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PALEOGENE CARBONATE FIRST TRAP PLAY IN THE NORTHEAST JAVA BASIN USING A SUB-BASIN APPROACH

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ABSTRACT

The hydrocarbon occurrences within the Northeast Java Basin (NEJB) indicate that the area is primarily oil-prone. The Miocene Kujung Limestone holds most of the hydrocarbon resources and appears to be overexplored, but the Paleogene interval remains underexplored in this region. The current study will look solely at the sub-basin containing undrilled Paleogene carbonate. The G&G evaluation uses the KKPJM dataset and the technique is based on a play-based exploration workflow, from basin to play focus, followed by lead and prospect identification. The identified source rocks were sequence A, sequence B, sequence C, and sequence D. Most of hydrocarbon generation is believed to be coming from sequences A and B. Most of the first traps of Paleogene carbonate play suggest that the trap is placed near to the charge access. The Paleogene carbonate build-up seismic character forms mounded structure with onlap features, located in the Ngimbang Low. These build-ups can be mapped in the Pagerungan sub-basin area. Based on the subsurface data, the Paleogene carbonate can be divided into reefal in the lower part and carbonate debris in the upper part of the sequence; the porosity average of Oligocene carbonate is about 15%. H-1 well ecountered Ngimbang Eocene carbonate, reported to have good porosity and excellent permeability with strong indication of the karstification. The carbonate reservoir is dominated by muddy limestone, with strong indication of reworked carbonate materials existance. The Paleogene carbonate play likely extends further east northeast with potential presence of many untested closures. Exploration opportunities of Paleogene carbonate in the Ngimbang Low, North Madura, and Pagerungan sub-basins remain very promising with a lot of potential drillable buildups are identified.

INTRODUCTION

The Northeast Java Basin (NEJB) encompasses the northern onshore and offshore areas of East Java, including the Bawean, Madura, and Kangean Islands (Figure 1). It is an oil-prone prolific basin. The 10.3 BBOE total discovered resources are made up of 66% oil, 33% gas, and 1% condensate. Miocene Kujung limestone in the Neogene sequence holds most hydrocarbon resources such as in the Banyu Urip field (onshore) and the region reservoirs are in limestone, and this play appears to be over-explored.

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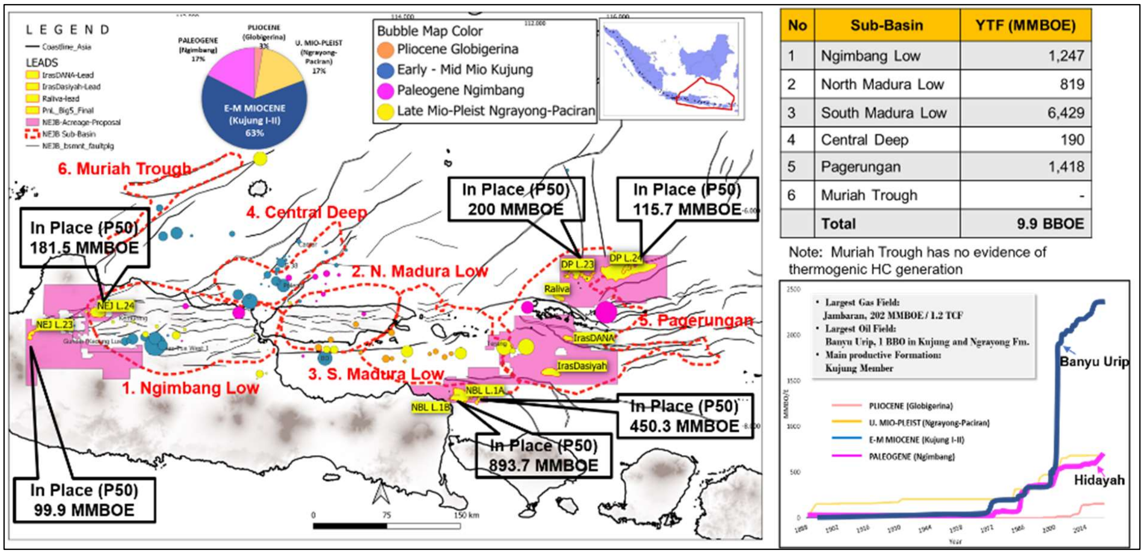


Figure 1 - Kujung carbonate in the Miocene is the most productive reservoir, accounting for up to 63% of hydrocarbon production in NEJB.

Some wells in the Paleogene sequence failed due to targets on structural not first trap play. However, H-1 (2020) in North Madura and K-1 (2022) onshore Northeast Java discovery proved that Paleogene is the new play in this area. The most recent basin modelling sub-basin approach shows that about 9.9 BBOE YTF (Yet to Find) in-place may be found in six (6) sub-basins within NEJB. Furthermore, geochemical studies reveal differences between the eastern and western regions of NEJB. The Paleogene play could still be explored despite its remaining high CO_2 challenge, primarily in the western region. The eastern sub-basins, on the other hand, offer exploration potential with lower CO_2 content. Furthermore, overpressure in the South Madura Deep exhibit challenging exploration target in the deeper section, despite its YTF in-place could be up to 6.4 BBOE (Figure 2).

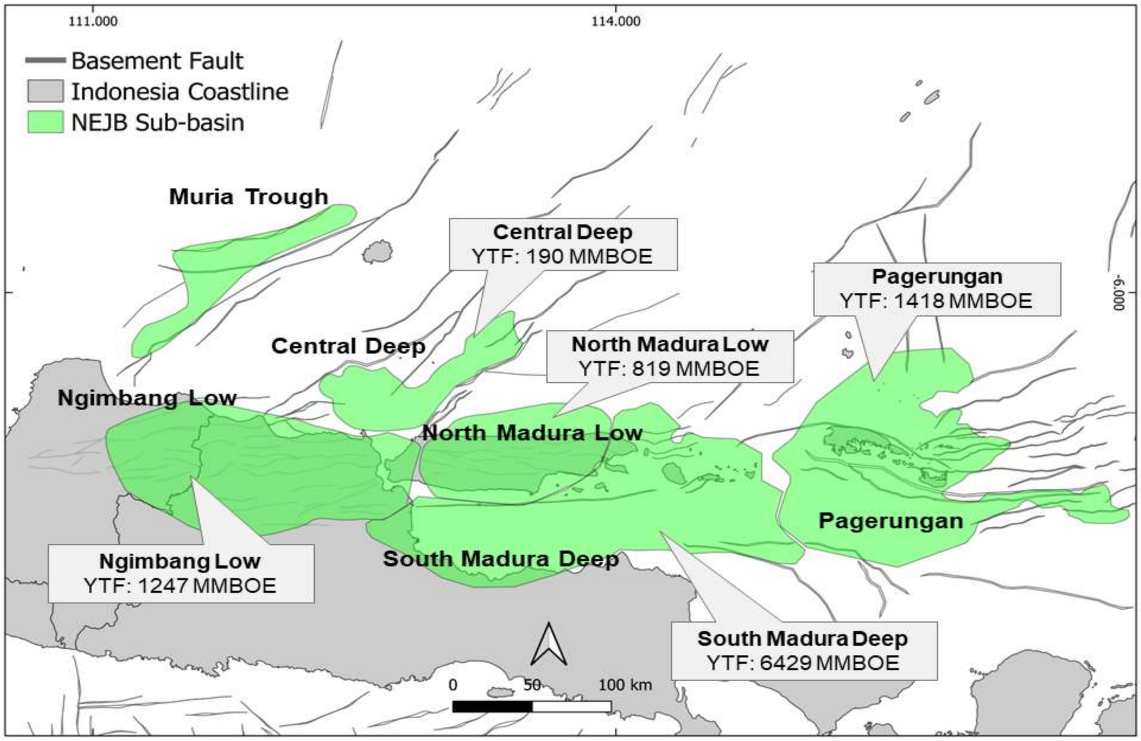


Figure 2 - Six sub-basins have been identified: Ngimbang Low, North Madura Low, Central Deep, South Madura Deep, Pagerungan, and Muria Trough. Four sub-basins with significant YTF include Ngimbang Low, North Madura, South Madura, and Pagerungan.

Regional Geology

The regional tectonic analysis of NEJB supports the collision of a micro-plate (drifted continent) with Sundaland, which occurred between the Late Cretaceous and the Middle Eocene or maybe the Late Paleocene, according to the current study. NEJB has two primary structural trends: The E-W trend and the NE-SW trend. The presence of Paleocene-Eocene pre-Ngimbang clastics in a synclinal depression on the Northern platform Pagerungan. According to the stratigraphy and age of the basin's oldest sedimentary unit, the E-W structural trend is slightly older than the NE-SW trend (Sribudiyani et al., 2003). The oldest sediment fills in the E-W trend of the EJ-1 well range in age from Paleocene to Early Eocene. So far, data suggests that this unit is exclusively seen in E-W trends. This evidence supports the theory that the E-W trend systems from the microcontinent's pre-existing structural propensity. This model opens up significant exploration opportunities in the eastern half of NEJB, specifically south of the Sakala Fault Zone (Figure 3).

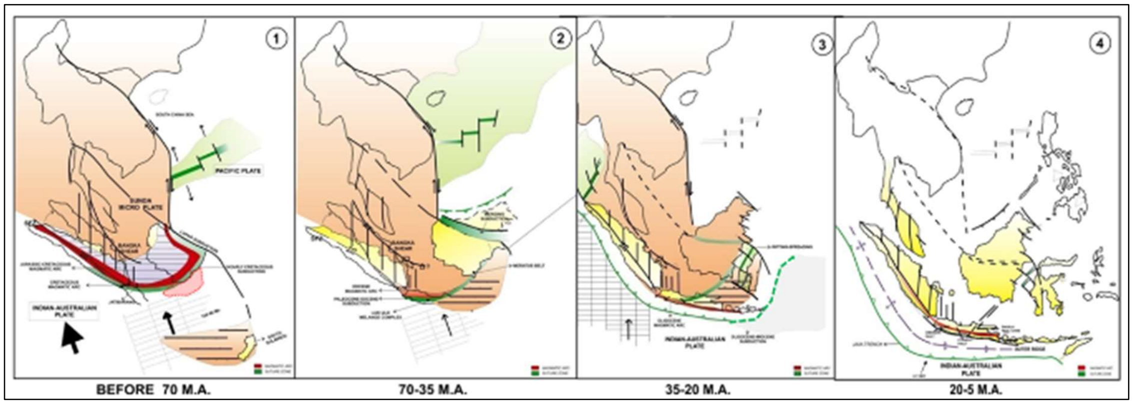


Figure 3 - The regional tectonic of NEJB supports the collision of a micro-plate (drifted continent) with Sundaland, which occurred between the Late Cretaceous and the Middle Eocene or might be Late Paleocene from the current study. East Java has two primary structural trends: E-W and NE-SW trend (Sribudiyani et al., 2003).

Stratigraphy

The study region is very broad, encompassing the North Central Java Basin, South Central Java, Kendeng Zone, Southern East Java Arc Basin, and Northeast Java Basin, which comprises various sub-basins ranging from Muria Trough in the west to Doang Platform in the east. Each of these basins has a unique stratigraphic order and naming. For the discussion, correlation, and data integration of all basins and sub-basins in the study area, a stratigraphic equivalence for the entire study area is established using biostratigraphic analysis data distinct into A sequence (Paleocene) to K sequence (Holocene). Need further elaboration on sequence A, sequence B, sequence C, and sequence D.

Figure 4 depicts a summary of general stratigraphy and its equivalence with formation names from numerous places, including the North Central Java Basin, South Central Java Basin, and Northeast Java Basin, each represented by several areas. The summary of the stratigraphic column in general shows how each basin's stratigraphy evolves, both vertically and laterally. Tertiary sedimentation in the study area began in the Paleocene in the Sepanjang area and progressed to the younger unit further west to the North Central Java Basin. Except in the Southern Central Java Basin, sedimentation usually begins with filling fine-coarse clastic sediments, typical of syn-rift deposits. During the Eocene-Oligocene, these basins had a transgression defined by the presence of limestone in various locations.

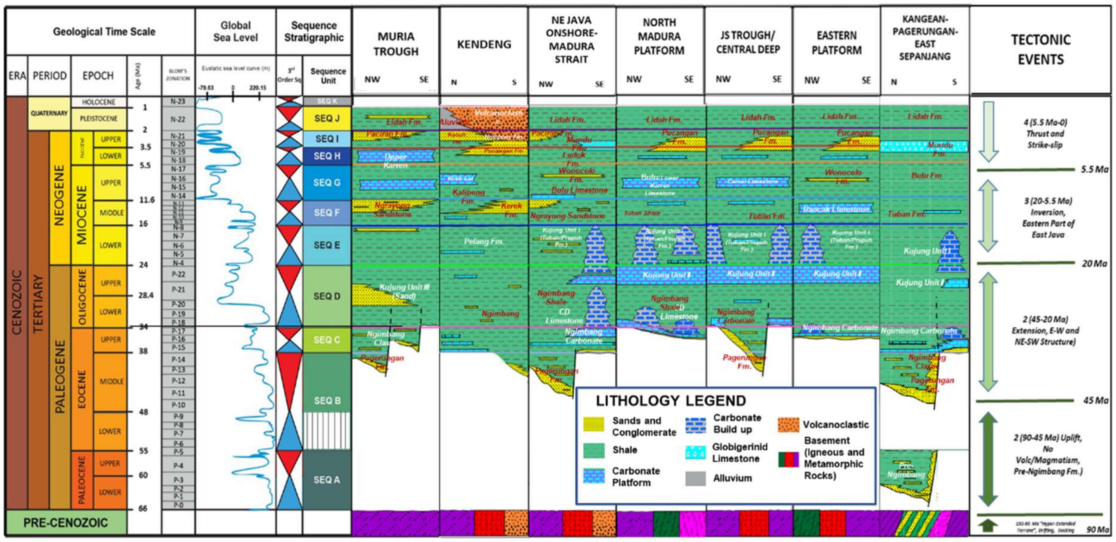


Figure 4 - Regional stratigraphic framework (source KPPJM Study, 2020).

The transgression process in general continues and reaches a climax in the Early Miocene, when limestone deposition spreads broadly throughout practically every area. Volcanism occurred concurrently with the transgression phase in the Southern Central Java Basin and the Southern East Java Basin, as evidence of Oligocene volcanic activity (Old Andesite Formation). Several areas had a regression process during the Middle Miocene, as evidenced by the existence of coarse clastic sediments deposited in a fluvial-deltaic environment to the deep sea until sea inundation resumed in the Late Miocene. The final sedimentation cycle involves the deposition of fine clastic-dominated sediments, which are associated with quaternary volcanic activity. The next sub-chapter provides a full discussion of each Basin's stratigraphy.

METHODS AND MATERIALS

To address increasingly exploration challenges, oil and gas companies have been increasingly incorporating the Play-Based Exploration (PBE) approach into their exploration activities. PBE is a multidisciplinary integrated exploration methodologies approach that relies on a thorough integration of the basin's regional geology, petroleum system, play, and exploration history. PBE is a better technique for exploring frontier basin and can help to make a more integrated geological-based decisions. The PBE technique has significantly aided the successful exploration of the world's top oil and gas firms. PBE's initial focus was on developing a fundamental understanding of regional geology and petroleum system within a basin (Basin Focus). The review of all geological and geophysical data, added with creativity and innovation are the effective steps for identifying new potential plays, even in mature basin. Basin Phase products include plate tectonics and regional geological setting, tectonostratigraphic framework, basin structural evolution and depositional history, stratigraphic sequence, and petroleum system analysis. Leads Focus is the final stage of the PBE, which includes identifying prospects and leads, volumetric and risks, and assessing Yet to Find (YTF) in-place of hydrocarbon opportunities. This assessment is conducted within the context of the petroleum system, play distribution, and exploration history, resulting in a considerably more trustworthy assessment of prospect, lead, and basin potential.

The data used in this paper was mostly from Pertamina KKPJM (Komitmen Kerja Pasti WK Jambi Merang: budget allocated by Pertamina for this studies outside Jambi Merang) project, which include seismic and well data. The seismic data consists of 4996 2D seismic lines and 16 cubes of 3D seismic, whilst well data consists of 581 final well reports, log data in LAS file format, and other supporting data. In addition to the mentioned data, secondary data are also utilized for this study. They include regional geological maps of East Java and its surroundings carried out by the Geological Survey Centre, regional gravity maps derived from satellite data, and gravity data measured in several areas conducted by PT Geoservices, as well as laboratory analysis reports (biostratigraphy, petrography, and geochemistry), some of which were obtained from PT Geoservices investigation reports.

RESULTS

Sub-Basins of Northeast Java

The tectonic history comprises rifting episodes from the Eocene to the Early Oligocene, resulted the construction of multiple half grabens, followed by a period of quiescence, local deformation, and volcanic activity. The onshore fold belt is intricate and thought to develop from oblique basement wrenching and inversion containing unstable shale phases (possibly incorporating gravity-induced growth faults). Active wrenching along east-west trends resulted the production of broad and relatively young inversion structures in the offshore area East of Madura. At least three thermogenic petroleum systems (PS) have been proven in the Northeast Java Basin, named as Ngimbang–Ngimbang PS, Ngimbang–Kujung PS, and Tertiary–Miocene PS.

The Ngimbang-Kujung PS is actively pursued in Madura and Cepu, with a focus on the Kujung and CD carbonate reservoirs. Further East, major offshore gas discoveries have been made in the late Ngimbang-Ngimbang PS, including the Kangean area offshore. This gas is most likely derived from Ngimbang fluvial-deltaic coaly shale source rocks, which have also tested oil (e.g., the JS53 well), Terang-Sirasun is the biogenic gas field in the Muria Trough and Tertiary-Pliocene system..

The basin modeling was carried out using the KKPJM study (2020) as a reference. The standard principle and workflow to construct the basin modelling were applied. The primary difference between this study and the KKPJM study resides in the fact that this study conducts modeling at the sub-basin scale, whereas the KKPJM study treated the North East Java Basin as a single basin.

The sub-basins approach enables a more in-depth assessment of potential generative hydrocarbon capacity, which then validated with the in-place volume of hydrocarbons discovered. The basic idea was that each sub-basin might have distinct characteristics from others. If a sub-basin has a richer source rock and is fully mature, it could increase charge capacity to fill the specific traps near the structural highs. For exploration purposes, the sub-basin approach could provide insight into potential remaining hydrocarbons that have most likely been generated but have yet to be discovered (Yet to Find, YTF).

The key motivation to apply the sub-basin approach is lack of understanding of the previous basin modeling to explain how and which sub-basins were responsible for the giant discoveries in Banyu Urip and Pagerungan. Although those fields are located in the same basin, in the North East Java Basin, their hydrocarbon characteristics differ significantly. As a result, those fields could have been charged from various sub-basins with different source rock organofacies.

To define the sub-basins, some assumptions were made including a mature sub-basin is defined based on maturity with a minimum Ro of 0.6% as a cut-off and the minimum cut-off of the transformation ratio (TR) is approximately 0.4 to define the corresponding sub-basin. Based on those assumptions, six (6) sub-basins were identified such as Ngimbang Low, North Madura Low, South Madura Deep, Central Deep, Pagerungan, and Muria Trough (Figure 2).

The geochemical study was used to generate hydrocarbons in basin modeling studies. The initial TOC and HI were determined and used as property inputs for basin modeling. The isopach and gross depositional environment maps were also employed in basin modeling. The remaining hydrocarbon that might remain in the sub-basin (YTF) is identified as the difference between the Hydrocarbon Accumulation (HCA) and the previously discovered resources of fields or wells along a sub-basin migrating path. The HCA is considered to be 10% of the total hydrocarbon generated (HCG) in a sub-basin. The 10% assumption has been chosen and applied to all sub-basins to account for the lost of generated volume during the primary and secondary migration, loss to the surface, and loss due to the non-commercial accumulation. However, it is understood that others may use other numbers and assumption Regardless, the accurate efficiency numbers are extremely difficult to estimate. The comparison of each basin's HCA to its discovered resource volume will generate ideas for sub-basins that may contain the undiscovered resources. The discrepancy between HCA and discovered volume is classified as Yet to Find in the corresponding sub-basins. Figure 2 displays the results, including the numbers of YTF for each sub-basin. The largest YTF is located in the South Madura Deep. The underexplored area below the overpressure zone in the South Madura Deep may provide opportinities of the remaining undiscovered resource in this sub-basin. This sub-basin is also suitable for biogenic gas exploration. The Ngimbang Low and North Madura Low are also predicted to have significant remaining YTF opportunities, they are attractive exploration targets. A new exploration target of Paelogene play identified in Pagerungan posted exploration interests of the area.

To calibrate the HCG results from each sub-basin basin modeling results, a comparison was made between drainage area and total in-place with comparable basins throughout the world. A plot of each sub-basin/drainage region vs. total in-place of the North East Java Basin, indicating that the modeling assumptions were reasonable and outcomes are comparable with the worldwide trend. The generation capacity of each sub-basin in the North East Java Basin is different from each other. This may be associated with different organofacies of the source rock, such as quality and quantity, heat flow history, maturity, transformation ratio, and others. The result and comparing it with the discovered resource volume may help in identifying potentially prospective areas for exploration.

DISCUSSIONS

The NEJB exhibits a comprehensive hydrocarbon proved play in both clastic and carbonate reservoirs that extends from the Eocene to the Plio-Pleistocene. The recent revisit the areas identifed at least 16 established plays and 13 new ones. The primary play is believed to be Miocene Kujung carbonate which dominating the hydrocarbon production to date. They contribute up to 63% of oil and gas production in the East Java area, particularly from the Ngimbang Low sub-basins (Figure 1).

This paper mainly discusses the Paleogene first trap play, recently tested by discoveries in H-1 and K-1 wells. The study revealed several Paleogene first trap potential play of the carbonate build-ups in the study areas. The first trap play is where the build-ups trap face the mature kitchen/basin and are in route of hydrocarbon migration. It also discusses carbonate types in seismic, covering reservoir features, facies, diagenesis, and risk of the first trap play.

Figure 5 shows several carbonate types of morphology versus age. The build-ups have variety properties to be used for assessing the hydrocarbon accumulation. Each of carbonate buildup from or style is described in each sub-basin, including temporal porosity development and hydrocarbon migration, both of them are important to evaluate first trap play risk.

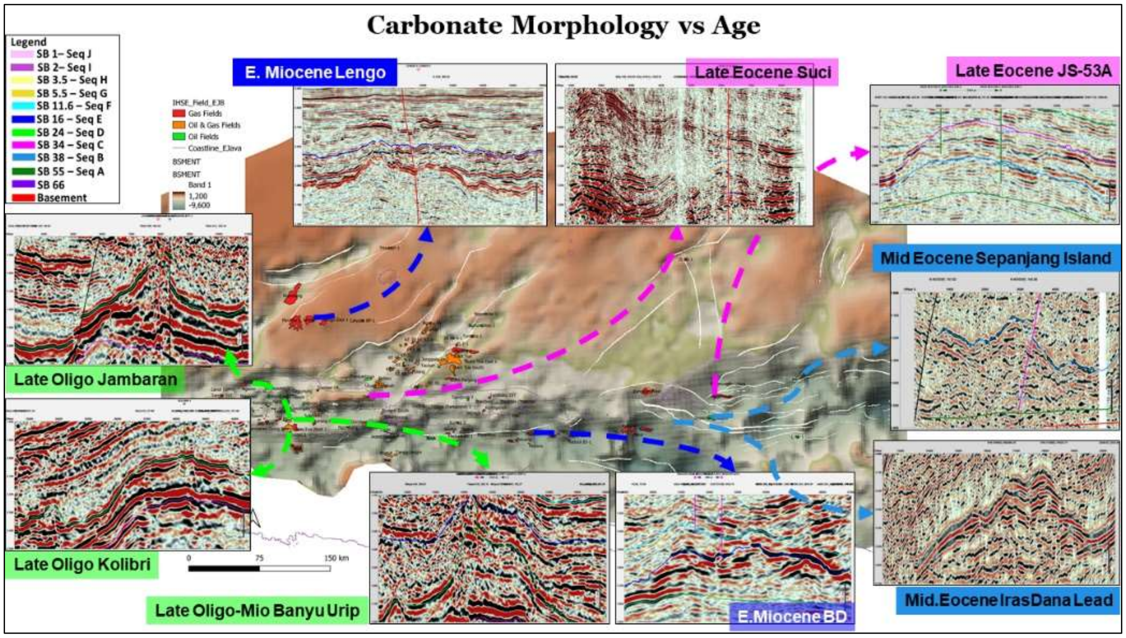


Figure 5 - The carbonate morphology versus age through time which are captured in NEJB sub-basins. Many of the build-up shows especially for the Miocene are high relief and mostly aggrade and retrograde. For the Paleogene, carbonate is mostly parallel and folded due to faulting, but different thicknesses of the build-ups are identified in Mid Eocene IrasDana and Late Oligocene Jambaran.

This study mapped at least six sub-basins, however only four will be discussed in detail as the play focus basins. The rationale for this is that these four sub-basins contain considerable amounts of yet-to-be-discovered hydrocarbon, and various first trap plays have been identified but not tested.

Paleogene Play Focus-Ngimbang Low Sub-Basin

Exploration activities have been very active in the Ngimbang Low sub-basin, The basin contributed to more than half of production form the whole greater NEJB basin. The earliest tertiary sediment in the Ngimbang Low is the Middle Eocene, formed in a syn-rift setting and served as the hydrocarbon source interval as well as reservoir zone. The post-rift is characterized by half graben-horst existance that the well-known Oligo-Miocene carbonate buildups Kujung Formation developed on highs, which serve as the primary carbonate reservoir and is sealed by the Tuban Formation shale. Based on the residual gravity map of this area, several lows and highs are well identified. GGMPlus's (Curtin Gravity Modelling) onshore residual gravity of East Java-Madura reveals various sub-basins, including Pati Low, Kening Low, and Kemandung Low, which are separated by the East-West Cepu high (Figure 6). The mature sub-basin in the southern section is the East-West Ngimbang sub-basin, which created a billion of potential hydrocarbon accumulations in the Kolibri, Banyu Urip, and Jambaran-Tiung Biru fields. Carbonate buildups dominated the high area from the Early to

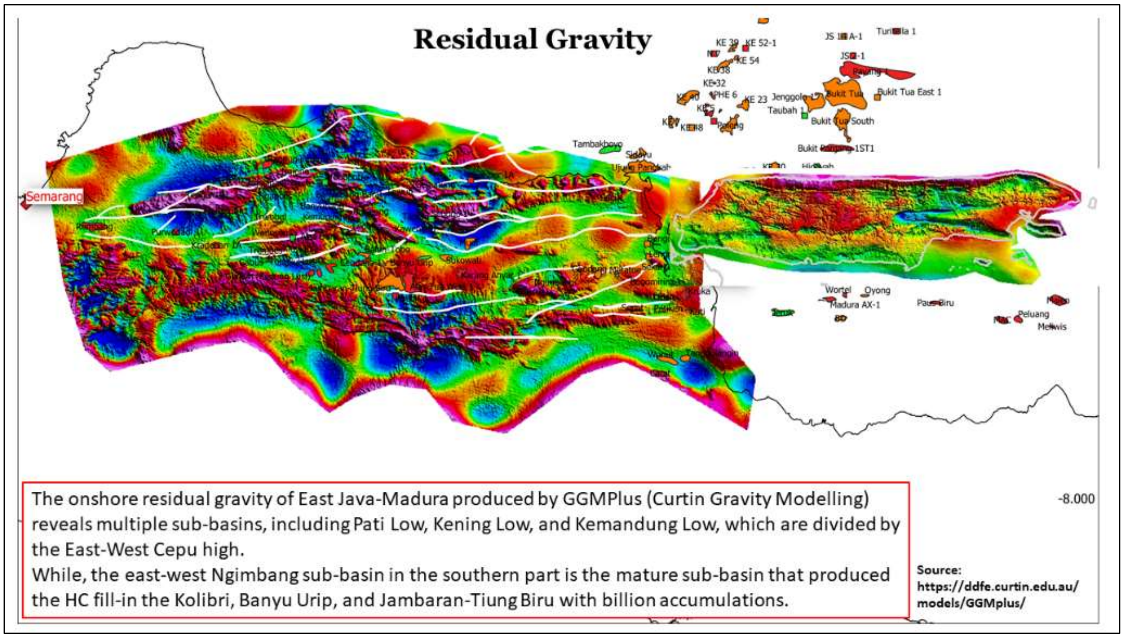
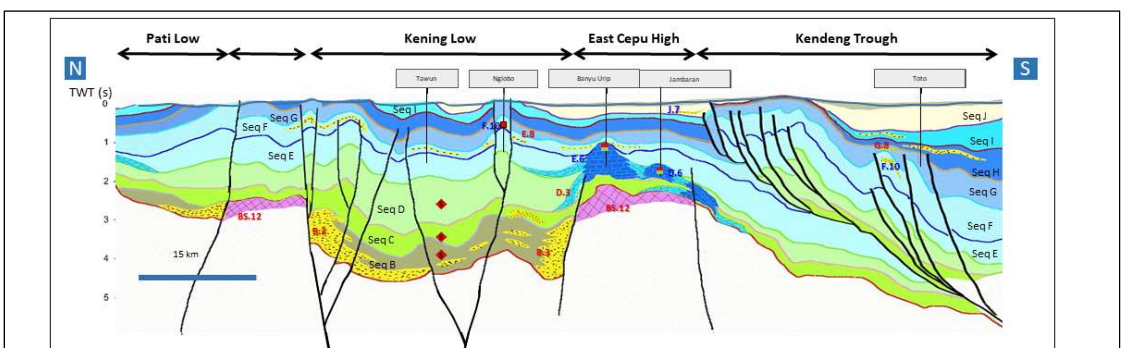


Figure 6 - The residual gravity showing localized low surrounding the high. Based on basin modelling the low acting as an active source rock charges the trap in the high area. The high area was dominated by carbonate from the early Miocene to the Late Miocene. In turn, the slope area developed older carbonate acting as the first trap facing the low area.

Late Miocene periods. In turn, the slope area formed older carbonate, which served as the first trap for the localized basins. Figure 7 depicts the play concept for the Ngimbang Low sub-basins and the Kendeng Zone. Six established plays and three new potential plays were identifed in this area. The West-East direction of Rembang Madura Kangean Sepanjang RMKS transpressional fault affected the play elements, particularly in traps style and migration pathways.



Play Classification	
Code	**Proven Play**
J.7	Up.Pliocene-Pleistocene Inner-Middle Shelf sandstone
H.8	Lo. Pliocene (Mundu) outer shelf sandstone (calcarenite)
F.10	Middle Miocene (Ngrayong) Sub Marine fan sandstone
E.6	Lower Miocene (Kujung I) Carbonate Build up
D.6	Oligocene (Kujung II) Carbonate Build up
Code	**New Play**
I.7	Up.Pliocene Inner-Middle Shelf sandstone
G.8	Upper Miocene Outer Shelf Sandstone
D.3	Oligocene (Kujung II) Fan-Deltaic sandstone (calcarenite)
B.3	Mid.Eocene (Ngimbang) Fan-Deltaic sandstone
BS.12	Basement Fracture

Figure 7 - The schematic cartoon shows the play that exists in the Ngimbang Low sub-basin. The first trap play annotated by D3 was drilled in 2023 and discovered gas, the well-named K-1. The East Cepu High is the main producing field of Banyu Urip, with Miocene carbonate build-ups capped by Ngrayong as a thief zone.

Figure 8 shows the Paleogene initial carbonate buildup trap play, which was examined by K-1 well and yielded a gas discovery. This carbonate buildup developed in the slope system. In this system, reservoir quality due to diagenesis and timing of hydrocarbon charge could pose some risks. K-1 is located in the slope area, grew at the topography high and bounded by normal fault. Carbonate succession in K-1 is dominated by carbonate build-up at the base, containing coral bioclastic packstone/wackestone, and debris carbonate facies, such as planktic foram bioclastic packstone/packstone with corals interbedded with marl (slope) in the upper part of the sequence. According to the K-1 petrophysics analysis, the average porosity for the carbonate is 14%, with carbonate to non-carbonate net to gross (N/G) ranging from 24 to 43% (Raufan et al., 2024). Based on average porosity and the presence of stylolite, this Paleogene's first trap is late charging. Carbonate dolomitization in the Ngimbang Low ranging from East to West, with the western half being more dolomitized. This could be related to the abundance of magnesium there, particularly in the Kendeng Low.

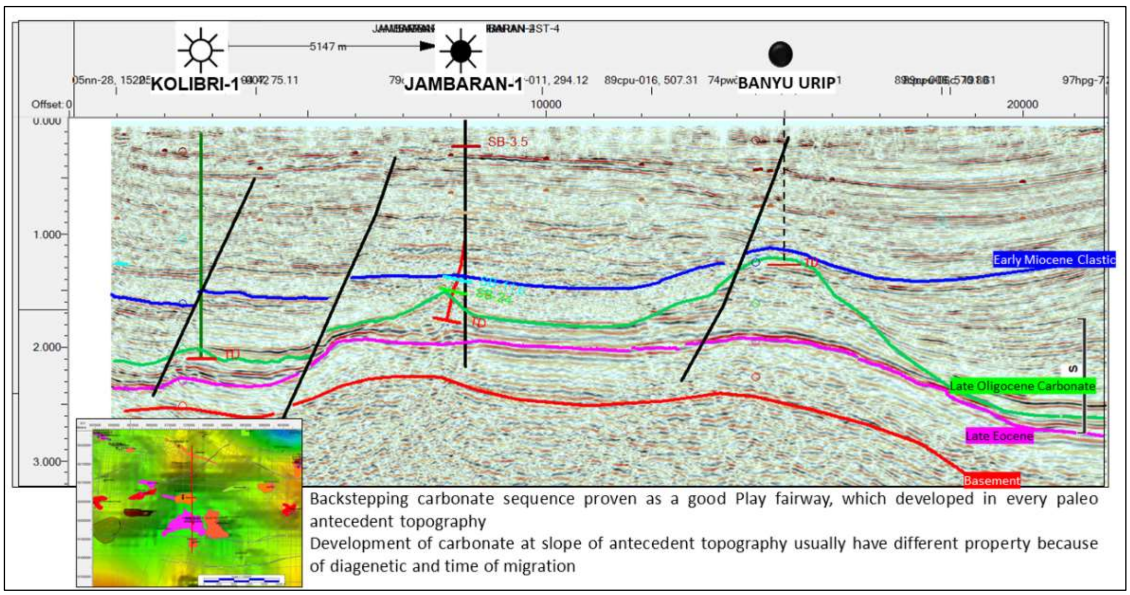


Figure 8-The backstepping carbonate as the first trap is working very well, due to the time of porosity development and the charge is relatively matched.

Deep through Kendeng zone can produce a greater amount of magnesium, which is responsible for the dolomitization. The timing of charge is critical; paragenesis of carbonate rocks will continue, particularly in deep burial situation where temperature and chemistry are the primary factors influencing reservoir quality. All of this paragenesis will come to a halt once hydrocarbon is present in the reservoir. Thin section shows that at a depth of 3596m MSL, KDL-1 dolomitization obstructed their carbonate pore space. Calcite and some dolomite occlude the pore space of coral portions at CDN-1 to the west. In comparison, there is less dolomite in the JAM-1 thin-sections . This phenomenon will influence exploratory play in thisarea, particularly the initial trap. Carbonate build-ups in slope settings normally require a short time to form a carbonate factory. Evidence of deepening upward sequence appears in the K-1 well, this might also occur in other sub-basins as well. Backstepping carbonate style in the Ngimbang Low is a good reference to evaluate the potential similar carbonate features may exist in other highs and lows of the nearby sub-basins. Other Paleogene's first trap was identified in the eastern part of the Ngimbang Low. Some of the deeper carbonate plays are undrilled and they posted the potential significant opportunities. Composite seismic lines illustrate the potential first trap in the eastern part of the Ngimbang Low, near Sumber-1, Suci-1, and below Grigis-1 wells (Figure 9). The flattening in the Middle Miocene indicates that numerous carbonate build-ups developed near the hinge margin and along the potential hydrocarbon migration route.

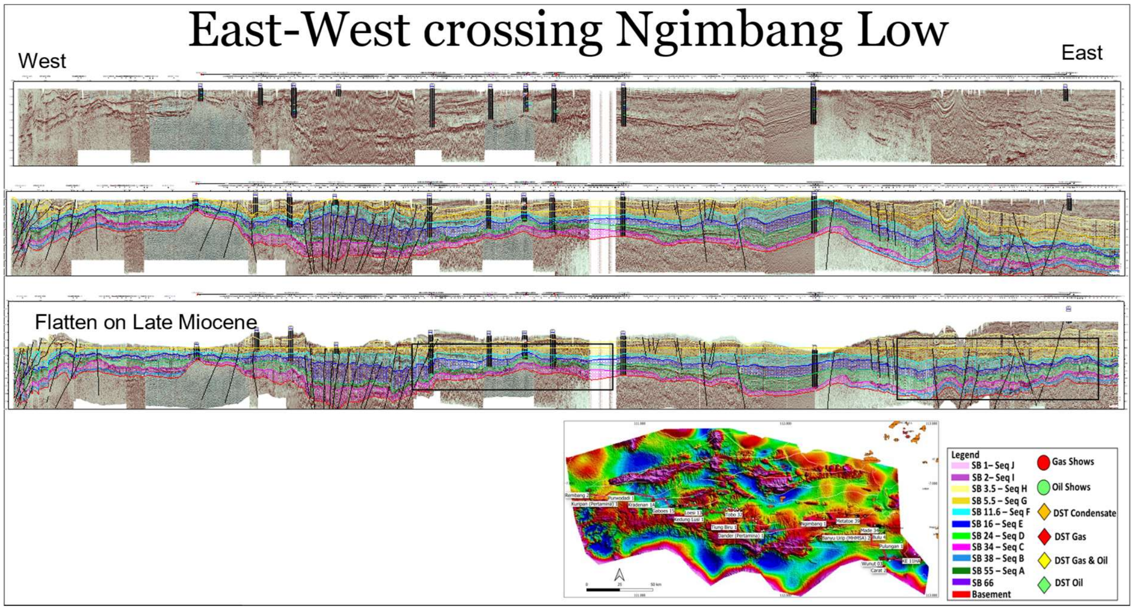


Figure 9 - The composite seismic section shows the potential first trap that exists in the east-west across Ngimbang Low marked by the white dashed line square. The flattened in the Middle Miocene shows the hinge margin that was filled by carbonate build-ups as a first trap.

Paleogene Play Focus-North Madura Low Sub-Basin

North Madura Low basin is a unique sub-basin in that it is relatively small compared to the other sub-basins in the NEJB, and the deepest part of the basin uplifted since the Pliocene. The overall stratigraphy of the North Madura sub-basin is similar to that of the Ngimbang Low sub-basin, started with Eocene rifting and followed by carbonate grow on the slope of antecedent topography from the earlier structures. During the post-rift period, all high regions are inundated by marine, hence carbonate build-ups occur with open marine to the south. The North Madura sub-basin from the north-south cross-section is rather narrow, having east-west orientation. Several part of sub-basins are proven to be active kitchens, including Central Deep, North Madura, and South Madura. According to this study, Bukit Tua Field is believed to be charged by the North Madura sub-basin and the Central Deep.

Several carbonate build-ups have been observed going east-west along the paleo slope or paleo antecedent topography as a result of Eocene structural formation. Carbonate succession eventually becomes the first trap when the basin mature and begins to expel in the Lower Miocene. The east-west cross-section of the North Madura and Pagerungan sub-basins reveals potential multiple untested first traps. Interpretation to the existing seismic data reveals the Paleocene section of green horizon onlapped the high area in the North Madura sub-basins (Figure 10). That marks the boundary between the two sub-basins. To the east, the basin has a different stratigraphy and structure. The eastern section of the basin is likely began in the Paleocene, while the western section could be in the Middle Eocene. This will affect petroleum system in both basins. The geological model of Paleogene's first trap play in the North Madura sub-basin is supported by hydrocarbon oil discovery of H-1 well. Late Eocene carbonate build-ups on slopes serve as the primary reservoir. In general, carbonate formed on the slope typically has the primary reservoir porosity issue due to quickly drawning phase, however either diagenesis process or unique facies composition of the carbonate could enhance this primary porosity. A good example is reservoir quality of carbonate in H-1 well. They are believe to experience karstification, resulting in considerable secondary porosity enhancement with an average porosity of 25% with porosity as high as 35% at the top section of the build-up (Darmawan and Wijaya, 2022). Seismic study and well data analysis reveal that the Paleogene carbonate developed in three stages, they are Stage 1 of carbonate Initiation Phase, Stage 2 of carbonate Aggradation Phase, and Stage 3 of carbonate Backstepping Phase.

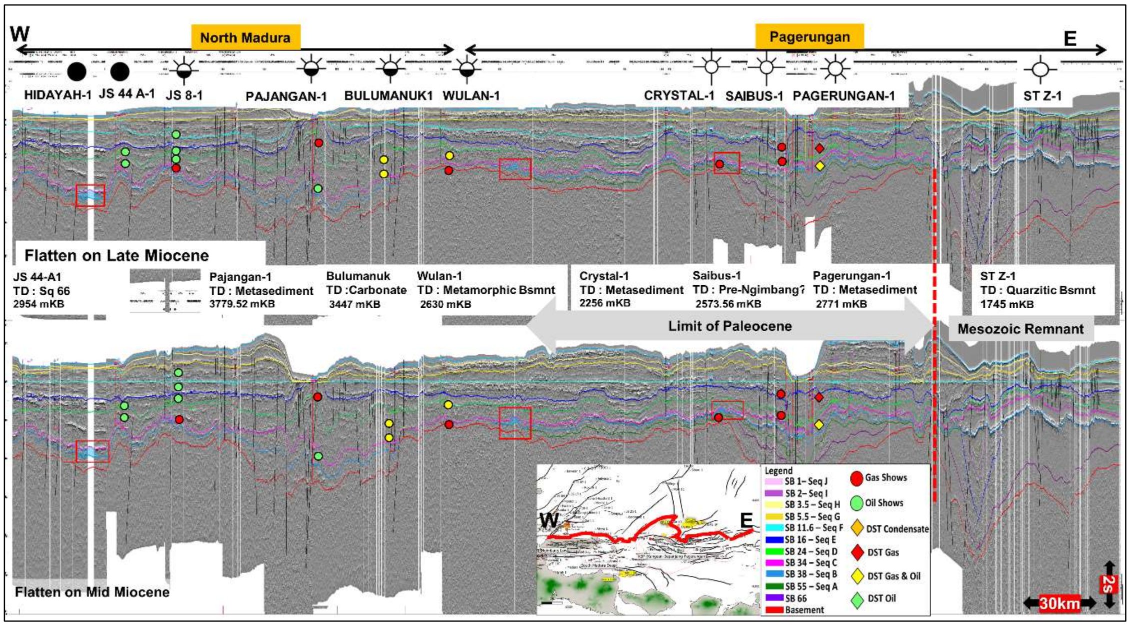


Figure 10 - An east-west cross-section from the North Madura and Pagerungan sub-basins shows several first traps which have not been tested marked in red square. Note that the Paleocene section in green horizon onlapping to the high area in the North Madura sub-basin.

According to log data and petrography thin-section analysis, secondary porosity in Ngimbang carbonate was induced by substantial dissolution-karstification associated with subaerial exposure, fracturing, and dissolution during the later diagenesis phase.

Other similar build-ups potential in the slope setting were also discovered to the east of H-1 well, along the paleo slope that runs east-west (Figure 11). These leads are located in open areas outside the existing PSC working areas . These carbonate leads developed on the paleo slope, similar to the H-1 structure. This type of play is interpreted to be present along the Paleo slope from east to west, up to the Pagerungan sub-basins. H-1 well’s discovery is a game changer for the Paleogene's first trap. The similar opportunitesi have been mapped resulted many potential leads identified in all sub-basins of NEJB, particularly in the Ngimbang Low, Pagerungan, and South Madura areas.

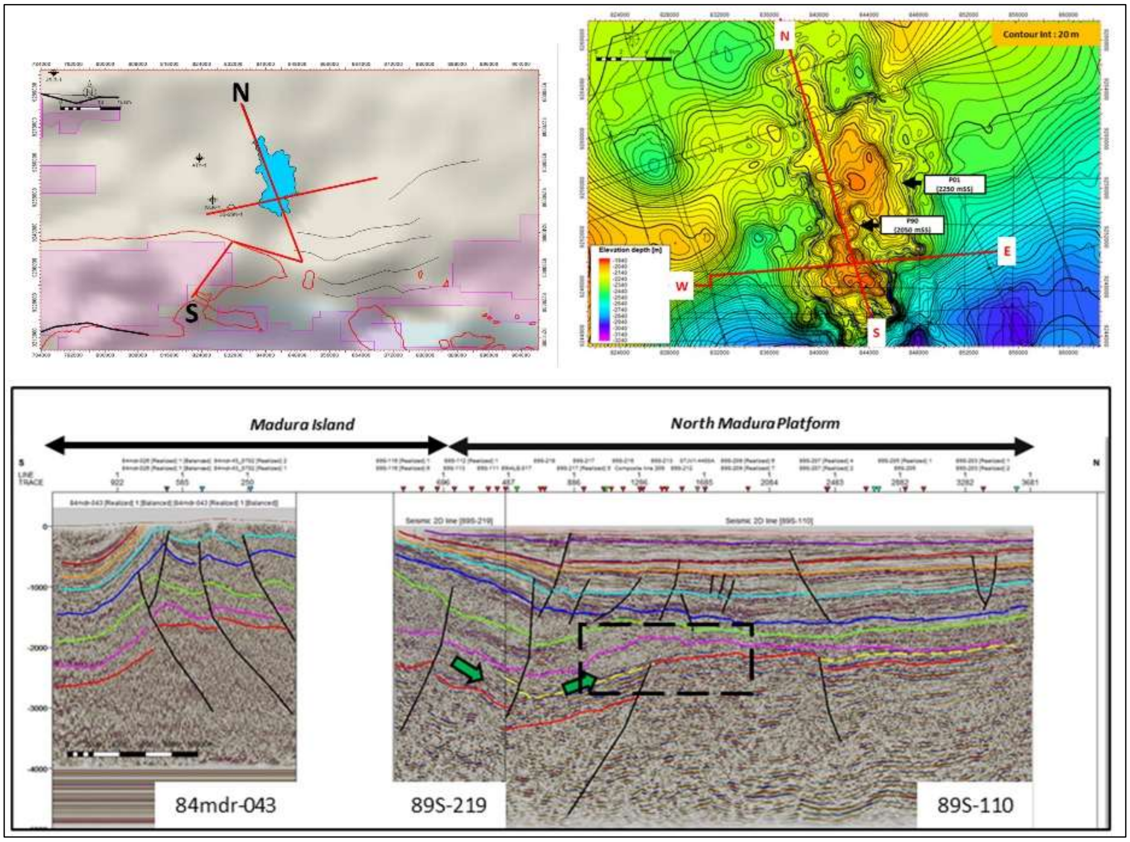


Figure 11 - The example carbonate build-ups towards the East from H-1 which has not been drilled. This carbonate developed in a paleo slope similar to H-1. This kind of play exists along the Paleo slope trending east-west.

Paleogene Play Focus-South Madura Deep Sub-Basin

South Madura Deep sub-basin is the largest sub-basins in the NEJB. To the north, the South Madura Deep is bounded by by the south thrust fault trending east-west and the Madura Island. To the east bounded by the NE-SW fault trend. Several lows developed within the South Madura Deep, running NE-SW. The overpressure zone exist in the basin, caused multiple wells to only penetrate the Neogene section. Several wells in South Madura only reached the Neogene section, where hydrocarbon accumulated in the Carbonate Kujung and Pliocene Globigerina sandstone. Based on the seismic interpretation, several well-penetrated Oligocene carbonate (KE-11E well) zones with strong oil and gas shows suggest that the Paleogene opportunity should still be attractive for exploration, particularly the first trap play. Stratigraphically, the Southern Madura Deep resembles the Ngimbang Low and North Madura sub-basins. The possible source rock in this basin is Upper Eocene and Lower Oligocene, with the main reservoir being carbonate build-ups from the Lower to Upper Miocene. Paleogene opportunity has not been fully explored. Existing wells in this sub-basin show the occurrence of Paleogene sequence in the deeper section, this posted potential exploration target in the future, although the risk remains associated with the reservoir properties.

The north-south cross-section from Madura Island to South Madura Deep demonstrates a loading system formed by the complex geology and highly thick Neogene sequence, which may result in the maturation of Late Eocene Lower Oligocene of potential source rock. Kujung

Carbonate build-ups are located in high positions orientated NE-SW and serve as the primary reservoirs for BD-1 build-up. The BD ridge slope may contain the first trap of Paleogene sequence (Figure 12). This cross-section can also identify a potential depocenter in the North Madura Low, which is surrounded by the RMK inversion structure, as well as a depocenter toward the Madura Strait, which is bounded by the BD Ridge. The Kendeng fold-thrust system appears to continue south of the Madura strait, where rifting has stopped since the Middle Eocene. According to basin models, the South Madura Deep matured in the Lower Miocene (21-20 ma), with peak hydrocarbon generation in the Middle Miocene-Late Miocene. Figure 15 displays an overview of play types in the South Madura Deep, with at least ten plays are identified in this sub-basin. The first trap play consists of potential Oligocene carbonate build-ups on the slope and sandstone reservoir in the rifting system. The east-west seismic cross from the South Madura Deep to Pagerungan reveals two distinct basin types, each with its own stratigraphy and structural characteristics. Regional seismic cross-section also revealed potential multiple Paleogene carbonaye first traps. Their seismic's flattened in the Late Miocene shows that all build-ups in slope setting became the potential sweet spots (Figure 13). The north-south-east cross-section from Anggur-3, KE-11E, and BD-1 wells within the South Madura deep delineates carbonate build-ups as the first trap not yet explored; nonetheless, almost all wells penetrated Neogene section above the overpressure zone had hydrocarbon shows. This demonstrates oppotunities in the deeper section of the Paleogene first trap are attractive (Figure 14).

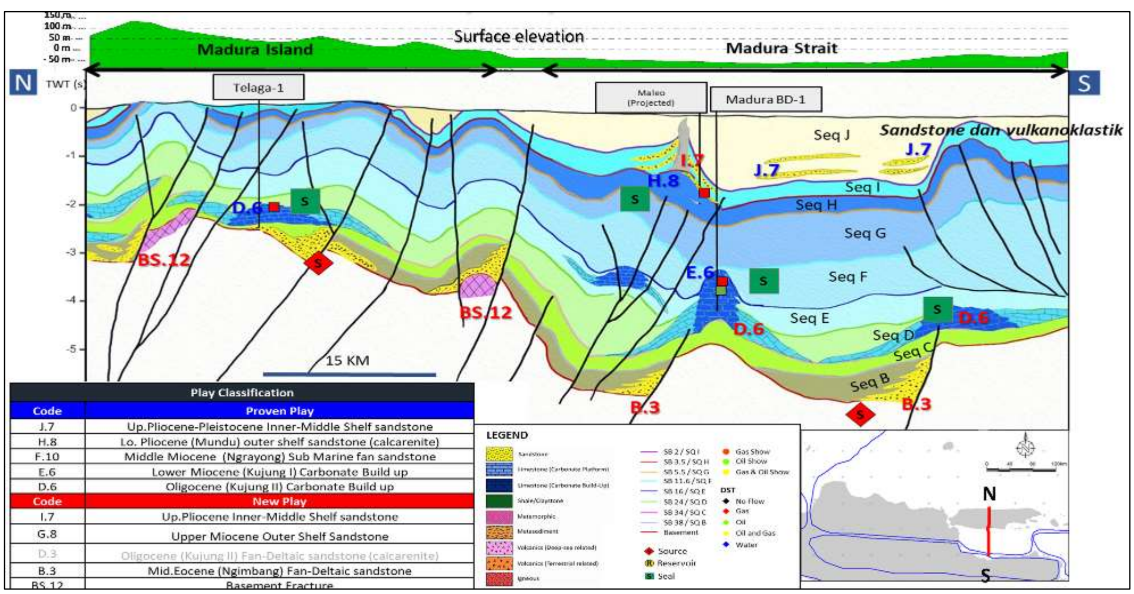


Figure 12 - The schematic cartoon shows the play type that exists in South Madura Deep. The Miocene carbonate is still the main target; however, several Paleogene first trap plays are identified in the southern part of the basin.

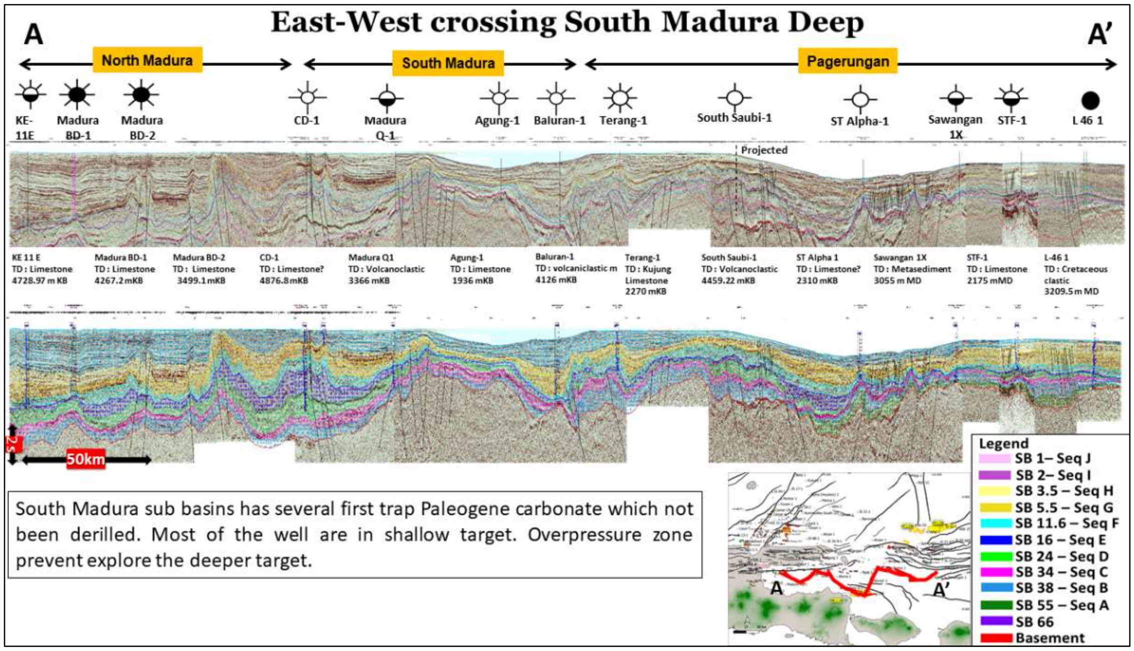


Figure 13 - An east-west composite seismic cross section across South Madura Deep, with several Paleogene carbonates, has not been drilled.

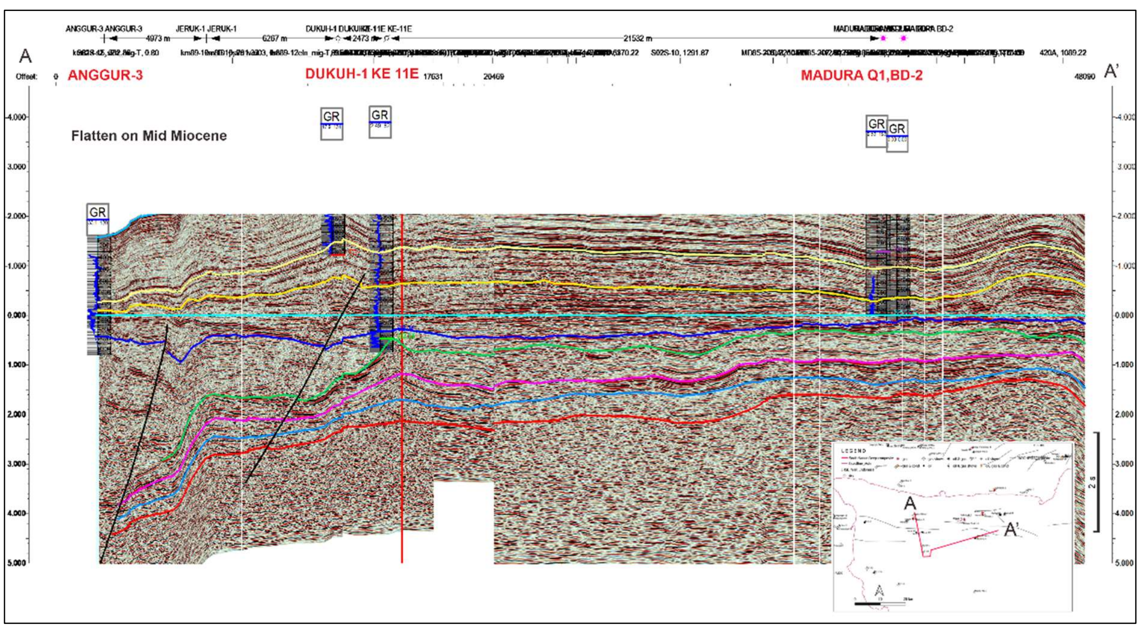


Figure 14 - The flattened section shows that the first trap between Anggur and Dukuh is the potential first trap play that needs to be tested.

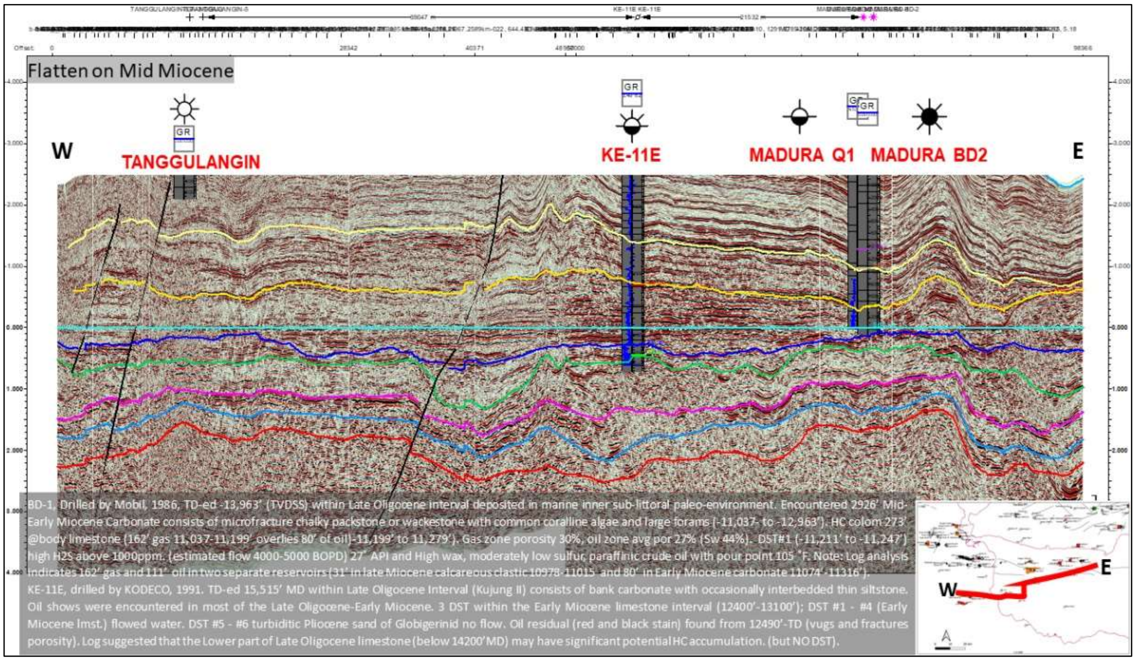


Figure 15 - A flattened seismic section in the Middle Miocene shows the build-ups for the first trap are present. Therefore, any first trap below the existing well in this cross-section is worth to investigate for maturing the leads.

The other regional seismic cross-section from onshore to offshore to the northeast also reveals multiple Paleogene leads beneath the existing well. Several undrilled structures are identified, particularly located between Tanggulangin and KE-11E well (Figure 15). Flatten seismic in the Middle Miocene, when hydrocarbon migration is at its peak, reveals several potential build-ups as the first trap opportunities, they are sit at the primary migration route.

Paleogene Play Focus-Pagerungan Sub-Basins

This study identifies potential additional sub-basins known as Pagerungan. This could explain why the L46-1, Pagerungan, and West Kangean fields were discovered. The Pagerungan sub-basins are located east of NEJB and divided into three areas: Pagerungan North, Central High, and South Pagerungan. The Paleocene succession, or sequence A, is a prominent character of the Pegerungan sub-basin. The integrated geological and geochemical study of hydrocarbonand source rock revealed that hydrocarbon in the JS-53 well and the Pagerungan gas field were produced by Eocene and pre-Eocene source rocks in an east-west trending synclinal kitchen area that connects these two fields.

The Late Eocene age Ngimbang clastic source facies (coaly shale and carbonaceous shales) are geochemically connected to the oil at JS-53 and the condensate at the Pagerungan field. Basin models indicate that gas in the Pagerungan field originated in the Paleocene-Middle Eocene Pre-Ngimbang Formation. Cretaceous sediments are found to be overmature and non-generative (Phillips et al., 1991). The penetration chart indicates that the Paleocene series was only deposited in the Pagerungan Sub-basin, both in the north and south. The stratigraphy is likewise distinct from that of other sub-basins; the basin begins in the Paleocene and progresses through the Eocene period. In a composite cross-section from west to east, the Paleocene limit pinches out in the Wulan High (Figure 16). This affects the petroleum system in the Pagerungan and North Madura sub-basins. The flattened section also shows several leads as the potential Paleogene first traps, which is shown in red. Other leads have also been identified in the north-south direction (Figure 17).

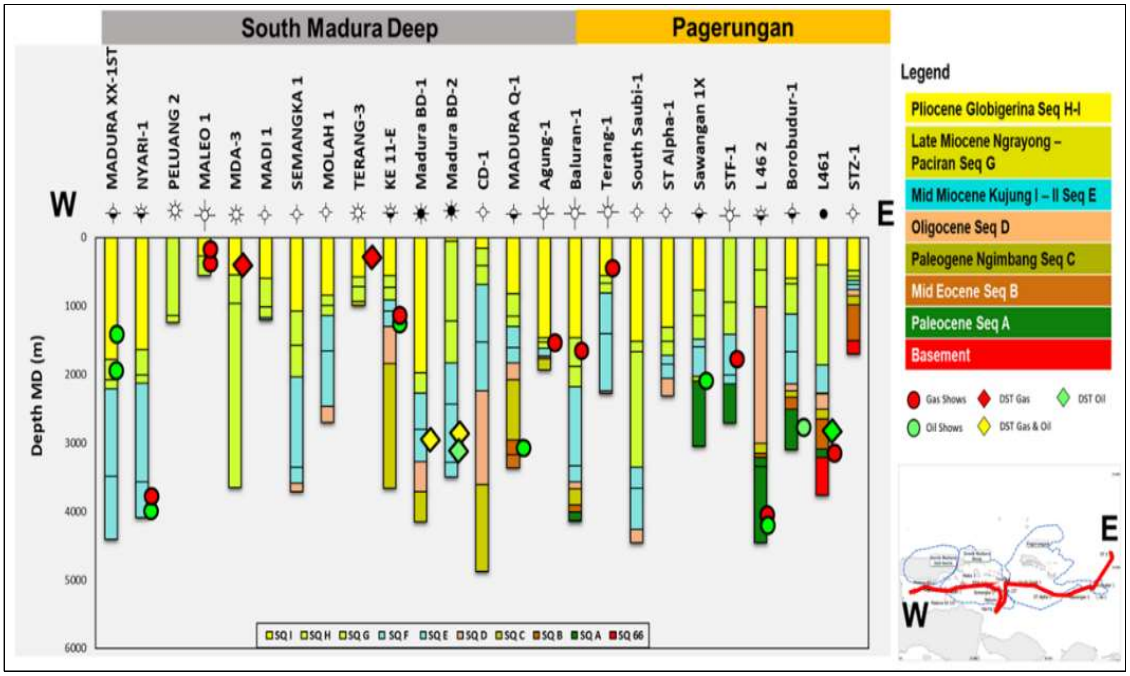


Figure 16 - The well penetration chart shows the Paleocene sequence only deposited in Pagerungan sub-basin both in northern and southern parts.

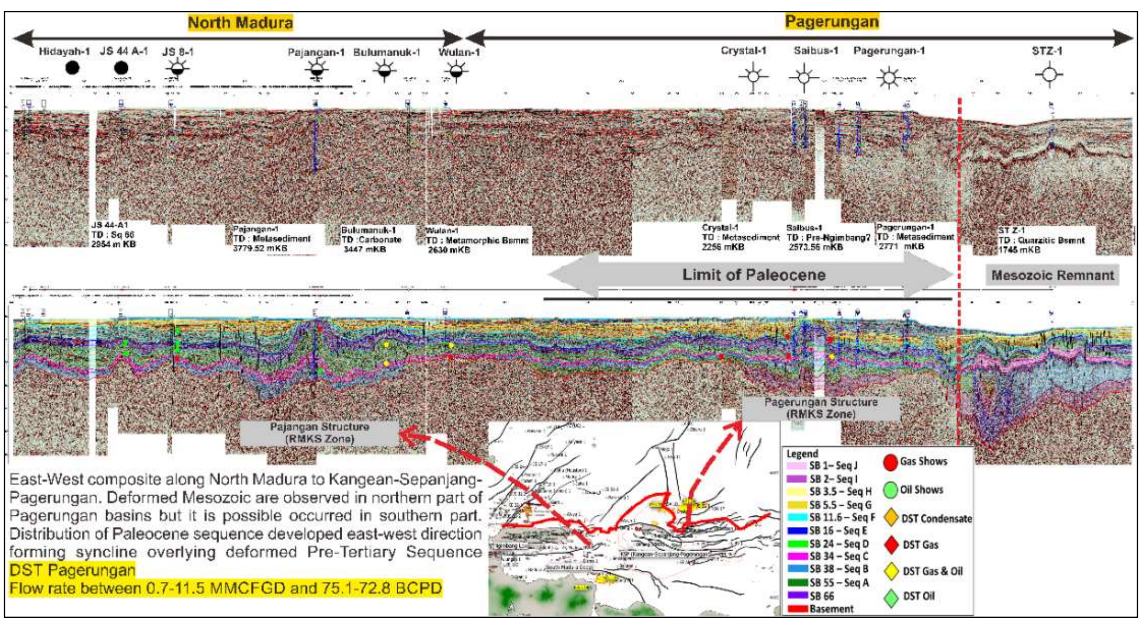


Figure 17 - A composite cross-section from west to east shows the limit of the Paleocene sequence is in the edge of the polygon of the sub-basin, or onlapping to a high area close to Wulan-1 well. This has a significant impact on the source rock and play type.

The carbonate reservoir quality in this sub-basin varies refers to the wells data in the area. The cross-section schematic diagram from north to south illustrates the Paleogene first trap play, which has not been explored in either the northern or southern Pagerungan (Figure 18). This schematic graphic shows the Paleogene's first trap in the southern basin as a candidate for the potental lead, it is likely located at the primary hydrocarbon migration route before the hydrocarbon moving toward the Sepanjang Island-1 well discovery. This also happened in the Northern basin, multiple carbonate leads were identified along the primary hydrocarbon migration route from south to north. The hydrocarbon source is interpreted from Paleocene and Lower Eocene source rocks (sequence A and sequence B).

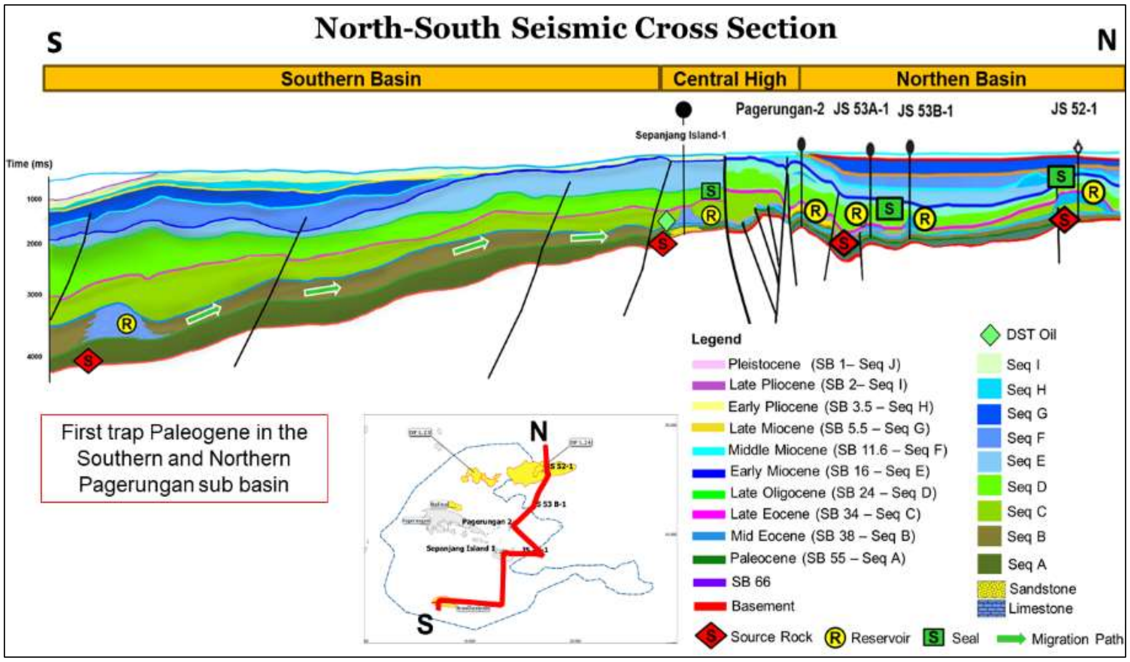


Figure 18 - The schematic cartoon across Southern Central High, and Northern of Pagerungan sub-basin. This cartoon shows that Paleogene's first trap in the southern basin is a candidate for leads because it sits on the migration route to the Sepanjang Island-1 discovery. This also occurred in the Northern basin where several leads sitting on the route of migration from south to north from Paleocene and Lower Eocene Source rock (sequence A and sequence B). This Paleocene succession only occurred in the Pagerungan sub-basin with an east-west orientation following the low paleo slope.

Several potential leads were identified in the Pagerungan sub-basin from this study, however only two will be discussed in detail, they are Raliva and Irasdana.

1. Raliva Lead (Northern Pagerungan sub-basins)
   The Raliva lead is a mounded carbonate build-up identified in multiple vintages of 2D seismic at line spacing of more than 5 km (Figure 19). The carbonate closure is roughly 54 square kilometers and extends east-west, north of the RMKS zone and 49 kilometers northwest of the Pagerungan field. The Raliva lead is classified as the Paleogene play, with Eocene Ngimbang Limestone Formation (sequence B) serving as the primary reservoir target.A shallow target of Oligo-Miocene Kujung formation (sequence D and sequence E) reservoir may occur too. The seismic data shows that during the Miocene period, the reefal carbonate build-up already developed and ready for charge. Meanwhile, the Igangan-1 well failed to display hydrocarbon accumulation, probably due to the

structure was not there when the hydocarbon migration occured, leaving hydrocarbon shows only. The seismic section shows that Raliva lead could have several reservoir targets. In addition to the Paleogene play (sequence B and sequence C), the Neogene play of Miocene Kujung (sequence E) shallow target is likewise a promising play. Primary risk of the Raliva lead is likely to be the reservoir quality, as shown by several wells in the neighboring locations. Nonetheless, wells penetrated the reservoir had good to reasonable porosity and permeability, as seen in the Pagerungan and West Kangean Fields.The lead is covered by old vintages of 2D seismic data that their seismic data quality is relatively poor, therefore its trap geometry has some uncertainties. Infill 2D or 3D seismic data is recommended to mitigate trap uncertainty, also to evaluate the potential direct hydrocarbon indicator (DHI) feature to further de-risk of hydrocarbon presence in the lead.

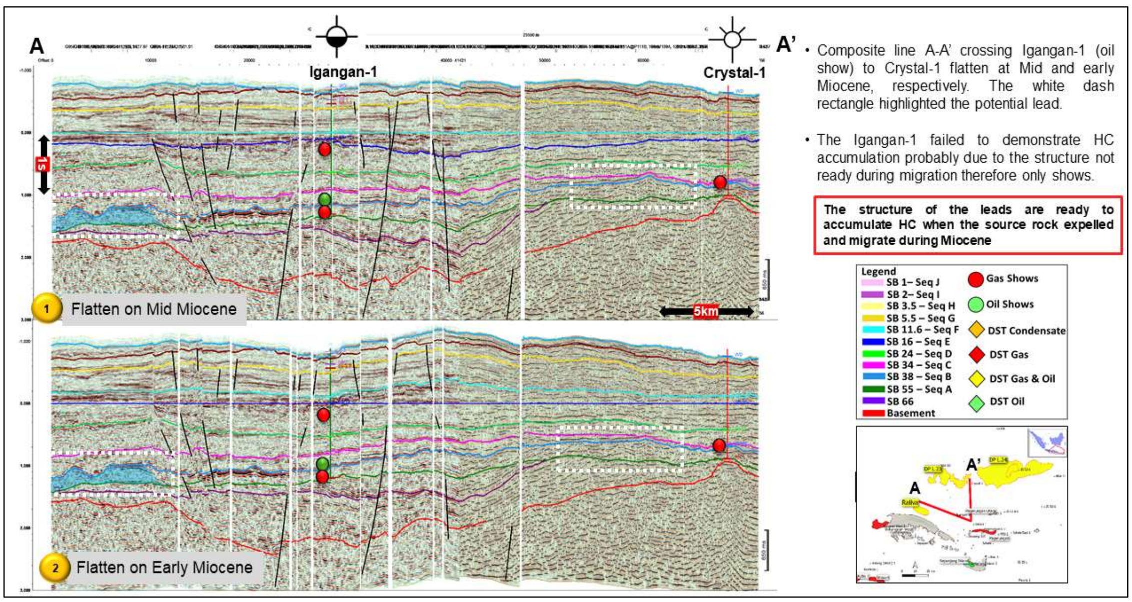


Figure 19 - A composite line crossing Igangan-1 (oil show) to Crystal-1. The white dash rectangle highlighted the potential Raliva Lead.

2. IrasDana Lead (Southern Pagerungan sub-basin)
   The IrasDana lead is a mounded carbonate build-up seen in many different vintages of 2D seismic, at line spacing of more than 5km. The seismic section connects the IrasDana lead with the Sepanjang Island-1 oil discovery in the Middle Eocene Ngimbang Carbonate Formation (Figure 20). The reefal closure is around 43 square kilometers and runs east-west, south of Kangean Island (south of RMKS) zone and 25 kilometers southwest of the Sepanjang Island-1 well.

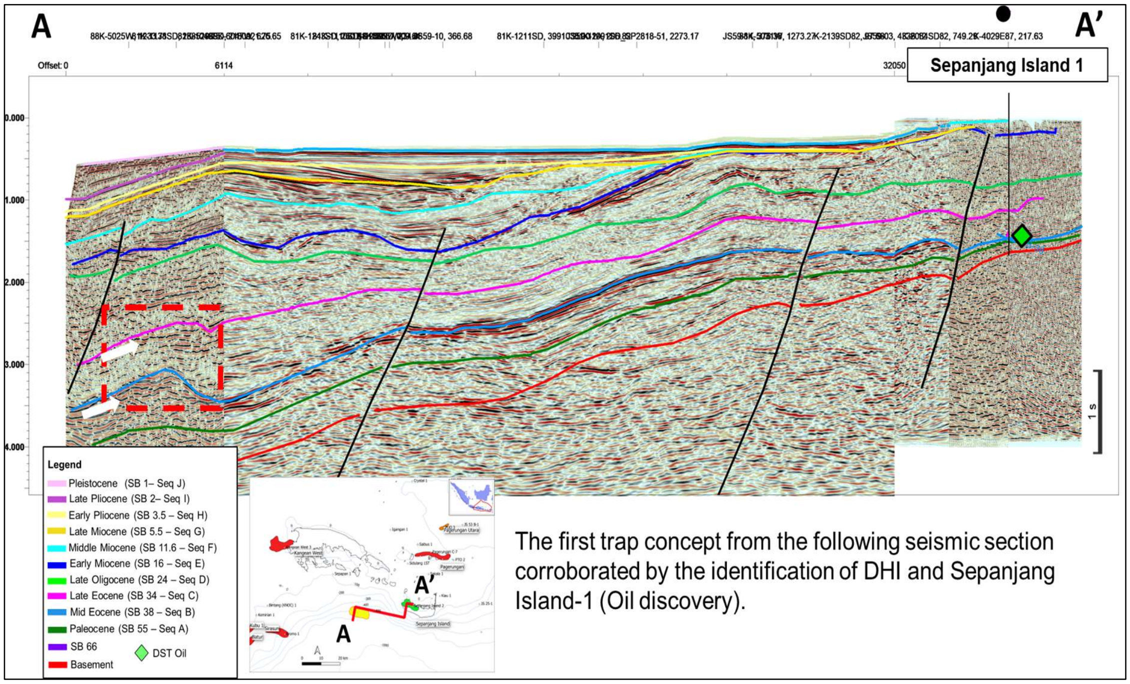


Figure 20 - A composite northeast-southwest line crossing the potential IrasDana lead is highlighted by the red-dash rectangle.

The IrasDana is a Paleogene play that is most likely an oil-prone first trap, with the Eocene Ngimbang Limestone Formation (sequence B) serving as the primary reservoir. Refer to the recent Basin Modelling of the Pagerungan sub-basin, hydrocarbon generation began in the Late Oligocene, with maximum generation occurredin the Late Miocene, shortly before RMKS was inverted. The seismic interpretation and mapping work indicates the developed reefal carbonate was suitable for hydrocarbon charge happen in the Late Oligocene.

Discussion of Paleogene First Trap Play

This section addresses advantages and disadvantages of the Paleogene First Trap play in the NEJB sub-basins particularly Ngimbang Low, North Madura, South Madura Deep, and Pagerungan.

Advantages of the Paleogene First Trap

- Eocene to Oligocene carbonate build-ups developed at the slope system are facing towards the mature hydrocarbon kitchen and experience to be the first opportunities to charge.
- Most of the identified Paleogene first play leads have material volume for hydrocarbon accummulation.
- Carbonate reservoir quality can be excellent with high porosity and permeability due to the secondary reservoir enhancement. However, further evaluation is required to understand the play risk particuralry time of porosity development versus time of hydrocarbon charge and facies of reservoir versus paragenesis process before hydrocarbon chargeoccured.
- The Ngimbang Low sub-basin has several potential first trap Oligocene carbonate build-ups facing towards the mature kitchens.
- The North Madura sub-basin has potential attractive Paleogene carbonate first trap plays. They may have excellent porosity and permeabulity. Play fairways of the identified build-ups exist along the paleo slope in the east-west direction.

- The South Madura sub-basin has potential untested Paleogene first trap plays located below the deeper overpressure zone. If charged with hydrocarbon, they could be full to spill.
- The Pagerungan sub-basin offers several potential Paleogene first traps in the northern and southern areas. Same potential flat spots in the leads are identified, they indicate the potential presence of hydrocarbon accumulation. All of the identified leads are located along the path of potential hydrocarbon migration.

Disadvantages of Paleogene First Trap

- Timing of the hydrocarbon migration may not matched with timing of the secondary porosity enhancement of the buildups if they are drawned quickly. This situation resulted hydrocarbon accumulated in the low quality reservoir .
- Carbonate paragenesis due to variaty of maturation rates across sub-basins controlls the reservoir quality. Different porosity across sub-basins is also controlled by local structure and its evolution.
- Existance of overpressure zone has been the challenge for exploring the Paleogene first trap, particularly in the South Madura Deep sub-basin.

CONCLUSIONS

- Six sub-basins are identified in this study. Each of themhas its own play characteristics associated with hydrocarbon maturation timing, volume of hydrocarbon generation, and reservoir properties.
- The Paleogene carbonate first trap potentials are identified in each sub-basin posted , numerous leads opportunity, awaiting to be explored.

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