Rethinking the Paleogene Tectonostratigraphy and Petroleum Systems of Indonesia: Moving Beyond Simplistic Basin Models

Ian Longley

GIS-Pax, Perth, Australia

Corresponding author: ilongley@gis-pax.com

ABSTRACT

A pervasive paradigm in Southeast Asian geosciences posits a uniform, synchronous tripartite sequence for Paleogene basin evolution: regional rifting, thermal sag, and middle-to-late Miocene structural inversion. However, critical evaluation of hard chronostratigraphic and structural data reveals this rigid model is overly simplistic and frequently inaccurate. Instead, the Paleogene basins of Indonesia exhibit highly localized, diachronous, and episodic tectonic events that cannot be explained by regional generalizations like the rigid "Tapponnier Extrusion Model."

This paper deconstructs these generalized assumptions by analysing three distinct tectonostratigraphic settings: non-marine syn-rifts (e.g., Central and South Sumatra) characterized by episodic extension and poor palynological age control; marine syn-rifts (e.g., East Java) where early marine incursions provide high-confidence biostratigraphic dating and robust seals; and mixed syn-rift/sag non-marine sections (e.g., West Natuna and Malay Basins) where a massive post-rift lacustrine sag sequence hosts the primary petroleum systems. Regional data demonstrates that tectonic initiation was highly diachronous, spanning from the Middle Eocene to the Miocene, while structural records preserve multiple, independent compressional phases dating back to the Early Oligocene.

Ultimately, true chronostratigraphic control remains weak across non-marine Paleogene intervals in Western Indonesia due to a reliance on long-range data. To reduce exploration risk and accurately assess petroleum systems, geoscientists must abandon generic, synchronized structural templates. Instead, exploration strategies must adopt rigorous, data-driven frameworks supported by localized mapping of distinct rifts, sags, and multi-phase structural inversions.

Keywords: *Paleogene, tectonostratigraphy, rift initiation, rift fills, diachronous rifting*

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INTRODUCTION

A pervasive paradigm in Southeast Asian geosciences is the generalized model of basin evolution that posits a uniform tripartite sequence: synchronous Paleogene regional rifting, followed by late Paleogene to Neogene thermal sag, and culminating in a widespread middle to late Miocene structural inversion. Widely popularized by foundational literature such as Doust and Sumner (2007, Fig. 1), this elegant structural workflow has been broadly integrated into regional exploration strategies.

However, critical evaluation of hard chronostratigraphic and structural data reveals that this rigid model is overly simplistic and, in many cases, fundamentally inaccurate. Rather than a series of synchronous, regional events, the Paleogene basins of Indonesia exhibit highly localized, diachronous, and episodic rifting and compressional events.

The primary objective of this paper is to deconstruct these generalized assumptions by highlighting the critical work of researchers like Lunt & van Gorsel (2013) and Morley et al. (2015), who emphasize high-resolution biostratigraphy and precise structural mapping. To accurately evaluate regional tectonic frameworks and reduce exploration risk, geoscientists must accurately date Paleogene sequences, identify localized extensional or compressional pulses, and distinguish between true rift architectures and post-rift sag complexes.

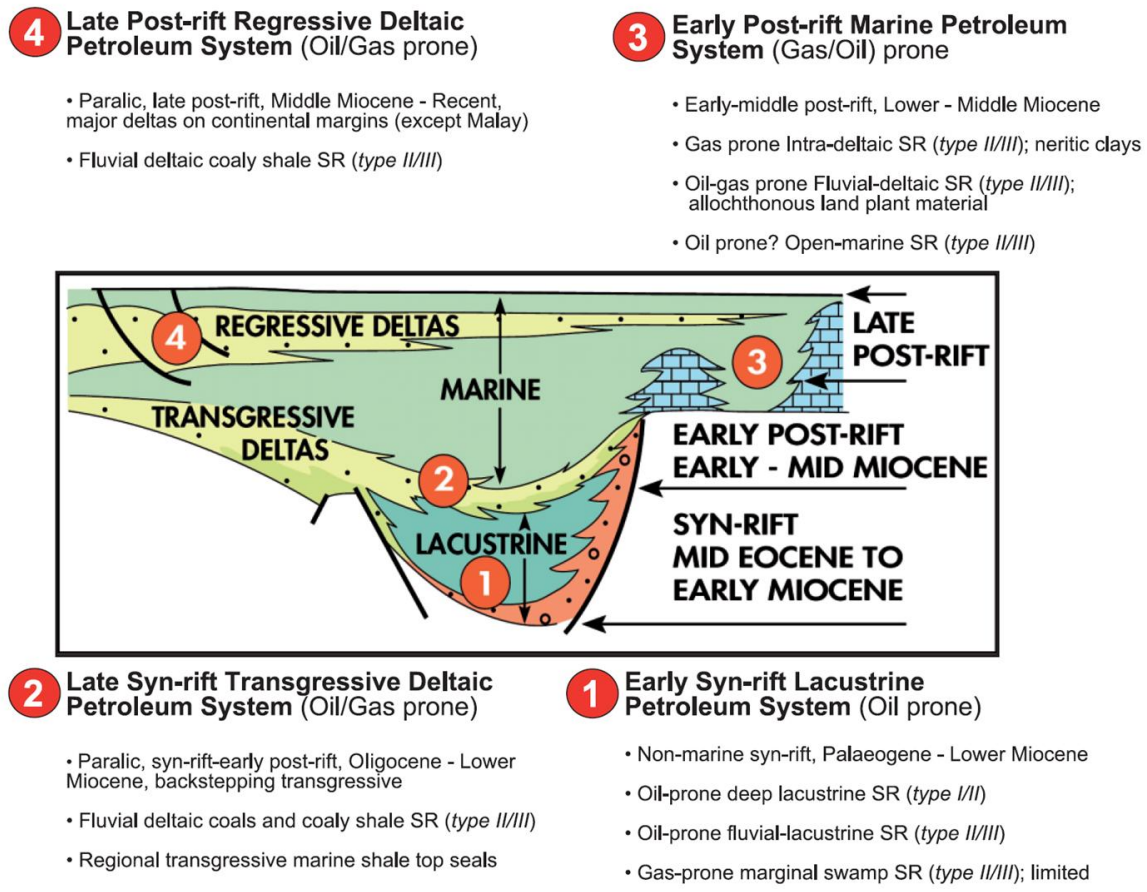


Fig. 1. *Conceptual basin evolution by Doust and Sumner (2007) which is broadly used but probably oversimplified.*

INDONESIAN PALEOGENE SECTIONS

Paleogene successions across Southeast Asia and the Indonesian archipelago can be categorized into three distinct tectonostratigraphic settings, each possessing independent structural histories, depositional regimes, and petroleum systems (Fig. 2).

1. Syn-Rift Non-Marine Sections (e.g., Central and South Sumatra)

The back-arc basins of Sumatra exemplify syn-rift sections dominated by entirely non-marine depositional settings. Structurally, these areas do not record a single, prolonged extensional event; instead, they exhibit multiple, distinct extensional pulses where rift activity fluctuates periodically (Fig. 3).

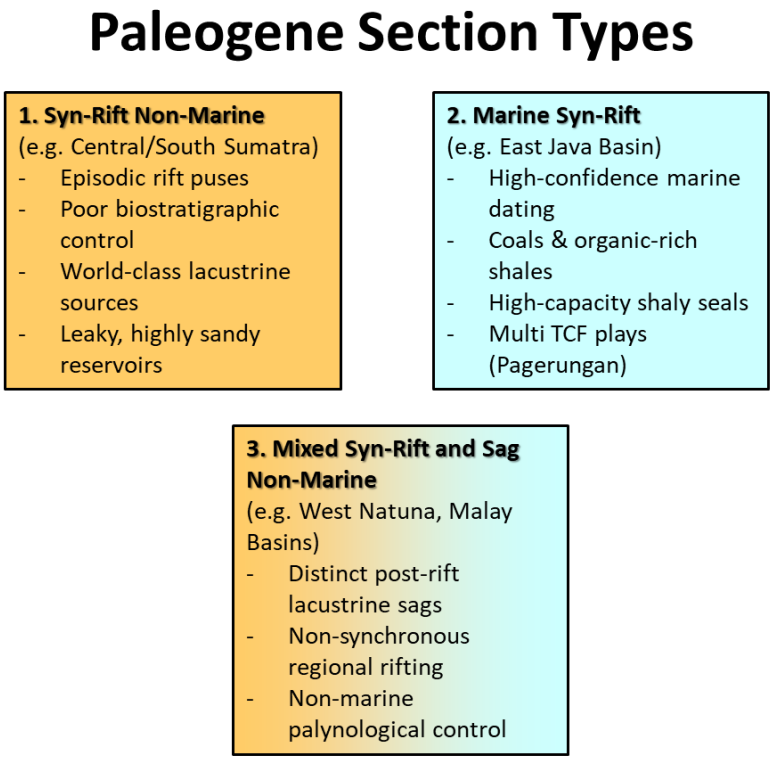


Fig. 2. *The 3 types of Paleogene sections.*

- **Chronostratigraphic Control:** Age dating in these sections is notoriously poor. The absence of marine microfauna forces a reliance on long-range spore and pollen (palynology) assemblages, which frequently lack the resolution required to identify precise bounding unconformities or true rift-onset ages.

- **Petroleum Systems:** These sections generate world-class source rocks when deep, restricted lacustrine systems develop (such as the Eocene to Oligocene Pematang Brown Shale in Central Sumatra). However, because these early rift fills are highly sand-dominated, the systems are inherently "leaky." The absence of extensive, intra-rift regional top-seals prevents massive hydrocarbon accumulations within the active syn-rift section itself. Consequently, most generated hydrocarbons migrate upward into the post-rift, Miocene transgressive reservoir-seal pairs.

2. Marine Syn-Rift Sections (e.g., East Java)

In stark contrast to the Sumatran style, the East Java Basin represents a marine-filled syn-rift setting, which invalidates the generalized rule that all Paleogene rifts are exclusively lacustrine (Fig. 3).

- **Chronostratigraphic Control:** Due to early and persistent marine incursions during the Eocene, these syn-rift intervals can be confidently and accurately dated using marine microfossils (e.g., larger foraminifera and planktonics), as documented in the foundational work of Matthews & Bransden (1995)

and synthesized by Lunt & van Gorsel (2013).

- **Petroleum Systems:** The source rock profile here typically consists of deltaic coals or restricted organic-rich marine intervals, which generally exhibit lower oil-potentials than their purely lacustrine counterparts. However, these systems are bounded by thick, highly effective marine shale seals. This combination creates highly productive traps within the syn-rift architecture itself, exemplified by the multi-TCF recoverable gas accumulation in the Pagerungan Field.

3. Mixed Syn-Rift and Sag Non-Marine Sections (e.g., West Natuna and Malay Basins)

The third section type, which is frequently mischaracterized in regional literature, is the mixed syn-rift and sag non-marine section observed in the West Natuna and Malay Basins (Fig. 3).

- **Tectonostratigraphic Architecture:** In these basins, the Paleogene is emphatically not synonymous with active rifting. The active syn-rift architecture (such as the Eocene to early Oligocene Benua Lama formation) is unconformably overlain by a massive, post-rift sag sequence that remains completely non-marine. This post-rift interval hosted a vast, interconnected, sub-

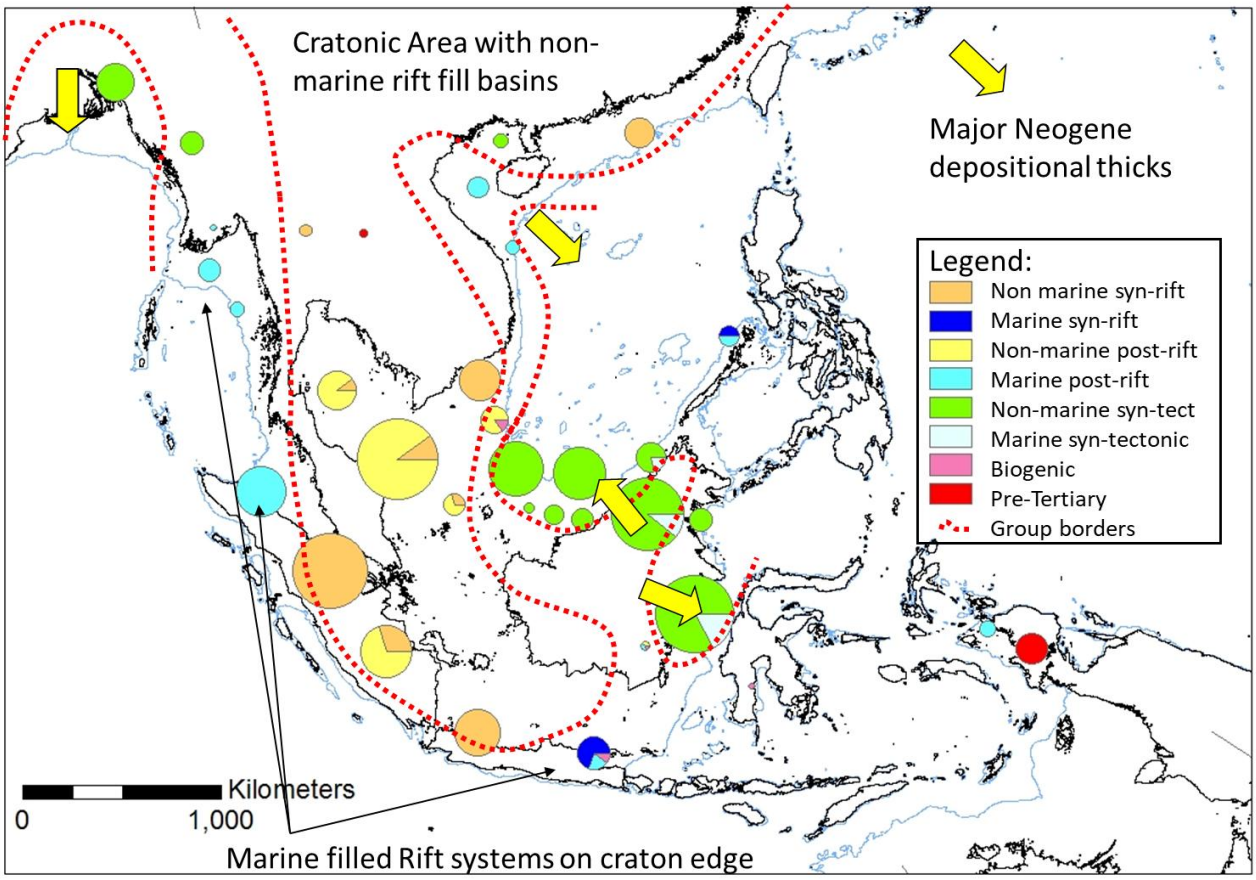


Fig. 3. *Distribution of the Cenozoic basin types related to their genetic type. The bubbles show their relative size in term of hydrocarbon accumulation. Yellow arrows indicate their depositional thickening direction.*

regional lake system that expanded across the Sunda shelf.

- **Petroleum Systems:** This post-rift lacustrine sag sequence contains primary source rocks, such as the Oligocene Group K in the Malay Basin and the equivalent Keras Shale in West Natuna. These units are bounded internally by high-quality lacustrine and floodplain shales, producing robust, self-contained petroleum systems like the Belida field (post-rift play) and the Kakap/Kra fields (syn-rift plays).

DISCUSSION

The Pitfalls of Generalized Chronostratigraphy

The widespread application of standardized chronostratigraphic charts has led to systemic errors in regional geological models. The "green-shaded rift, blank sag, and compressed inversion" cartoon popularized in literature implies regional synchronicity that does not exist.

A critical review of the oldest identifiable marine indicators—the point at which a basin subsides sufficiently to receive high-confidence marine biostratigraphic markers—reveals severe gaps in our understanding of non-marine intervals is displayed in Table 1. Because everything below these marine markers in Sumatra, West Natuna, and the Malay Basin is non-marine, the actual ages of early rift initiation remain highly speculative. This stratigraphic ambiguity is clearly visible in the evolution of institutional charts (e.g., ESDM, 2024 summaries, Fig. 4), where the age of Sumatran rift onset has arbitrarily shifted between the lower, middle, and upper Eocene across successive publications without new supporting data. Models constructed on these unverified ages propagate structural frameworks built on highly flawed foundations.

Diachronous Rifting and Multi-Phase Inversions

The regional data shows that tectonic onset was highly diachronous across Southeast Asia:

Table 1. A comparison of oldest marine indicators/onset age, biostratigraphic confidence and rift onset age in different basins in Southeast Asia.

Basin / Region	Oldest Marine Indicator / Onset Age	Biostratigraphic Confidence	Rift Onset Age
Central & South Sumatra	Early Miocene / Late Oligocene	Poor (Long-range spore/pollen)	Highly Uncertain (Eocene to Oligocene pulses)
Northwest Java	Early Miocene (Talang Akar Transgression)	Poor (Terrestrial/Deltaic)	Uncertain
East Java	Middle Eocene (Ngimbang Marine)	High (Marine Microfauna)	Confirmed Middle Eocene
West Natuna & Malay	Base Miocene (Group J Transgression)	Poor in sub-J section	Diachronous (Oligocene rifting/post-rift lakes)

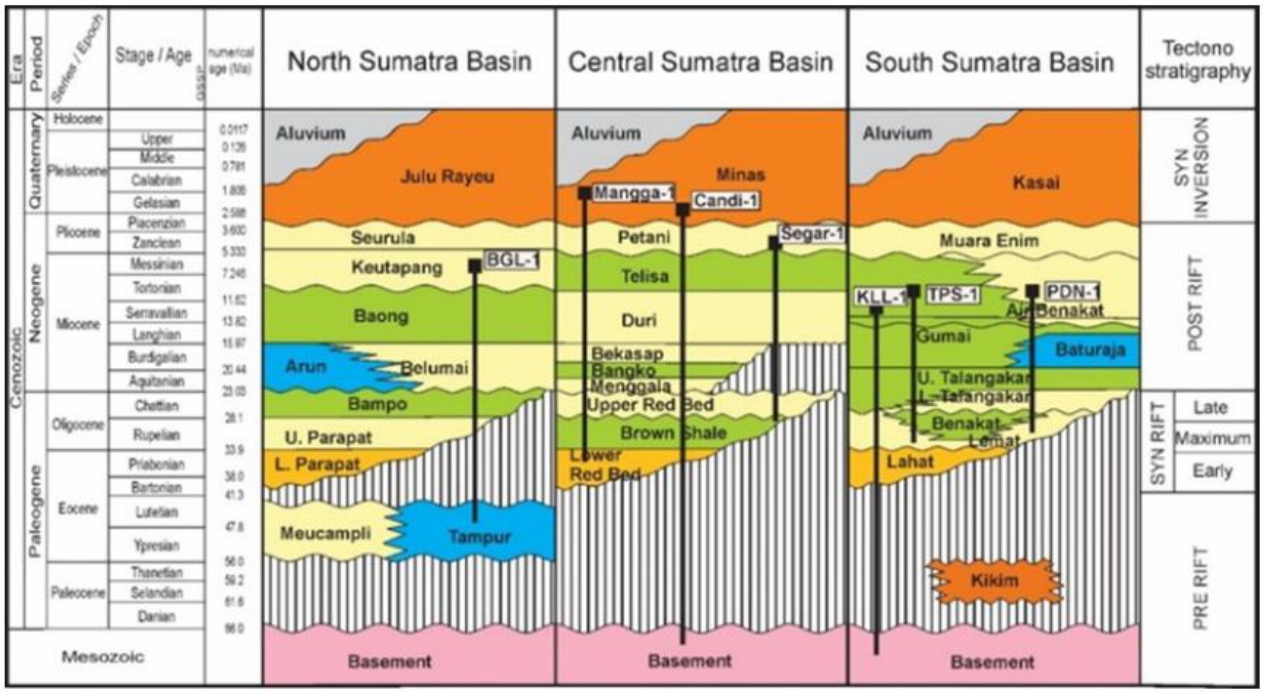


Fig. 4. *Stratigraphy of Sumatra back-arc basins (ESDM, 2024; after ITB, 2007).*

- **Middle Eocene:** Active marine rifting initiated in East Java.
- **Oligocene:** Extensional rifting initiated at varying times across the Malay and West Natuna areas.
- **Miocene:** Active rifting commenced onshore in Thailand.

This structural variation proves that rifting was driven by localized stress regimes rather than a singular, synchronous, regional tectonic event.

A similar complexity is observed in compressional and inversion phases. While exploration literature focuses heavily on the mid-to-late Miocene inversion event, structural mapping reveals a series of older, independent compressional events:

- [Early Oligocene] > Inversion & uplift in the Andaman Sea & North Sumatra.
- [Latest Oligocene/Base Miocene] > Major structural inversion in West Natuna (e.g., Ginger et al., 1993).
- [Mid-to-Late Miocene] > Classical regional inversion (Central Sumatra & Malay Basins).

A prime example of a poorly understood but critical localized event occurs at the termination of the Pematang lacustrine system in Central Sumatra. Commonly mis-characterized as a simple, passive rift-to-sag transition, this boundary represents a distinct structural inversion event.

During this phase, the active Pematang depocenters were structurally inverted, creating a localized topography that offset subsequent deposition of the overlying Menggala sandstones. This structural inversion fundamentally controlled regional petroleum migration. In the Bengkalis Trough and Malacca Straits, this inversion diverted migrating hydrocarbons out of the deep Pematang lacustrine kitchens

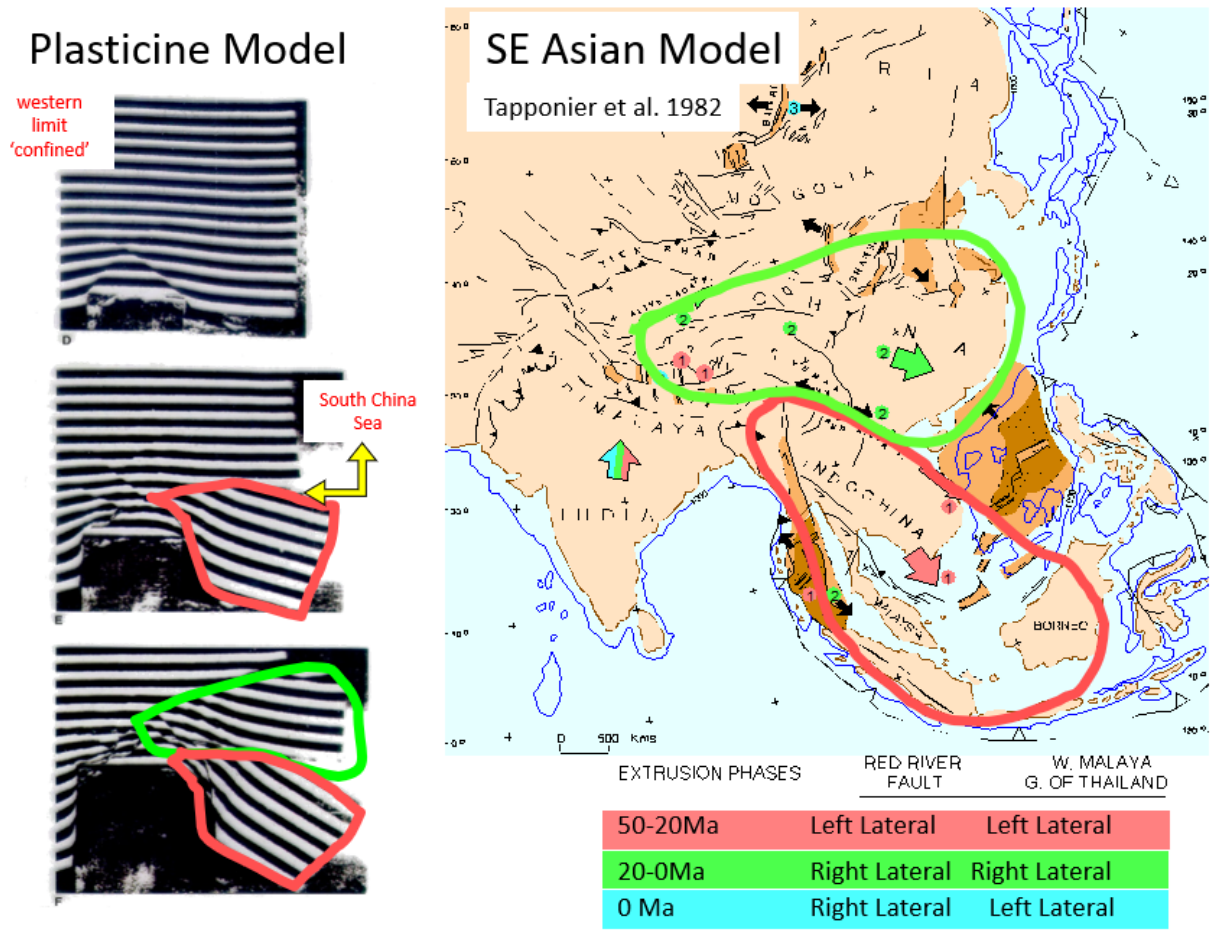


Fig. 5. *Tapponier's Extrusion Tectonic Model which is insufficient to explain local variations. It fails to account for the distinct temporal and spatial differences in rift initiation and inversion timing documented across individual Indonesian basins.*

preferentially to the west (into the historic Caltex blocks), leaving the eastern structural flanks relatively un-prospective.

Deconstructing Extrusion Tectonics

The complex, non-synchronous, and multi-phase structural records preserved within these basins demonstrate that the classic "Tapponnier Extrusion Model" (Fig. 5)—which attributes Southeast Asian basin evolution entirely to the rigid escape tectonics driven by the India-Asia collision—is insufficient to explain local variations. The extrusion model provides an appealing regional generalization but fails to account for the distinct temporal and spatial differences in rift initiation and inversion timing documented across individual Indonesian basins.

Conclusions

1. **Rejection of Synchronous Models:** The Paleogene evolution of Southeast Asia cannot be modelled as a simple, synchronous rift-sag-inversion sequence. Both extensional rifting and structural inversions were highly diachronous and varied significantly between individual basins.

2. **Stratigraphic Ambiguity:** True chronostratigraphic control over non-

marine Paleogene sections in Western Indonesia remains weak due to a reliance on long-range palynological data. High-confidence dating is restricted to marine-filled syn-rifts, such as the Middle Eocene of East Java.

3. **Complex Petroleum Systems:** Exploration strategies must adapt to specific basin styles. Syn-rift non-marine plays are highly sand-prone and prone to leaking into younger reservoirs; marine syn-rifts require robust top-seals to preserve multi-TCF gas plays; and mixed systems rely heavily on massive post-rift lacustrine sag sequences for core source rock development.

4. **Requirement for Data-Driven Frameworks:** Geoscientists must abandon generic, published chronostratigraphic templates that lack local data control. Reducing exploration risk requires rigorous, localized mapping of distinct rifts, sags, and multi-phase structural inversions supported by hard biostratigraphic and structural data.

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