HYDROCARBON PROSPECTIVITY AND PETROLEUM SYSTEM IN WEST SUMATRA FOREARC BASIN

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ABSTRACT

West Sumatra forearc basin lies in the western part of Sumatra island extending from the north to the south. The forearc basin is considered not having potential to produce hydrocarbon due to its low geothermal gradient. However, indications of hydrocarbons were found in Bengkulu A-1X and Arwana-1 wells, which suggest that the Bengkulu forearc basin area has matured source rocks. The Paleogene syn-extensional sediments which are expected to be the main source rock are still under explored, especially those in the outer forearc region. Furthermore, in the Sibolga basin, the Paleogene sediments have not been well explored. Some wells were only drilled up dip of the Paleogene graben and did not penetrate the deeper Paleogene sediments. In addition, Sumatra's forearc region can also have unconventional play potential such as gas hydrate.

INTRODUCTION

The Sumatra island has a history as a starting point of the oil and gas industry in Indonesia and has been extensively explored and exploited until now. A comprehensive re-evaluation of existing data with new technology is needed to locate a new discovery, especially in areas that have not been well studied before, such as the forearc basin in the western part of Sumatra island. This forearc basin is currently considered less prolific compared to Sumatra back-arc basin. The forearc basins are marine depositional basins on the trench side of arcs. These basins vary in size and abundance during evolution of an arc. They overlie the accretionary prism, which may be exposed as forearc ridge within and between forearc basins. Sediments in forearc basins chiefly include turbidites with sources in the adjacent arc system, ranging up too many kilometres in thickness (Condie, 2016).

Sediments deposited in forearc basins are typically immature clastics composed of unstable clasts derived from rapid erosion of volcanic mountains or uplands of plutonic and metamorphic rocks within the arc massif. In equatorial regions, reef-carbonate associations are also commonly source sediments. Sedimentary facies of turbidites, shelf sequences, and fluvio-deltaic complexes within forearc basins are governed by the elevation of the basin thresholds, rate of sediment supply, and rate of subsidence of the substratum (Dickinson & Seely, 1979).

Generally, the forearc region is less deformed except in the subduction zone which has extremely high and intensive deformation. On the contrary, deformation in the back-arc basin is usually characterized by folding and thrusting.

Sumatra's Forearc is located in the western part of Sumatra island and extends from the north to south. In the Sunda Arc of Indonesia, forearc basins length range up to 1000 km along strike. The West Sumatra forearc basins are divided into four sub-basins: Sibolga, Nias, Mentawai and Bengkulu basins (Figure 1). The history of basin filling is strongly influenced by tectonic developments in this area. The sediments are very thick with varying lithologies which were deposited in shallow marine slopes to deep marine environments. These sediments do not only come from the eastern part of the basin but can also be transported from the western part where the

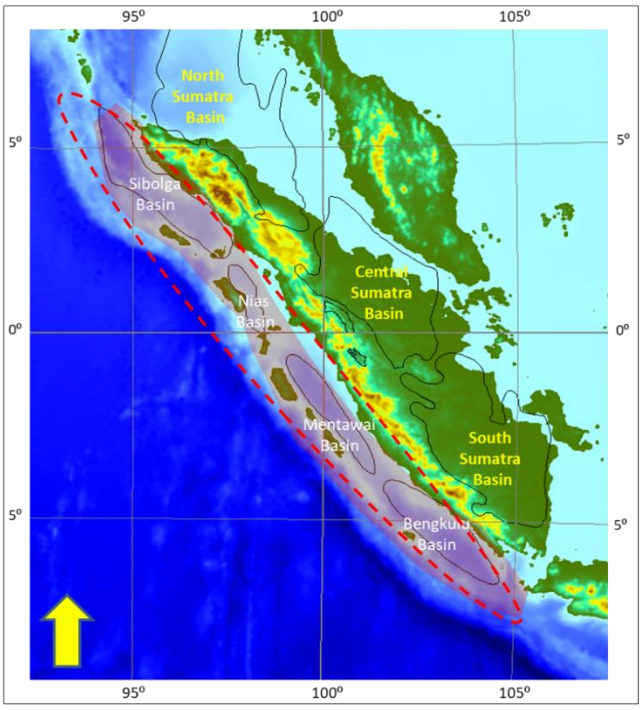


***Figure 1**. The distribution of Back arc and Forearc basin in Sumatera. Red dash ellipse indicates the area of study.*

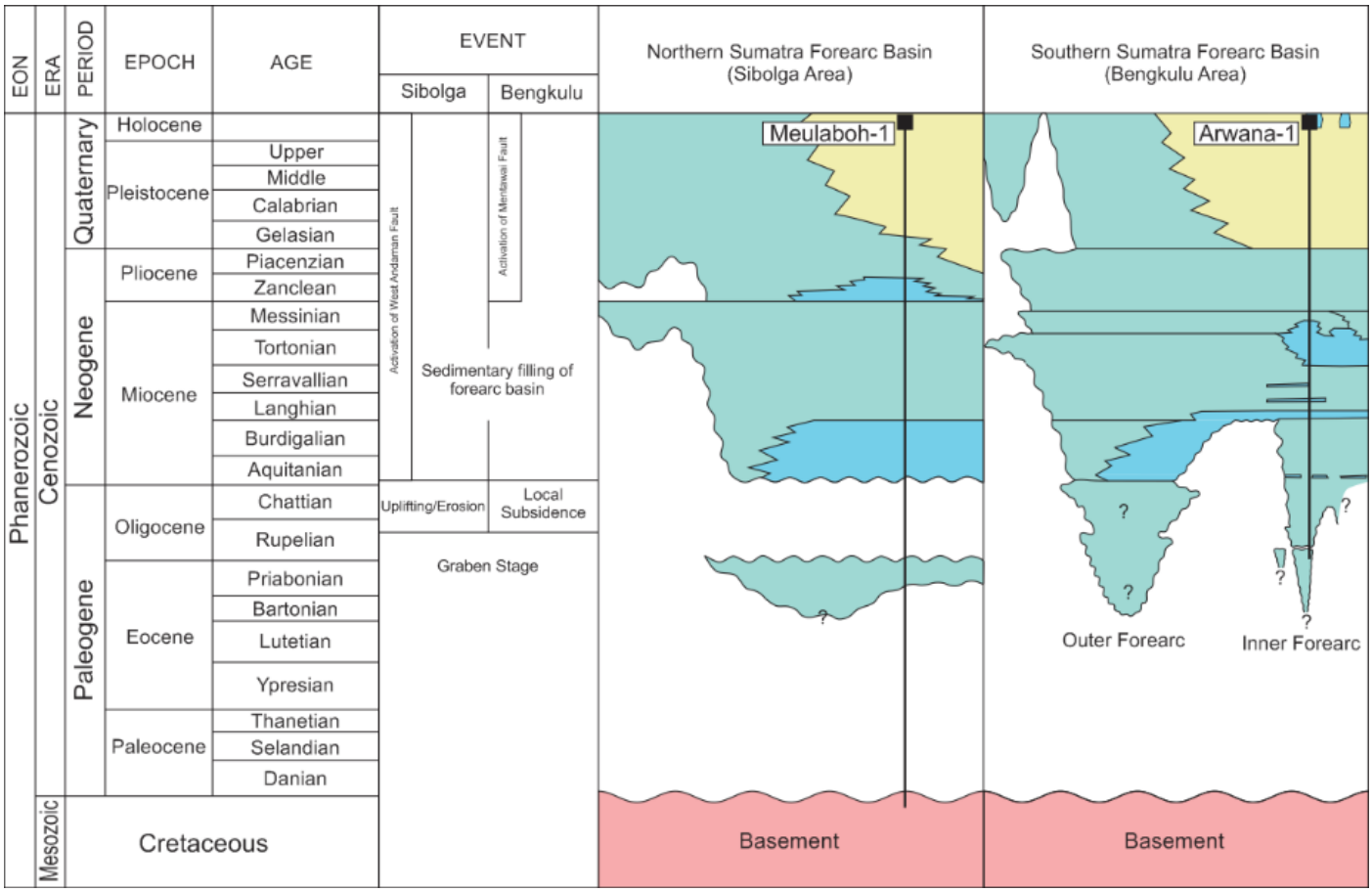


***Figure 2**. Generalized stratigraphic column in the forearc basin of Sumatera.*

accretionary prism zone lifts the deep-water sediments and delivers sediments to the east.

Forearc region is considered to have low hydrocarbon prospectivity due to its low heat flow values (~40 mW/m2). It is also considered that the forearc basin is colder than the back-arc basin. However, several wells drilled in this area show the presence of hydrocarbons.

This study delineates opportunities for petroleum systems in the forearc area and possibilities for a new play, a challenging target for future exploration.

GEOLOGICAL SETTING

Sumatra's pre-Tertiary tectonic framework consists of an amalgamation of continental and oceanic microplates. The formation of sutures in cratonic fragments occurred in the Mesozoic era and ended with the accretion of Woyla Terrain which underlies most of the West Sumatra forearc (Pulunggono and Cameron, 1984; Barber et al., 2005). Generally, the Cenozoic tectonostratigraphic framework can be divided into several phases: Firstly, the Late Eocene to Early Oligocene syn-rift phase, a regional extension forms horsts and grabens which control stratigraphic development. Sedimentation of eroded sediment from local horst occurred in isolated extensional basins. These basins extend from the Barisan Mountains (Ombilin Basin) to the current position of the forearc basin area (i.e. Bengkulu basin). In the Late Oligocene, the Barisan Mountains were still limited in height and width. Secondly, Early to Middle Miocene post-rift transgression phase. During the Early to Middle Miocene, marine transgression occurred, and the high area is more limited. Thirdly, Middle Miocene - Pliocene post rift regression. During the Middle Miocene, the uplifting of Barisan Mountains and island arc are faster than regional sagging resulting in further subsidence along back arc and forearc basin. This movement coincided with the inversion of the sedimentary basin during the Miocene (Barber et al., 2005). Fourthly, Plio-Pleistocene syn-inversion, regional uplifting and sagging in the Miocene was followed with fault reactivation, folding, and developed regional unconformities within the sediment sequences. These movements may be related to various angles and velocities of the Sumatra subduction system which lead to extension or compression in the back-arc basin region (Cameron et al., 1980).

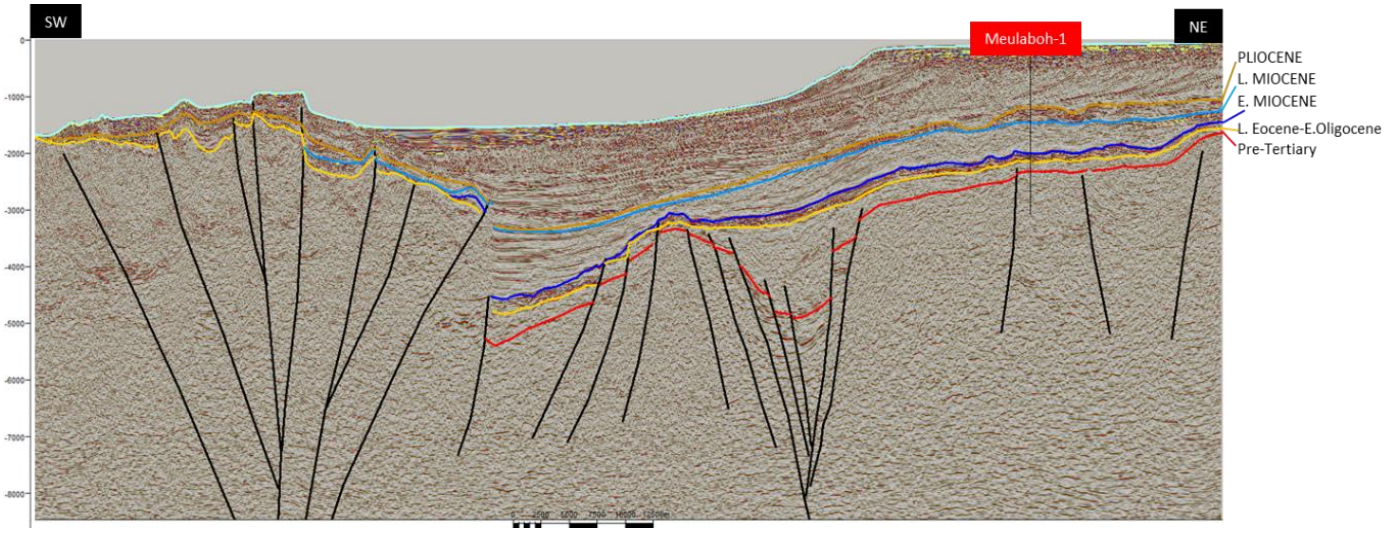


Figure 3. *Regional cross section in Sumatra forearc basin.*

General stratigraphy in West Sumatra Forearc basin consists of Pre-Tertiary and Cenozoic units. The Pre-Tertiary unit is penetrated by the Raja-1, Meulaboh-1 and Tuba-1 wells. The Pre-Tertiary unit penetrated by Raja-1 well consists of dolomitic limestone. The deep-water environment siltstones and shales that are more compact than the overlying Eocene shales are penetrated by Meulaboh-1 and Tuba-1 wells. They are considered to be an economic basement. The economic basement penetrated in Bengkulu A-1X consists of pyroclastic rock, while in Bengkulu A-2X consists of gabbro quartz (Howles, 1986). In the South Manna Basin, Hall et al. (1993) estimated the depth of the basement at 6000 m.

The Cenozoic stratigraphy of Sumatra's forearc basin is divided into two sedimentary units: the Paleogene and the Neogene. The Paleogene unit generally fills the graben and half graben, while the Neogene unit fills the forearc basin at the time of subsidence in the centre of the basin. The uplift in the western part of the basin is associated with subduction along the western boundary of Sumatra. Stratigraphic comparison of Sumatra's forearc basin can be seen in Figure 2.

Several workers that studied the Bengkulu basin in the past such as Howles (1986), Mulhadiono and Asikin (1989), Hall et al. (1993) and Yulihanto et al. (1995). show the same conclusions in which Bengkulu Basin has similar stratigraphy and depositional history with South Sumatra Basin (Sapiie et al, 2015).

RESULTS

The Neogene sediments in the forearc basin are relatively undeformed, except in the accretionary prism (Figure 3). The western part of the Sumatra's forearc basin was uplifted and thrusted striking NW-SE due to subduction. In this area the strike slip fault develops a NW-SE flower structure. The Paleogene grabens and half grabens show NW-SE, N-S, and NE-SW trends in the Bengkulu area.

Several wells that were drilled in the forearc basin show indications of hydrocarbons. Meulaboh-1 well was drilled vertically by the Union Oil Company in 1970 to reach a depth of 3,072 m. The target of this well is a reef build up limestone at 1,219 m and a possible structure below 2,743 m. Methane gas was found at 1,149 - 1,155 m intervals with maximum flow 6.7 MMCFD. The Suma-1 well was tested with gas flow about 14.5 MMCFD from the Middle Miocene limestone reservoir (Pertamina-BEICIP, 1985). Both wells were drilled in the Northern Sumatra forearc basin.

The Bengkulu A-1X well recorded the appearance of oil show with 29° API on the Middle Miocene basal limestone, while Mentawai A-1 and C-1 wells only showed indications of methane gas. All wells were plugged and abandoned being uncommercial. The Arwana-1 well showed indications of oil at Baturaja Limestone eq (?) interval and volcanic sandstones, this well was later abandoned due to poor reservoir rock potential. All wells mentioned above were drilled in Mentawai-Bengkulu basin.

PETROLEUM SYSTEMS

SOURCE ROCK

The Paleogene syn-extensional deposits are expected to become the main source rock in Sibolga and Mentawai-Bengkulu Basins. The results of geochemical analysis from Miocene to Oligocene outcrop samples in Nias Island indicated that the organic material of source rock has good quality

but poor in hydrogen content or tends is gas prone (Pertamina-BPPKA, 1997).

In Mentawai-Bengkulu Basin, the Paleogene source rock is expected from shale and clay rich organic material which are equivalent to the Talang Akar and Lahat Formations. Talang Akar Formation eq. (equivalent?) source rock which penetrated by Arwana -1 well has Ro 0.6, TOC 1 to 2%, and an HI 100 to 300 (Hall et al., 1993).

Another potential source rock potential is the Miocene organic material rich sediment, but it may not have reached maturity in Sibolga basin. In the Bengkulu Basin, the Miocene sediments of Seblat Formation (Gumai Formation eq.) have good quality TOC content 0.5 - 2.0%, The kerogen type II-III source rocks are dominant in this area. Based on heat flow generated from wells data, the Sibolga Basin has exceptionally low heat flow gradient (1.8 °C/100 m in average). Low heat flow gradient is one of the major problems in the Sibolga Basin and other forearc basins in general. In the Bengkulu basin, the heat flow gradient of Arwana-1 well about 2.8 °C/100 m (Hall et al., 1993).

RESERVOIR

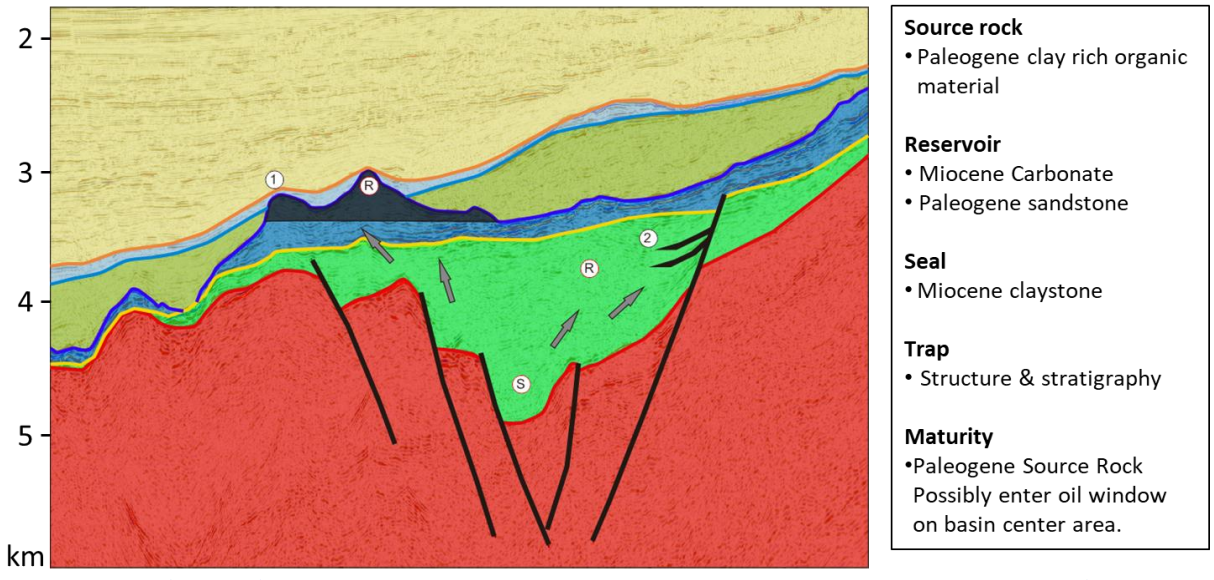
One of reservoir potentials in Sumatra forearc basin is the Miocene build up limestone. Based on Bubon-1 and Meulaboh-1 wells, the Early-Middle Miocene limestone has good reservoir quality with average porosity ranging from 14.5 to 28.2% (Pertamina internal study 2015, unpublished).

The underexplored Miocene and Pliocene clastic sediments are the next target. In addition, the clastic sediments that fill the Paleogene graben could be another reservoir target. In the inner forearc of Bengkulu (South Manna Basin), the sandstones of Talang Akar Formation eq. have average porosity between 10 to 15% (Hall et al., 1993).

In the northern area, gas accumulations were found at six locations by Union Oil drilling activities in the Sibolga basin (Rose, 1983). Five of them were found in the limestone reservoirs and one in the sandstone reservoir. The Meulaboh-1 well found methane gas in the Late Miocene-Early Pliocene limestone layer. In the Nias area, methane gas was found in the Late Miocene reef reservoir in the Keudepasi-1 and Singkel-1 wells (Rose, 1983). In the Bengkulu area, oil shows were observed in Arwana-1 at the Early Miocene limestone interval (equivalent to the Baturaja Formation) and Bengkulu A-1X at the Middle Miocene interval (N9) (previously interpreted as the equivalent of Baturaja Formation).

SEAL

The regional seal rock is widely distributed in this area. It consists of transgression sequence shales covering the limestone and sandstone deposits.



Type	Play		
	Age	Lithology	Trap
1	Early Miocene	Limestone	*Reef Build up*
2	Eocene/Oligocene	Sandstone	*Fault block*

Figure 4. *Petroleum systems play concept in Sumatra forearc basin.*

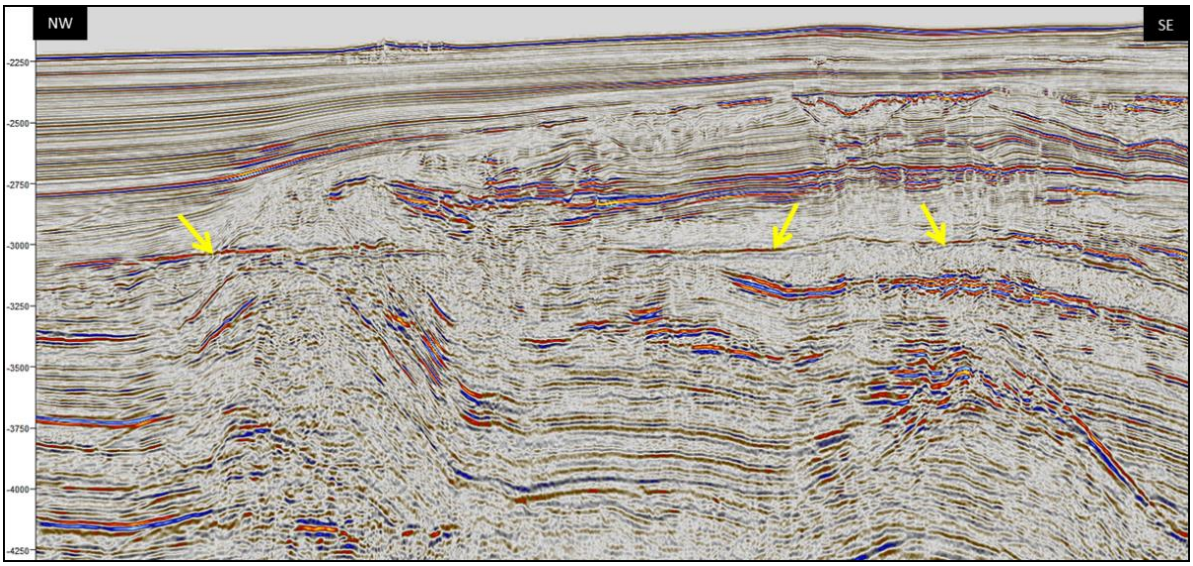


Figure 5. *The indication of BSR from seismic in Sumatra forearc basin.*

The seal rock includes possibly shales from the equivalent Baturaja, Gumai, and Muara Enim Formations. The Gumai shale will be a good seal rock for Baturaja Limestone, while Muara Enim will act as good seal rock for Parigi Formation. The intraformational shale, present in almost all formations, is also a good potential for seal rock.

TRAP

The hydrocarbon traps consist of four-way dip closure, fault bounded anticline, and tilted fault blocks. The other potential traps are stratigraphic such as carbonate build-up, facies changes (wedge-out) and onlapping sediments to the basement.

PLAY CONCEPT

The Miocene build up limestone which is distributed widely in Sumatra forearc basin is the main hydrocarbon play (Figure 4). The next hydrocarbon play is associated with the Paleogene syn-extensional systems. The Eocene-Oligocene sandstone pinch outs, erosional truncations, and fault tilted blocks are possible targets of another play. Some of these deposits were thrusted in several areas resulting in structural traps. The Miocene anticline play developed in the forearc basin is associated with the activity of the Mentawai and West Andaman faults.

DISCUSSION

Many forearc basins are considered to be less prolific hydrocarbon basins due to their low heat flow gradients. However, indications were found of hydrocarbons in Bengkulu A-1X and Arwana-1 wells. This indicates a mature source rock in the Bengkulu area. The Paleogene sediments which are expected to be the main source rock are still underexplored, especially those in the outer forearc area. Other evidence of gas indications in this area, especially biogenic gas potential, was found in Meulaboh-1. However, it has not been studied in detail in the Sibolga Basin. The deeper Paleogene sediments in the basin centre are not penetrated yet and still underexplored.

Based on the Arwana-1 well, the Oligocene source rock has reached the mature stage, while the Early Miocene source rock has reached early maturity due to low heat flow gradient. In the onshore area of Bengkulu, the Early-Late Miocene source rocks have reached early maturity to post maturity.

Structural patterns with NW-SE, N-S, NE-SW, and some E - W trends have been observed in this area. These patterns are evidence of the pull-apart basin development during Paleogene with the main strike slip fault striking NW-SE. In contrast to the Neogene where the slip partitioning occurred between the subduction zone and right - lateral

movement of Sumatran fault zone (SFZ) resulting in the oblique slip of the Mentawai fault zone trending NW-SE. This movement along laterally offset basement faults generates positive flower structures in this region.

The expected main play in Sumatra's forearc basin is the Miocene-Pliocene reefal build up limestone. Generally, most of the wells penetrated the carbonate shelf, while some of the wells in the Sibolga Basin such as Tripa-1 well penetrated more distal carbonate. This shows that the Miocene reef play is still underexplored.

Apart from conventional plays, Sumatra's forearc area still offers opportunities for unconventional plays such as gas hydrate. Gas hydrate forms when methane and water freeze at high pressures and relatively low temperatures. The Bottom Simulating Reflectors (BSR) as an indication of the gas hydrate presence is observed on seismic lines in the western part of forearc basin where heat flow gradients are expected to be lower than average heat flow in this area (Figure 5). However, further research is needed to unlock this potential.

CONCLUSION

The northern area of Sumatra forearc has a low geothermal gradient which is only 1.8°C/100 m, while the southern area has geothermal gradient about 2.8°C/100 m and it will probably lower to the west, nearer to the subduction zone.

The southern area of Sumatra forearc has hydrocarbon potential shown by oil shows on Bengkulu A-1X and Arwana-1. The source rocks at Arwana-1 well reach early maturity (Baturaja Formation equivalent) to maturity (Upper Lahat Formation equivalent). Most of the wells in the northern area show the presence of gas methane (biogenic gas), which is probably caused by immaturity of Eocene source rock. Deeper Eocene grabens can be recognized on seismic cross section and might reach early mature to mature.

The Miocene reefal limestone is the main reservoir target. This limestone is laterally distributed and has a build-up geometry, recognized on many outer forearc seismic lines. For the unconventional play, biogenic gas is shown at the Pliocene limestone of the northern forearc area, while hydrate gas is present at the southern forearc area as shown by the occurrence of BSR. The BSR and associated reflections are known as an indicator to identify gas hydrates and free-gas accumulation bearing sediments. However further studies are needed to evaluate all risk aspects of gas hydrate occurrences, using high resolution seismic reflection data.

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