Introduction

The East Java Basin is a productive Tertiary Basin that has been producing oil and gas up to 4 BBOE. During the basin forming and development, East Java Basin has gone through three major geological events, including Late Cretaceous to Paleocene convergence, Paleogene divergence creating a series of northeast – southwest half grabens, and Neogene convergence that resulted in a major basin inversion trending west to east across the basin. North Madura Platform is located in the northern part of the East Java Basin, formed during the paleogene divergence. During all the basin development stages, North Madura Platform has been undisturbed by any tectonic disturbances, constantly stable since it was formed until present day, allowing carbonate to grow and develop across the platform.

Identifying the varieties of the carbonate has been an integral part of the basin analysis in East Java Basin, as most of the proven reservoirs in North Madura Platform are found in the Eo-Oligocene Kujung carbonate. Various types of carbonate have been seen and identified using the seismic data, including shelf edge carbonate, platform carbonate, and patch reefs. Through the years, exploration wells have been drilled through Kujung carbonate and found hydrocarbon in each type of carbonate.

A series of seismic reprocessing has been conducted through out the years to support the studies of Kujung carbonate characteristics in North Madura Platform, as well as to eliminate the pushdown effect from Kawengan carbonate. Latest seismic FWI PSDM reprocessing in 2019 has shown tremendous improvement in resolving carbonate seismic facies in North Madura Platform. Detailed carbonate facies has been identified inside Kujung Carbonate interval, showing different facies and internal characteristics of the carbonates in different regions. This study will showcase the varieties and complexities identified in the carbonates that have been developed in North Madura Platform based on seismic facies characteristics from the latest seismic 3D FWI PSDM reprocessing.

North Madura Platform Stratigraphy

The stratigraphy in East Java Basin, particularly in North Madura Platform, started with the Pre-Tertiary that consists of meta-sediments and igneous rocks, then overlain by Tertiary sediments. The Tertiary stratigraphy starts with the transgressive mega sequence that consists of several sedimentary cycles, including Ngimbang, CD, and Kujung cycle. It is associated with tensional tectonic and rifting episodes. A major clastic influx over the extensive Kujung carbonate marked the onset of a regressive mega sequence, which consists of the Tuban, Ngrayong, Kawengan, and Lidah Cycle. It is associated with compressional tectonic, subduction and volcanic arc in the south, basin inversion and wrenching (Figure 1).

The CD and Kujung Cycle marked a major subsidence in the southern part of the basin and the initial developments of a regional east-west trending shelf edge. On the paleo-shelf in the northern part of East Java Basin, including North Madura Platform, the sedimentation is dominated by shallow marine limestones interbedded with shales in the lower part and thick platform carbonate with patch reef at the top. Barrier reefs grew along behind the shelf edge. The top of the Kujung represents a major maximum flooding surface, which ended the transgressive mega sequence (Juliansyah et.al., 2016).

History of Seismic Studies in North Madura Platform

Seismic activities in North Madura Platform have been very vigorous since 2002. 3D seismic data was acquired and processed in 2002 that covered the whole North Madura Platform. While the seismic data shows moderate quality, it has also presented the pushdown effect across the North Madura Platform. The pushdown effect was created by the low velocity zone in the Kawengan Carbonate interval, generated a fake saddle effect down to pre-tertiary basement; altered the true seismic amplitude below the low velocity zone and gave deeper prognosed depth of approximately 30 meter compared to the actual depth encountered during well drilling. First seismic APSDM reprocessing was done in 2013 but failed to resolve the fake saddle issue. Seismic 3D FWI Reprocessing was then conducted in 2019 and has shown better improvement in eliminating the pushdown effect, correcting the depth that was previously affected by the channel and recovered the seismic amplitude (Figure 2).
Upon the successful result of the latest reprocessing, further seismic interpretation and analysis have been conducted, specifically in Kujung Carbonate interval. Kujung Carbonate in North Madura Platform is divided into 3 types: platform carbonate, shelf edge carbonate, and patch reefs. Depth slice was taken at 1,500 m (Figure 3) that cuts through Kujung Carbonate across the North Madura Platform and shows distinct seismic facies differences. Patch reefs are identified in the northern part of the platform that shows a complex of circular structure with strong seismic amplitude reflectivity. Platform carbonate can be seen in the centre of North Madura Platform and continued with shelf edge carbonate that marks the southern edge of North Madura Platform.

**Shelf Edge Carbonate Seismic Expression and Evidence of Progradation**

North – south seismic section that goes through different carbonate facies was generated to analyse the internal characteristics of Kujung carbonate inside each carbonate type (Figure 4). The evidence of progradation can be distinctly identified in the shelf edge area. The shelf edge has been developing since Ngimbang interval as it grows vertically, and it starts moving further south from CD up to Kujung. Seismic shows facies difference between the shelf edge and the slope, as shale starts developing in slope, shown by the dimming and blurry seismic reflectivity compared to the shelf edge carbonate. Seismic velocity profile was also generated to show the lithology differences between shelf edge and the slope. Four exploration wells were drilled through shelf edge carbonate, proving the thick carbonate section started from Kujung down to Ngimbang with no disturbance of shale.
Figure 3. Seismic depth slice at 1,500m that cut through Kujung Carbonate. Distinct facies difference can be identified with patch reefs dominate the northern part, platform carbonate in the centre, and shelf edge carbonate to the southern part of North Madura Platform.

Figure 4. N-S seismic section that goes through different Kujung Carbonate types. Seismic event of progradation can be seen in the shelf edge. The seismic shows facies difference between shelf edge carbonate and the slope with more dimming, blurry seismic characteristics.

Platform Carbonate Development through Kujung Time

Four depth slices were generated at various depth to analyse the development of the platform carbonate through time. During the early Kujung Carbonate development, small carbonate patch reefs were developed, shows in the depth slice as black spots that spread throughout the platform. As the carbonate grew through time, each small patch reefs were grown into wider carbonate islands that were separated by intra channels, and finally merged into one unified platform carbonate at the end of Kujung development (Figure 5). Eight exploration wells were drilled through platform carbonate that penetrated clean carbonate at the top of Kujung Interval and followed by shaly carbonate in the lower section.

New Emerging Carbonate Build-Ups Potential in Deeper Ngimbang Interval

Latest seismic reprocessing has also shown better image quality in the deeper part North Madura Platform. One seismic depth slice has been generated in the deeper depth equivalent to Ngimbang Interval that shows a complex of carbonate build-ups in the southern part of the platform, past the shelf edge (Figure 6). With no exploration activities and wells ever encountered these carbonate build-ups, current findings has provided new insight of deeper reservoir potential in Ngimbang carbonate.
Figure 5. Depth slices showing development of Kujung Carbonate. Small, wide spread patch reefs were first developed during early time (a) that grew into one unified platform carbonate (d).

Figure 6. A Complex of Ngimbang Carbonate interval observed and identified in seismic depth slices as new exploration potential in North Madura Platform.

Conclusions

Seismic 3D FWI Reprocessing in 2019 has shown significant improvement in seismic quality, opening a room for more comprehensive facies analysis of Kujung interval in North Madura Platform. By conducting seismic facies analysis study supported by depth slices and seismic sections, Kujung carbonate can be differentiated into 3 types, including patch reefs, platform carbonate, and shelf edge carbonate. Further facies analysis was conducted in shelf edge carbonate showing the evidence of progradation from early time through Kujung interval. Additionally, facies difference is present between shelf edge carbonate and the slope. More comprehensive carbonate development history in the platform was introduced; showing the presence of small, wide spread carbonate patch reefs and later formed as one big platform carbonate. Kujung development story is highly beneficial to generate Kujung gross depositional environment and to extend its production performance to full potential. Carbonate development in Ngimbang interval has also been observed in the southern part of the platform, as carbonate build-ups are identified through depth slices and sections. Ngimbang Carbonate build-up complex will be the new play opener in North Madura Platform exploration potential.

References
