dominantly 65.5%-94.5%. Both formations data indicate oxidizing marine or lacustrine depositional environment kerogen.

Analyses result shows similarity with AM-01 geochemistry report [4], stated that Oligocene-Miocene samples are NFA-rich kerogen, on the other hand the Eocene samples dominated by vitrinite and inertinite. NFA-rich kerogen presence on Sirga Formation samples, consistently related to marine depositional environment. On the other hand, in Pre-Faumai Formation, vitrinite and inertinite are encountered on samples, thus reassuring input of land terrigenous material presence. Kerogen composition in Pre-Faumai shows differences between geochemical report and kerogen.
composition study based on result of AM-01 well, presumably it is because vitrinite has been changed by NFA, which originated from deeper samples.

Kerogen type data based on the result show that in 3 wells Sirga Formation was dominated by mixture of type II/III showing as marine and land (transition) environment effects.

Interpretation similarity is also due to petroleum geochemistry samples analysis from SF-1X and SAR-1X wells which identifies that the oil is categorizes wax (3.57%) with very low Sulphur containment (0.024% - 0.028%) and has heavy carbon isotope elements (-22 to -23). Result of GC-MS (m/z 191) analysis identifies oleanana presences as biomarker from Tertiary land plants. Based on geochemical analysis data above it, indicated that trapped oil in Sirga Formation derive from fluvio-deltaic depositional environment source rock [1].

4. Conclusions

- Sirga and the Pre-Faumai Formation are believed to be the two formations as hydrocarbon producing source rocks in the Salawati Basin based on geochemical characteristics analysis.
- Maturity based on %R₀ in Sirga Formation shows that maturity level is between immature to early mature. Based on T_max parameter, in Sirga Formation show immature to peak condition. On the other hand, in Pre-Faumai Formation shows maturity at peak mature level. Thermal maturity data based on 1D basin modelling on Warir-1X and WIR-1A wells, show that maturity evolution in Lower Klasaman Formation, Klasafet Formation, and Kais Formation reached higher level of early to mid-mature, and occurred in Middle Pliocene.

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