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GEOLOGY

Endogenous Factors of the Formation of Oil Fields in the Crystalline Basement of the Cuu Long Basin, South Vietnam Shelf

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The study of formation constraints of oil-and-gas (hereafter, petroleum) fields in the Precambrian–Mesozoic basement rocks of sedimentary basins or crystalline basement is of special importance in determining the regularities of naphthide genesis and petroleum accumulation. It is known that most oil fields in the basement are related to combined traps composed of outliers of the weathering crust, fractured zones in the basement, and diverse forms of basal bed wedging in the sedimentary cover of its inliers.

Data on oil geochemistry often suggest the probability of a common source of hydrocarbons (HC) during the formation of oil fields in the sedimentary and crystalline rocks. These data made it possible to interpret petroleum accumulation in the basement from the viewpoint of sedimentary-migration theory (SMT), which is a paradigm of petroleum geology of 20th (and 21st [1]) centuries.

The detection of a strong economic-grade oil flow from the Mesozoic basement in the South Vietnam sector of the South China shelf (Fig. 1) in 1988 led to the discovery of the unique White Tiger and other deposits (Dragon, Rang Dong, Black Lion, and others). Their giant HC resources are confined to the cavernous-fractured granitoid reservoirs [2–6]. These oil fields occur in the basement inliers (reverse faults, low-angle overthrusts, and torsion structures) and extend to depths of 4.6–5.0 km. Therefore, petroleum geologists believed that oil accumulation in the basement is related to the long-term continuous migration of HC from adjacent Oligocene (Chaku and Chatan) formations (Fig. 2).

The Cuu Long Basin, which hosts the deposits mentioned above, is a complex tectonodynamic (subduction-riftogenic) petroleum basin (PB) [2]. This basin exhibits the highest oil potential of basement rocks among presently known PBs. Therefore, some researchers suggested that the granite layer of the Earth's crust is a new petroleum horizon of lithosphere [3].

More than 92% of explored oil reserves are concentrated in basement rocks of the White Tiger deposit. In this area, the coefficient of HC reservoir filling regularly decreases near the top of the section from 1.0 in basement granitoids to 0.6–0.7 in the Lower Oligocene reservoirs and 0.4–0.5 in the Upper Oligocene–Lower Miocene reservoirs. In addition, the formation pressure in oil-saturated basement zones is 0.5–0.7 MPa higher than that in the adjacent Lower Oligocene horizons. All these facts indicate a predominant role of vertical HC migration during formation of oil fields in the basement of the White Tiger deposit.

At the same time, oils in the basement inliers and surrounding Lower Oligocene rocks have similar compositions in terms of the typical physicochemical characteristics and other parameters, such as the pristane/phytane ratio equal to 2.31 (in the oil from basement) and 2.33 (in the oil from Lower Oligocene rocks); coefficients $Ki = (i\text{-}C_{19} + i\text{-}C_{20})/(n\text{-}C_{17} + n\text{-}C_{18})$ equal to 0.307 and 0.308, respectively; $CPI = (C_{15} + C_{16} + C_{17} + C_{18})/(C_{23} + C_{24} + C_{25} + C_{26})$ equal to 1.065 and 1.082, respectively; and $Kn = (n\text{-}C_{27} + n\text{-}C_{29})/2 \cdot n\text{-}C_{28}$ equal to 1.14 and 1.13, respectively.

In addition, oils from basement and Lower Oligocene fields, as well as HC extracts from mudstones of the Chaku Formation, contain identical porphyrines and some other chemofossils. Oils from the basement and Lower Oligocene fields have similar carbon isotopic composition ($\delta^{13}C$ from –25 to –26‰).

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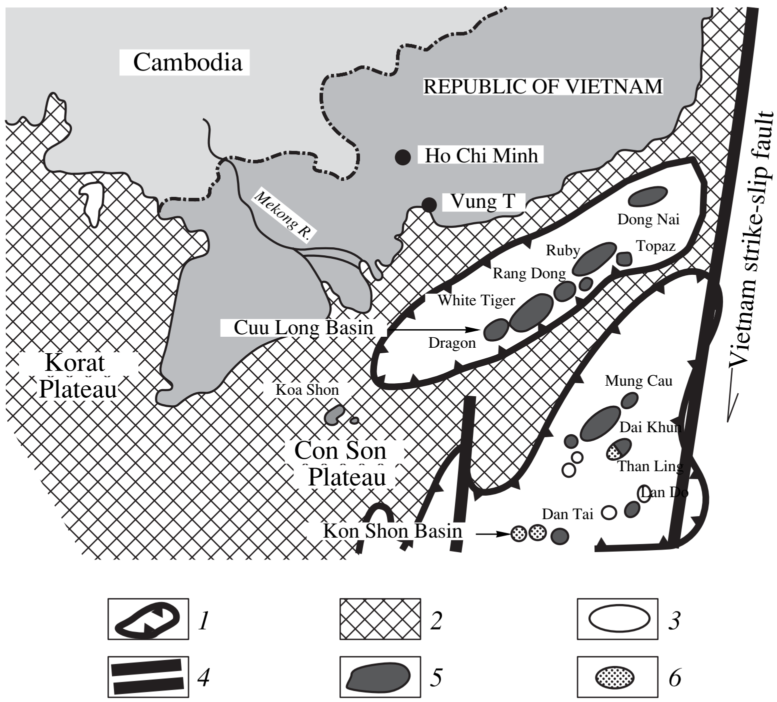

Fig. 1. Scheme of petroleum basins on the shelf of South Vietnam. (*1*) Basins; (*2*) rises; (*3*) local structures; (*4*) strike-slip faults; (*5, 6*) oil and gas deposits, respectively.

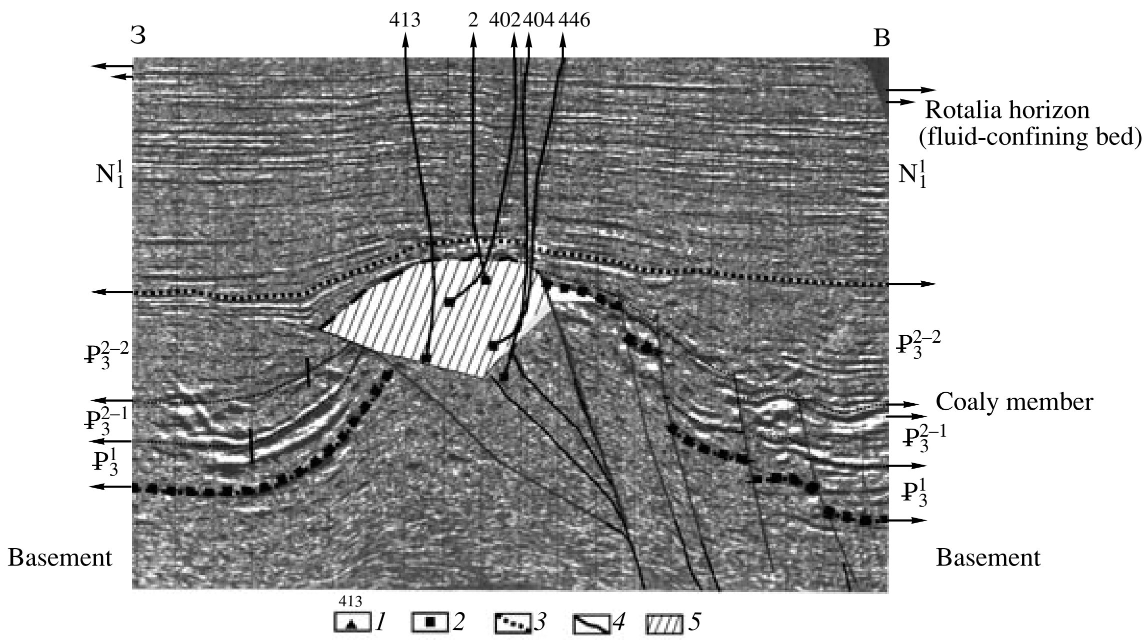

Fig. 2. Temporal seismic profile of the Central dome of the White Tiger deposit. (*1*) Well number; (*2*) bottomhole; (*3*) boundary of stratigraphic units; (*4*) deep-seated faults; (*5*) oil-saturated zone of the basement crystalline rocks.

The leading role in the formation of massive reservoirs in the basement belongs to the interrelated hydrothermal metasomatism [7] and adiabatic fracturing. The latter is represented by fractures of natural hydrorupture and seismic brecciation that are the main factors of the formation of dilatation zones. The intensity of chemical alteration in this process varied from weak hydrogen metasomatism to strong sodium metasomatism with intense zeolitization of feldspars. Hydrothermal processes occurred in several stages (before and after the main phases of the naphthide formation). Hypogenic allogenesis, the major factor of decompaction [8, 11], was responsible for the formation of the columnar massive fractured reservoirs (uncorrelated subvertical zones in the temporal sections), extremely high oil production rate (up to 2000 t/s), and absence of data on the VOC recovery despite great (up to 5.3 km) depths of wells [2].

An attempt to explain the formation of HC fields in terms of SMT, i.e., long-term (tens of millions of years) filling of morphologically complex giant reservoirs with oil globules transported by elision waters was doomed to failure. For example, volumetric and genetic estimates of oil-producing potential of organic matter scattered in Oligocene rocks using pyrolysis data showed that the total amount of HC generated by inferred Oligocene source rocks is insufficient to provide the reserves available in the basement and Lower Oligocene reservoirs of the White Tiger deposit. The calculated value of initial HC potential of oil source rocks of the Chaku and Chatan formations (P_{init} = 21.69 and 33.29 kg/t, respectively) and total volume of the inferred Oligocene source rocks (100 km^3) virtually rule out the possibility of accumulation of large oil reserves (>600Mt) in the basement and Lower Oligocene rocks. Moreover, the mechanism of uninterrupted (for millions of years) accumulation of oil globules in giant cavernous basement reservoirs with an intricate morphology of pore space is also invalid.

Data on fluid inclusions in the basement rocks and geochemistry of genetically different naphthides, which accompany the multiphase fracturing in the basement, indicate spatiotemporal synchronism of the formation of reservoirs and their filling with oil. One should also note that durations of hypogenic-allogenetic and sedimentary-migration (drop by drop) processes of oil and gas accumulation are absolutely incompatible in time. At the same time, the stadial analysis of secondary processes in the oil-bearing rocks indicates a complex multiphase genesis of naphthides. The oldest naphthides are represented by black soots on the fissure walls at a depth of more than 4500 m [2]. Detailed study showed that they represent injections of dark pelitomorphic polymineral matter (DPPM) developed along the natural hydroruptures. They are abundant at depths more than 4–5 km in silicified sandstones, limestones, and other lithified rocks of sedimentary cover and basement of the Dnepr–Donetsk, Caspian, and other riftogenic PBs [11, 12]. Their mineralogy and geochemistry suggests genetic relation with the injection of deep-seated fluids [11]. The DPPM coating along hydroruptures in the basement rocks of the White Tiger deposit have sulfur isotopic composition similar to that of meteoritic troilite standard ($\delta^{34}S = \pm 0.5‰$) and isotopically heavy carbonate carbon composition ($\delta^{13}C_{carb}$ 12–14‰). Hydrogen of sooty matter of this generation (δD = –40…–45‰) is significantly heavier than that of the oil (δD from –120 to –145‰). Discrepancy in the isotopic composition of C_{org} (from –19 to –25‰) is not so significant, since basement oils from the White Tiger deposit have heavier carbon isotopic composition ($\delta^{13}C$ from –24 to –26‰) than most deposits of normal PB. Thus, the basement oils are similar to the condensates of the deep-seated (4–6 km) complexes of the Dnepr–Donetsk Depression [10].

The younger (relative to DPPM injections) naphthide generations occur as asphalt and maltha films along fractures, caverns, and crush breccias. Their isotopic–geochemical composition is similar to that of the common oil, which is characterized by the wide range of δD (from –120 to –145‰). In the $\delta^{13}C$–δD diagram, data points are grouped in fields corresponding to the different tectonogeodynamic types of PB [9]. The studied samples from the oil reservoir in the basement of the White Tiger deposit are confined to the boundary between riftogenic and subduction PBs.

In addition to oil, basement rocks contain abundant sorption of light HC and fluid inclusion-hosted HC. The inclusions also contain large amounts of free hydrogen. In particular, the average H_2 and CH_4 contents in fluid inclusions in granitoids of the Central dome are 10.24 and 24.10 cm^3/kg rock at depths of 3050–4000 m, respectively (12.5 and 24.55 cm^3/kg, respectively, at a depth of >4000 m).

The data presented above indicate multiphase genesis of naphthides at riftogenic and postriftogenic-syneclise stages, as well as the presence of several naphthide-generating systems, i.e., rock substrates, the interaction of which with the ascending flow of deep-seated high-enthalpy fluids provides an avalanche generation of HCs and formation of their reservoirs [10]. Such systems are represented by HC inclusions in crystalline rocks and naphthide generations in the basement rocks mentioned above. The geochemical similarity of oils from the basement fields and scattered OM from Oligocene depressions rocks make it possible to consider these structures as potential naphthide-generating substrates.

Influx of deep-seated fluids in the Central and Northern domes of the White Tiger deposit is accompanied by periodical anomalous emissions of methane. This phenomenon emphasizes the cyclic recovery of volumes of the associated gas during the exploitation of oil reservoirs in the basement (Fig. 3).

Data on the petroleum potential of the basement on the shelf of South Vietnam testify to the leading role of endogenous factors in the formation of zones of intense petroleum accumulation in the lithosphere. Moreover, they confirm modern concepts of physics of the Earth, geochemistry, petrology, and chemical geodynamics suggesting an exclusive role of superdeep fluids generated in the liquid core–layer D system. These high-energy fluids represent an ultrahigh-pressure gas mixture with high hydrogen and methane contents. These fluids play an active naphthide-generating role, includ-

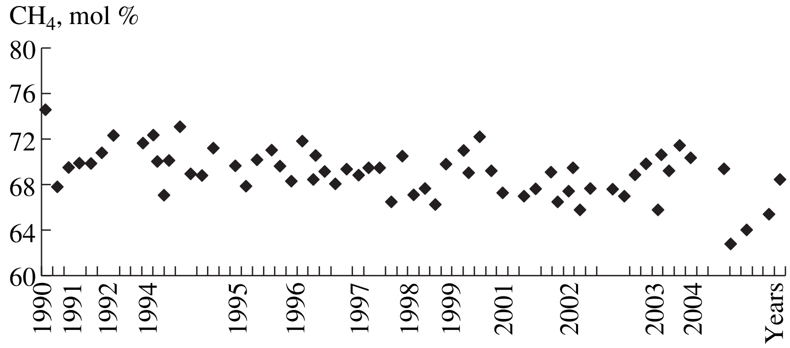

Fig. 3. Variations of the CH_4 content in the associated gas during exploitation of oil field at the basement of the White Tiger deposit.

ing avalanche production of HC during interaction with various substrates (domanikoids, naphthides of different generations, and others). Thus, the White Tiger and other deposits of the Cuu Long PB can be considered reference objects of great significance for the study of naphthide generation and petroleum accumulation in the basement rocks of the sedimentary PB.

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