Petroleum Potential of Continental Slopes in the World Ocean:  
A Tectonic Aspect

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Abstract—Discoveries of giant oil and gas fields in the deep part of the World Ocean during the last six years undoubtedly merit special attention. The Recent continental slopes are highly prospective for oil and gas. Search, exploration and development of hydrocarbons are currently carried out at water depths of 800–3000 m in the Gulf of Mexico; on slopes of the Brazilian, West African, and West Australian margins; in the North Sea and California Borderland; and elsewhere. Continental slopes of passive margins are subdivided into margins that experienced or did not experience tectonic reactivation in the Cenozoic. There are also progradation slopes and slopes complicated by subsided submarine plateaus. Accretionary and erosional slopes are recognized at active continental margins. The sea basins adjacent to the Alpine Foldbelt, actively developing in the Cenozoic, occupy a particular place. Thick and widespread turbidite-type reservoirs with porosity of 28–30% and permeability of 3–5 darcy, which may serve as an excellent repository for oil and gas accumulations, are established at continental slopes of passive margins. Impermeable cap rocks, for example, clay and salt, combined with highly prospective mature source rocks provide prerequisites for the giant hydrocarbon accumulations in these deepwater areas of continental margins. On continental slopes of active margins, the main prospects for oil and gas are also related to gravitational deposits of terrigenous, terrigenous–siliceous, and, probably, calcareous compositions.

INTRODUCTION

Continental margins of the World Ocean belong to those few areas of our planet which are now considered to be promising for discovery of large oil and gas fields. Almost all the giant hydrocarbon accumulations that have been discovered recently occur in deepwater parts of continental margins. Owing to these discoveries, oil and gas reserves in some regions grew several times. Many researchers believe that over 90% of the undiscovered hydrocarbon resources are confined to a depth exceeding 800 m, that is, a depth corresponding to continental slopes and their rises. According to the forecast given in [10], the oil and gas resources of the continental slopes of the World Ocean should be distributed as follows: western Africa, 32%; Gulf of Mexico, 27%; Brazil, 22%; northwest Europe, 8%; Asia and Pacific, 7%; and elsewhere, 4% (Fig. 1).

At present, oil companies explore for hydrocarbons in many areas of the World Ocean, mainly within a depth interval of 800–3000 m: the Gulf of Mexico, the Atlantic continental slopes of South America and western Africa, western Australia, the Bay of Bengal in the Indian Ocean, and the California Borderland of the Pacific Ocean in North America. Deepwater areas of the North, Norwegian, Barents, and Beaufort seas are also subjects of intense exploration.

The petroleum potential of particular regions of the World Ocean has been considered [10, 12, 13] in terms of lithology. However, the relationships between the hydrocarbon distribution and the tectonic setting of slopes on continental margins and, hence, the tectonic factors controlling their undiscovered resources have attracted attention only recently [9].

Continental margins and their slopes are highly diverse with respect to tectonics. First and foremost, they are divided into continental slopes of passive margins of the Atlantic, Indian, and Arctic oceans and those of active margins that are concentrated mainly within the Circum-Pacific Belt (Fig. 2).
CONTINENTAL SLOPES OF PASSIVE MARGINS

Zones of ocean–continent transition developing in the passive tectonic regime comprise widespread margins of reactivated epiplatform orogenic uplifts and nonreactivated areas of ancient cratons and margins of continental rifts or aulacogens [1, 6].

Although passive margins were originally characterized by a similar structure of continental slopes, their subsequent evolution followed different tectonic trends and resulted in substantial and diverse changes of their initial state.

Subsidence and sedimentation were the main processes that determined the prolonged evolution of slopes. The nonuniform subsidence of particular crustal blocks at the stage of breakdown of ancient continents resulted in the stepwise structure of continental slopes. Peculiar depressions (pockets) that appeared at boundaries between nonuniformly subsiding blocks were transformed with time into half-grabens and grabens; these served as traps for sedimentary material that was removed from the shelf or settled from the water column. Relicts of these structures are recorded by geophysical methods as troughs buried under young sediments.

Frequently, marginal parts of the ancient shelf were also involved in subsidence, which was particularly intense during the formation of large barrier reefs, the growth rate of which could be as high as several hundred meters per million years. The Atlantic margin of North America, south of the island of Newfoundland, did not experience subsequent tectonic reactivation, subsidence of the slope and sedimentation therein were very sluggish such that the bulk of the sedimentary material was transported toward the rise. Continental slopes of this type may be called relicts, because their structures have remained almost unchanged since the young ocean opening. This circumstance predetermined the low hydrocarbon potential of the Atlantic slope of the United States, where only one small gas field has been found in the course of long-term exploration.

The history of the Atlantic margins originated from the breakup of the ancient Gondwanaland was richer in events. Some of the half-grabens that left from that time (Aptian–Albian) have been partially incorporated into the African margin and others became elements of the American margin. In the late Eocene, both were transformed into a system of troughs and basins, which accumulated large bodies of sediments removed from the shelf edge. Erosion of epiplatform orogenic structures in the marginal parts of these continents led to the mobilization of terrigenous, clastic, and clayey materials, which were transported by debris and other gravitational flows down the slope and filled separate basins and troughs. These flows were responsible for the formation of turbidite and other gravitational sequences that are frequently characterized by excellent reservoir properties. Large hydrocarbon pools were recently discovered in precisely these formations.

The continental slope of Brazil (Fig. 3), with giant hydrocarbon fields recently discovered within a depth...
interval of 600–2330 m, should be mentioned as an example (table). Up to 80% of the oil is confined here to the Albian–Turonian and Santonian–Miocene pay formations. These sequences of rhythmically intercalating sandstones, siltstones, and clays are dominantly characterized by gradation bedding as a signature of their gravitational (and probably) turbidite origin [3]. The drilling results and geophysical data indicate that this sequence becomes clayey in composition in the upper part of the slope and particularly in the shelf-break zone such that the rocks with good reservoir properties are missing. Thus, it is evident that the host formations on continental slopes are deepwater sediments that accumulated under the influence of gravitational processes which developed on relatively high-angle seafloor segments. Among these, grain and turbidity flows and slumps are the most important.

The sediments, which were deposited as a result of these processes, are commonly described as turbidites;

Giant oil fields on the continental slope of the Campos Basin

<table>
<thead>
<tr>
<th>No.</th>
<th>Field</th>
<th>Year of discovery</th>
<th>Water depth, m</th>
<th>Specific weight of oil</th>
<th>Recoverable reserves, Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1984</td>
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<td>0.889</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
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<td>800–2200</td>
<td>0.890</td>
<td>76</td>
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<tr>
<td>3</td>
<td>Marlim</td>
<td>1985</td>
<td>800–2200</td>
<td>0.930</td>
<td>300</td>
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<tr>
<td>4</td>
<td>Malim Sul</td>
<td>1985</td>
<td>–</td>
<td>0.930</td>
<td>165</td>
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<td>5</td>
<td>Marlim E</td>
<td>1992</td>
<td>1800</td>
<td>0.930</td>
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<tr>
<td>6</td>
<td>Barracuda</td>
<td>1989</td>
<td>1000–1300</td>
<td>0.900</td>
<td>152</td>
</tr>
<tr>
<td>7</td>
<td>Roncador</td>
<td>1996</td>
<td>1000–1800</td>
<td>0.900</td>
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</tr>
</tbody>
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Despite they include some other sediments having a gravitational origin, we also call them turbidites. At present, it has become evident that the turbidite sequences cover vast areas in the deepwater part of the Atlantic margin of South America, at least off the coast of Brazil, that is, in the Campos, Espíritu Santo, and other basins. The productive sequence is 155 m thick and includes rocks with excellent reservoir properties. For instance, the porosity of Oligocene–Miocene turbidite sandstones may be as high as 30%, and their permeability attains 5 darcy. The petroleum fields discovered on the continental slope of Brazil are multilevel; they comprise from 6 to 8 pay units that spread over 100–500 km$^2$. The pool caps are usually composed of clay, although evaporates have been mentioned in some cases. The source rocks are composed of Senonian clayey rocks enriched with organic matter.

Similar turbidite sequences are also widespread at other Atlantic continental margins, for instance, off northwestern and southwestern Africa, Scandinavia, and the British Isles; in deepwater basins of the Gulf of Mexico; and in ancient riftogenic troughs of the North Sea. Several tens of hydrocarbon fields have been discovered recently in these areas.

The structure and evolution of most Atlantic margins of Africa may be referred to as margins of epiplathetic orogenic belts characterized by an erosional-type coast and both a narrow shelf and a rather low-angle continental slope piled up by slump sediments and frequently complicated by salt diapirs. Exploration for hydrocarbons on Atlantic slopes of many African countries has been extremely successful. Over 60 large hydrocarbon (mainly oil) fields have been discovered during the last four years in the belt extending from Cameroon, Gabon, and Congo to Angola and Namibia; thus, the identified hydrocarbon reserves of most of these countries have increased several times. The petroleum accumulations are mainly related to the turbidite formations and to the genetically similar sediments of the Aptian–Cenomanian and Oligocene–Miocene deepwater fans (Fig. 4).

As in turbidite formations on the continental slope off Brazil, the reservoir rocks in deepwater basins of the Atlantic margin off Africa are composed of sandstones and siltstones and characterized by high porosity (28–30%) and permeability (3–4 darcy). The hydrocarbon-bearing formation, 223–300 m thick, commonly consists of several pay units; in places, their thickness reaches 94 and even 100 m [13]. The pools are largely confined to the traps of stratigraphic, tectonically screened, and combined types. It is suggested that the Upper Cretaceous and middle Paleogene clayey

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**Fig. 4.** Correlation of stratigraphic sections in the west African continental margin [4]. (1) sandstone; (2) silt; (3) salt; (4) shale; (5) limestone; (6) volcanics; (7) oil- and gas-bearing beds; (8) faults.
sequences, the so-called black shales that accumulated in deepwater settings under anoxic conditions, served as a source rocks in this region. This follows from the high organic matter content in these sediments and the high degree of their maturity.

The meridional trend along the deepwater basin of the Atlantic margin off Africa from Namibia and Angola to Cameroon and Nigeria [4, 11], where all the large hydrocarbon fields have recently been discovered, extends further northward to the continental slope and to the rise off Morocco, Mauritania, and Senegal. The high hydrocarbon potential of this region has been confirmed by discovery of new oil and gas fields during the last two years [5]. It is of interest that only insignificant hydrocarbon accumulations have been found here on the shelf and in the coastal plain, where exploration has gone on for several decades.

Thus, in sedimentary basins of reactivated craton margins, including most of the African margins in the Atlantic and Indian oceans, it becomes evident that main expectancies in respect to oil and gas are related to the formations that occur in the middle and lower parts of the continental slope and, probably, at the adjacent rise, which are targets of exploration drilling.

A special setting is typical of the margins, where continental rifts and aulacogens open toward the ocean. Continental slopes of such margins are composed of extremely thick terrigenous complexes [8, 10] in the mouths of large river systems; these rivers have discharged their clastic load derived from dry land over many million years. The submarine river deltas located on the shelf pass into the deepwater fans on the continental slope, prograding seaward, and gradually increase the continental margin. Such progradational slopes serve as depositories of the world’s thickest (no less than 15–20 km) sedimentary sequences located in the Gulf of Guinea and the Bay of Bengal. The African margin in the Gulf of Guinea and south of it, where large rivers such as the Niger, Ogowe, Congo, and Cuanza are discharged, is the most striking example. At the moment, 220 oil and gas fields containing a total of 3.1 Bt of identified oil reserves have been found in this region. More than half of them were explored within a deepwater fan at a depth of 900–3000 m [4].

A specific geological setting characterizes the extended margin of the Gulf of Mexico in the United States [7]. The enormously thick sedimentary lens of clastic material removed by the Mississippi River makes up the shelf, continental slope, and rise. In this, one of the richest petroleum regions in North America, oil and gas are recovered from the subaerial and submarine parts of the delta. During previous decades, exploration spreading over the deepwater portion of the Mississippi fan yielded impressive results. 1.7 of the 5 Bt of total oil resources estimated in the Gulf of Mexico are expected to be recovered from the deepwater fan and other segments of the continental slope within a depth interval of 900–3000 m. Main expectancies are related to the Cretaceous and Neogene turbidite formations.

Shelf sedimentary basins on Eurasian margins of the young Arctic Ocean are largely inherited from its previous tectonic evolution [2]. They underwent only weak destruction during ocean formation and are composed of sedimentary sequences covering a wide stratigraphic range. The sedimentary formations are thick and comprise a few structural stages and a number of beds with oil and gas accumulations, for instance, in the Prudhoe Bay field. The discovery of several giant hydrocarbon fields in the shelf areas of these basins such as the Shtokman and Ledovoe gas condensate fields in the Barents Sea, the above-mentioned Prudhoe Bay field in Alaska, Leningradskoe and Rusanovskoe fields in the Kara Sea, and others was followed by the discovery of similarly large fields on the continental slope. The Troll gas field found in the Norwegian segment of the continental slope in the Barents Sea is one of such discoveries. The demonstrated hydrocarbon reserves of continental slopes in the Barents Sea and in the Norwegian and Beaufort seas are estimated to be 1.2 Bt of oil and 2–3 trillion m³ of gas. Like in other regions of the World Ocean, they are mainly hosted in turbidite formations and in sediments similar to them in origin.

Continental slopes of passive margins complicated by submerged plateaus are also very promising targets for exploration, as can be illustrated by the Exmouth Plateau on the continental slope off northwestern Australia. The largest hydrocarbon fields on margins surrounding this continent have been found precisely in the basin of the Carnarvon–Exmouth Plateau. Hydrocarbon accumulations of more than 20 oil and gas fields contain relatively small reserves. Nevertheless, their discovery has provided new insights into prospects of the deepwater areas off northwestern Australia. For instance, if the recoverable oil reserves in fields of the Australian shelf are currently estimated to be ~500 Mt, then these reserves contain 210 Mt of oil and 150 trillion m³ of gas in the Carnarvon–Exmouth Plateau and other basins on the continental slope. The Upper Triassic–Lower Jurassic deltaic and alluvial sandstones and Middle Jurassic–Lower Cretaceous terrigenous sediments are the main pay formations in this region. This productive complex is traceable along the entire northwestern Australian margin of the Indian Ocean. The Kangaroo Basin, 300,000 km² in area, is the most promising structure in this region.

CONTINENTAL SLOPES OF ACTIVE MARGINS

The structure of continental margins in tectonically active transition zones, most of which are located around the Pacific, is quite different. Continental slopes in these zones are commonly steep and devoid of an accumulative rise. The sedimentary masses mobilized by turbidity currents in the marginal part of the shelf and on the slope rarely accumulate in its midst and lower parts but are removed into deepwater trenches;
they are subducted there, along with blocks of oceanic crust, and participate in the formation of accretionary complexes. Thereby, the sedimentary material is subjected to intense transformation and becomes unable to accumulate hydrocarbons. Therefore, most of continental slopes in the Pacific show little promise for discovery of oil and gas fields.

The Nevada-type active margins are an exception. The California and Oregon margins of the United States are the most striking examples. The bulk of these spacious margins is formed by giant accretionary structures that occupy both the submarine part of the margin and a considerable portion of its subaerial zone. Accretionary bodies are mostly composed of deepwater sediments deformed and metamorphosed in the Benioff zone under high temperatures and low pressures. Giant folds composed of Mesozoic turbidites, hemipelagic and slope sediments, including the rocks typical of the oceanic bottom, for example, basalts, make up so-called California Borderland; this is a system of uplifts and basins of the submarine margin and the Coast Range of California, as well as the basement of the Great Valley. The Nevadan-type margins are a relatively rare variety of active continental margins.

Dissimilar to the Andean-type margins that developed under erosion of the continental edge, the Nevadan-type margins resulted from vigorous accretionary processes. Small basins in the accretionary orogen, which are, however, characterized by a high subsidence rate, accumulate thick sedimentary sequences. The basins of the California Borderland are filled with young Neogene or less abundant Eocene–Oligocene terrigenous or cherty–terrigenous sediments. The sedimentary basins that inherit these depressions are located in both subaerial and submarine parts of the borderland. Turbidites and genetically similar sediments are predominant, especially in the lower part of the section. In contrast to other active continental margins, volcanic eruptions are rare, and the deepwater trench is absent. The continental slope is relatively low-angle and composed of strongly deformed and metamorphosed rocks that form a giant accretionary prism. The submarine portions of the largest Ventura, Santa Barbara, Sacramento, San Joaquin, and Los Angeles basins filled with sedimentary sequences, 6–8 km and more thick, are currently being explored for oil and gas. Undiscovered recoverable hydrocarbon resources in the submarine part of the California Borderland are estimated to be as great as 1.7 Bt of oil and 200 billion m$^3$ of gas [13].

The Upper Miocene siliceous rocks of the Monterey Formation, up to 2 to 3 km thick, deserve special consideration. The largest hydrocarbon accumulations in this region have been found precisely in this formation. These, relatively young sediments are composed of diatoms and other siliceous microorganisms. The bloom of their population was related to an ancient upwelling zone that has continued to develop until now. Siliceous sediments initially accumulated in the outer shelf and in the adjacent continental slope. Subsequently, most of these sediments were redeposited by turbidity and other gravitational flows, as is evident from structures typical of slumping sequences and from the cyclic structure of many Monterey Formation sections. The cyclic units consist of siliceous siltstone and terrigenous sandstone and siltstones, in addition to diatomite, porcellanite, and diatomaceous clay. The turbidite origin of the sediments is also indicated by gradation lamination observed in many cyclic units. It is clear that main prospects for hydrocarbon accumulation in deep-water parts of active margins pertain to gravitational deposits composed of terrigenous, siliceous, terrigenous–siliceous, and, probably, calcareous sediments.

**SLOPES OF THE BLACK AND CASPIAN SEAS**

The sedimentary basins that are localized on continental margins of the Black and Caspian seas adjoining the zones of Alpine folding deserve special consideration. Continental slopes and rises in these basins are often complicated by systems of growing anticlinal folds, clay diapirs, and submarine mud volcanoes. Hydrocarbon seeps on the seafloor suggest that hydrocarbons, largely gas accumulations, exist in these sedimentary basins.

**CONCLUSIONS**

Thus, the segments of passive continental margins, where continental rifts open toward the ocean, as well as the passive margins of epipalatform orogenic belts (slopes of deepwater parts of sedimentary basins in the Gulf of Mexico and off Africa and South America), should be estimated as the most prospective for oil and gas accumulation. Lesser in this regard are the segments of continental slopes that are complicated by submarine plateaus and the slopes of inactive ancient cratons such as the Atlantic margin of North America. This may be explained by the absence of significant tectonic movements in the post-Mesozoic history of these margins; these movements play a significant role in the formation of traps and in reactivation of gravitational processes, which are responsible for accumulation of turbidites on continental slopes and at their rises. Intense tectonic movements also favor postsedimentation transformation of organic matter contained in rocks that could play a role in source rocks.

The data discussed above testify to the high probability of discovering oil and gas fields hosted in formations of the continental slopes that extend for a great distance along oceanic coasts [12]. Already to date, the recoverable hydrocarbon reserves in the fields found on the continental slopes of the Atlantic and Indian oceans are estimated to contain 4 Bt of oil and 2 trillion m$^3$ of gas. The undiscovered resources of oil and gas in basins of continental margins in the Arctic Ocean are 42.5–54.0 Bt and 74.2–85.8 trillion m$^3$, respectively. Approx-
imately one-third of these reserves are expected to be discovered on the continental slope of the Arctic Ocean. Taking into consideration that geological explorations have been conducted in areas with known petroleum occurrences, whereas on many continental slopes explorations have not yet or only just started, it may be stated with assurance that the deepwater parts of continental margins are a true hydrocarbon repository. This is a tremendous reserve for economic development in the 21st century.

REFERENCES


Reviewer: Yu.A. Volozh