

Detrital Zircon U-Pb Geochronology Reveals Sediment Pathways and Depositional Systems for Lower Miocene Reservoirs, Cuu Long Basin, Vietnam

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Abstract

The oil and gas industry faces increasing challenges in replenishing reserves. Enhancing exploration efficiency requires the integration of diverse datasets to build robust geological models. This study investigates the provenance and depositional systems of Lower Miocene sandstone reservoirs in the Cuu Long Basin (CLB), offshore Vietnam. We integrate 3D seismic, wireline log, conventional core, and detrital zircon U-Pb geochronological data to build a comprehensive source-to-sink model. Our findings reveal that the clastic components of the Lower Miocene sandstones (formations BI.1 and BI.2) predominantly originate from Cretaceous (ca. 105–108 Ma) magmatic rocks of the adjacent Dalat Zone on the Vietnamese mainland, with minor contributions from recycled older crustal sources. Seismic and well data show deposition occurred in environments ranging from alluvial-fluvial plains to more marine-influenced deltaic and coastal plain settings. This work provides new, high-resolution constraints on the provenance, depositional systems, and tectonic controls that influenced reservoir development in the Early Miocene CLB, offering crucial insight for future hydrocarbon exploration in the region.

Keywords:

Cuu Long Basin; Lower Miocene; U-Pb zircon; provenance; tectonic evolution

1. Introduction

Determining the provenance and depositional controls of sedimentary sequences, particularly in complex offshore basins, presents significant challenges (Dung et al., 2018; Breiffeld et al., 2022). Factors influencing sediment generation, transport, deposition, and diagenesis are numerous and intertwined (Ta et al., 2021; Thanh et al., 2021). Identifying the source of clastic minerals within sedimentary rocks provides crucial insight into paleogeography, erosion patterns, and sediment routing pathways (Tran et al., 2007; Breiffeld et al., 2020). Understanding the relationship between origin of the material and reservoir characteristics necessitates a multi-faceted approach, combining geophysical, sedimentological, and geochemical methods (Shellnutt et al., 2013; Liu et al., 2020).

The CLB offshore southeast Vietnam is a significant Cenozoic hydrocarbon reservoir (Breiffeld et al., 2022; Hieu, 2015). Although studies have established a gen-

eral stratigraphic framework and identified key petroleum systems (e.g. Dung et al., 2018; Ta et al., 2021; Hennig-Breiffeld et al., 2021), the specific provenance and depositional controls on the economically important Lower Miocene sandstone reservoirs (formations BI.1 and BI.2) remain debated. Accurate knowledge of the characters of these reservoirs, including their geometry, petrophysical properties, and compositional variability, is critical for optimizing ongoing exploration and production (Faure et al., 2018; Nguyen et al., 2019). Isotopic dating techniques, such as U-Pb geochronology on detrital zircons, offer powerful tools for tracing sediment provenance and correlating strata (Boehnke et al., 2013; Hieu et al., 2017; Tod et al., 2021; Pham et al., 2022). Previous studies (Hieu et al., 2022; Pham et al., 2022; Shellnutt et al., 2013) have documented that the Cretaceous magmatism in potential source regions like the Dalat Zone (e.g. 107–75 Ma, Tod et al., 2021; 91 Ma, Pham et al., 2022), might provide significant detritus of the Lower Miocene sandstone. However, a dedicated study integrating detailed core analysis, well log stratigraphy, seismic interpretation, and detrital zircon U-Pb is still lacking, specifically for the Lower Miocene reservoir intervals across the northwestern and central CLB.

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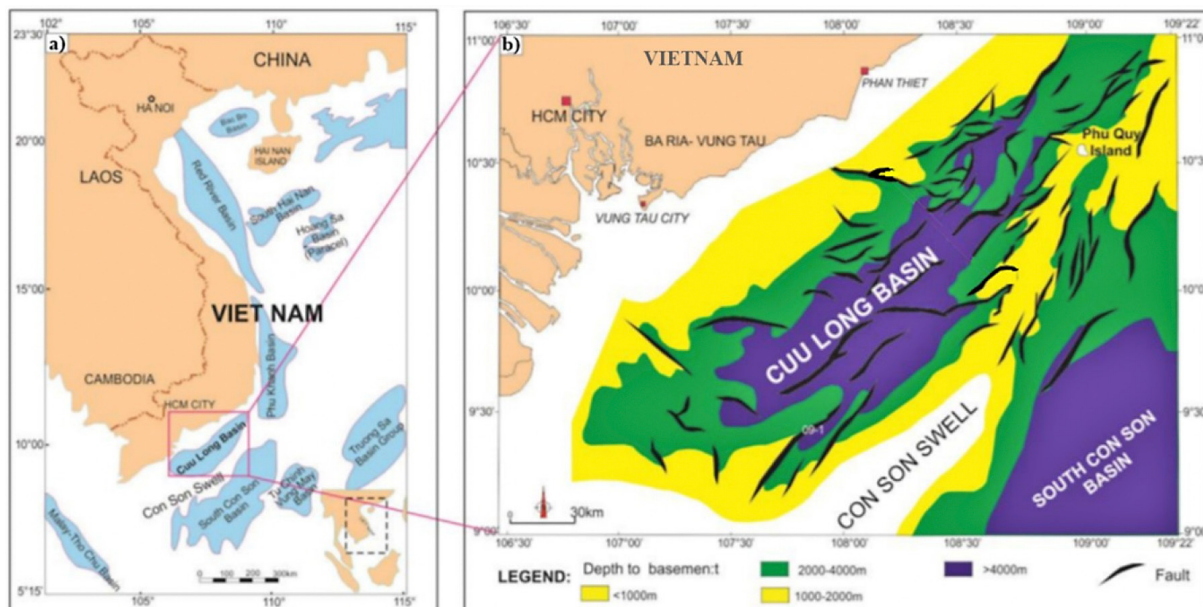


Figure 1. Location map of the Cuu Long Basin. (a) Regional map of Southeast Asia showing the location of the Cuu Long Basin (CLB). (b) Detailed map of the CLB showing major structural elements, the study area, the locations of key wells used in this study (including WT₁₀ and WT₁₉ for U-Pb dating), and the location of the collected samples as shown in **Figure 3**. (Modified from VNOGG, 2019; Breitfeld et al., 2022).

This study aims to fill this gap by providing a comprehensive analysis to determine the provenance, depositional processes, and tectonic context controlling the formation of the Lower Miocene (BI.1 and BI.2) sandstone reservoirs in the CLB. The objectives of this research are: (1) To refine the seismic stratigraphic framework for the Lower Miocene section; (2) To characterize the lithological and petrophysical properties of the reservoir intervals using well log and core data; (3) To determine the provenance of the reservoir sandstones using detrital zircon U-Pb geochronology; and (4) To synthesize these datasets to interpret the depositional environments and assess the influence of regional tectonics on reservoir development. The novelty of this research lies in its integrated approach, providing new, high-resolution U-Pb zircon age constraints directly from the reservoir units. These new data explicitly link to seismic and well log data to build a coherent tectono-sedimentary model for the Early Miocene evolution of the CLB.

2. Geological Background

The Cuu Long Basin (CLB) is a major Cenozoic rift basin located on the southern continental shelf of Vietnam, extending partially onto the Mekong Delta (Thanh et al., 2021). It is one of the most prolific hydrocarbon areas in Southeast Asia, with significant oil and gas accumulations primarily within Oligocene to Miocene clastic reservoirs and fractured granitic basement. The basin exhibits an oval shape, arching southeastward, and lies between 9°00'N and 11°00'N and 106°30'E to 109°00'E (see **Figure 1**). It is bounded by the coast to

the northwest, the Con Son uplift zone (separating it from the Nam Con Son Basin) to the southeast, the Tuy Hoa fault zone (separating it from the Phu Khanh Basin) to the northeast, and the Khorat-Natuna uplift zone to the southwest (Hieu, 2015).

The tectonic evolution of the CLB is characterized by several major phases:

Pre-rift phase (Pre-Cenozoic Basement): The basement largely comprises fractured granitoids and metamorphic rocks, which are important hydrocarbon reservoirs in some fields (Tran et al., 2007).

Syn-rift phase (Oligocene to Early Miocene): This phase involved extensive rifting, driven by the collision between the Indian and Eurasian plates. This led to the formation of numerous horst and graben structures, which controlled initial sediment deposition. Sedimentary infill during this phase includes coarse clastics (conglomerates, sandstones) and shales, often with volcanic interbeds (see **Figure 2**).

Post-rift thermal sag phase (Early Miocene to Quaternary): Following rifting, the basin underwent thermal subsidence, leading to the deposition of a thick Cenozoic sedimentary succession. This phase is characterized by a transition from continental to marine-influenced environments.

Exploration in the CLB commenced in 1967, with the first wildcat well drilled in 1974 (Bach Ho structure), providing foundational geological data (Dung et al., 2018; Breitfeld et al., 2022). The general stratigraphic column (see **Figure 2**) comprises a pre-Cenozoic basement overlain by a Cenozoic sedimentary succession punctuated by several volcanic events. This study fo-

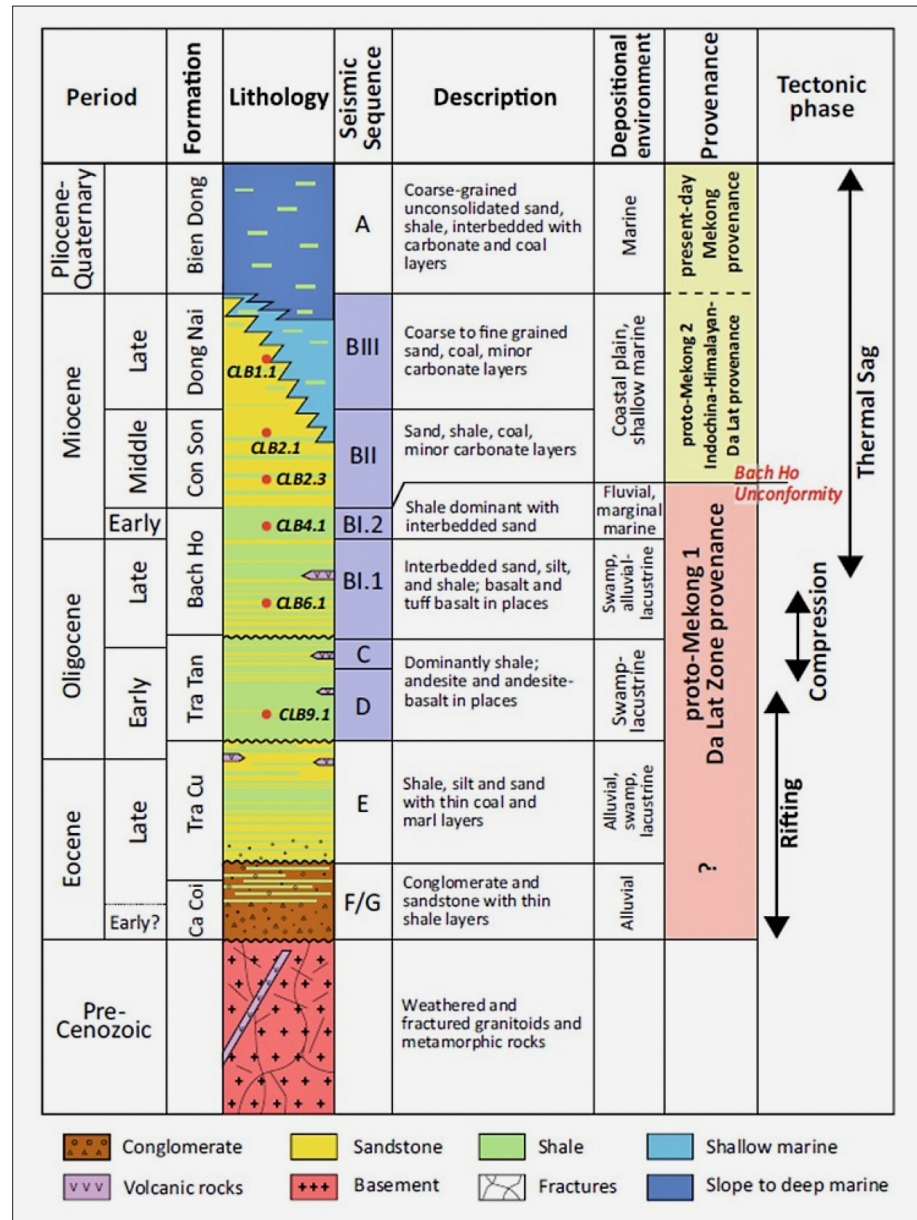


Figure 2. Generalized stratigraphic column for the Cuu Long Basin, showing key formations, seismic sequences, depositional environments, tectonic phases, and interpreted provenance signatures. The Lower Miocene interval of interest (BI.1 and BI.2) is highlighted. (Modified from Breitfeld et al., 2022).

cuses on the Lower Miocene sedimentary section, specifically the BI.1 and BI.2 sequences (see **Figure 2**), which are well known for significant hydrocarbon accumulations. These formations represent key targets for exploration and production, and understanding their provenance and depositional history is critical for optimizing resource recovery.

3. Methods

We integrated various datasets to investigate the Lower Miocene reservoirs.

3.1. Seismic and Well Data

Approximately 2,000 km of 2D and 4,800 km² of 3D seismic reflection data across the northwestern and central CLB were utilized. We performed sequence strati-

graphic analysis by identifying and mapping key sequence boundaries (specifically SH-5 and SH-7, which bound the Lower Miocene). Seismic facies distributions were mapped based on reflection characteristics (amplitude, continuity, configuration) and calibrated by tying seismic data to 32 well locations. Well log interpretation (**Rider, 1996**) and conventional core data provided direct lithological and environmental information, allowing us to ground-truth the interpretation of seismic patterns (e.g. chaotic, high-amplitude reflections corresponding to channelized sandstones).

3.2. Core and Petrographic Analysis

Two conventional cores from the Lower Miocene section in wells WT10 (sample BK03) and WT19 (sample BK04) were strategically chosen for U-Pb dating to represent different positions within the basin. An additional

200 thin sections from various wells were analyzed for petrography. This involved point counting (minimum 300 points per slide) to determine mineralogical composition. To aid in provenance interpretation, modal compositions from the petrographic dataset (N=200) were plotted on a Quartz-Feldspar-Lithic fragment (QFL) ternary diagram following the methodology of Dickinson (1985).

3.3. Detrital Zircon U-Pb Geochronology

Zircon grains were separated from the two core samples (BK03, BK04) using standard heavy liquid and magnetic techniques. Cathodoluminescence (CL) imaging was performed to reveal internal structures and guide laser spot placement. U-Pb isotopic analyses were conducted in-situ using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS), following procedures described by Hieu et al. (2013). Raw data were processed using GLITTER software (Griffin et al., 2008). Analytical results exhibiting discordance greater than 10% were excluded from the final geological interpretation to ensure data robustness. For zircons <1000 Ma, the $^{206}\text{Pb}/^{238}\text{U}$ age is used; for grains >1000 Ma, the $^{207}\text{Pb}/^{206}\text{Pb}$ age is preferred. Age distributions were plotted as probability density plots (PDPs) with kernel density estimates (KDE) using IsoplotR (Vermeesch, 2018). Age peaks were statistically identified from the maximum on the generated KDE curves.

4. Results

4.1. Seismic Stratigraphy and Facies

The Lower Miocene interval is clearly bounded by regional seismic horizons SH-5 (base) and SH-7 (top) and comprises two main sequences, BI.1 and BI.2 (see Figure 3). An illustrative seismic line shows the typical basin architecture, with fault-bounded horst and graben structures inherited from earlier rifting phases. Seismic facies analysis reveals significant lateral variations. In the northwestern part of the study area, the BI.1 and BI.2 intervals are often characterized by discontinuous, chaotic to sub-parallel, moderate-to-high amplitude reflections (see Figure 4). Tying these facies to wells reveals they correspond to sections with blocky, sand-prone log signatures, interpreted as channelized fluvial and distributary channel systems. Towards the east and southeast, these facies transition into more continuous, parallel to sub-parallel, lower-amplitude reflections, which correspond to more heterolithic log signatures, interpreted as lower-energy coastal plain, floodplain, or distal deltaic deposits as illustrated on the seismic profile (see Figure 3) and paleo-environmental maps (see Figure 4).

4.2. Well Log Characteristics and Reservoir Properties

Well log correlation across the study area shows that the Lower Miocene interval generally thickens from

west to east (see Figure 5). The BI.2 reservoir interval ranges from 250 m to over 600 m thick. In the SD field, petrophysical analysis indicates good reservoir quality with porosity (ϕ) from 17% to 27% and net-to-gross (NTG) from 28% to 61.5%. The underlying BI.1 reservoir varies from 110 m to over 650 m thick. In the HS area, it exhibits porosities of 19-22% and NTG of 55-70% (see Table 1).

4.3. Core Lithology and Sandstone Composition

Core observations from the BI.1 and BI.2 intervals show light- to dark-gray, fine- to medium-grained sandstones with features including cross-bedding, laminations, and fining-upward trends (see Figure 6). Petrographic analysis reveals the sandstones are predominantly Arkose and Lithic Arkose. They are compositionally immature, containing abundant feldspar (32-34%, mostly K-feldspar) and lithic fragments (2-8%, mostly volcanic and granitoid), in addition to quartz (30-33%) (see Table 2). The modal composition data, when plotted on a Dickinson (1985) QFL diagram, falls overwhelmingly in the "Dissected Arc" and "Transitional Arc" provenance fields (see Figure 7). This strongly indicates that the sediment was derived from the erosion of a magmatic arc terrane.

4.4. Detrital Zircon U-Pb Geochronology

The U-Pb dating results from both samples (BK03 and BK04) are strikingly similar (see Figure 8). Sample BK03-WT10 yielded a dominant Cretaceous age population (63.3% of grains) with a prominent peak at ca. 108 Ma. Sample BK04-WT19 also yielded a dominant Cretaceous age population (67.4% of grains) with a prominent peak at ca. 105 Ma. Both samples also contain subordinate populations of older, likely recycled zircons, including Permian-Triassic (ca. 210-280 Ma), Ordovician-Silurian (ca. 440-460 Ma), and Precambrian grains. The Cretaceous zircons are typically euhedral to subhedral with clear oscillatory zoning, indicative of a magmatic origin and relatively short transport (see Figure 9).

5. Discussion

5.1. Provenance of Lower Miocene Sediments

The detrital zircon U-Pb age data provide robust, quantitative evidence for the primary sediment source. The overwhelming predominance of Cretaceous zircons (ca. 105–108 Ma) in both samples points unequivocally to the Dalat Zone on the adjacent Vietnamese mainland as the principal source terrane (see Figure 8). This age range correlates perfectly with the well-documented Cretaceous granitoid intrusions and volcanic rocks of the Dalat Zone (Shellnutt et al., 2013; Hieu et al., 2017; Tod et al., 2021). This interpretation is strongly supported by the petrographic data, as the arkosic composition classifies the sandstones within the "Dissected Arc" field on the QFL diagram (see Figure 7), a classic

Figure 3. The map shows key sequence boundaries SH-3 (top) and SH-7 (base) bounding the Lower Miocene formations BL.1 and BL.2. Note the underlying horst-and-graben basement structure. The seismic facies transition from chaotic/sub-parallel in the west (interpreted as fluvial/proximal deltaic) to more parallel/continuous in the east (interpreted as distal deltaic/coastal plain) is highlighted. The “collected sampling area” refers to the region where core samples for U-Pb dating were acquired.

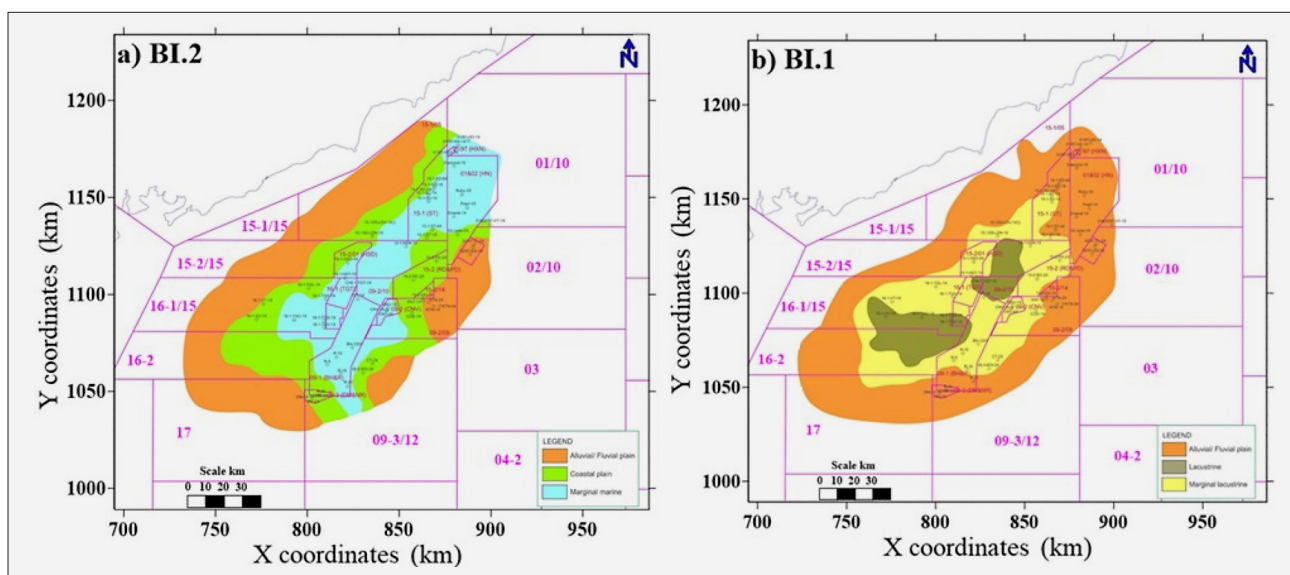
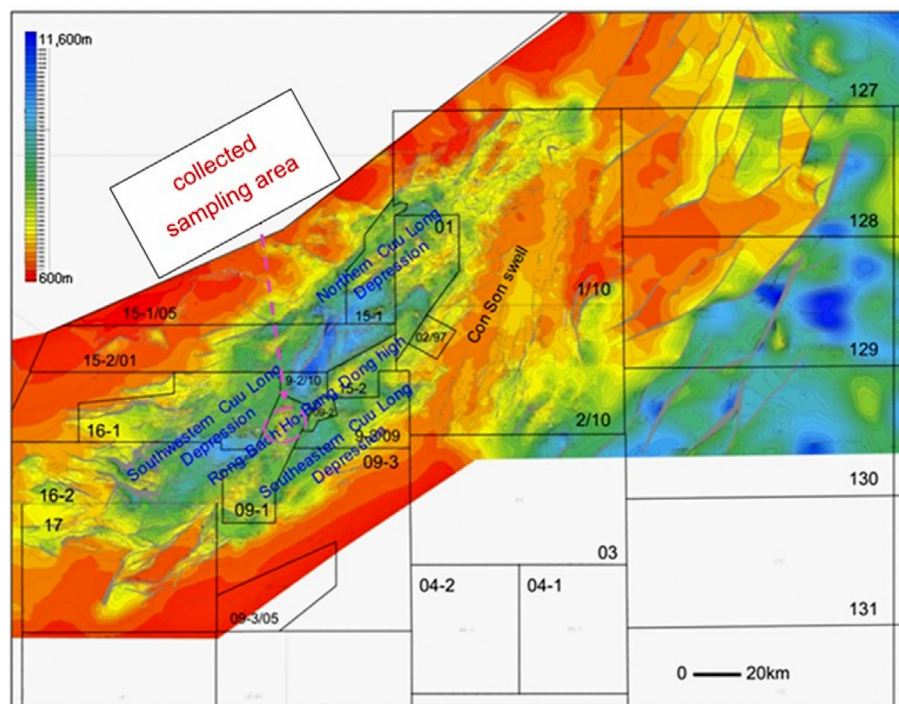


Figure 4. Interpreted paleo-environmental maps for the Lower Miocene sequences a) BL.1 and b) BL.2 based on seismic facies analysis calibrated to well data. The maps illustrate the distribution of depositional systems, transitioning from fluvial-dominated in the west to more deltaic/marine-influenced in the east.

signature of sediment derived from an eroded granitic-volcanic arc. The euhedral to subhedral morphology of the Cretaceous zircons (see **Figure 6**) suggests relatively short transport distances, consistent with derivation from the adjacent mainland.

Our results provide the first direct geochronological confirmation for the provenance of these specific reservoir units. While previous studies (e.g. **Breitfeld et al., 2022**) inferred a Dalat Zone source, our data quantify its dominance (~65%). Furthermore, the lack of a significant Permian-Triassic zircon peak, which is characteris-

tic of the Mekong River system, suggests that a “Proto-Mekong” source had minimal to no influence on deposition in the northwestern CLB during the Early Miocene. The subordinate older zircon populations were likely recycled from Paleozoic-Mesozoic sedimentary cover rocks or basement terranes exposed within the Dalat Zone’s eroding hinterland.

5.2. Depositional Environments and Pathways

Integrating core, well log, and seismic data allows for a refined interpretation of depositional environments.

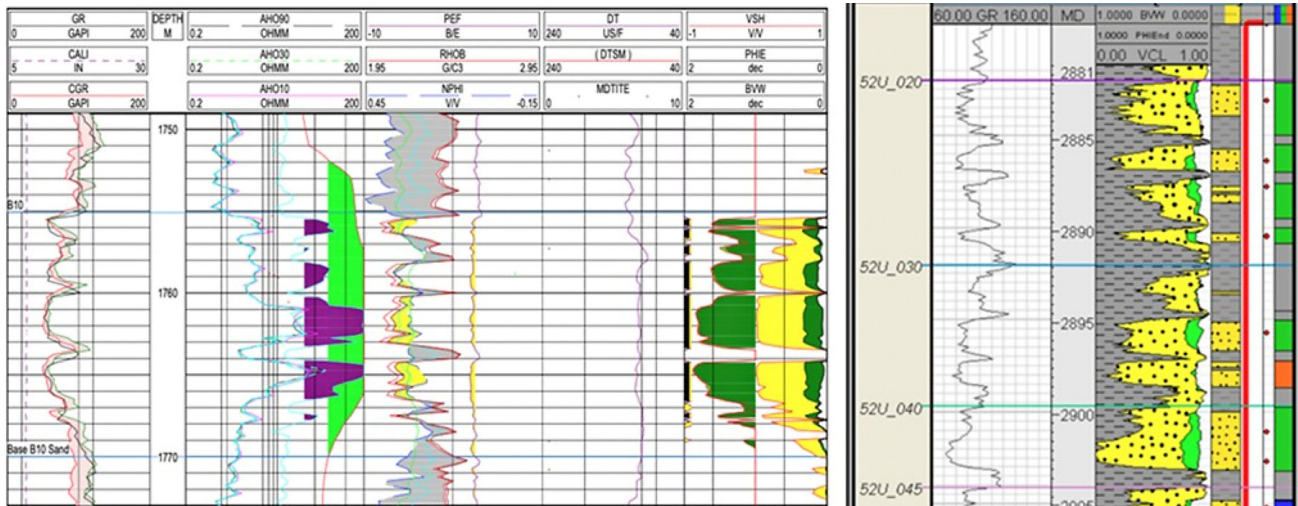


Figure 5. The map shows well logs from two different wells. Gamma Ray (GR) and Resistivity (RES) logs are displayed. Low GR (yellow) indicates sand-prone intervals, while high GR (green/gray) indicates shale-prone intervals (Modified from Tran and Phung, 2007).

Table 1. Summary of Reservoir Properties for BI.1 and BI.2 Formations.

Formation/Area	Average Porosity (%)	Average Water Saturation (%)	Average Net-to-Gross (%)	Depositional Environment
BI.2 (HS Field)	19	45	62	Delta Front / Distributary Channel
BI.2 (SD Field)	16	65	35	Lower Delta Plain / Interdistributary Bay
BI.1 (Central Area)	22	40	70	Fluvial Channel Belt (Braided/Meandering)
BI.1 (Basin Margin)	15	55	45	Alluvial Plain / Floodplain

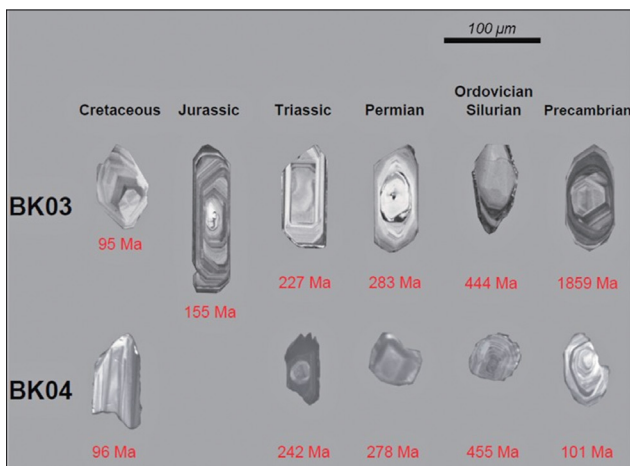


Figure 6. Cathodoluminescence image of pre-Cambrian zircon grains and cathodoluminescence image of ordovician-silurian zircon grains in core samples BK03 and BK04.

The Lower Miocene succession records a transition from terrestrial to marine-influenced settings.

Formation BI.1 is interpreted as being deposited primarily in alluvial and upper delta plain environments. The blocky, sand-prone seismic and well-log facies represent fluvial channel belts.

Formation BI.2 represents a landward shift of environments, with deposition occurring in lower delta plain to coastal plain and marginal marine settings. The inter-

Table 2. Summary of Petrographic Modal Data for Lower Miocene Sandstones.

Component (%)	Sample BK03	Sample BK04	Range (N=200)
Framework Grains			
Monocrystalline Quartz	30.5	28.6	25-35
Polycrystalline Quartz	2.2	3.7	1-5
K-Feldspar	32.1	30.3	28-35
Plagioclase Feldspar	1.8	3.1	1-4
Volcanic Lithic Fragments	2.5	8.1	2-10
Granitoid Lithic Fragments	1.0	1.5	< 2
Matrix (Detrital Clay)	6.7	7.2	5-10
Cement (Authigenic)	13.2	7.5	5-15
<i>Provenance Classification</i>	<i>Lithic Arkose</i>	<i>Feldspathic Litharenite</i>	<i>Arkose / Lithic Arkose</i>

bedded nature of sands and shales reflects deposition in distributary channels, mouth bars, and adjacent lower-energy interdistributary bays or floodplains.

The overall sediment transport pathway was from the uplifted Dalat Zone in the northwest towards the subsiding basin center in the southeast. Reservoir quality is

highest in the sandstone facies associated with higher-energy channel axes (see **Table 1**).

5.3. Tectonic Controls on Sedimentation

Early Miocene sedimentation occurred during the post-rift thermal sag phase of the CLB's evolution. The primary control on sediment supply was the significant uplift and erosion of the Dalat Zone magmatic arc. This uplift was likely driven by a combination of regional tectonic forces, including post-rift thermal doming and far-field stresses related to the ongoing India-Asia collision (**Hieu, 2015; Breielfeld et al., 2022**). The creation of accommodation space was controlled by regional thermal

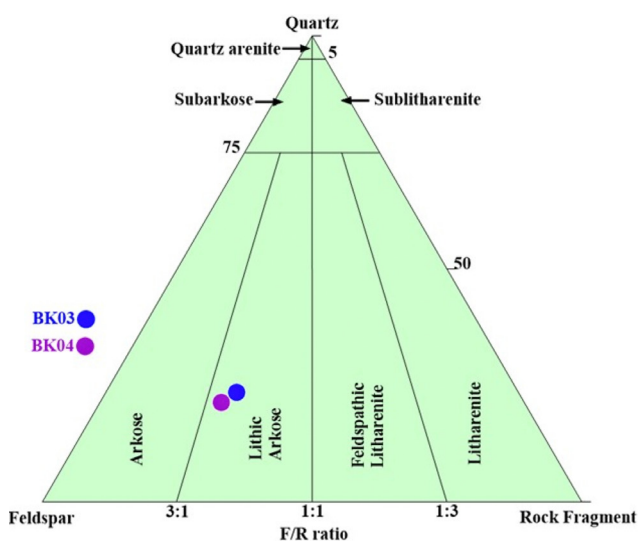


Figure 7. Quartz-Feldspar-Lithic (QFL) fragment ternary diagram for sandstone classification. The diagram is plotted using modal composition data from 200 thin sections across the study area.

subsidence, while the distribution of depositional systems was heavily influenced by the underlying basement topography of horsts and grabens, which focused sediment fairways into structural lows. The overall landward-to-seaward transition from BI.1 to BI.2 reflects a relative sea-level rise, consistent with a long-term transgressive-to-highstand sequence set. The stacking patterns observed on seismic data, with fluvial systems (BI.1) overlain by more widespread deltaic/coastal systems (BI.2), are consistent with a long-term transgressive-to-highstand sequence set (see **Figure 3**).

5.4. Implications and Limitations

This integrated study provides a robust source-to-sink model for the Lower Miocene reservoirs in the CLB. The confirmation of a proximal, stable Dalat Zone source and the delineation of depositional fairways controlled by basement structure are critical for predicting reservoir distribution and quality in less explored parts of the basin. The provenance conclusions are based on two sample locations, and while their consistency provides confidence, further spatial variability could exist. Similarly, the density of well and core data limits the resolution of paleo-environmental mapping. Future research could expand the detrital zircon dataset to other parts of the basin to test for spatial or temporal changes in provenance and further refine sequence stratigraphic models.

6. Conclusions

This integrated study of the Lower Miocene reservoirs in the Cuu Long Basin provides significant new insight into their origin and distribution. Our key conclusions are:

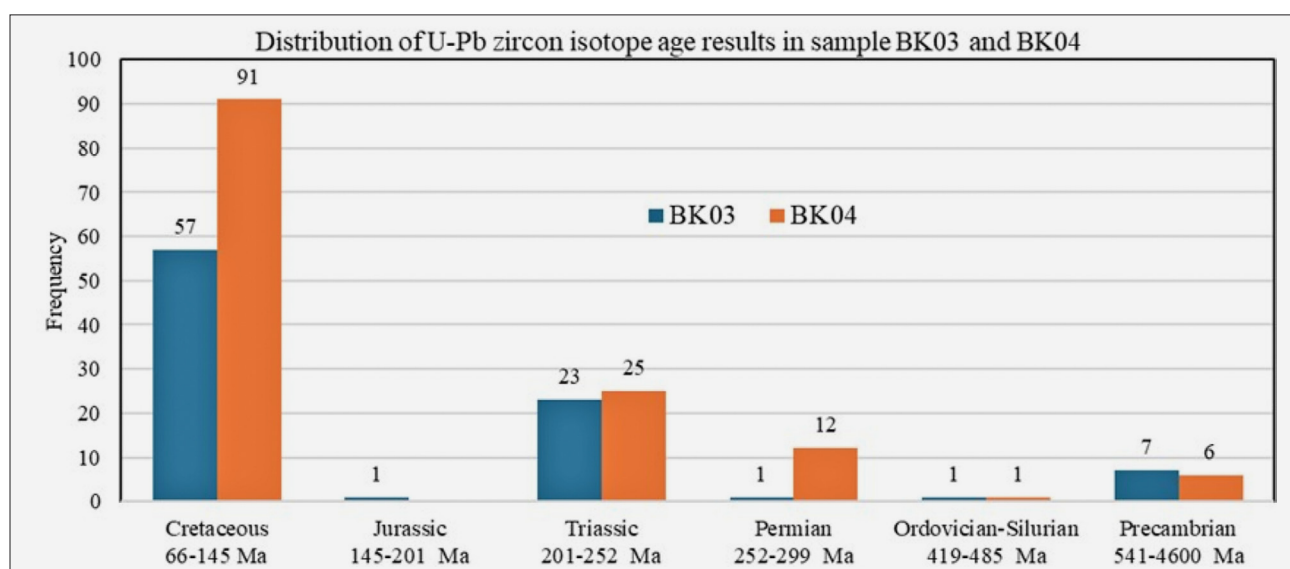


Figure 8. Probability Density Plots (PDP) of detrital zircon U-Pb ages for Lower Miocene sandstone samples from the Cuu Long Basin with sample BK03-WT10 (n=90) and sample BK04-WT19 (n=135). Both samples are dominated by Cretaceous age peak between 100-110 Ma.

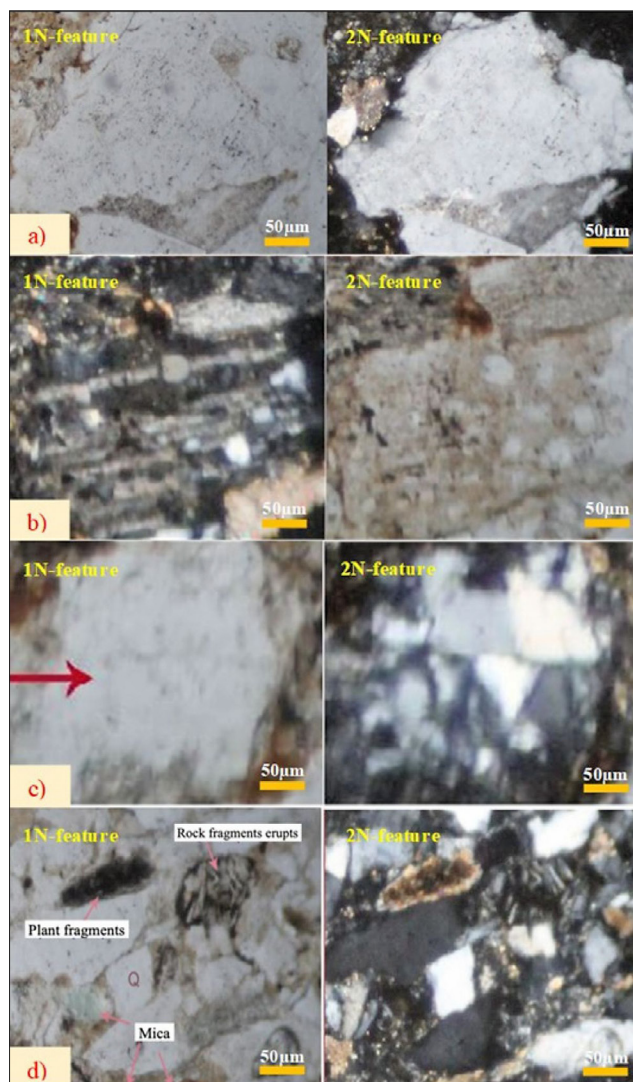


Figure 9. Photomicrographs of Lower Miocene sandstones from the Cuu Long Basin. Granite rock fragment composed of a) multiple feldspar minerals b) plagioclase with albite twinning, c) Poly quartz fragment and thin section photomicrograph BKO₃ under polarizing microscope d) plant debris, volcanic rock fragments, mica fragments, quartz (Q).

Primary Provenance Confirmed: Detrital zircon U-Pb geochronology definitively establishes the Cretaceous (ca. 105-108 Ma) magmatic rocks of the Dalat Zone as the primary sediment source for the BI.1 and BI.2 sandstone reservoirs. Contributions from other sources, such as a Proto-Mekong River, were negligible in the study area.

Depositional Systems Delineated: Sedimentation occurred in a range of environments transitioning from alluvial/fluviial plains (predominantly BI.1) to deltaic and coastal plain settings (predominantly BI.2), with sediment transport directed from northwest to southeast. Reservoir heterogeneity is directly linked to these depositional sub-environments.

Tectono-Sedimentary Model Refined: Early Miocene sedimentation was controlled by the interplay of

tectonic uplift of the source terrane, post-rift thermal subsidence creating accommodation space, and underlying basement structures influencing sediment pathways.

Ultimately, this study provides a robust, integrated geological framework that reduces exploration risk by improving predictions of reservoir presence and quality. The methodologies and findings presented here are not only crucial for the Cuu Long Basin but also serve as a valuable case study for hydrocarbon exploration in other tectonically complex rift basins in Southeast Asia.

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SAŽETAK

Interpretacija taložnih sustava i izvorišta materijala donjomiocenskih naslaga u bazenu Cuu Longa, Vijetnam, na temelju U-Pb geokronologije detritičnih zrna cirkona

Naftna i plinska industrija suočava se sa sve većim izazovima u obnavljanju rezervi ležišta. Povećanje učinkovitosti istraživanja zahtijeva integraciju različitih skupova podataka kako bi se izgradili pouzdani geološki modeli. Ova studija istražuje podrijetlo i sustave taloženja ležišta donjomiocenskih pješčenjaka u bazenu Cuu Longa (CLB) na obali Vijetnama. U okviru rada integrirani su 3D seizmički, karotažni te konvencionalni podatci iz jezgara uz analize detritičnih zrna cirkona U-Pb metodom za utvrđivanje starosti. Provedena analiza načinjena je u svrhu izrade modela transporta od izvora do taložnoga prostora. Rezultati su pokazali da klastične komponente donjomiocenskih pješčenjaka (formacije BI.1 i BI.2) pretežno potječu iz magmatskih stijena kredne starosti (otprilike 105 do 108 milijuna godina) koje se nalaze u susjednoj Dalat Zoni na vijetnamskome kopnu, uz manji broj starijih, višestruko resedimentiranih zrna. Seizmički i bušotinski podatci pokazuju da se taloženje događalo u raznim okolišima, od aluvijalno-fluvijalnih ravnica do deltskih i obalnih ravnica koje su bile pod većim utjecajem mora. Ovaj rad pruža nove, vrlo precizne informacije o podrijetlu, taložnim sustavima i tektonskim značajkama koje su utjecale na razvoj ležišta u donjomiocenskim naslagama CLB-a, nudeći ključne uvide za buduća istraživanja ugljikovodika u regiji.

Ključne riječi:

bazen Cuu Longa, donji miocen, U-Pb datiranje cirkona, podrijetlo, tektonska evolucija

Author's contribution

Quoc T. Truong (PhD), characterized the samples, and contributed to the process. **Nguyen Tuan** (PhD), **Quoc T. Truong** (PhD), **Huu X. Mai** (PhD) and **Huynh T. Nguyen** (PhD) contributed to laboratory analyses, analyses result processes, and described the characterization and evaluation of the final products. **Xuan K. Nguyen** (PhD) and **Van X. Tran** (Assoc. Prof.) evaluated the results, reviewed the draft manuscript, and provided technical suggestions. **Van X. Tran** (Assoc. Prof) and **Truong A. Dang** (Assoc. Prof.) edited the entire draft. The entire work was written collaboratively by all the authors.

All authors have read and agreed to the published version of the manuscript.