Extended Abstract

De-risking the Deep: Insights from FWI processing for Legacy and Modern Seismic Data, Case Studies in the East Java Region

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Introduction

The East Java region covers a wide area from the East Java mature basin to the prolific back-arc Lombok Basin. It is a diverse hydrocarbon exploration hotspot, driven by existing discoveries and infrastructure. The basin's sedimentary history, with significant carbonate and clastic deposits coupled with complex Tertiary tectonics, has created ideal conditions for hydrocarbon generation and traps in various structural configurations.

Regional Geological Setting

The East Java Basin sits along the active southeastern margin of the Eurasian Plate and reflects a complex history of interactions of the Indo-Australian, Philippine, and Pacific plates. Its geological evolution can be broadly understood through three principal phases. First, during the Middle Eocene to Early Oligocene, the basin experienced extension and rifting. Regional tensional stresses created a series of NE–SW-trending rift basins and half-grabens. In the eastern region of the basin, particularly the Pagerungan area, structural trends are dominantly east–west. This extensional phase was followed by the post-rift period in the Late Oligocene to Early Miocene. Thermal subsidence resulted in marine transgression and the development of extensive carbonate platforms. From Middle to Late Miocene onward, renewed compressional tectonics driven by northward motion of the Indo-Australian Plate resulted in basin inversion, reactivated earlier extensional faults, and led to the development of compressional structures, including uplift of the Rembang-Madura-Kangean-Sakala (RMKS) zone and the emergence of Madura Island (Mudjiono & Pereno, 2001).
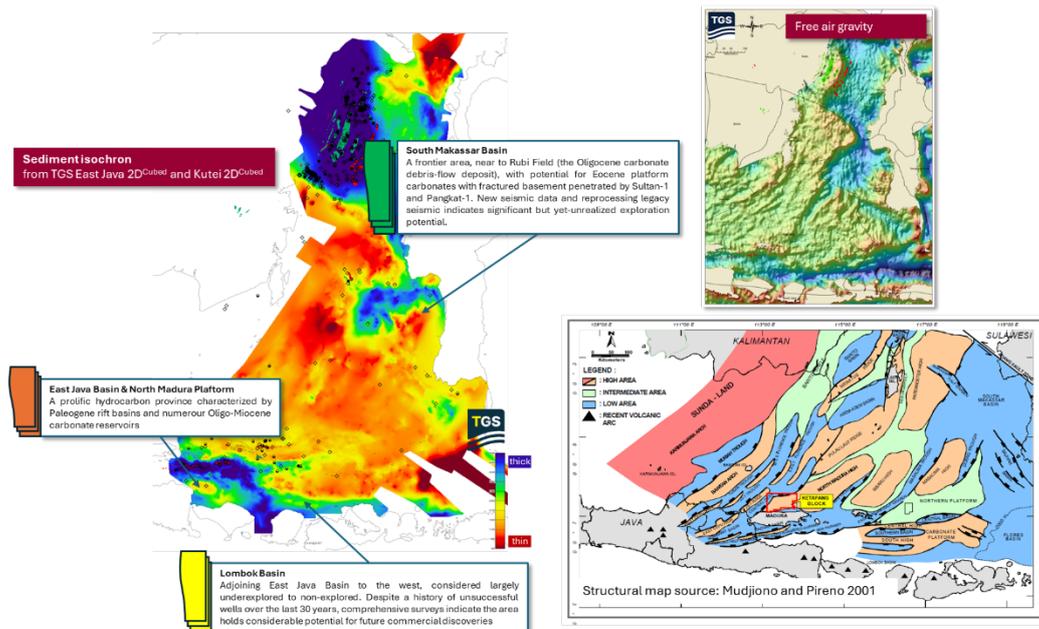
Figure 1. *The regional tectonic framework of the East Java region encompasses a broad domain extending from the East Java Basin eastward into the prolific back-arc Lombok Basin, continuing across the Masalina Platform, and into the South Makassar Basin. This regional continuity is consistent with free air gravity and sediment isochron patterns interpreted from the TGS East Java 2D^{Cubed} and Kutei 2D^{Cubed} datasets, which indicate a linked tectonostratigraphic evolution across these basins.*

Stratigraphy

Many studies show that the stratigraphy of the region spanning the East Java Basin and Lombok Basin is unified by a shared history of Paleogene rifting and Neogene tectonic modification, though specific depositional environments and structural responses vary by location.

The East Java Basin stratigraphy overlies a Pre-Tertiary basement of metasediments and igneous rocks, initiating with the Paleogene Syn-Rift "Ngimbang Cycle". This phase deposited Paleocene to Early Eocene Pre-Ngimbang sediments in East-West lows and Middle to Late Eocene Ngimbang Clastics in Northeast-Southwest grabens, culminating in Late Eocene Ngimbang Carbonate build-ups. The subsequent Oligo-Miocene Post-Rift "Kujung Cycle" featured widespread transgression and prolific Kujung Formation reefs, eventually drowned by regional Tuban Formation seals. Neogene inversion later triggered regressive sequences like the Ngrayong sandstones, followed by deep marine Wonocolo marls, Pliocene Mundu limestones, and Pleistocene Lidah volcaniclastics.

The adjoining Lombok Basin serves as an underexplored eastern extension, structurally distinguished by East-West trending fault systems along the Sakala-Lombok Ridge rather than the Northeast-Southwest trends typical of the Central Deep. Despite a history of unsuccessful wells, the basin offers significant potential through stratigraphic continuity with East Java, specifically hosting Ngimbang carbonate and clastic play concepts.

Future exploration is anticipated to target these deep Paleogene sands and carbonate build-ups, as well as Late Oligocene carbonates, with trap styles such as anticlinal drapes over basement and inversion structures.
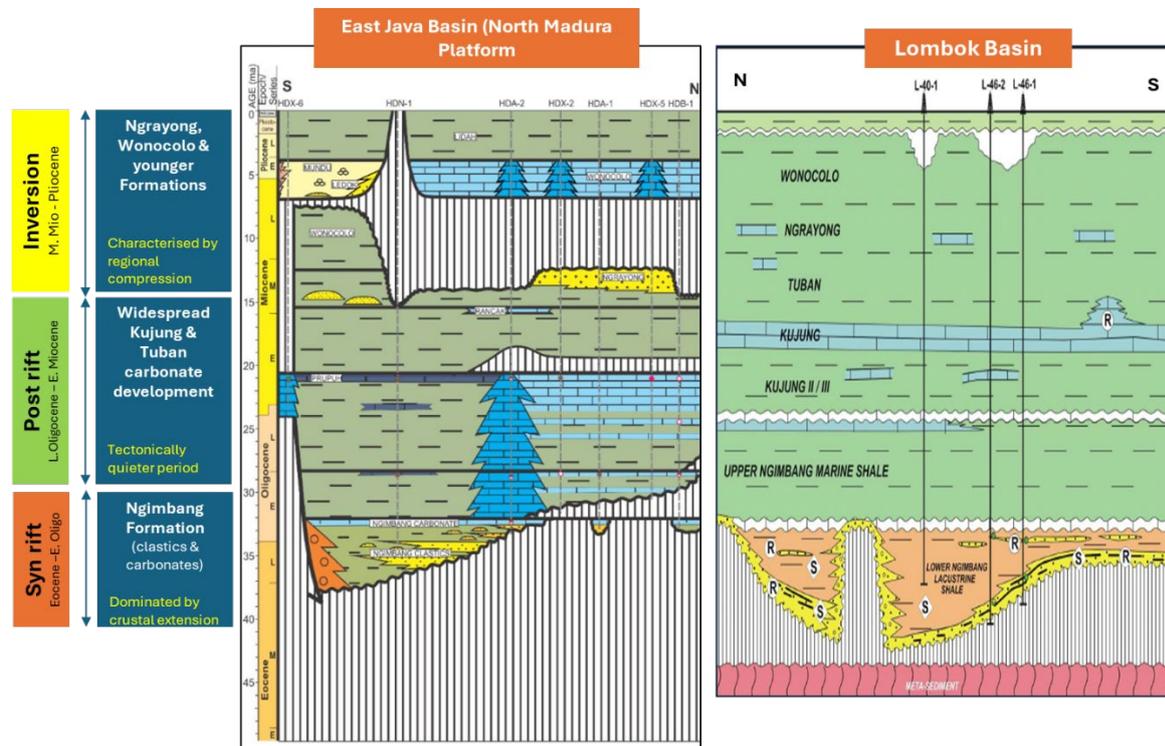

Figure 2. Stratigraphy Comparison: East Java vs Lombok Basin, modified from Nugraha et al, IPA 2016 and Gadjah E. Pireno, IPA 2004

Exploration Histories of East Java Region

The East Java Basin is mature, has been producing for more than 100 years, and remains very attractive. Initial hydrocarbon exploration in the East Java Basin started in the late nineteenth century. It was mostly restricted to onshore areas and relying only on surface geological indicators including anticlines and oil seeps, with drilling focused on shallow post-Tuban formations such as the Lidah, Ngrayong, Kawengan, and Mundu units. Kuti-1 was the first hydrocarbon discovery in 1888 and confirmed the presence of petroleum but reflected the limited depth and scope of early exploration. In the late 1960s 2D seismic acquisition was introduced, bringing a significant advancement which enabled offshore exploration and improved imaging of deeper pre-Tuban targets, particularly the Oligo–Miocene Kujung reefal carbonates and Ngimbang clastic intervals. This led to several significant discoveries, including Camar, Poleng, Terang, and Pagerungan. Driven by the widespread advanced application of 2D and later 3D seismic techniques, this progressively refined the basin's geological understanding and supported numerous additional discoveries. The Kujung and Ngimbang plays became established as the dominant hydrocarbon systems in the basin, with the Kujung play alone contributing more than half of the total discovered resources, estimated at approximately 2.2 billion

barrels of oil and 13 TCF of gas from over 600–700 exploration wells and more than 140 discoveries (Wijaya, 2022).

As the remaining shallow prospects have become smaller and harder to define, exploration has moved toward pre-Kujung and deeper Paleogene targets. The deeper targets are viewed as underexplored rather than unproven. Legacy seismic in the East Java Region was unable to image below the Eocene–Miocene carbonate platforms. Strong lateral velocity contrasts between carbonates and clastic units generated significant inaccuracies in the velocity model and time structure "pushdown" in the deeper section.
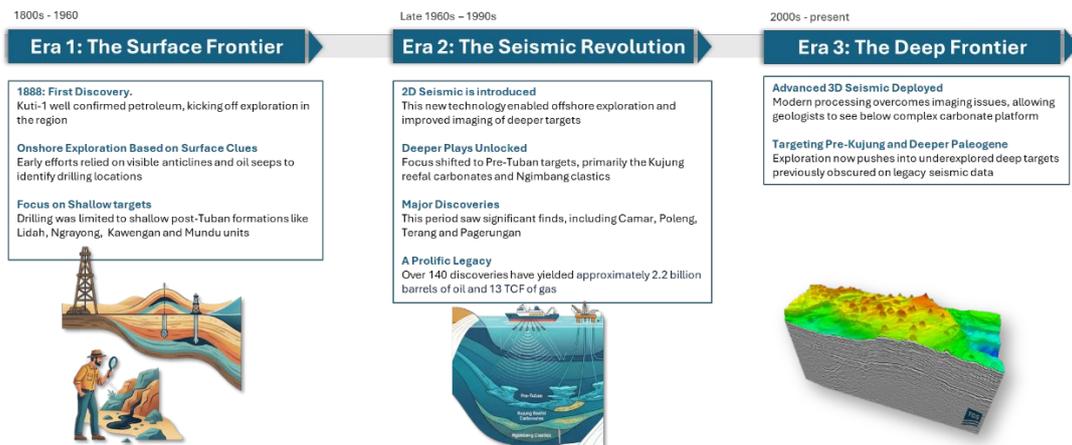

Figure 3. *Exploration histories of East Java Region. Its evolution demonstrates a clear pattern where new technologies have consistently pushed the frontier of discovery from shallow (visible surface feature) to deep (seismically defined targets).*

Proven Impact of FWI on Legacy and Modern Seismic Data

Full Waveform Inversion (FWI) is a major step forward in velocity model building compared with conventional ray-based tomography. It uses the full seismic wavefield, including travel time, amplitude, and phase, and solves the full wave equation to produce high-resolution subsurface models. These models can resolve sharp lateral velocity contrasts caused by complex geology, such as gas-filled channels and incised carbonate platforms. As a result, FWI corrects push-down and pull-up distortions that are commonly missed by traditional methods.

The depth and resolution of FWI depend on the type of seismic energy used in the inversion. Early FWI applications relied mainly on diving waves, which are effective for shallow updates but are limited in depth by the streamer length. Modern FWI workflows now include reflection energy, allowing velocity updates to extend into deeper sections of the subsurface. To ensure stable convergence and to avoid cycle skipping, FWI is applied using a multiscale approach, starting from low-frequency data to build the long-wavelength background model and then adding higher frequencies to resolve finer

details. For this reason, the availability of good-quality low-frequency signal is critical for successful FWI results (Rønholt., et.al., 2014).

The East Java Basin is a prolific hydrocarbon province, but it presents major imaging challenges due to its complex overburden. A key issue is the shallow Wonocolo carbonate platform, which is deeply incised by gas-filled channels. These features create strong lateral velocity contrasts between slow channel infill and fast carbonate rocks. In legacy time-domain seismic data, this results in strong push-down effects that distort deeper structures and obscure exploration targets.

These velocity-related distortions have historically made prospect mapping difficult in East Java. The impact is most severe in deeper intervals, such as the Eocene Ngimbang Formation and the basement, where the true structural geometry is masked. As a result, many potential traps have remained poorly defined or underexplored. Advanced depth imaging supported by FWI is therefore essential to reduce uncertainty and improve confidence in prospect evaluation.

During 2023–2024, TGS acquired new multi-client seismic data in the Lombok Basin, which forms part of the broader East Java regional setting. This includes the South Kangean 3D survey covering about 1,600 km^2 in the western area and the South Kangean 2D survey with around 2,400 km of new lines in the eastern area to infill existing 2D coverage. The surveys are located in an Eocene to Oligocene extensional basin, with Oligocene to Early Miocene carbonates developed on structural highs. To the south, a fold-and-thrust belt formed during Neogene compression, with associated structural inversion, adds further geological complexity.

The region is influence by volcanic activity, with volcanic rocks encountered in several wells. These rocks often have seismic responses similar to carbonates, making them difficult to distinguish using conventional methods. To address this, both legacy and modern seismic datasets were processed using advanced depth-imaging workflows supported by FWI-derived velocity models. Reprocessing of approximately 2,900 km of legacy 2D data, together with the modern surveys, has significantly improved subsurface imaging by correcting velocity distortions associated with complex overburden. The resulting high-resolution imaging has revealed clearer graben geometries, improved definitions of steep sealing faults, and previously unseen carbonate platforms and isolated build-ups. These improvements are crucial for de-risking exploration in this frontier area by providing new insights into regional kitchens, charge access pathways, and the potential of deeper Ngimbang clastic and basement plays.
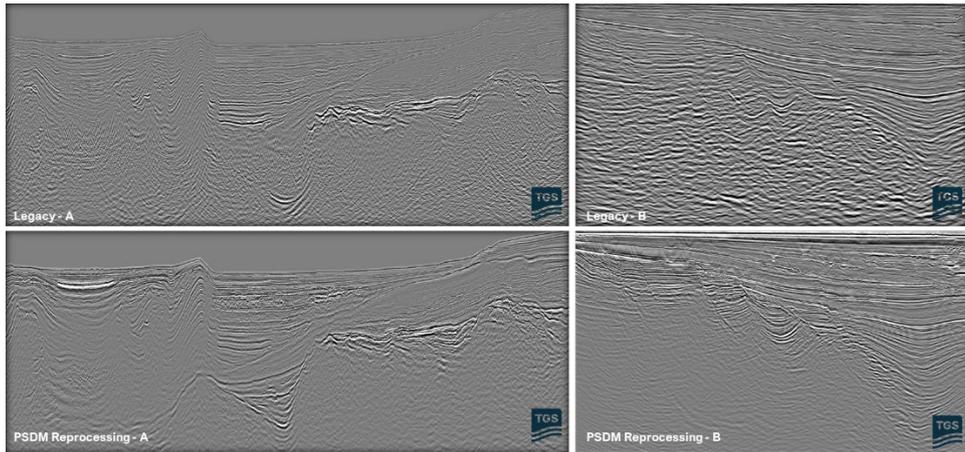
Figure 4. *The comparison of the 2D legacy and reprocessing with FWI, resulting the bandwidth enhancement, better demultiple and denoise, improved deeper imaging, and data coherency.*
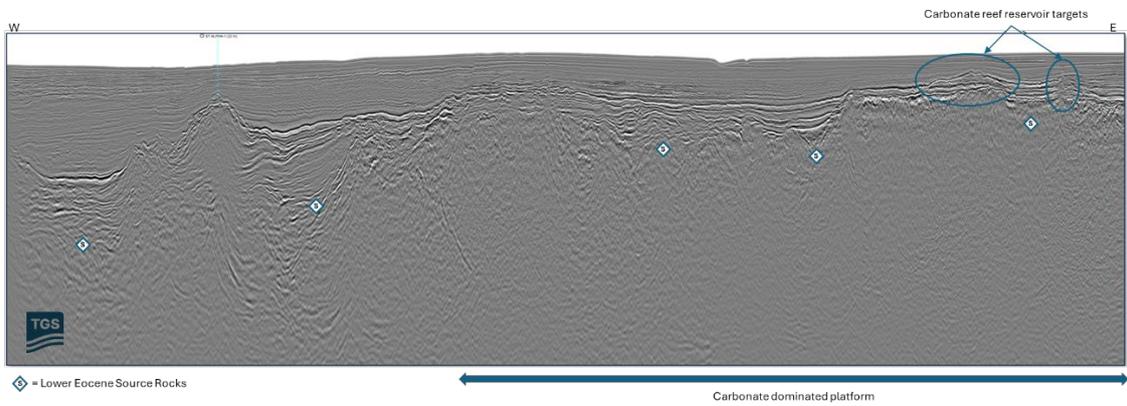

Figure 5. *New South Kangean 2D acquisition provides high-quality depth imaging of carbonate reservoir targets deposited directly over the Lower Eocene source rock interval across the South Kangean platform area.*
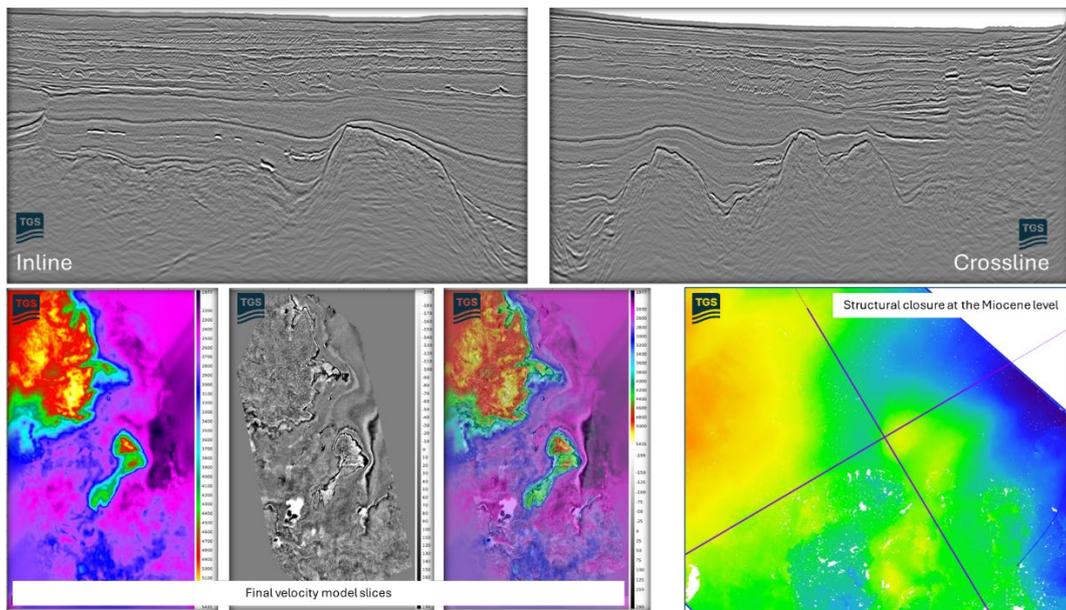

Figure 6. *New South Kangean 3D acquisition resulting high-resolution imaging which is crucial for de-risking exploration in the frontier area*

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