



OPEN Three-stages tectonic evolution controls the differential distribution of hydrocarbons in the West Java backarc basin

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The West Java Basin is a typical back-arc basin in Southeast Asia and one of Indonesia's main petroleum provinces. In the past ten years, it has been found that the new hydrocarbon reserves are on the rise, and a amount of resources to be discovered is significant. The distribution of hydrocarbon resources and the tectonic evolution characteristics of the basin are systematically explored, and the differences in hydrocarbon distribution and its main controlling factors in the back-arc basin of West Java are analyzed. The uneven distribution pattern of hydrocarbon is mainly controlled by the differential distribution of source rocks in the subsidence period. The distribution of the main source rocks is influenced by the "three-stage" tectonic development process that governs the distribution of sedimentary facies in various sedimentary environments throughout the tectonic subsidence period. Second, the weakening of the crust and magmatism facilitates the production of high heat flow values in the shallow strata of the back-arc area, thereby accelerating the pyrolysis and hydrocarbon generation of source rocks. The study delineates the formation and distribution of various types of oil and gas across various blocks. Prospective basin exploration sites include the shallow-deep water zones in the basin's south-central sector, as well as underexplored terrestrial regions. The exploration history and hydrocarbon resources identified within the West Java back-arc basin support these findings.

Hydrocarbon resources are one of the products of the evolution of the earth system, which are closely related to plate movements and global events such as supercontinent accumulation and dispersion, large igneous provinces, climate change^{1–3}. Based on the theory of tectonic evolution, the study of hydrocarbon enrichment and its differences is a hot topic. Southeast Asia is one of the regions with the most complex tectonic characteristics in the world, Southeast Asia has proven oil recoverable reserves of $86.45 \times 10^8 \text{ m}^3$ and natural gas recoverable reserves of $11.15 \times 10^{12} \text{ m}^3$, distributed in forty-two basins. Among them, The West Java backarc Basin is the most typical, as Indonesia's leading petroleum provinces, the West Java Basin has a recoverable oil and gas reserve of 6778 MMboe, ranking at the forefront of the Indonesian region. This area is in the Tethys tectonic domain, the world's recognized petroleum provinces. Enormous oil and gas fields, such as Widuri and Subang have been discovered, demonstrating enormous potential for oil and gas exploration^{4–6}. Therefore, this area is an ideal place to study the coupling relationship between tectonic evolution and petroliferous basins.

"Oil and gas intermingled" is the distribution pattern seen in the West Java back-arc basin. With recoverable oil reserves of 3979.19 MMboe and recoverable natural gas reserves of 2799.46 MMboe among the 293 discovered oil and gas fields, the distribution characteristics of oil-dominated and gas-supplemented fields are demonstrated by the oil-to-gas ratio of roughly 3:2⁷. At present, it is not clear what causes the difference in the distribution of this type of oil and gas, and there are few reports on the tectonic deposition and its resource effect in this area. Ongoing exploration is limited to the study of small blocks in the basin, and there is a lack of research on the difference in overall oil and gas areal distribution^{8,9}. Based on the analysis of source rock samples in the study area, combined with the characteristics of sedimentary facies environment, this paper closely links the tectonics with sedimentary response, discusses the distribution factors of oil and gas resources in the West Java back-arc Basin, and clarifies the evolution differences of source rocks in different formations. In addition to contributing to a deeper theoretical understanding of the regional variations in oil and gas generation, this will also help

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identify potential areas for future exploration that may be fruitful and offer direction for the oil-gas exploration in Southeast Asia.

Geological background

As part of the Sumatra-Java back-arc basin, the West Java Basin, developed on top of the Sunda Craton, is located on the eastern side of the Sunda Island Arc in the Indian Ocean. The basin extends from onshore islands to the northeast sea, and the southwest is the Sunda subduction zone formed by the subduction of the Indian Ocean Plate towards the Sunda Block. The basin's land area is 2.5×10^4 km², and the sea area is 1.2×10^5 km², three-quarters of the basin lies offshore^{10,11}. On the west, the West Java Basin is separated from the South Sumatra Basin by the Lampung High and on the east from the East Java Basin by the Karimunjawa Arch. The southern margin of the basin is marked by the contact with the volcanic arc of the southern Java Mountains, and the Sunda shelf forms its northern margin. The tectonic evolution of the basin is influenced by the subduction of the Indian Ocean plate under the Eurasian plate and the anticlockwise rotation of the Sunda block^{12,13}. Affected by plate subduction, while forming a volcanic island arc, the overlying crust behind the arc is in an extensional state due to the rise and convection of deep magma, resulting in the formation of three sub basins, namely the Sunda Sub-Basin, Ardjuna Sub-Basin and Biliton Sub-Basin, distributed from west to east. The basements are the Pre-Tertiary epimetamorphic rocks and Cretaceous magmatic rocks in the basin. The stage of rift development in the basin spanned from the Eocene to the early Oligocene, the Indian Ocean plate subducted in the NE direction, which caused the Java area to continue to suffer from the tensile stress perpendicular to the island arc direction. After the subduction of the island arc, a fault parallel to the island arc direction was formed, and the depression parallel to the island arc direction was mainly developed. The fault's activity gradually weakened from south to north, decreasing the scale of the sag from south to north. The primary filling of volcanic debris occurred during this time due to a sequence of volcanic island arc activities. At the beginning of the late Oligocene, the NW-SE tensile stress caused by counterclockwise rotation formed NE-SW trending faults. The fault activity weakened with the distance from the separation point of the two islands. The sags are mainly developed in the northwest of the basin, while the scale of the sags in the southeast is relatively tiny. The Early Miocene-Middle Miocene is the period when the fault activity is weakened until it stops. The basin has overall subsidence and large-scale transgression from south to north, and the basin is being filled with sediments. It is an essential period for forming clastic rocks and carbonate reservoirs. At this time, the sedimentary environment is varied, ranging from shallow sea to sea-land interaction. Uplifts and anticline folds have developed in the basin since the Miocene due to compression. An east-west-oriented fold structure, which is crucial cap rock for the preservation of oil and gas, is the result of this stress environment. Basin infill sequence from the bottom to the top: the Eocene-Early Oligocene Banuwati Formation, Late Oligocene-Early Miocene Talank Akar Formation, Early Miocene Batu Raja Formation, Middle Miocene Gumai/Air Benakat Formation, Late Miocene Parigi Formation and Pliocene to present Cisubuh Formation (Fig. 1). Among them, Banuwati and Talank Akar Formation are the main source rock sections. The primary source rocks in the basin formed during this time.

Samples and experiments

Drilling samples from the Eocene to the Oligocene in the northern Asri Depression of the Sunda Sub-Basin and southern Ardjuna Sub-Basin, used to analyse organic matter (OM) content and types in source rocks. The data relating to the oil and gas resources of the basin in this study are sourced from the IHS (2023) database centre, and the China National Offshore Oil Corporation (CNOOC) provided the two-dimensional seismic data. Drilling data will be used to calibrate seismic sequence stratigraphic interfaces to achieve precise seismic sequence stratigraphic interpretation. The seismic data used for structural interpretation comes from the latest 2D seismic data from 2010s to 2012s.

Source rock analysis

To determine the differences between the source rocks of the Asri Depression in the northern part of the Sunda sub basin and the Ardjuna Sub-Basin in the southern part of the West Java Basin, the source rock samples were measured by Rock-eval pyrolysis to determine OM content and kerogen type. Before the experiment, the samples were treated with a solution containing 10% hydrogen chloride at 60 °C, then dried at 50 °C for 24 h and a CS-230SH sulphur/carbon analyser measured the OM content. Rock-Eval 6 pyrolyzer is used to determine the basic geochemical parameters according to Espitalié et al. (1977)¹⁴. The temperature of the pyrolysis furnace was set between 300 and 600 °C, and high-purity N₂ (99.99%) was used as a carrier gas. Parameters measured were organic carbon content, expressed as mg HC/g rock when vaporized to a temperature of 300 °C, and the residual hydrocarbon generation potential, defined as mg HC/g rock between a temperature of 300 °C and 600 °C, and the temperature of the maximum pyrolysis yield.

Two-dimensional reflection seismic data

Regional two-dimensional seismic grid was available for interpretation the Asri Depression in the northern part of the Sunda Sub-Basin and the Ardjuna Sub-Basin in the southern part of the West Java Basin by CNOOC. All reflection profiles were processed by deconvolution, multiple suppression, time migration, and filtering to improve them to the highest quality. By seismic stratigraphic analysis allows identification of stratigraphic boundaries and thickness, which is in respond to sedimentary characteristics. All seismic profiles were interpreted with LandMark 2005 software on a workstation. Using Adobe Illustrator 2020 (Ai) drawing software to modify the profile to ensure the visualization of the picture.

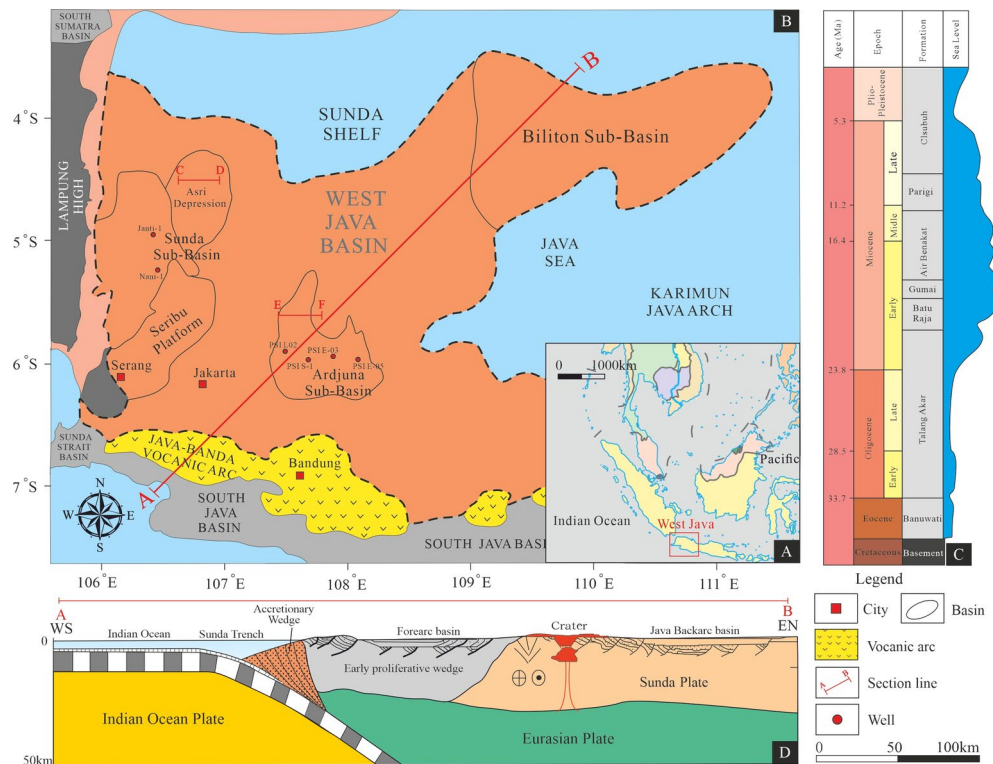


Figure 1. The geological overview map of the West Java Basin. (A) The location of West Java Basin, (B) geological map of the West Java Basin, (C) columnar section of stratum of the West Java Basin, (D) subduction pattern diagram across the section. (modified from IHS Markit and Bagus et al., (2023))^{7,9}.

Results

Source rock characteristics

The West Java Basin contains the two primary source rocks, the Eocene Banuwati Formation and the Oligocene Talang Akar Formation. The distribution area of deep lacustrine source rocks in the Banuwati Formation is relatively limited, only developing in the Sunda Sub-Basin in the northern part. The distribution area of hydrocarbon source rocks in the delta coal measures of the Oligocene Talang Akar Formation is wide and developed throughout the basin (Fig. 2).

Furthermore, the rock hydrogen index (HI), oxygen Index (OI) and pyrolysis Tmax curve can classify the types of organic matter¹⁶ (Mukhopadhyay et al., 1995). The total organic content (TOC) of the Banuwati Formation mudstone in the Sunda Sub-Basin is 4% to 8%, with a maximum HI of 700 mg/g. The TOC of the coal-bearing source rocks in the Upper Oligocene Talang Akar Formation is as high as 36%, and a shale TOC of up to 5%. The HI ranges from 10 to 500 mg/g, with a OI of 5–120 mg/g. The HI (mg/g) and Tmax (°C) cross-plot analysis revealed that the Banuwati Formation samples had significantly high HI values, with some of the samples falling within the I–II kerogen zone, while Talang Akar Formation samples almost all falling within II₂–III kerogen zone. The ratio of pristane to phytane (Pr/Ph) is considered an essential indicator of the redox environment at deposition, and some scholars have suggested that it also influences the type and maturity of organic matter¹⁷. From the Pr/Ph distribution characteristics of two types of sediment extracts, it can be seen that the Pr/Ph values of Banuwati Formation and Talang Akar Formation have obvious differences, the former generally less than 4.0, while those in the Talang Akar Formation are generally greater than 6.0, which reflects that the sedimentary environment of the West Java Basin significantly changed from Eocene to Oligocene (Fig. 3A). With heavy carbon isotopes in the shale of the Banuwati Formation, has a carbon isotope value range of −22.0‰ to −19.0‰, which is completely different from Talang Akar Formation, with a carbon isotope value ranges from −30.0 to −27.5‰ (Fig. 3B).

Seismic facies characteristics

Typical seismic profiles across the Sunda Sub-Basin and the Ardjuna Sub-Basin show that there are significant differences in stratigraphic characteristics between the southern and northern parts of the West Java Basin. From the seismic profiles across the Sunda Sub-Basin in the northern part of the basin, two sets of source rocks, the Eocene Banuwati Formation and the Oligocene Talang Akar Formation, were developed during the rifting period (Fig. 4A). The profile shows a obvious feature that the thickness of the Eocene Banuwati Formation is small, coarse clastic deposits are developed at its edge, and middle deep lacustrine deposits are developed in the center of the deep depression. At the top of the Eocene Banuwati Formation, a relatively thick layer of early Oligocene sediments is covered, which is the same as the southern Ardjuna Sub-Basin. Different from the Sunda

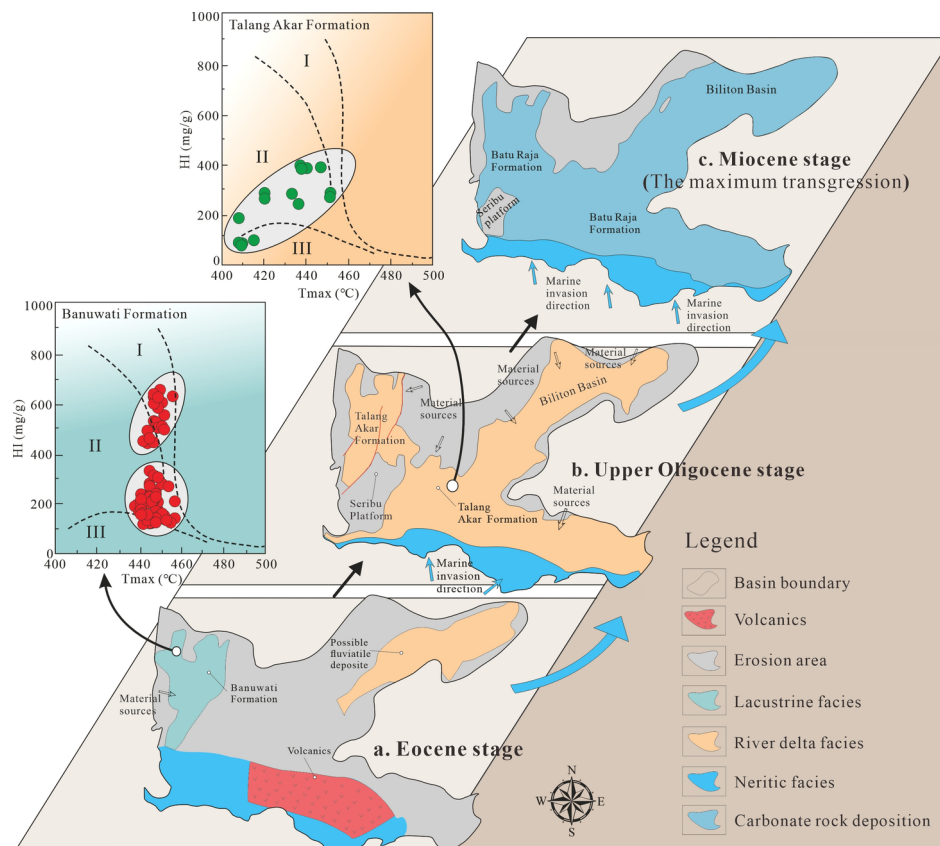


Figure 2. The relationship between sedimentary environment evolution and source rocks type. Source rock type in different sub-basins, and the characteristics of the sedimentary environment in three different stages (modified from (Pertamina, 1985; Lunt, 2019)^{10,15}.

Sub-Basin, the Ardjuna Sub-Basin developed a set of volcanic facies deposits of nearly 1000 meters in Eocene. On its top, a thick layer of lacustrine source rock was developed, which was also the only oil generating rock layer in the sub basin (Fig. 4B). It can be seen that Eocene Banuwati Formation is only developed in the Sunda Sub-Basin, while the the Oligocene Talang Akar Formation is widely distributed in the whole West Java Basin.

Discussion

Sedimentary environmental characteristics

N-alkanes and isoprenoids indirectly indicate important information, such as the origin of organic matters and sedimentary environment^{17,19}. Different sedimentary environments resulted in accumulation of the two different types of organic matter. The characteristics of saturated hydrocarbon ion fragments from two sets of source rocks validate this point. In the Ardjuna Sub-Basin, Upper Oligocene Talang Akar Formation organic matter extraction exhibits abundant n-alkanes in the full ion fragments, with nC_{29} as the main carbon peak, the dominant carbon peaks of n-alkanes are mainly concentrated between nC_{24} and nC_{35} . In its m/z 217 ion fragments, the content of regular steranes such as nC_{28} and nC_{29} is relatively high, indicating abundant terrestrial higher plant sources. Based on the above analysis, it is concluded that the Talang Akar Formation primarily consists of organic matter derived from terrestrial higher plants, with a minor contribution from algae, reflecting a transitional sedimentary environment between marine and terrestrial settings (Fig. 5A, B).

The organic matter extracted from the Banuwati Formation in the Sunda Sub-Basin with a predominance of light hydrocarbon components, the dominant carbon number of n-alkanes ranges from nC_{16} to nC_{20} , and is mainly input by lower plankton and algae.

The m/z 217 ion fragment ion shows a high content of rearranged steranes and predominantly nC_{27} regular steranes, indicating that the organic matter is primarily derived from algae in a closed environment (Fig. 5C, D). With heavy carbon isotopes in the shale of the Banuwati Formation. It is generally believed that abnormally heavy carbon isotopes are likely related to tropical climates, under which algal paleo-productivity was high, indicating high-quality source rocks with enormous hydrocarbon generation potential^{16,19–21}. The Pr/Ph ratio of Eocene to Oligocene sediments ranged from less than 4.0 to generally greater than 6.0, verifying the gradual transition of sedimentary environment from marine to continental facies. The parameters of biomarkers evidence indicate these two basins are within the range of oil generation windows, and the deep parts of local depressions are in a highly mature evolution stage. The thermal evolution degree of the Ardjuna Sub-Basin is mainly in a highly mature evolution stage, and a small part is in a mature evolution stage.

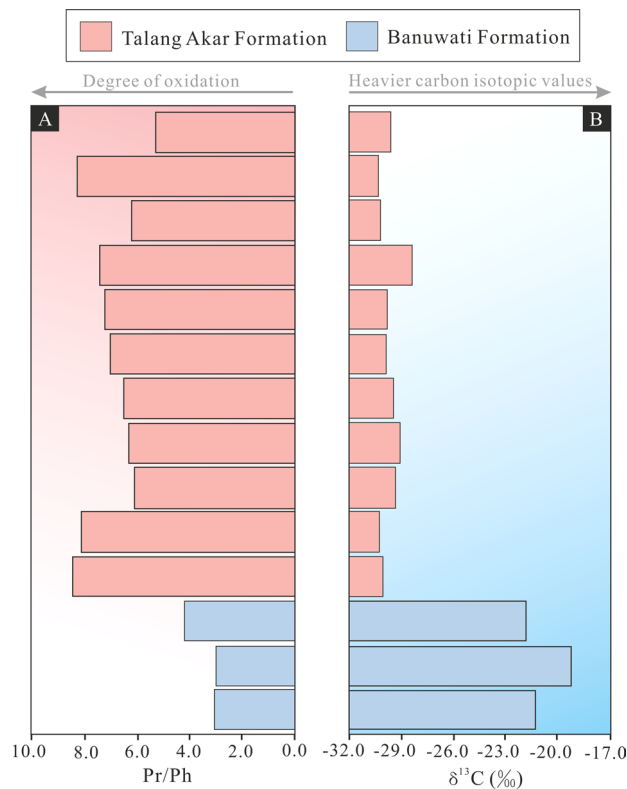


Figure 3. Histogram of Pr/Ph ratio and saturated hydrocarbon carbon isotopes in different formations of source rocks in the West Java Basin (the date from Michele, (2000))¹⁸. (A) The high ratio of Pr/Ph dominated by the Oligocene Talang Akar Formation. (B) The heavy carbon isotopes in the shale of the Banuwati Formation. The two parameters distinguish these two types of source rocks well. Compared with the Banuwati Formation source rocks, the Oligocene Talang Akar Formation source rocks have higher ratio of Pr/Ph and relatively low carbon isotope value of saturated hydrocarbons.

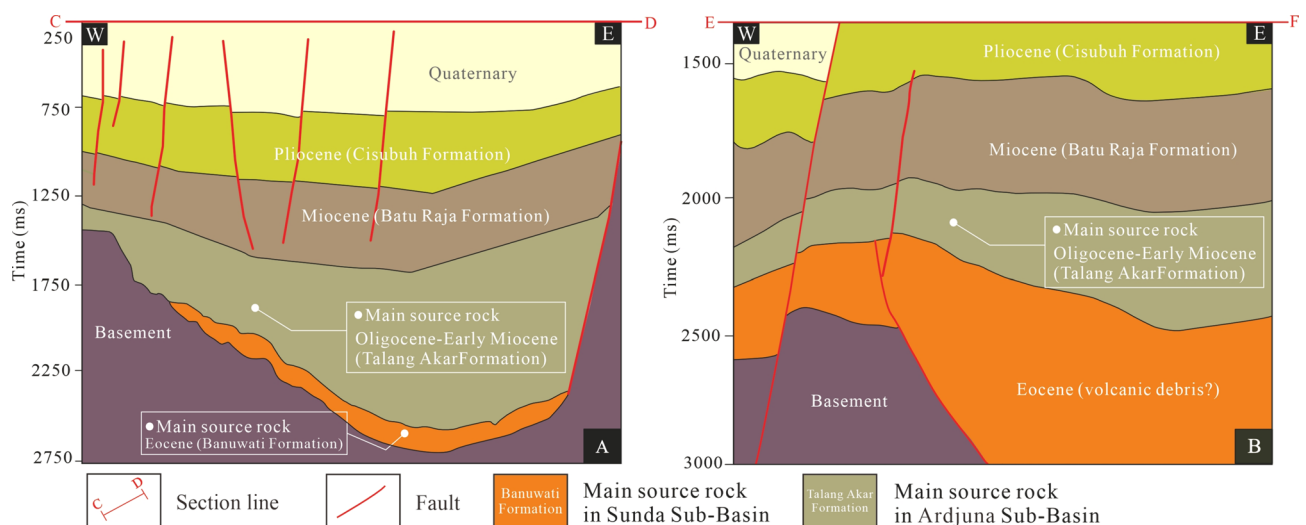


Figure 4. Seismic profile across the West Java Sub-Basin (A) The location of the seismic profile line in the Sunda Sub-Basin is given in Fig. 1. (B) The location of the seismic profile line in the Ardjuna Sub-Basin is given in Fig. 1. The Sunda Sub-Basin and the Ardjuna Sub-Basin have obvious differences in the thickness and scope of strata deposition in Eocene Banuwati Formation and the Oligocene Talang Akar Formation.

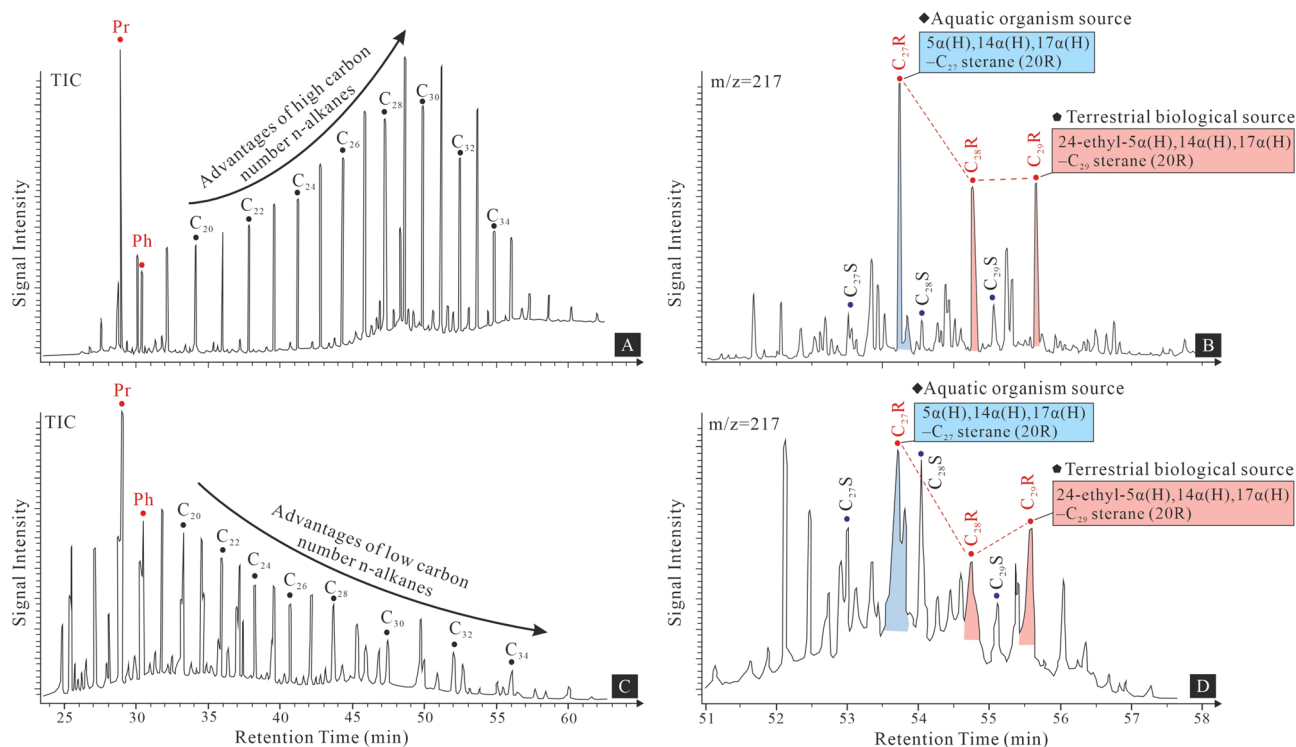


Figure 5. Chromatograms of organic matter saturated hydrocarbons from different strata in the West Java Basin. (A,B) Sediment extract of the Talang Akar Formation, (C,D) sediment extract of the Banuwati Formation (modified from Napitupulu et al., 1997; Bagus et al., 2023) ^{9,22}.

Organic matter differential enrichment mode

In the early stage of the fault activity, shear stress was generated in the Sunda continental shelf due to the collision of the subduction of the Indo-Australian plate to the southern margin of the Eurasian plate, resulting in apparent expansion of the back and front arcs. Under strong rifting, a series of grabens and half grabens were formed. In the basin's initial tension phase, the tectonic movements are intense. Due to the input of surrounding provenances, the basin is mainly composed of shallow lake sediments, most of the basin was filled with coarse clastic and volcanoclastic deposits. The Sunda Sub-Basin of the West Java Basin is a small-scale lake basin with shallow water. Due to the abundant supply of peripheral sources, fluvial-delta facies deposits are mainly developed (Fig. 6A). The central and southern West Java Basin is primarily filled with volcanic rocks and coarse debris. In the early stage of tectonic subsidence, the overall distribution of source rocks in the basin is limited, the quality is relatively poor, and the possible contribution to oil and gas accumulation is limited. In the middle stage of the tectonic subsidence, the basin develops large accommodation space as a whole, and the water body is deep and stable, which controls the basin zone to be dominated by fine-grained sediments. Furthermore, the steady transgression of seawater from east to west is controlled by the opening of the Makassar Strait. In the warm, humid, enclosed environment of the Sunda Sub-Basin, which is located in the northwest of the West Java Basin, high-productivity algae and other lower organisms have formed the basis for the creation of high-quality hydrocarbon source rocks during this time (Fig. 6B). The volcanic activity in the Ardjuna Sub-Basin is weakened, the water body is shallow, and the northern provenance supply is sufficient, forming a river-delta sedimentary system. Tectonic subsidence conversion dominated the basin during the late stage of tectonic subsidence, leading to the overall subsidence of the basin zone. This directly raised the relative sea level and caused widespread transgression. The basin zone's east and north faces continued to see seawater infiltration, creating a vast marine sedimentary environment. Large-scale delta deposits have formed in several basins due to the steady and plentiful source supply provided by the northern Sunda paleocontinent. Extensive fluvial-delta-shore-shallow marine deposits generate from northeast to southwest, while the West Java Basin develops the NNE-trending provenance system. The Upper Oligocene Talang Akar Formation's delta coal-bearing source rocks primarily contribute to the West Java Basin's substantial natural gas resources. These rocks are the primary source of type III kerogen (Fig. 6C).

The basement of the basin is generally shallow, and the crust in the back-arc area is affected by tensile thinning. The deep magma rises, and thermal convection occurs, increasing the geothermal gradient of the shallow structural interface ^{23–26}. The forearc areas, such as Meulaboh Basin, Nias Basin and Mentawai-Bengkulu Basin, are in sharp contrast to the back-arc basins. The heat flow value of the forearc areas are generally lower than 50 Mw/m², which is much lower than the temperature and pressure conditions required for the thermal evolution of organic matter. The average heat flow value in West Java Basin is 81.71 Mw/m², and the highest is more than 150 Mw/m². Due to the distance from the subduction centre, the heat flux values in the northern Sunda Sub-Basin are generally lower than those in the Ardjuna Sub-Basin. Abnormal gradient plays a favourable role in

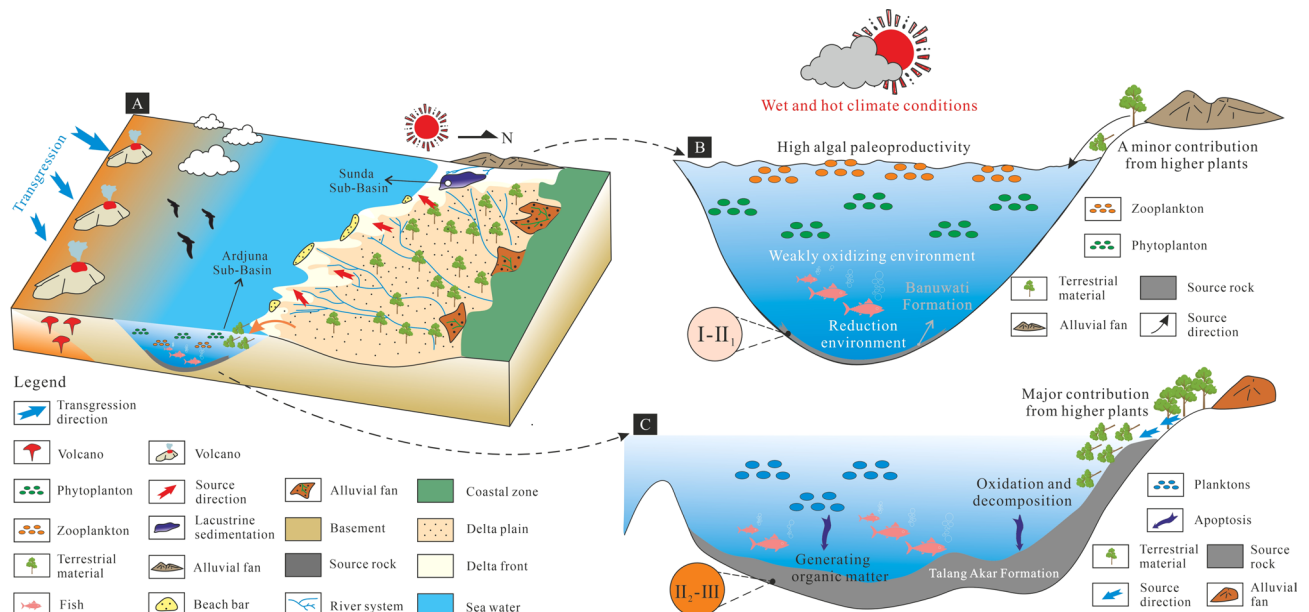


Figure 6. Organic matter enrichment patterns of Eocene Banuwati Formation source rocks and the Upper Oligocene Talang Akar Formation source rocks in the West Java Basin.

the thermal evolution of organic matter in source rocks^{27,28}. Affected by the baking effect of the intrusive rock mass on the source rock, it has reached the oil generation threshold, and the deep source rock in the sag is in the high-over mature stage. In addition, the difference of the source rock types in the north and south of the basin forms the current oil and gas difference distribution pattern in the West Java Basin. The West Java Basin is characterised by oil-dominated and gas-supplemented distribution (Fig. 7).

Advances in hydrocarbon resource exploration

According to the estimation of undiscovered oil and gas resources in Indonesia by the United States Geological Survey (USGS), the remaining undiscovered resources in the West Java Basin are high and still have excellent exploration potential. Gantar West 1, GQX 1, Haur Gede, Karunia 1X, and Pinus Harum 1 are the main areas of newly added oil and gas reserves in the past decade (Fig. 8).

The onshore exploration vacant area is the growth point of oil and gas reserves. Indonesia is located in the tropics, with a forest coverage rate of 67.8%, widely distributed jungle, land for swamps and tropical rainforest, in the 200 km wide vast plains, a large area covered with peat swamps. The growth of energy demand has led to the shift of oil and gas exploration from land to shallow-deep water, from plains to mountains and jungles. It was challenging for anyone to explore the primeval rainforest areas and deserted wetlands in the early days. These new strata, important heterogeneity reservoirs, and other subtle reservoirs and traps have been regularly recognized and discovered with the advent of high-resolution, three-dimensional seismic equipment. The Tethyan tectonic domain is widely recognized as a location rich in oil and gas^{4,5}. Within this tectonic domain, the Southeast Asian segment has exhibited significant variations in basin size and sedimentary fill during the evolution of the Tethys, leading to notable differences in the eventual accumulation and distribution of oil and gas reserves. The history of petroleum exploration and development in Southeast Asia spans over 100 years, yet there are still many areas that remain unexplored, such as the oil and gas reserves discovered in the Gantar West 1 and Haur Gede blocks in the West Java Basin in 2017 accounted for 68.26% of the total reserves in the basin.

Shallow-deep water blocks are new areas for basin exploration. About 76% of the West Java Basin is located in the offshore area of the West Java Sea. Its exploration degree is still at a low level. In the past ten years, 31.74% of the oil and gas found in shallow water areas, such as GQX 1 and Karunia 1X blocks, have seen considerable natural gas resources. In addition, as a new field of global oil and gas exploration, nearly 50% of the world's new large-scale oil and gas discoveries in the past ten years are from deep water areas^{29–32}. The shallow-deep water area in the basin accounts for a large proportion of the total area, but the degree of exploration is low, which is a new field of oil and gas exploration in the future.

Among the newly discovered oil and gas resources, natural gas resources as clean energy account for nearly 90 % and are mainly distributed in the southern part of the basin and around the basin, which is due to the results of the differential evolution of the above source rocks. Indonesia's regional economic development requires both favorable resource support and sustainable green development. Using natural gas makes the global economy consistent with the sustainable development strategy, reduces environmental pollution, and is compatible with the concept of energy conservation and, emission reduction and low-carbon environmental protection. In the future, natural gas exploration and development in this area will have broad prospects.

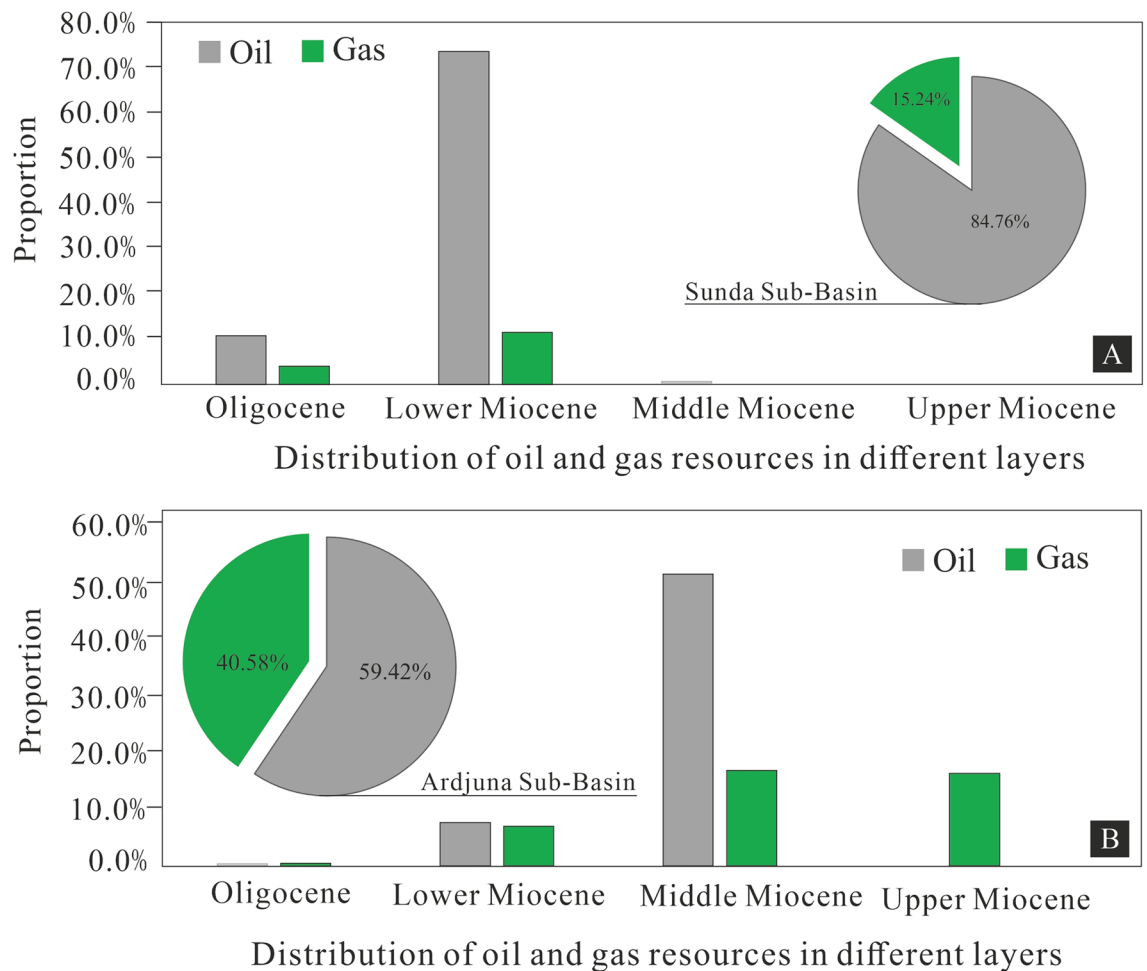


Figure 7. Distribution characteristics of oil and gas types in different horizons (A) Northern Sunda Sub-Basin, (B) Southern Ardjuna Sub-Basin (the data is sourced from IHS Markit, 2023).

Conclusions

The West Java back-arc basin, located in the Southeast Asian segment of the Tethys, has exhibited distinctive features in oil and gas discoveries over the past decade. Variations in tectonic responses and significant differences in sedimentary environments have resulted in contrasting distributions of oil in the northern region and gas in the southern region of the basin.

Under strong rifting, a series of grabens and half grabens were formed at the first stage. In the second stage, the basin continued to tectonic subsidence, the Sunda Sub-Basin of the West Java Basin is a small-scale lake basin with shallow water, a humid and warm reducing environment, coupled with high productivity of algae, led to the formation of type I–II2 kerogen in the northern part of the basin. Affected by volcanic activity, the Ardjuna Sub-Basin is primarily filled with volcanic rocks and coarse debris. In the third stage, affected by the southwest transgression and the large-scale delta provenance in the north, extensive development of river deltaic facies and abundant supply of higher plants in the southern region facilitated the development of thick layers of hydrocarbon source rocks primarily generating natural gas. Moreover, the major natural gas discoveries in the past decade have predominantly originated from the Ardjuna Sub-Basin.

Significant portions of the basin remain underexplored, particularly vast areas covered by jungles and marshes, which may still hold potential for onshore oil and gas exploration. With a large proportion of the basin located in offshore areas, this represents a new frontier for future oil and gas exploration. Unconventional oil and gas exploration is still in its nascent stage in this region, and further exploration is required to fully understand its potential.

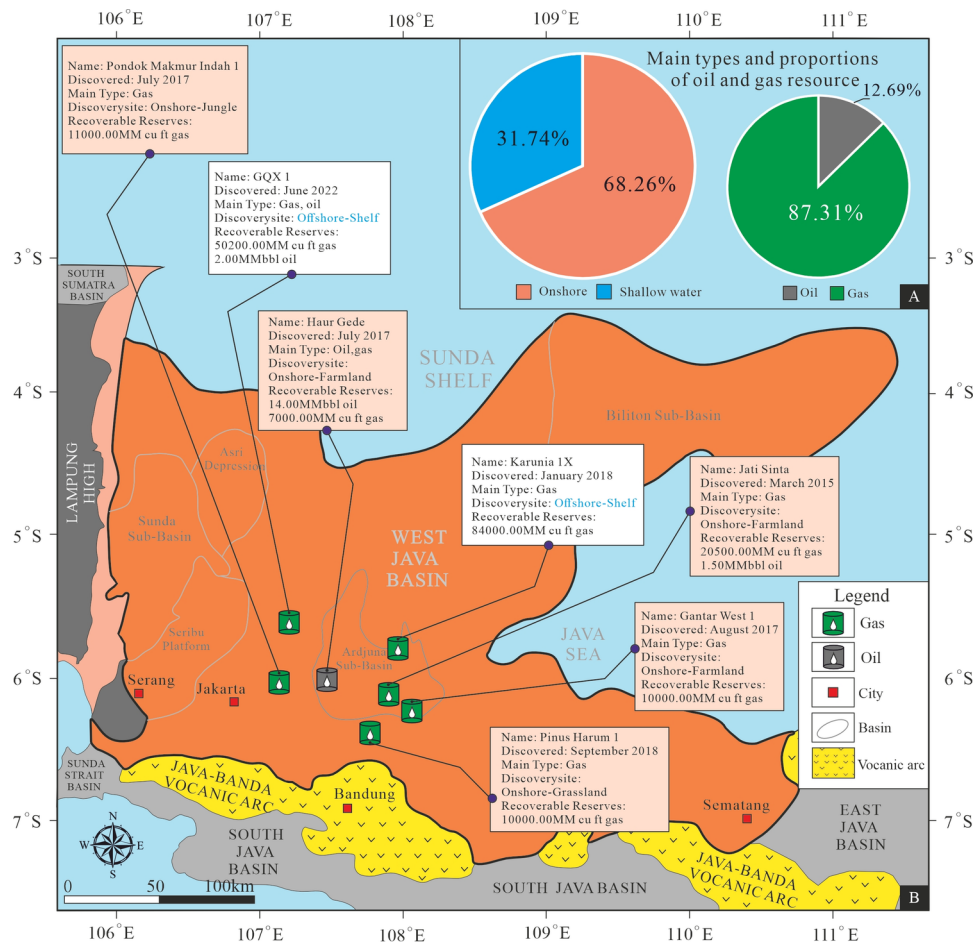


Figure 8. Discovery and distribution of hydrocarbon in the West Java Basin in the past decade, (A) types of oil and gas resources, (B) plan distribution map of newly added oil and gas reserves (the data is sourced from IHS Markit, 2023).

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Z.Z.: Conceptualization, formal analysis, writing-original draft, methodology. W.Z.: Methodology, investigation, formal analysis, data curation, supervision, funding acquisition. W.P.: Resources, investigation. H.S.: Resources, investigation. X.F.: Methodology, formal analysis, visualization. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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