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GEOLOGY

Back-Arc Zones of the Active West Pacific Margin: An Analog of Atlantic-Type Passive Margins and Their Petroleum Potential

Academician of the RAS V. E. Khain and I. D. Polyakova

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The origin of present-day continental margins of the oldest part of the Pacific Ocean is related to the Late Mesozoic. A single geodynamic system of marginal seas, island arcs, and deep-sea trenches, which emerged along the West Pacific margin in the Middle Cretaceous, continued to evolve and extended from the south to north throughout the Cenozoic. Back-arc spreading, which repeatedly showed up in the Cretaceous and Paleogene, played an important part in the development of seas. This process promoted the expansion and deepening of sea basins with the formation of deep-water basins in some areas. Therefore, the study region incorporates different proportions of shelf (adjoining macro- and microcontinents) areas with the consolidated crust and deep-water areas with the newly formed oceanic (or transitional to oceanic) crust.

Continental slopes of marginal sea basins up to 1000–1500 km wide represent nearly complete analogs of Atlantic-type passive margins. The close resemblance (in terms of the morphological similarity of both types of margins) was suggested previously in [1, 2]. Like classic passive margins, continental-margin parts of the West Pacific with the crust up to 30–40 km thick are characterized by intense rifting, high heat flow, thick sedimentary cover, and multistage structure of the continental slope owing to faults and thrusts. Their typical elements are deltas and prodeltas of large rivers, including the Amur River in the north and the Mekong and Irrowaddy rivers in the south of the Asian continent, as well as deltas of island-arc rivers (for instance, the Baram and Mahakam rivers of Kalimantan Island). Back zones of these active (in general) margins of the West-Pacific type are characterized by a higher hydrocarbon potential.

The major petroleum potential of these zones is related to back-arc seas and the adjacent mainland with continental-margin, shelf, and shelf–slope basins. Most of them are riftogenic structures, which appeared on the Paleozoic–Mesozoic and Mesozoic–Lower Paleogene folded basement and evolved during the Cenozoic. Their generalized section consists of three complexes reflecting the main stages of evolution. The lower (Paleocene–Eocene) rift complex is composed of mainly continental, lagoonal, and coastal-marine (often coal-bearing) sediments with volcanic bodies. The middle (Eocene–Oligocene) complex accumulated in a wide trough is represented by a thick carbonaceous–clayey–tuffaceous sequence in southern seas and by a siliceous–clayey–tuffaceous sequence in northern seas. The upper (Neogene) complex is most often represented by delta and prodelta units. In the coastal zone, they are composed predominantly of coarse-grained sediments (with carbonaceous and tuffaceous materials), which graded into clay fans crosscut by sandy channels. The age of each complex varies substantially in different basins.

In the Circum-Pacific, the richest petroliferous basins are located at the western margin (Fig. 1), where more than 700 fields were discovered, including large and very large fields. Initial recoverable resources in these fields make up ~25 Gt o.e. [3]. The continental margin and island arcs incorporate the North Java, North Sumatra, Central Sumatra, South Sumatra, Malaya, Mekong, Bakbo, Pearl River, and Anadyr basins that are related to river systems. Materials transported by them settle on the wide shelf and do not reach the continental slope. The upper (Neogene) part of the sedimentary sequence in the basins is composed of delta and prodelta deposits with petroleum potential. The thick East Asian continental rift system, which incorporates several large petroliferous basins (Sunliyao, Bohaiwan, and others), extends onto the continent.

Back-arc zones of the West Pacific-type (generally, active) margin also include petroliferous basins, which extend onto both the shelf and continental slope (Brunei–Sabah, Sarawak, Sulawesi, and Kutei basins surrounding Kalimantan Island). The Kalimantan repre-

Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 109117 Russia; e-mail: khain@ilran.ru

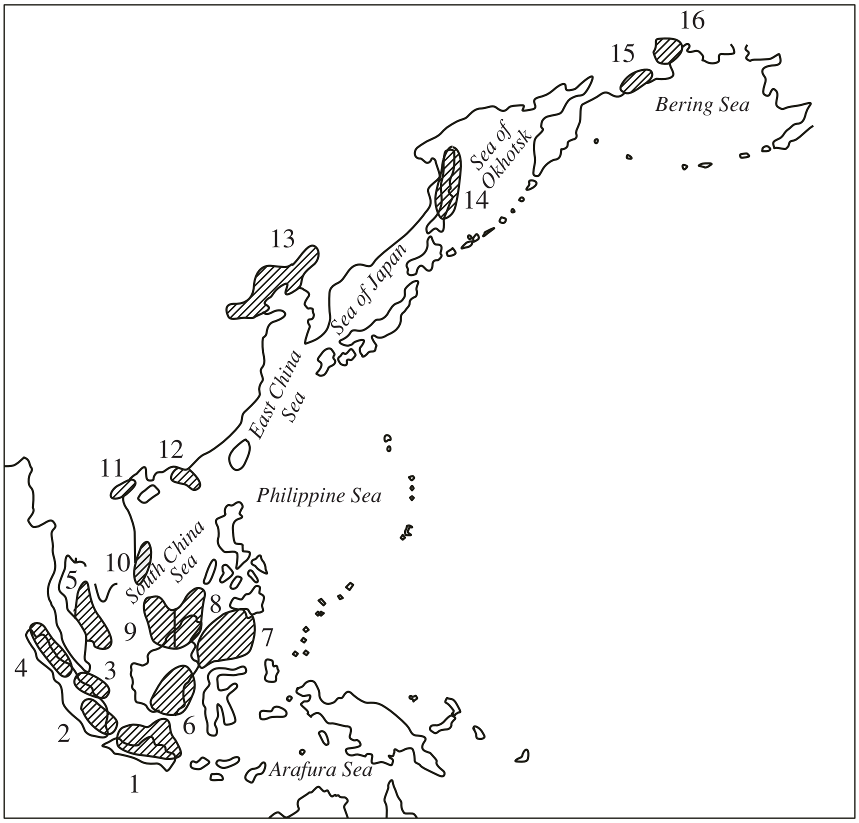

Fig. 1. Schematic location of oil-and-gas basins (OGB) at the West Pacific margin. OGB: (1) North Java, (2) South Sumatra, (3) Central Sumatra, (4) North Sumatra, (5) Malay, (6) Kutei, (7) Sulawesi, (8) Brunei–Sabah, (9) Sarawak, (10) Mekong, (11) Bakbo, (12) Pearl River, (13) Bahaiwan, (14) North Sakhalin, (15) Khatyr, (16) Anadyr.

sents a microcontinent-outlier, the central part of which includes mountains that served as provenances since the Late Oligocene [4]. In the Miocene–Pliocene, the carbonaceous shelf was overlain by terrigenous sediments of thick fans, which extended from the south and east over a considerable area of the Java and Sulawesi seas, the Makassar Strait, and a part of Java and Madura islands. In the northwest of the Kalimantan, the underwater part of the Baram River delta extended to the slope of the South China Sea basin. Fans in this area are up to 5–7 km thick. Gas, gas condensate, and oil fields were discovered in shelf-slope basins adjoining Kalimantan Island.

Since the end of the past century, exclusively important discoveries have been made in deep-water parts of passive margins, and architectural details of the sedimentary cover have been studied. Especially large hydrocarbon (HC) pools are confined to fan deposits of large rivers, such as the Mississippi, Amazon, Niger, and Congo. The fans are located at a depth of up to 2–4 km below the water level and extend to the continental slope, its rise, and the abyssal plain in some places. Giant oil and gas fields occur near the coast of South America, southwestern Africa, northwestern Australia, southeastern India, and in the Gulf of Mexico. Discoveries have been made on the continental slope in recent years. In 2006, two wells (Jack 2 and Caskida) drilled at a depth exceeding 2000 m penetrated the sedimentary cover down to depths of 6 and nearly 10 km, respectively. They became the first wells to discover oil in Eocene sandstones at the base of the continental slope in the Gulf of Mexico [5].

Discoveries of large oil and gas fields in deep-water parts of Atlantic-type passive margins compel us to be more careful in the study of the structurally similar back-arc zones of the West Pacific-type active margins. The similarity is expressed in architectural features of fans of both types: the tongue-shaped form, replacement of facies in the progradation direction from the coal-bearing sediments to sandy–clayey sediments on the shelf, and mainly clayey sediments on the continental slope. The fans are cut by canyons in transit complexes of the steep part of the slope. Downward along the slope, the fans are replaced by branched channels, which served as conduits of turbidite sediments. Sand and gritstone were deposited after multiple rewashing of the sediments. Channels are missing at the slope base, like in terminal complexes of the Niger and Congo fans [6–8]. However, fans at the base of the continental slope terminate as large sand deposits in some places (e.g., the Kettle Canyon and Ridge, Gulf of Mexico [5] and the Makassar Strait connecting the Java and

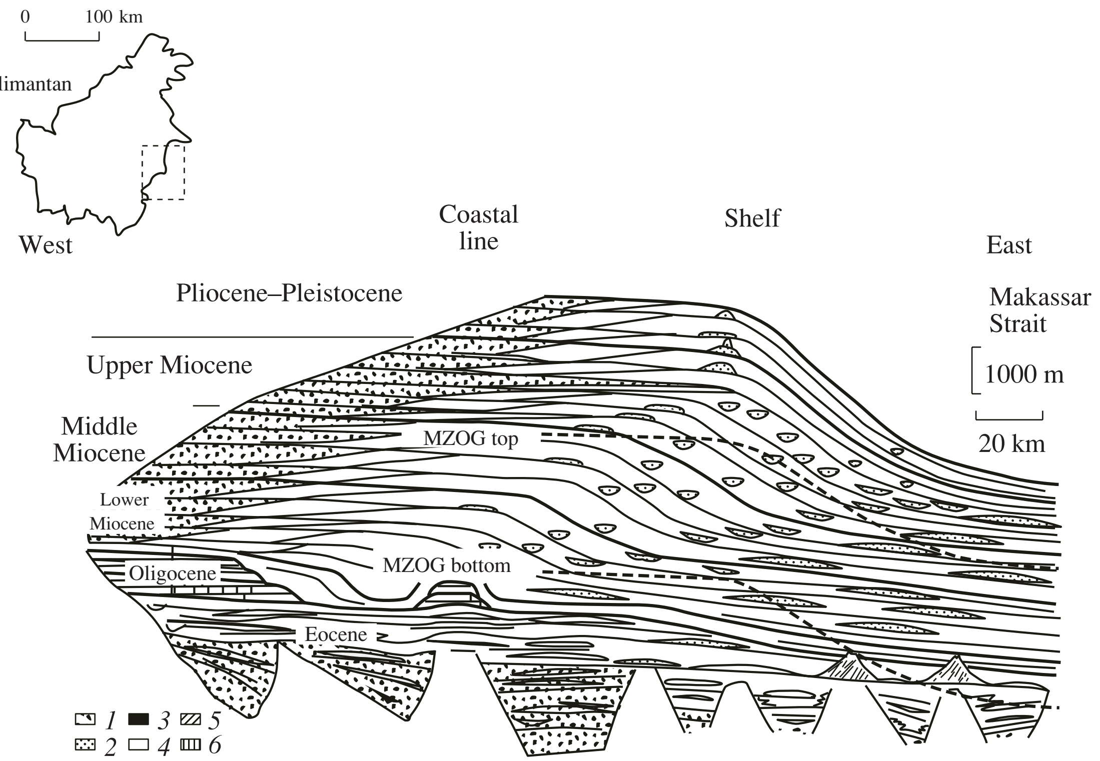

Fig. 2. Schematic geological profile of the Kutei basin reflecting three stages of its evolution: rifting (Paleocene–Eocene), flat basin (Oligocene), and delta progradation of the Mahakam River (Miocene–Holocene). (MZOG) Main zone of oil-and-gas formation (3000–6000 m) [4]. (*1*) Alluvial sand, (*2*) coal; (*3*) volcanics, (*4*) marine sand, (*5*) shale, (*6*) limestone.

Sulawesi seas [4]). Canyons and channels show up in the fan profile as numerous sand lenses. They are clearly observed at the West Pacific margin in the Mahakam fan (Fig. 2), which structurally resembles fans of large rivers of South Atlantic margins. The thickness of fan deposits is 5–7 km, reaching 10 km in some places.

The fans are characterized by a combination of high-quality source rocks and reservoirs favorable for the formation and accumulation of oil and gas. The organic material is different in the sediments. Continental margins of the South Atlantic include source rocks of the highest grade with high concentrations of organic material (mainly types I and II), which is characterized by the hydrogen index equal to 500–700 mg HC/g C_{org}. They generated huge volumes of hydrocarbons, which were accumulated in sand deposits of canyons and channels. Large and giant oil fields are related to these reservoirs.

Clay deposits of submarine fans of southeastern Asia include organic material of type III, which is characterized by a relatively small hydrogen index (50–180 mg HC/g C_{org}) and the ability to produce mainly methane. Liquid hydrocarbons in these fans were generated mainly by the organic material of fossilized remains of thick-coriaceous tree leaves accumulated as laminas in sandstones. Kerogen released from such material belongs to type II with the hydrogen index varying from 200 to 500 mg HC/g C_{org} [4]. Shelf-slope basins of southeastern Asia are characterized by gas and gas-condensate fields with oil fringes.

The North Sakhalin industrial petroliferous basin with hydrocarbon reserves stands out in northeastern Asia [9] (Fig. 3). The Neogene part of the sedimentary sequence in this basin is made up of up to 7.5-km-thick deposits of the pra-Amur prodelta. The deposits host carbonaceous siliceous–clayey source rocks, which comprise phytogenic matter (mainly of type III) with a high bituminosity. This matter can generate HC even at a low maturity corresponding to protocatagenesis. The host sequences of diatomites, opoka-type silicites, and siliceous mudstones have properties of both oil-source beds and fissure-pore reservoirs. In other words, they are characterized by the authigenous oil potential in some places [10]. Oil-and-gas reservoirs were formed in sand deposits of the Amur paleodelta and its underwater part. Large oil-and-gas fields were discovered in them on the shelf.

When assessing the petroleum potential of water areas in the Russian Far East, it is worthwhile to dwell on the virtually unexplored deep-water economic zone in the Bering and Okhotsk sectors of the West Pacific margin. Many authors have assessed the oil potential for its shelf.

In the Bering sector, deep-water petroleum deposits may occur on the continental slope near the coast of

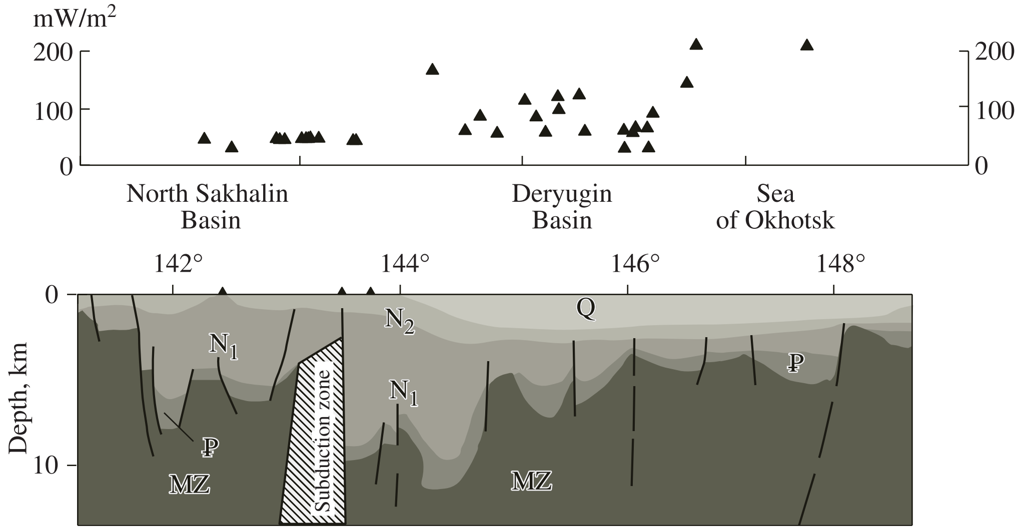

Fig. 3. Schematic geological profile of the North Sakhalin OGB and the Deryugin Basin [9, simplified]. The upper panel shows the distribution of measured heat flow values (mW/m^2) along the profile.

Koryakia, where fans with substantial oil inflow are now known. Of interest are the Shirshov and Bowers rises facing the Komandor Basin. As the result of erosion, they have a stepped structure with canyons and channels filled with turbidite sediments.

In the Okhotsk sector, the North Sakhalin petroliferous basin spans the northeastern part of the island and the adjoining shelf. The basin of the wide paleo-Amur fan extends to the slope of the deep-water Deryugin Basin. Here, the fan deposits are not only rejuvenated, but also exposed to the influence of a powerful heat flow and fluids flowing through faults and carrying products of mantle degassing [9, 11]. Therefore, processes of oil and gas formation should be reactivated and new large petroleum deposits can be discovered in such zones. The slope and foot of the Central Okhotsk Rise facing the South Okhotsk Basin seem to be promising, because they show a complete Paleogene section overlain by a thick Neogene sequence. The slope of the rise accumulated Oligocene–Lower Miocene sediments of wide fans, where oil-and-gas reservoirs may occur. Interesting discoveries may well take place in the Kuril Trough filled with a 6-km-thick (mainly, Neogene) volcanosedimentary sequence.

Thus, data on other similar regions of the world suggest that abyssal deposits of back-arc zones of the West Pacific-type active margins will be an important subject of investigation for several decades of the twenty-first century.

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