Structural–Tectonic Model of Hydrocarbons Formation in the Basement of the Vietnam Shelf

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Abstract. The purpose of this study is to identify patterns of hydrocarbon origin within the Pre-Cenozoic basement of the Vietnam shelf. It is shown that the formation of hydrocarbon deposits is associated with protrusive granite massifs that underwent structural–tectonic reworking at the prototectonic and posthumous (postmagmatic) tectonic stage. Together, the posthumous structure-forming processes led to changes in the viscosity properties of rocks, their tectonic and material inhomogeneity, lamination, and, as a result, vertical and lateral spatial redistribution with the formation of granite protrusions. The mechanisms by which voids and oil and gas traps formed within protrusions are considered. Possible mechanisms for hydrocarbon migration and accumulation in basement rocks are considered. It is confirmed that the formation of hydrocarbon deposits occurred due to lateral and downward migration of hydrocarbons via contact zones from Oligocene and Miocene oil source rocks into crystalline massifs: into voids and increased fracture zones in the protrusion body.

1. Introduction
A number of Cenozoic basins are distinguished in the structure of the Sunda shelf in the South China Sea, which is part of the Indosinian–Sunda intercontinental transition zone: the Pattani, Malay, Cuu Long (or Mekong), Nam Con Son, Sarawak, West Natuna (Anambas), and East Natuna. The basins are separated by relative uplifts with different heights and contours (Fig. 1). In the northwestern part of the shelf near the southeast coast of Vietnam are the Cuu Long (Mekong) and Nam Con Son troughs, which are important oil-and-gas-bearing provinces hosting massive hydrocarbon accumulations within the crystalline, predominantly granite, basement. Many researchers have studied the regional geological structure and formation of hydrocarbon deposits in the granite basement\cite{1-4}; however, the problems involved with their origin, the mechanism of their formation in crystalline rocks, the structural–tectonic features of formation of the granite massifs, and how they reached the upper horizons, remain extremely important. The aim of this paper is to determine the nature of oils in the granite massifs of the South China Sea (Vietnam) shelf and create a structural–tectonic model for the formation of hydrocarbon deposits therein based on an analysis of new factual material.
Figure 1. Diagram of principal morphostructural elements of Sunda shelf (using data of [3]). 1, land; 2, water area; 3, Cenozoic basins within confines of Sunda shelf: 1, Pattani, 2, Malay, 3, Mekong (Cuu Long), 4, Nam Con Son, 5, West Natuna, 6, East Natuna, 7, Sarawak; 4, axes of main basement uplifts: I, Narawat, II, Korat, III, Con Son, IV, Natuna, V, Nanysha.

2. Research methods
We used 3D modeling of hydrocarbon systems with basin modeling technology and Petromod software (Schlumberger, Ltd., United States) in order to reconstruct the chronothermobaric conditions and evolution of hydrocarbon generation sources, as well as to reconstruct their formation conditions and regularities of propagation of oil and gas accumulations on the Vietnam shelf. Here, a hydrocarbon system means a naturally occurring system consisting of a generation source and all its genetically related hydrocarbons. This system includes all necessary elements for hydrocarbon deposits to form in a sedimentary basin, such as oil-and-gas source rocks, reservoirs, seal rocks, as well as hydrocarbon generation, migration, accumulation processes, and trap formation [5]. In modeling hydrocarbon systems, the initial data are very important [6-8], which include the following: (1) geometrical characteristics of the basin (structural–tectonic framework); (2) lithological–facies characteristics of sedimentary complexes; (3) geochemical characteristics of oil-and-gas source rocks; (4) information on principal geological events (sedimentation periods, hiatuses, erosion); (5) boundary conditions (heat flow, paleobathymetry on the surface of the paleobasin floor).

3. Tectonics of Cuu Long basin granite
The structure of the Sunda shelf, which is part of the Indosinian–Sunda intercontinental transition zone (or Indosinian median massif), has a number of Cenozoic sedimentary basins separated by relative uplifts, among them, the Cuu Long (Mekong) Trough (see Figs. 1, 2).
Figure 2. Principal structural units of Cuu Long Basin and occurrence depth of roof of Pre-Cenozoic basement (1–5) occurrence depth of basement roof: (1) <1000 m, (2) 1000–2000 m, (3) 2000–4000 m, (4) 4000–6000 m, (5) >6000 m; (6) main faults revealed by displacement of basement roof (without interpretation of fault type).

Analysis of our own materials and published data [9-10] on the structure and evolution of the northeastern part of the Sunda shelf and Cuu Long Basin allows the following conclusions.

(1) The basin formed on the consolidated crust of the Sunda shelf by the end of the Cretaceous and was relatively leveled and overlain in individual areas by the weathering mantle. (2) The basin developed continuously–discontinuously throughout the Cenozoic. The most active period of tectogenesis and formation of the basin’s infrastructure corresponds to the Late Oligocene. This period witnessed the morphostructural differentiation of the Mekong Basin and is separation into a series of sedimentary basins filled with continental deposits and syndepositional uplifts consisting of basement granite. (3) In the Miocene and Quaternary, the intensity of tectonic movements decreased, the seafloor topography leveled, and the territory of the shelf became a single basin divided into flat sedimentary basins, separated by gently sloping uplifts. The influence of the basement on the structure of the shelf starting from the end of the Early Miocene was minimized. (4) Granite massifs broke through the sedimentary rock sequence and were tectonically emplaced therein. Uplift of the granite massifs commenced in the Early Oligocene and continued to the Miocene. Then, apparently, a relatively short hiatus ensued, which ended in the Middle Miocene with reactivated tectonic movements, disrupting the isostatic equilibrium at the basement–sedimentary cover boundary, as a result of which, morphostructural differentiation of the basement occurred, as well as emplacement of granite in the framing and overlying Cenozoic deposits. (5) The granite making up the basement of the Cuu Long Basin was subjected to intensive structural reworking related to prototectonic factors (autometasomatism, hydrothermal–pneumatolytic processes, contractional shrinkage, tectonic caisson effect), but mainly tectonic.

4. Features of postmagmatic tectonics of granite
The granite massifs hosting hydrocarbon deposits are characterized by dome structures and intensive structural reworking [10-12]. However, analysis of the formation of the morpho- and infrastructure of the granite massifs, including the Sunda shelf granite, based only on drilling and geophysical data, is insufficiently complete. After entering the basement, the granite bodies do not become passive
components; rather, they move, sometimes over a significant (tens and hundreds of millions of years) time frame after crystallization and cooling, into higher, relatively primary crustal horizons and form dome structures, expressed in the basement surface and the overlying sedimentary cover. In a number of cases, granites tectonically emplaced in sediments of the frame form piercement bodies. The granite protrusions identified and thoroughly studied in [13-15] are one variety of piercement bodies. Protrusions can form free-standing bodies with significant volume, but they can complicate the structure of large dome structures; a particular example is the Susamyr granite batholith of the Northern Tien Shan (Fig. 3).

![Figure 3](image_url)

**Figure 3.** Principal structural units of Cuu Long Basin and occurrence depth of roof of Pre-Cenozoic basement (1–5) occurrence depth of basement roof: (1) <1000 m, (2) 1000–2000 m, (3) 2000–4000 m, (4) 4000–6000 m, (5) >6000 m; (6) main faults revealed by displacement of basement roof (without interpretation of fault type).

5. **Structural–evolution model of the formation of hydrocarbon deposits in the pre-cenozoic basement of the Cuu Long basin**

Based on a study of the postmagmatic tectonics of granite in different regions and geodynamic stops, a conceptual model was proposed for the formation of structures that are real or potential hydrocarbon reservoirs in the crystalline basement [14, 16-19]. The essence of the model reduces to the following. As a result of structural–tectonic processes in bodies of the basements of ancient platforms and young plates, positive morphostructures are generated and develop (domes, protrusions), the cores of which are filled with disintegrated (granulated) rocks of the crystalline basement; the limbs and roof are filled with plate cover sediments. The most widespread among the structures of this type of piercement body is granite with increased permeability and porosity, which increases with uplift. These bodies are zones of relative decompression. Sedimentary rocks covering the uplift, on the contrary, are under compression and elevated pressure, including fluid pressure, resulting from the weight of the overlying cover complexes and growing dome. In the case when rocks of lower horizons of the cover host hydrocarbons, their flow and transfer commences from the sedimentary sequence into deconsolidated. This model can be used and, what is particularly important, refined on the specific example of hydrocarbon deposits of the basement of the Sunda shelf.

The question of the structure and tectonic evolution of the granite massifs of the Cuu Long Basin after they become magmatic bodies and enter the consolidated layer remains an important component of the region’s tectonics. Within the granite massifs and their surrounding rock masses, a peculiar
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The features of the infra- and morphostructure, the position of the sedimentary basin in the structure, and the stage-by-stage evolution of oil-bearing granite massifs of the Cuu Long Basin are obviously similar to the parameters of granite massifs in other regions.

We analyzed the main factors determining the formation and emplacement of oil and gas deposits within the Pre-Cenozoic granite basement of the Vietnam shelf:

1. The source of hydrocarbons in basement rocks;
2. The formation conditions of regional structures hosting hydrocarbon deposits;
3. The mechanisms for the occurrence of voids (reservoirs) and hydrocarbon traps;
4. The possible mechanism for hydrocarbon migration and accumulation in basement rocks.

In the area of the Sunda shelf, the time since the granite massifs entered the consolidated crustal layer to the recent stage is a period of active intraplate geodynamics, which is related to the mobility of basement rock masses, primarily granite, and their bulk mobility and spatial redistribution, which resulted in the formation of protrusive granite bodies.

**Figure 4.** Three-dimensional image of structure of Cuu Long Basin basement. (1) oil deposits: I, White Tiger; II, Dragon; III, Eastern and Southeastern Dragon; IV, Southern Dragon–Sea Turtle; V, Golden Tuna; VI, Dawn (Cuu Long); VII, Fuongdong; VIII, group of Topaz, Ruby, etc.; IX group of White Lion, Black Lion, etc.; X, Tamdao; XI, Black and White Sea Lion.
6. Conclusions
The results of the conducted studies have made it possible to refine the evolution of hydrocarbons in the Oligocene–Miocene sediments of the Cuu Long Basin, propose a model for the formation of petroleum deposits in granite massifs of the basement of the Cuu Long Basin, and draw the following conclusions. (1) The obtained qualitatively new material confirmed the organic nature of petroleum in the crystalline basement of the South China Sea (Vietnam) shelf. Oils occurring in the basement of the White Tiger oil deposit and oils in sedimentary strata of the Oligocene–Miocene cover complex were identified, as well as the complementarity of oils and organic matter hosted in the sediments. These data allow us to state with a sufficiently high confidence level that hydrocarbon accumulations in the basement of the Cuu Long Basin lie in secondary bedding and the source of their formation is organic matter from Oligocene productive sedimentary complexes. (2) Based on a comparative description of the postmagmatic tectonics of granite available for direct study and subsurface granite massifs in the basement of the Cuu Long Basin (Sunda shelf of the South China Sea), it was demonstrated that the granite forms piercement bodies—crystalline protrusions whose formation is related to viscosity inversion. It has been established that the main form of structural and compositional reworking of granite in the basement of the Cuu Long Basin is bulk disintegration (granulation) of rocks ( cataclasis of various scales); the main form of movement is bulk cataclastic flow. These processes govern the formation of increased porosity and the increase in secondary voids necessary for hydrocarbon accumulations. (3) As protrusions developed, a dynamic system of compression zones (in the sedimentary cover) and decompression zones (in the body of granite protrusions) arose, resulting in fluid flow from cover sediments into empty zones of lower pressure in the body of granite protrusions and the formation of hydrocarbon deposits.

References
[1] Areshev E G 2004 Petroleum Basins of the Pacific Mobile Belt (AVANTI, Moscow)
[2] Gavrilov V P 2000 Petroleum potential of granites (Geol.Nefti Gaza) pp 44–49
[3] Shnip O A 1998 Doctoral Dissertation in Geology and Mineralogy (Moscow)
[4] Guliyev I S, Mustaev R N, Kerimov V Y, Yudin, M N 2018 Degassing of the earth: Scale and implications (Gornyi Zhurnal) pp 38–42
[5] Magoon L B and Dow W G 1991 The Petroleum System – from Source to Trap (AAPG Mem.)
[6] Fyhn M B W, Boldreel L O and Nielsen L H 2009 Geological development of the Central and South Vietnamese margin: Implications for the establishment of the South China Sea, Indochinese escape tectonics and Cenozoic volcanism Tectonophysics pp 184–214
[7] Kerimov V Y, Gordadze G N, Lapidus A L, Giruts M V, Mustaev R N, Movsumzade E M, Zhagfarov F G, Zakharchenko M V 2018 Physicochemical Properties and Genesis of the Asphalites of Orenburg Oblast Solid Fuel Chemistry pp 128-137
[8] Mustaev R N, Hai W N, Kerimov V Y, Leonova E A Generation and Conditions Formation of Hydrocarbon Deposits in Kyulong Basin by Simulation Results Hydrocarbon Systems Geomodel 2015 - 17th Scientific-Practical Conference on Oil and Gas Geological Exploration and Development
[9] Pospelov V V and Shnip O A 1997 Geological structure and petroleum potential of the Sunda offshore zone Geol. Nefti Gaza pp 32–37
[10] Sitiadikova L M and Izotov V G 2002 Geodynamic conditions of formation of destructive hydrocarbon reservoirs in deep crustal horizons Georesursy pp 17–22
[11] Guliyev I S, Kerimov V Y, Osipov A V, Mustaev R N 2017 Generation and accumulation of hydrocarbons at great depths under the earth’s crust SOCAR Proceedings pp 4-16
[12] Kerimov V Y, Leonov M G, Osipov A V, Mustaev R N, Hai V N 2019 Hydrocarbons in the Basement of the South China Sea (Vietnam) Shelf and Structural–Tectonic Model of their Formation Geotectonics pp 42-59
[13] Lavrushina E V 2015 Tectonic structures of granites in the activated side zone of the Kochkor Basin, Tien Shan in Tectonics and Geodynamics of Continental and Oceanic Lithosphere
(GEOS, Moscow) pp 32–35
[14] Leonov M G 2008 Tectonics of the Consolidated Crust (Nauka, Moscow)
[15] Przhialgovskii E S and Leonov M G 2012 Structures, mechanisms, and premises of posthumous rheid deformations in granites Proceedings of the III All-Russia Tectonophysical Conference pp 39–42
[16] Kerimov V Y, Mustaev R N, Osipov A V 2018 Peculiarities of Hydrocarbon Generation at Great Depths in the Crust Doklady Earth Sciences pp 1413-1417
[17] Lapidus A L, Kerimov V Y, Mustaev R N, Movsumzade E M, Zakharchenko M V 2018 Caucasus Maykopian kerogenous shale sequences: Generative potential Oil Shale pp 113-127
[18] Kerimov V Yu, Gordadze G N, Mustaev R N, Bondarev A V 2018 Formation conditions of hydrocarbon systems on the Sakhalin shelf of the sea of okhotsk based on the geochemical studies and modeling Oriental Journal of Chemistry pp 934-947
[19] Kutsenko M, Ovcharuk V, Solovev D B 2019 Application of Singular Value Decomposition Method for Acoustic Emission Data Analysis 2019 International Science and Technology Conference "EastConf", International Conference on. [Online]. Available: http://dx.doi.org/10.1109/EastConf.2019.8725314

Acknowledgments
This study was supported by the Ministry of Education and Science of the Russian Federation (state contract no. 10.6569.2017/BCh).