International Journal of Petroleum Technology, 2025, 97-107

Publishers

Published by Avanti Publishers

International Journal of Petroleum Technology

ISSN (online): 2409-787X

Unveiling the Geological Mysteries: Tectonics, Evolution, and Hydrocarbon Play Types of the Andaman–Nicobar Basin from Seismic Data

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ARTICLE INFO

Article Type: Research Article

Academic Editor: Saber Mohammadi

Keywords:
Tectonic evolution
Rifting and subduction
Hydrocarbon play types
Seismic data interpretation
Arc–trench–backarc system
Basin stratigraphy and petroleum potential

Timeline:
Received: August 29, 2025
Accepted: October 10, 2025
Published: November 18, 2025

Citation: Gorain S. Unveiling the geological mysteries: tectonics, evolution, and hydrocarbon play types of the Andaman–Nicobar Basin from seismic data. Int J Pet Technol. 2025; 12: 97-107.

DOI: https://doi.org/10.15377/2409-787X.2025.12.7

ABSTRACT

The Andaman–Nicobar Basin, located at the convergent margin between the Indian and Eurasian plates, is one of the most tectonically dynamic and geologically complex frontier basins in the northeastern Indian Ocean. Utilizing over 23,500-line kilometers of newly acquired 2D seismic data (2021–2023) integrated with legacy datasets and well information, this study redefines the basin's tectonic framework, stratigraphic evolution, and hydrocarbon potential. Seismic interpretation delineates a classic arc–trench–backarc system comprising the Andaman Trench, accretionary prism, volcanic arc, and backarc spreading centers, reflecting ongoing subduction and extensional tectonics. Paleo-flattening and facies analyses reveal a multi-phase evolution involving initial rifting in the Late Eocene–Oligocene, post-rift marine transgression with carbonate platform development, and Miocene to Recent inversion related to India–Eurasia collision. Four key hydrocarbon play types are identified: syn-rift clastic, early post-rift carbonate, early post-rift clastic, and late post-rift clastic systems, with reservoir porosity ranging from 12% to 25% and thickness up to 2.5 km. This work refines earlier tectono-stratigraphic models by delineating new structural highs, spreading centers, and untested plays in forearc and western backarc sectors. The results highlight promising exploration potential, particularly within early post-rift carbonate and late post-rift clastic plays, offering a robust framework for future hydrocarbon exploration in this frontier basin.

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1. Introduction

The Andaman–Nicobar Basin, situated in the southeastern sector of the Bay of Bengal, forms a critical part of the convergent boundary system between the Indian and Eurasian plates. Covering an area exceeding 225,000 km², the basin occupies a unique position in the northeastern Indian Ocean and represents an active subduction zone where the Indian Oceanic Plate is being obliquely subducted beneath the Sunda microplate [1, 2]. This ongoing subduction gives rise to a complex arc–trench–backarc system, encompassing the Andaman-Nicobar Island chain, a forearc basin, an accretionary prism, and a backarc spreading region. Morphologically and structurally, the basin presents a series of interlinked tectonic elements that collectively control sedimentation patterns, structural deformation, and potential hydrocarbon accumulation [3, 4].

Exploration of the Andaman–Nicobar Basin has historically lagged behind other Indian offshore basins such as the Krishna-Godavari and Cauvery basins. Early evidence of hydrocarbon presence emerged in the 1960s through observations of mud volcanoes, natural oil seepages, and limited shallow drilling, highlighting the basin's potential as a frontier petroleum province [5]. Systematic hydrocarbon exploration gained momentum only after acquisition of extensive 2D and 3D seismic surveys covering approximately 55,000-line kilometers, primarily targeting eastern backarc portions of the basin. Despite these efforts, hydrocarbon discoveries have been limited to Miocene reservoirs east of Andaman Island, with western and deeper forearc sectors remaining largely underexplored [3, 6].

The basin's tectonic complexity is further compounded by the presence of the 90° East Ridge, a major volcanic feature extending over 5,000 km, interpreted as the product of Late Cretaceous mantle plume activity. This feature influences regional subsidence patterns, sediment transport, and structural segmentation [7]. Furthermore, the backarc basin demonstrates active seafloor spreading, with extension rates estimated at ~3.8 cm/year, contributing to the formation of extensional fault systems and subsiding sedimentary depocenters [3, 8, 9].

The recent seismic acquisition campaign (2021–2023) by the Directorate General of Hydrocarbons (DGH) India, adding approximately 23,500-line kilometers of 2D seismic data, provides an unprecedented opportunity to re-evaluate the basin's structural, stratigraphic, and hydrocarbon potential (Fig. **1**). These data cover previously underexplored forearc and backarc sectors, enabling refined mapping of tectonic elements. Integrating these seismic observations with legacy wells and geophysical datasets allows reconstruction of paleo-tectonic and paleoenvironmental histories, critical for identifying prospective hydrocarbon play types in a basin characterized by complex subduction-related deformation.

Understanding the basin's geological evolution requires a multi-disciplinary approach, combining structural geology, seismic stratigraphy, sedimentology, and basin modeling. Previous studies [1, 2, 6] provided valuable insights into basin segmentation, depositional patterns, and hydrocarbon prospects but were limited by incomplete data coverage and low-resolution imaging. Integration of new high-quality seismic datasets enables refined structural interpretations and improved identification of key stratigraphic units, unconformities, and potential reservoir-seal systems.

The objectives of this study are threefold: (i) to delineate and map the tectonic and structural features of the Andaman–Nicobar Basin using new seismic data; (ii) to reconstruct the basin's paleo-tectonic and paleoenvironmental evolution, highlighting the role of rifting, post-rift subsidence, and backarc extension; and (iii) to conceptualize dominant hydrocarbon play types by integrating structural, stratigraphic, and sedimentological data. This combined approach aims to provide a comprehensive framework for future exploration, reduce geological uncertainties, and enhance understanding of the basin's hydrocarbon potential, particularly in underexplored frontier regions.

2. Geological Setting

The geological framework of the Andaman–Nicobar Basin was initiated during the Cretaceous, driven by subduction of the Indian Oceanic Plate beneath the Burmese-Malay Microplate (Fig. **2**) [1, 10]. This process formed an accretionary prism and a forearc basin, located between the volcanic island arc and the trench [1, 11]. The volcanic arc uplift formed the Andaman and Nicobar Island chain, structurally significant in delineating basin tectonics [3, 12, 13].

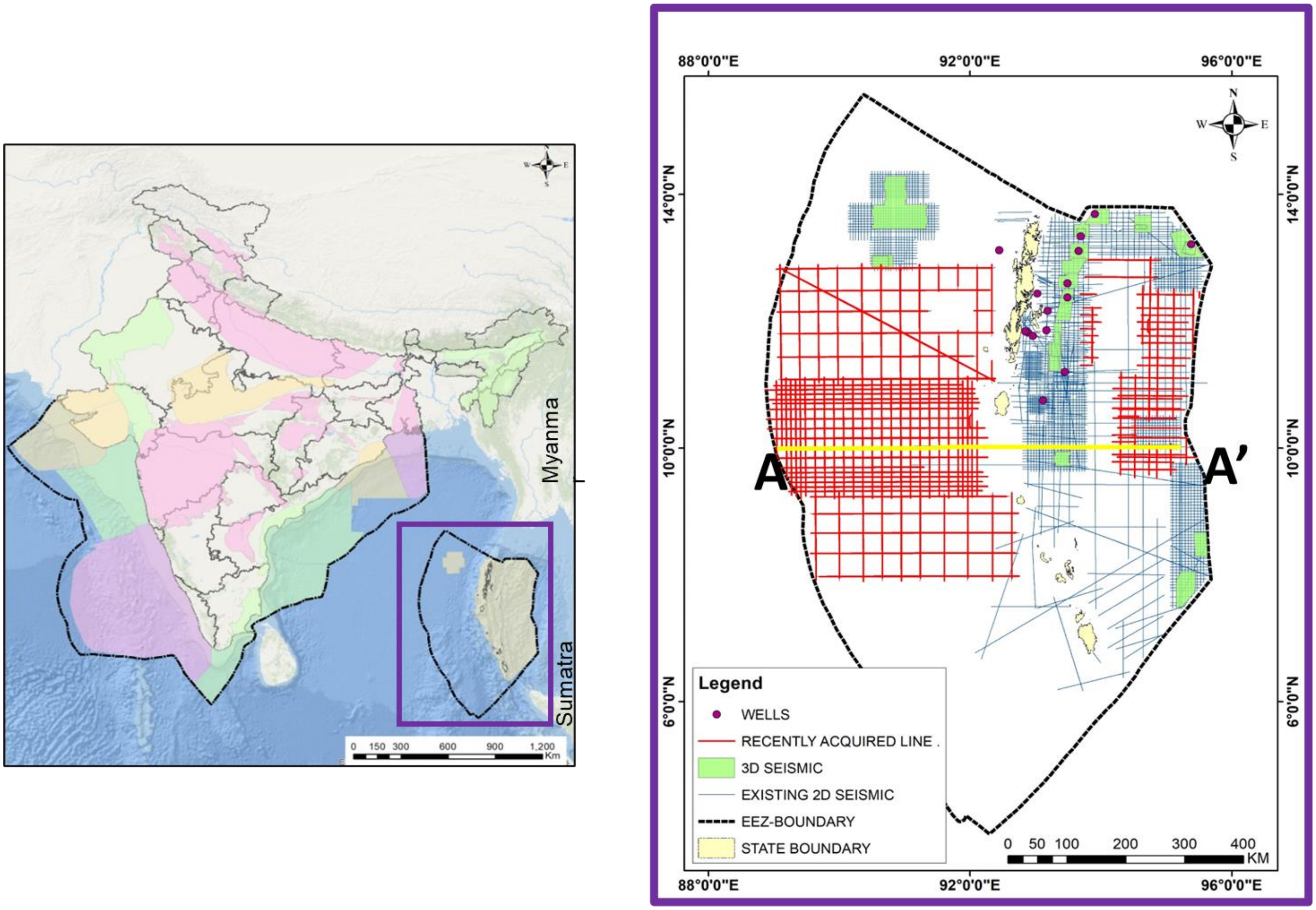

Figure 1: Geographic and bathymetric map of Andaman-Nicobar Basin showing seismic and well data distribution [2].

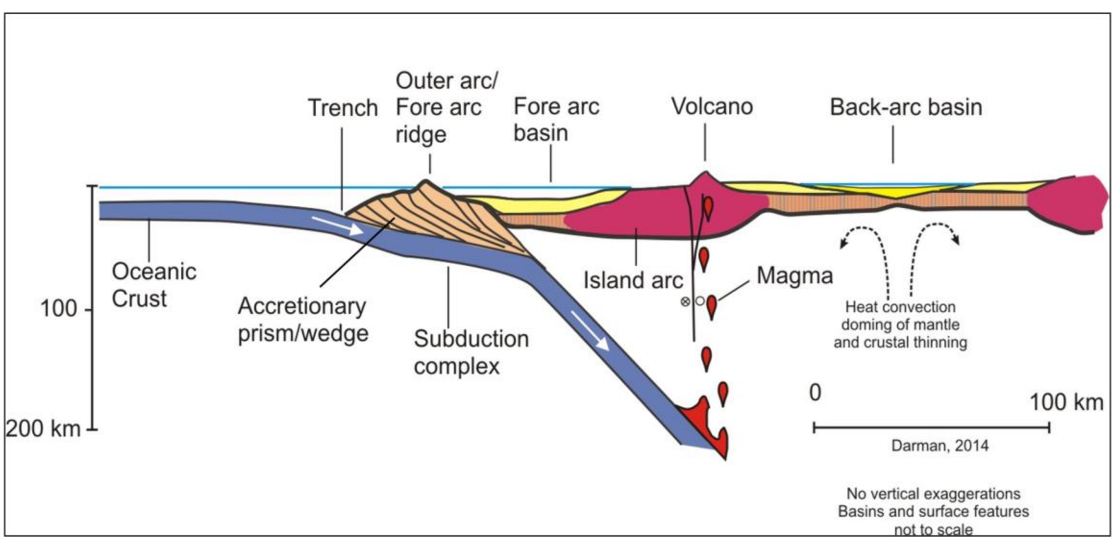

Figure 2: Schematic arc-trench system illustrating key geological elements [1].

The basin is part of the widely recognized “Great Indonesian Island Arc System,” known for its active volcanism and complex plate interactions involving slab rollback, trench retreat, and backarc extension [14]. Morphologically, the basin contains key features, including the deep Andaman Trench marking the subduction interface (Fig. **2**). The trench slope break or outer high results from lithospheric flexure, while the volcanic arc comprises a curved chain of active volcanoes and seismicity [4]. The forearc basin is a sedimentary depocenter receiving detrital input from arc and prism zones, transported into the backarc basin, characterized by active seafloor spreading and volcanic activity [8, 15].

The existence of the 90° East Ridge, a prominent volcanic feature likely associated with Late Cretaceous mantle plume activity, extends over 5,000 km and plays a significant role in regional geology and tectonics [7]. The basin’s geological evolution was marked by important phases of rifting, sedimentation, and inversion, driven by regional tectonics of subduction, collision, and backarc extension. Recent seismic data facilitate an updated understanding of these processes crucial for hydrocarbon exploration.

3. Methodology

3.1. Delineation of Key Features

Decades of geological work, drawing on Curray [1], McNeill & Henstock [8], and Srivastava *et al*. [2], facilitated identification of tectonic elements (Fig. **3**). Recent 2D seismic data clearly reveal trench, accretionary prism, island arc, forearc basin, volcanic arc, and back-arc basin, allowing preparation of a revised tectonic map [16]. Additional geomorphological features such as the seafloor spreading center and 90° East Ridge are also mapped.

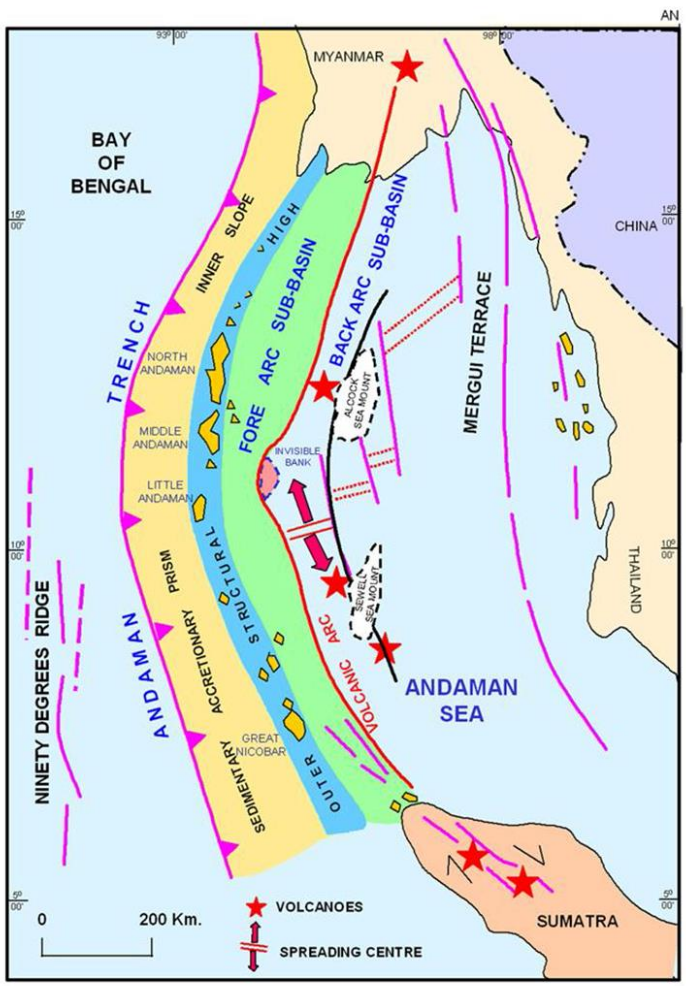

Figure 3: Historic tectonic map showing primary structural elements [17, 1].

3.2. Evolutionary History and Paleo-environmental Analysis

Multiple studies including Arora & Misra [17], Chakraborty & Pal [13], Cochran [9], and Gorain [18] contributed to the basin's tectonic framework understanding. The paleo-tectonic evolution is reconstructed via paleo-flattening principles into three basin development phases: syn-rift, early post-rift, and late post-rift.

4. Results

Extensive geological research since the 1960s shaped the basin's tectonic framework [1, 6, 11, 12, 17, 19-21]. The 2021–2023 seismic data significantly advanced the tectono-stratigraphic framework across forearc and backarc sectors, vividly capturing major tectonic and geomorphological features (Fig. **4**) [16].

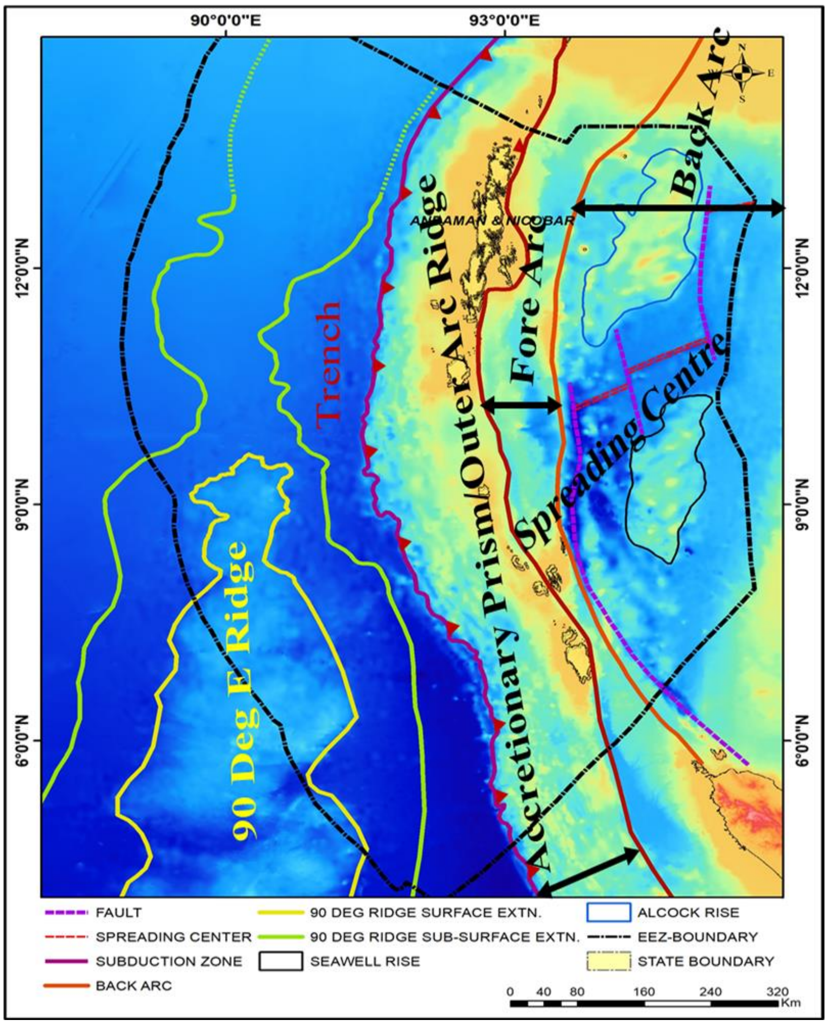

Figure 4: Updated tectonic map with newly interpreted features using recent seismic data [23].

4.1. Seafloor Spreading Center and Backarc Development

A key seismic feature is the well-defined seafloor spreading center in the East Andaman Backarc Basin (Fig. **5**) [3]. Active since the mid-Miocene, the spreading occurs at a rate of approximately 3.8 cm/yr, resulting in about 400 km of crustal opening [6, 8]. Distinct geomorphic expressions include symmetrical ridges, volcanic cones, and normal faults indicative of sustained extensional tectonics. Strike-slip faulting along the spreading axis produces lateral offsets and segmentation, consistent with oblique subduction. The eastern backarc is characterized by complex fault systems and tilted fault blocks that control sediment accommodation and depositional patterns, creating conditions favorable for hydrocarbon accumulation.

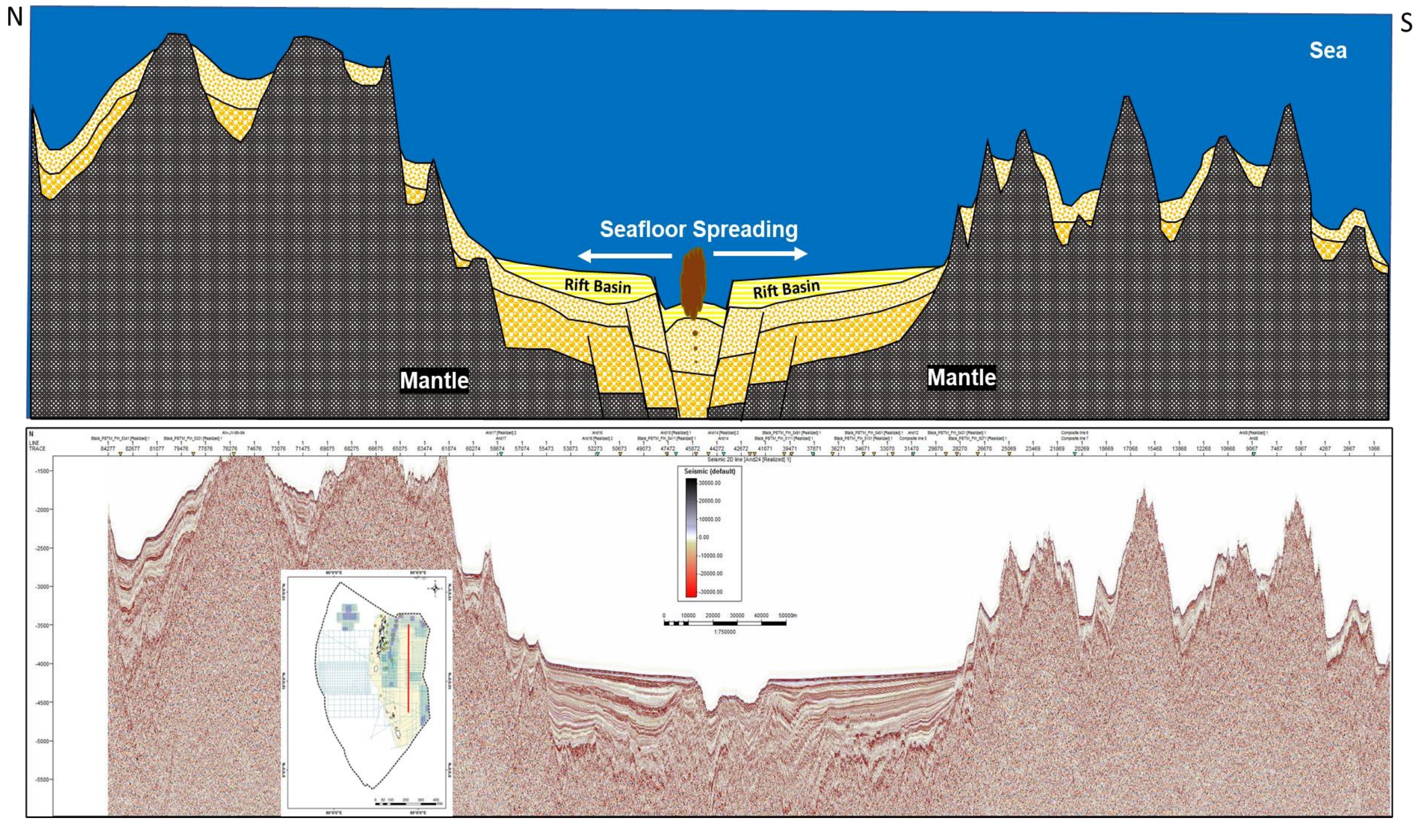

Figure 5: Seafloor spreading zone profile with extension data [3].

4.2. Structural and Morphological Features

Seismic and bathymetric data illustrate the complex arc–trench system morphology. Major tectonic elements include the trench, accretionary prism, forearc basin, volcanic arc, and backarc basin. The trench forms a deep linear depression marking the Indian-Sunda subduction interface [22]. The accretionary prism consists of imbricated thrust slices grading into a forearc basin filled with Miocene–Recent sediments. The volcanic arc forms structural highs and volcanic edifices separating forearc and backarc depocenters [4]. Strike-slip faults trending NW–SE accommodate lateral spreading ridge displacement, influencing structural traps and secondary porosity.

4.3. The 90° East Ridge: Structure and Regional Influence

The 90° East Ridge (90ER) is a major lithospheric-scale volcanic feature extending >5,000 km, formed by Late Cretaceous mantle plume activity near the Kerguelen hotspot [10, 7, 23, 24]. It trends nearly N–S with 200–400 km width and elevations 1.5–2.5 km above surrounding seafloor. Its highest peaks lie ~2 km below sea level with volcanic cones and seamount chains indicating multiple eruptive phases (Fig. **6**). The ridge controls regional stress and subsidence patterns, influences sediment influx from the Indian margin, and affects reservoir facies composition and distribution.

4.4. Basin Evolution

Seismic interpretation and geology suggest three tectono-stratigraphic phases: syn-rift, early post-rift, and late post-rift (Fig. **7**).

- **Syn-Rift Phase (Late Eocene–Oligocene):** Basin initiation by extensional faulting and rifting through NW–SE strike-slip faults. Fluvial–lacustrine sediments in half-graben structures form primary syn-rift clastic plays with organic-rich lacustrine shales as source rocks [6, 2].

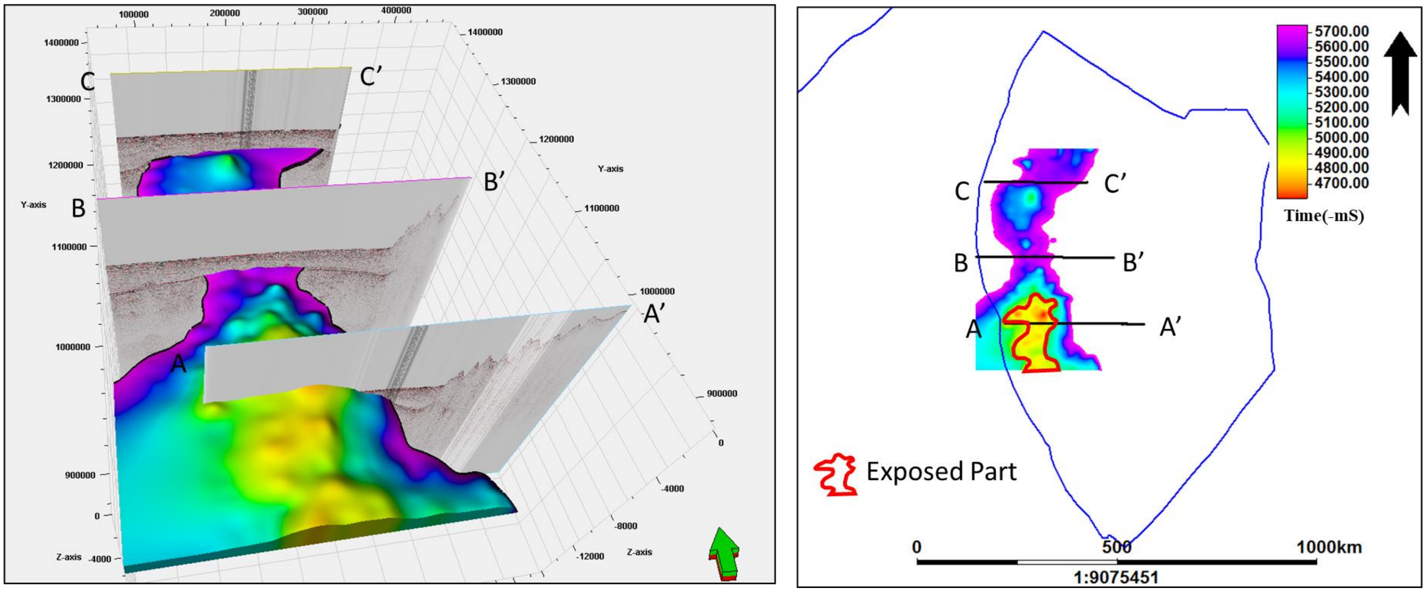

Figure 6: Morphological details of the 90° East Ridge, including volcanic cones [7].

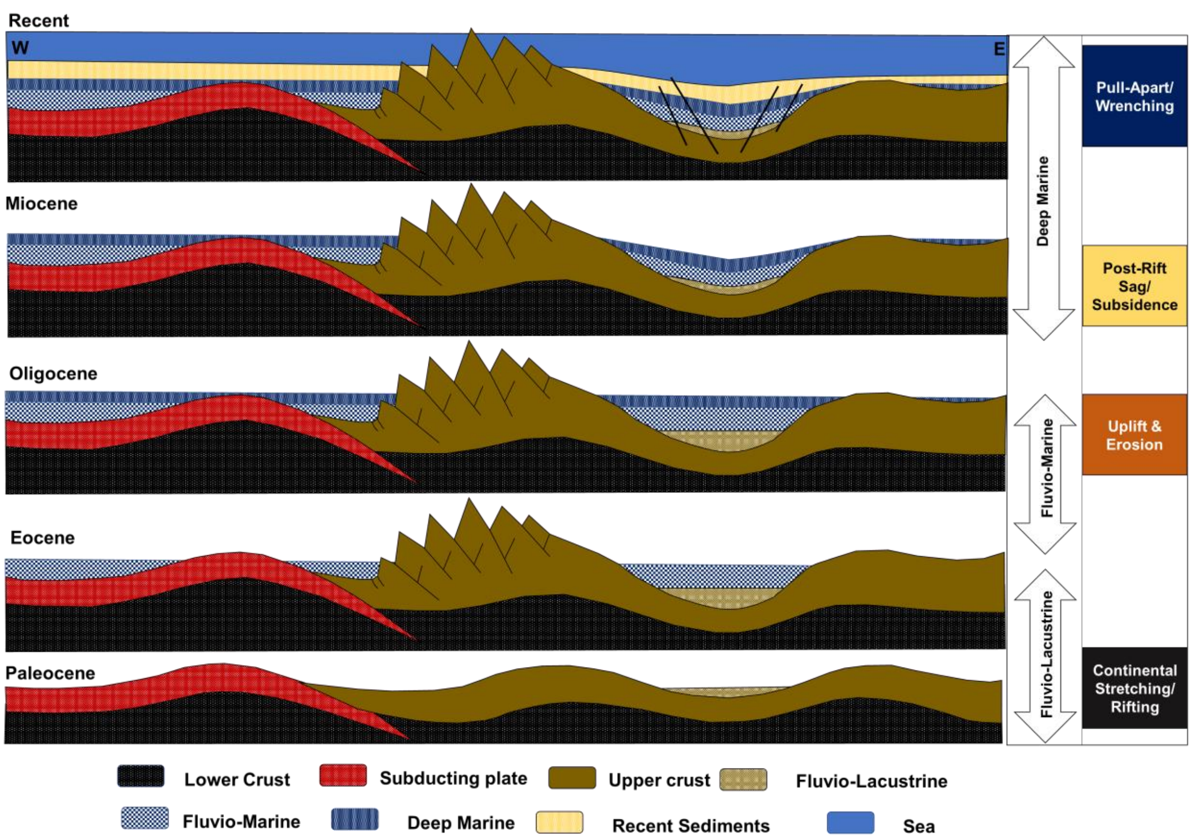

Figure 7: Paleo-structural evolution diagrams through geologic time [2].

- **Early Post-Rift Phase (Late Oligocene–Early Miocene):** Regional thermal subsidence and marine transgression deposited shallow marine clastics and carbonates on structural highs, creating carbonate plays. Reactivated faults created traps [6, 16, 7].
- **Late Post-Rift Phase (Middle Miocene–Recent):** Compressional deformation and inversion from India–Eurasia collision caused folding, thrusting, and continued backarc rifting. Regressive deltaic and deep marine fan sandstones form late post-rift clastic plays with intra-formational shale seals [16, 6, 25].

A schematic, derived from the seismic profiles shown in Fig. (**8**), effectively illustrates an ideal east–west arc–trench system. This profile enhances understanding of the basin's tectonic evolution, clearly delineating the trench, accretionary prism, island arc, forearc basin, volcanic arc, backarc basin, and seafloor spreading—key elements that collectively define the basin's geological development.

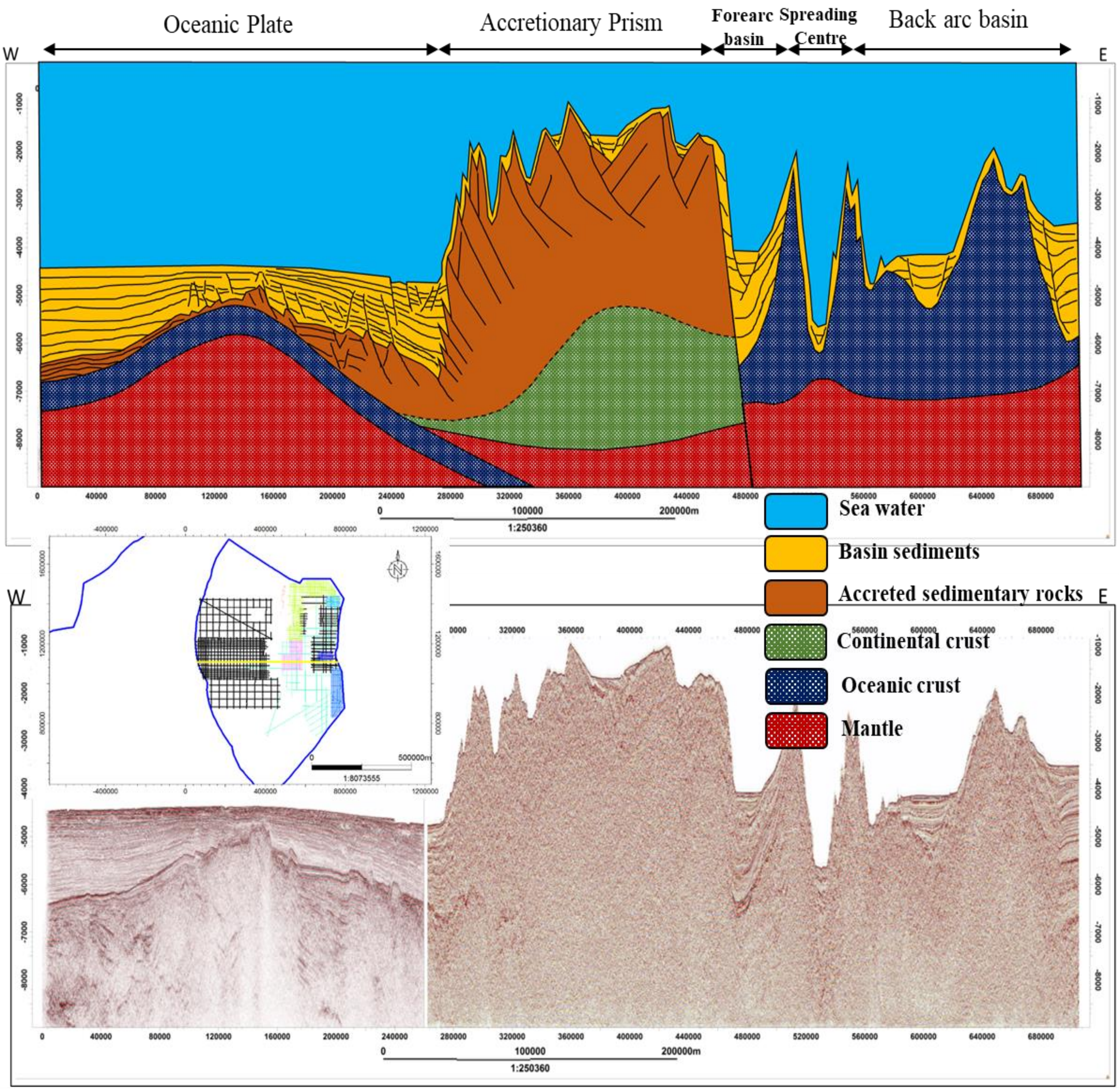

Figure 8: Annotated seismic line showing trench, accretionary prism, arc, and backarc features.

4.5. Hydrocarbon Play Types

Integration of paleo-tectonic reconstruction, seismic stratigraphy, and sedimentological data enables the identification of four principal hydrocarbon play types [26] within the Andaman Basin (Fig. **9**; Table **1** & **2**):

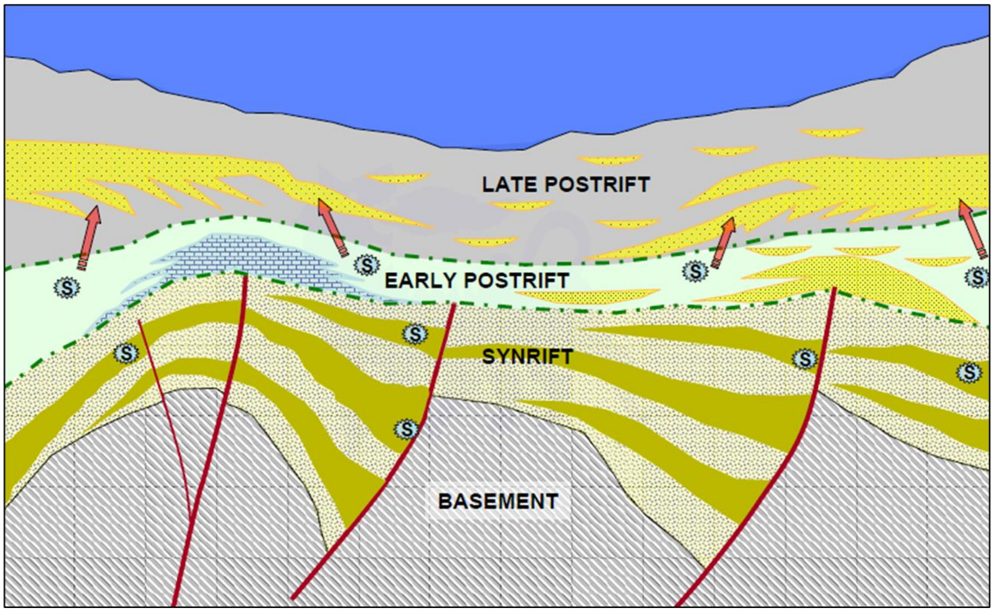

Figure 9: Conceptual hydrocarbon play types integrating source, reservoir, seal, and trap.

Table 1: Summary of hydrocarbon play types identified in the Andaman–Nicobar Basin.

Play Type	Source Rock	Reservoir	Seal	Trap Type	References
Syn-rift clastic	Lacustrine and fluvial shales	Fluvial to marine sands	Syn-rift lacustrine shales	Structural and stratigraphic	[3, 2]
Early post-rift carbonate	Lacustrine/marine shales	Reefal and platform carbonates	Marine shales	Structural highs	[2, 16, 7]
Early post-rift clastic	Marine shales and siliciclastic intercalations	Deltaic sands and shallow marine	Transgressive-regressive shales	Stratigraphic draped traps	[2, 3]
Late post-rift clastic	Marine shale	Regressive deltaic and fan sands	Intra-formational shale	Fault and inversion traps	[16, 3, 2]

Table 2: Estimated thickness, porosity range, and corresponding data sources for the identified hydrocarbon play types in the Andaman–Nicobar Basin.

Play Type	Estimated Thickness (km)	Porosity (%)	Data Sources
Syn-rift clastic	0.5 – 1.5	12 – 18	[3, 2]
Early post-rift carbonate	0.8 – 2.0	15 – 22	[16, 6, 7]
Early post-rift clastic	1.0 – 2.5	15 – 25	[3, 2]
Late post-rift clastic	1.2 – 2.5	18 – 25	[16, 3, 2]

5. Discussion

Since the 1960s, the Andaman Basin has been the focus of extensive research by numerous geoscientists. They have meticulously mapped its key tectonic features and provided interpretations of its evolutionary history. The published literature contains several tectonic maps and hypotheses about the basin's evolution. Significant contributions to this field include the works of Arora & Misra [17]; Curray [1]; Ghosh *et al*. [16]; Kamesh Raju *et al*. [27]; Mukhopadhyay [19]; Pal *et al*. [12] among others. Their investigations primarily relied on non-seismic data and a conceptual understanding of the basin's configuration.

The advent of newly acquired seismic data, especially from the basin's western region, has been crucial in providing a clear framework for understanding the paleo-tectonic evolution. This data illustrates the revised tectonic and geomorphological features within the basin (Fig. **4**). The seismic profiles, depicted in Fig. (**8**), serve as excellent representations of an ideal arc-trench system in an east-west orientation. This profile not only enriches our understanding of the basin's tectonic evolution but also reveals the trench, accretionary prism, island arc, fore-arc basin, volcanic arc, back-arc basin, and seafloor spreading which are the key tectonic elements that help in forming the comprehensive narrative of the basin's evolution. The extensive study of the basin's evolutionary history unravels its geological mysteries, providing a phase-wise account of tectonic evolution across geological time, as demonstrated in Fig. (**7**). The study encompasses various stages of rifting and their associated paleo-environments, crucial components for understanding the basin's petroleum system. The integration of tectonic and paleo-environmental analyses aids in conceptualizing key play types within the basin, as highlighted in Fig. (**9**). In essence, this comprehensive study successfully achieves its key objectives of the study. Therefore, this comprehensive study stands out due to its utilization of recent seismic data, contributing to an updated tectonic map, examination of the basin's paleo-tectonic evolution, and prediction of the paleo-sedimentary environment. This insightful approach enhances our understanding of the geological dynamics, paving the way for future hydrocarbon exploration efforts in the basin.

This study builds on but surpasses earlier models [1, 3, 27, 28] with direct imaging of tectonic segmentation, refined spreading center locations, and identification of previously uncharted hydrocarbon plays, effectively integrating seismic data and structural evolution to predict prospective areas.

6. Conclusions

The integrated seismic and structural analysis of the Andaman–Nicobar Basin provides a comprehensive understanding of its tectono-stratigraphic evolution and hydrocarbon potential. The basin developed through distinct phases of syn-rift, early post-rift, and late post-rift tectonics, which controlled sedimentation patterns, structural configurations, and depositional environments. Detailed interpretation of seismic data reveals a classic arc–trench–backarc system, including the trench, accretionary prism, volcanic arc, forearc and backarc basins, as well as newly identified spreading centers and structural highs. This multi-phase evolution has created a range of hydrocarbon play types, including syn-rift clastic, early post-rift carbonate, early post-rift clastic, and late post-rift clastic systems, characterized by significant thicknesses, porosities, and trap configurations. The western forearc and backarc regions, previously underexplored, are now identified as prospective areas for future exploration. Overall, this study not only refines the understanding of the basin's geological history but also provides a robust framework for identifying and prioritizing hydrocarbon targets, offering critical insights to guide future exploration and development in this tectonically complex and frontier basin.

Conflict of Interest

The author declares no conflicts of interest.

Funding

The study received no financial support.

Acknowledgments

Thanks are extended to the Directorate General of Hydrocarbons and Dr. Kaustav Nag (ADG-E, DGH) for permission to publish this work. Special thanks to Dr. Ravi Mishra and reviewers for valuable feedback.

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