region based on the geological and geophysical data package. *Geology and Development of Oil Fields in the South of Russia : Collected Papers*. Rostov-on-Don : YUNC RAN, 2006. pp. 174–176.
11. Aliev M. M. Cretaceous paleogeography of the southeastern Great Caucasus. Stratigraphy and paleogeography of oil- and gas-bearing regions of young platforms. Moscow : Nauka, 1982. pp. 6–23.
12. Levin L. E., Senin B. V. Deep structure and dynamics of sedimentary basins in the Caspian region. *Doklady Akademii nauk*. Vol. 338, No. 2. pp. 216–219.
13. International tectonic map of the world : 1981. Leningrad, 1984.
14. Mustaev R. N., Lavrenova E. A., Kerimov V. Yu., Mamedov R. A. Peculiarities of Tertiary petroleum systems evolution under prograding shelf environment on the continental margin of the East Siberian Sea. *Journal of Petroleum Exploration and Production Technology*. 2021. Vol. 11(2). DOI: 10.1007/s13202-021-01280-5
15. Tal-Virskiy B. B. Geophysical fields and tectonics of Central Asia. Moscow : Nedra, 1982. 271 p.
16. Senin B. V. Evolution of the sedimentation environment in the Caspian Sea in the Late Paleozoic–Cenozoic. *AAPG Regional International Conference: Exploration and Production in difficult and sensitive areas. Abstracts Poster Present*. St. Petersburg, 2001. Vol. 2. p. 8.
17. Kerimov V. Yu., Shilov G. Ya., Mustayev R. N., Dmitrievskiy S. S. Thermobaric conditions of hydrocarbons accumulations formation in the low-permeability oil reservoirs of khadum suite of the Pre-Caucasus. *Neftyanoe Khozyaystvo*. 2016. No. 2. pp. 8–11. EM

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THE STRUCTURE AND ROLE OF FAULTING AND FRACTURING SYSTEM IN SPATIAL OIL SATURATION OF ROCKS AND IN OCCURRENCE OF OIL RESERVOIRS WITHIN CHEZHEN SAG OF JIYANG DEPRESSION IN THE BOHAI BAY BASIN IN EAST CHINA

The article reports the integrated analysis of the history, geodynamics, modern faulting system, internal structure and spatial occurrence of Paleozoic and Paleogene (Eocene) accumulations of oil in the promising Chezhen block of the Chezhen sag of the Jiyang depression in the Bohai Bay Basin in East China. After review of the new geological, geophysical and field studies, the authors find out that in this structurally complex system of faults and fractures of different age, orientation and types, the present-day spatial occurrence of oil reservoirs is governed by the neofaults which blanket the whole geological section, including the Paleozoic period.

The studies (analysis of polished sections) into internal structure (micro fracturing) and oil saturation of rocks produce some new data of interest for the theory and practice. The studies of samples from the reservoir and non-reservoir rocks in exploration drilling in the Shahejie pay horizon show that oil saturation is connected with the presence of the younger age system of micro fractures (permeable) of horizontal and vertical (faults) orientation.

The further exploration in the promising Chezhen block of the Shenli oil field is recommended to continue in the zones of the Cenozoic faults as any rocks (irrespective of their lithology, including low-porosity rocks) can be saturated with oil in these zones which contain the best-type reservoirs (fractured) and feature active fluid neodynamics.

Keywords: *Bohai Bay Oil Basin, Shenli oil field, Chezhen sag, faulting system, drillhole, rocks, polished section analysis, micro fractures, oil reservoir*
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Introduction

The Chezhen hydrogen block of the Shenli field, which is China's second largest oil and gas reservoir [1], spatially coincides with the Chezhen sag (2nd order structure) of the Jiyang depression (1st order structure) in the Bohai Bay Basin (**Fig. 1**). Tectonically, this is one of the largest rift basins (its length is around 2600 km and the width is around 1200 km [2, 3]) within the East China Cenozoic Rift Zone in the northeast of the ancient North China.

The relevance of this research topic is defined by the need to support geological exploration in the Chezhen sag which possesses a high oil and gas potential but is yet underexplored [4, 5]. Oil occurs in the complicated geological conditions in the Chezhen sag: there are many productive strata with numerous and diverse faults, and ore reservoirs spatially gravitate to the systems of faults [1, 6–14].

This research aims to reveal tectonic conditions of such spatial selectivity of oil occurrences within the Chezhen sag boundaries.

According to [1, 10, 11, 15–20], geological history of the East China Rift Zone territory underwent a number of tectonic reconstructions under the influence of large-scale and differently directed horizontal tectonic movements (Fuping, Taishan, Caledonian, Hercynian, Indosinian, Yanshan, Himalayan). After multiple changes in geodynamic conditions, the modern geology of this territory, including the Bohai Rift, is complex (structures induced by compression, shearing and tension)

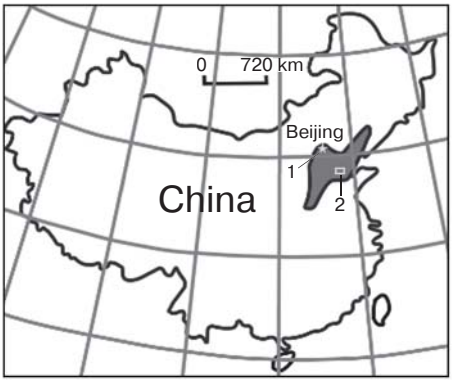

Fig. 1. Map of Bohai Bay Basin (1) and Chezhen sag (2)

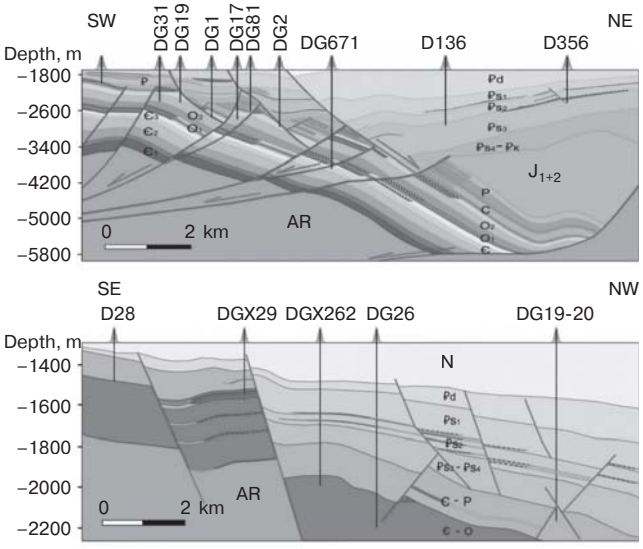

Fig. 2. Geological–geophysical profiles across the center of Chezhen sag (the best explored area of Davanbei)

Drillhole D63.
Siltstone, sampling depth 2544.30 m.
Stratum SH-2.

Drillhole DG674.
Mudstone, sampling depth 2363.90 m.
Stratum SH -2.

Drillhole D107.
Marl, sampling depth 3010.10 m
Stratum SH-4.

Fig. 3. Core samples from various strata in the Shahejie pay horizon (Eocene) in the Chezhen block of the Shenli oil field

[20–22]. The tectonic evolution of the Chezhen sag has four distinct periods [23]: Indosinian (Triassic, compression), early Yanshan (early and middle Jurassic, left-path shearing of the Tan-Lu fault, which is the main fault in the rift system), late Yanshan (late Jurassic and Cretaceous, compression), Himalayan (Paleocene–early Eocene, tension). Up to date, the sag, and the whole territory of the Bohai Basin, develops under conditions of active tectonic tension and is the zone of neodynamic sagging [16, 17, 22, 24–29].

The modern geological structure of the whole China territory formed in the Miocene–late Pleistocene or Holocene [16]. All pre-Mesozoic rift systems in the region, composed of marine sediments, are overlaid with a thick cover of the continental Mesozoic and Cenozoic deposits. The continental deposits within the limits of the Bohai rift accumulated their maximum thickness (10–12 km) in the Eocene and Oligocene periods. For the comparison, the other rifts are 3 to 6.5 km thick. The total thickness of the sedimentary cover reaches 32–34 km [1].

The all-aged system of faulting in the Chezhen sag features various orientations (horizontal, vertical and steep dipping), various types (normal and reverse, strike-slips, shift faults, overthrusts) and ranks (from small-amplitude to regional-scale faults rooted in the basement) [1, 9, 13, 14]. The differences in the characteristics and activity of the faults are connected with their geological age and location [23].

Figure 2 presents two geological–geophysical profiles across the center of the Chezhen sag (3rd order structure of Davanbei sag [30, 31]). The structure of this sag includes many Mesozoic and Cenozoic faults. The Mesozoic faults developed till the end of the Paleogene and then became inactive. The amplitude of the displacement over the plane of these faults is the first tens to hundreds meters. The Cenozoic faults (with the displacement amplitude up to 500–100 m and more) dissect the whole section, including the Paleozoic, and some of them have their roots in the basement [13, 14].

The most oil reservoirs in the Chezhen sag, as in the whole Bohai Bay Basin, have either tectonic screening (such reservoirs dominate) or stratigraphic screening, and their spatial location is connected with the geodynamic history of the territory [1, 2, 4–14, 21, 31–33]. At the same time, there are rare stacked reservoirs bounded by nothing. Such reservoirs are detected in the Paleogene strata in the Eocene deposit of the Shahejie formation (Fig. 2).

Thus, this research focuses on the detailed examination of the tectonic conditions of petroleum generation in the Eocene deposits within the boundaries of the Chezhen sag. The scope of the studies encompasses the internal structure of the Eocene age rocks (jointing), deformation characteristics of small-amplitude faults (micro fractures) and their contribution to the local oil saturation.

Laboratory research procedure and equipment

Alongside with the accomplished analysis of the new geological–geophysical information, the framework for this research is also the analysis of transparent petrographic polished sections

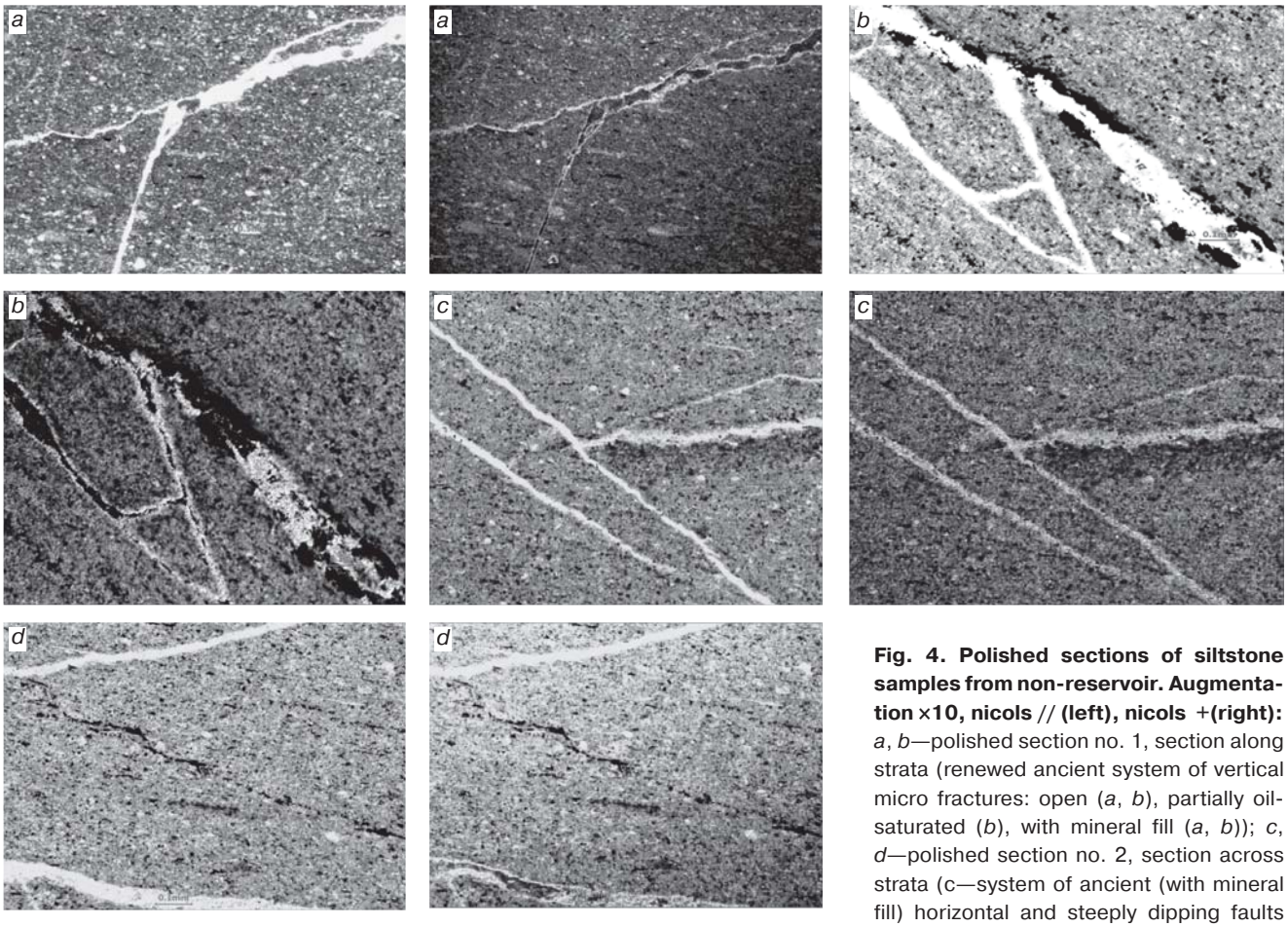

Fig. 4. Polished sections of siltstone samples from non-reservoir. Augmentation ×10, nicols // (left), nicols +(right): *a*, *b*—polished section no. 1, section along strata (renewed ancient system of vertical micro fractures: open (*a*, *b*), partially oil-saturated (*b*), with mineral fill (*a*, *b*)); *c*, *d*—polished section no. 2, section across strata (c—system of ancient (with mineral fill) horizontal and steeply dipping faults of two generations (change in identical incline of separation planes in case of faults of both orientations)); *d*—young (oil-saturated) inclined system of micro fractures

manufactured from cores sampled in all reservoirs (strata SH-1, SH-2, SH-3 and SH-4) and non-reservoirs (caps, by GIS data) in the Shahejie pay horizon (Eocene). The polished sections are examined using the scanning electron microscopy. All in all, the studies included 26 samples of rocks from 11 exploration holes drilled within the limits of the Chezhen sag. For the analysis of the spatial features of the internal structure and oil saturation of rocks, 52 polished sections were manufactured (section: along and across the strata).

Results and discussion

Internal structure (fracturing) of the Shahejie pay horizon rocks (Eocene). The internal structure analysis (macro and micro fracturing) of rocks sampled from all strata (SH-1, SH-2, SH-3 and SH-4) of the Shahejie pay horizon in the Chezhen block of the Shenli field reveals tectonic faults in all samples. Depending on the location of drillholes, small-amplitude faults are common in rocks (macro fractures, **Fig. 3**; micro fractures, **Figs. 4–6**). The faults belong to different systems of faulting and fracturing: in terms of orientation (horizontal, vertical and steep dipping), type (normal and reverse, strike-slips, shift faults, overthrusts) and age (ancient—closed, with a mineral fill, and young—permeable, saturated with oil).

Figure 4 illustrates micro fractures of different age and from different fault systems in the same sample. In particular, within the limits of drillhole D103 site, multiple gradient changes of the tectonic stresses took place, and each change was accompanied by rock fracture. For instance, the siltstone sample taken in drillhole D103 at the depth of 2076.20 m (Shahejie pay horizon, stratum SH-1) contains a system of micro fractures of different orientations (horizontal, vertical and steep dipping) and different ages (ancient—closed, with a mineral fill, and young—permeable, saturated with oil). The ancient fracture system underwent some refreshment, with some change in the orientation (azimuth, incline), in the fracture opening and its fill (partially open/partially closed, partially open/partially oil-saturated, partially oil-saturated/partially healed).

Figure 5 presents a rare example of the strike-slip micro fractures in the same sample. This is a dense limestone sample taken in drillhole D107 at the depth of 3016.50 m. The hade faults are oil-saturated, and the hade slips are young (the system of faults is block-wise displaced in them).

In the zones of the vertical faults, at great depths, fracturing embraces all rocks irrespective of their lithology, including rocks of low porosity (mudstone, marl, dense limestone, heavily clayey siltstone etc.) (see Figs. 3–5).

Spatial oil saturation of Eocene rocks

In the Chezhen block of the Shenli field, the most oil occurrences are connected with the faulting (see Fig. 2) as in the whole Bohai Bay Basin. The system of faults controls the

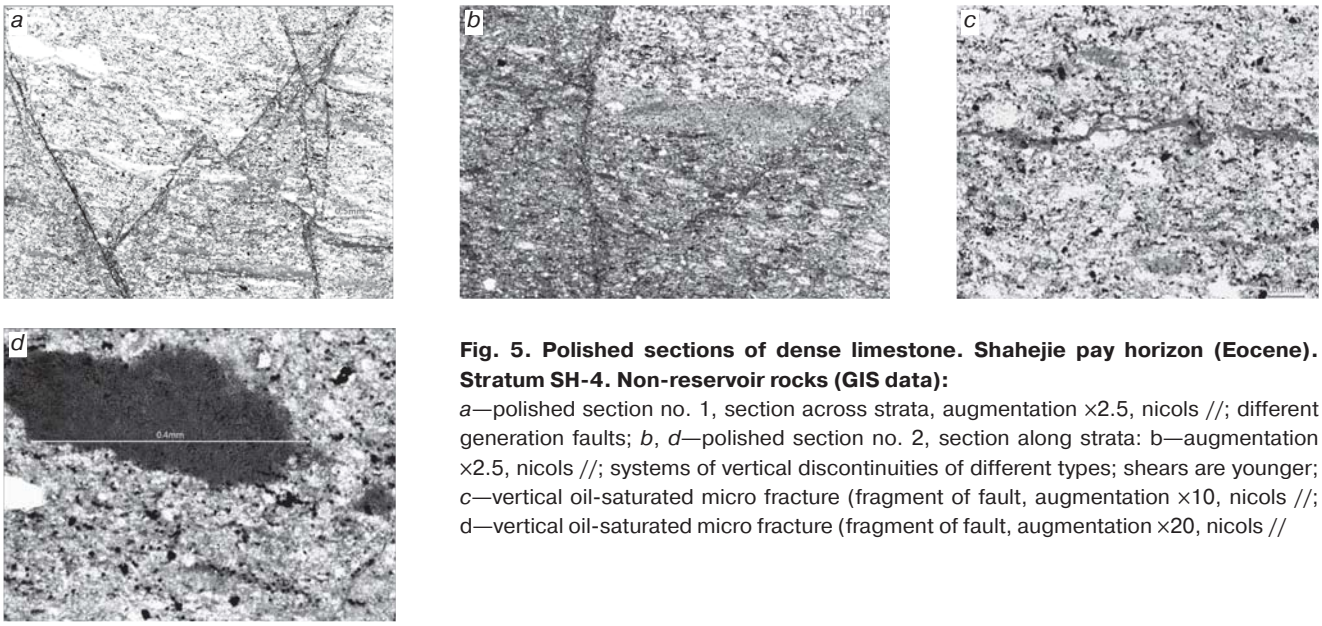

Fig. 5. Polished sections of dense limestone. Shahejie pay horizon (Eocene). Stratum SH-4. Non-reservoir rocks (GIS data):
a—polished section no. 1, section across strata, augmentation ×2.5, nicols //; different generation faults; *b*, *d*—polished section no. 2, section along strata: b—augmentation ×2.5, nicols //; systems of vertical discontinuities of different types; shears are younger; *c*—vertical oil-saturated micro fracture (fragment of fault, augmentation ×10, nicols //; d—vertical oil-saturated micro fracture (fragment of fault, augmentation ×20, nicols //

spatial (horizontally and vertically) oil saturation of rocks and, accordingly, the location of oil accumulations.

For example, the selective oil saturation of the Paleogene section rocks (only the Eocene-age Shahejie horizon is a pay zone) as well as the layered alternation of reservoir and non-reservoir rocks inside a single pay horizon (strata SH-1, SH-2, SH-3 and SH-4, Shahejie horizon) is conditioned by the presence of the horizontal oil-saturated fracture system in the Eocene formation. In terms of drillhole D63, the selective oil saturation of rocks inside a reservoir (SH-2), which is conditioned by the horizontal oil-saturation micro fracturing, is illustrated in Fig. 6.

The studies show that rare reservoir oil (bounded by nothing as seismics shows, Fig. 2), detected in drilling, is actually connected with the zones of tectonic faulting as well, namely, with the zones of horizontal oil-saturated stack micro fractures in Eocene age formation. These fractures have small amplitudes (without visible displacement of rocks), which complicates their detection using the conventional geophysical methods.

The drillholes in the younger zones in the neighborhood of faulting reveal the actual oil-saturated micro fractures in rocks of low porosity, less than (2–5% (mudstone, marl, dense limestone, heavily clayey and compact siltstone), as is demonstrated in Figs. 4 and 5. The same research made abroad arrived at the analogous conclusions regarding the other oil-and-gas-bearing and geodynamically unstable territories (Caspian Depression) [34].

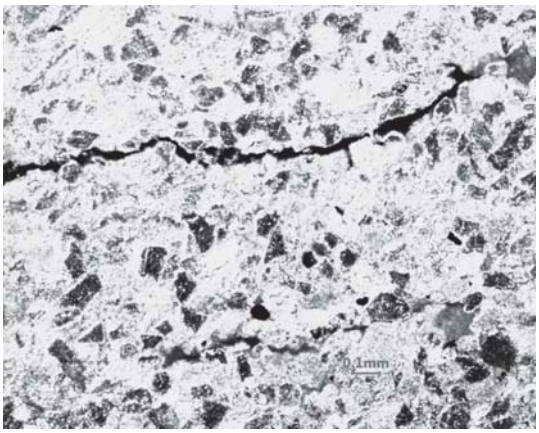

Fig. 6. Polished section of siltstone sample at depth of 2544.30 m, Shahejie horizon, stratum SH-2, reservoir rocks, section across stratum. Augmentation ×5, nicols //

Conclusions

The Chezhen sag under discussion repeatedly experienced drastic and vigorous changes in the stress–strain behavior in the crust at different geological ages, connected with the change in the geodynamic regime (compression, tension, shearing).

Seismics and drilling discover numerous different-rank (from small-amplitude to regional-scale faults) discontinuities belonging to fracture systems of different orientation (nearly horizontal, nearly vertical, with the dominant northwestward and northeastward azimuth), of different age (ancient Mesozoic–Paleozoic and younger Cenozoic) and of different type (normal and reverse, strike-slips, shift faults, overthrusts).

The location of oil and oil-saturated rocks within the boundaries of the Chezhen sag is governed by the younger age system of fractures and faults (Cenozoic age).

The section-selective (layered) oil saturation of rocks inside a pay horizon (Eocene-age Shahejie horizon) is connected with the presence of horizontal small-amplitude younger age micro fractures (permeable, differently saturated with oil).

The proved presence of oil-saturated micro fractures in the rock strata of low porosity (mudstone, dense limestone, heavily clayey siltstone, etc.) totally converts understanding of the poroperm properties of rocks and turns them from non-reservoirs (caps) to the best-type fractured reservoirs.

It is recommended to take into account these new data in oil exploration in the promising Chezhen block in Shenli oil field. In the authors' opinion, the top-priority objects for exploration are the Cenozoic faulting zones within which any rocks are fractured and saturated with oil, irrespective of the lithology and porosity.

References

1. Li G. Geology of Oil and Gas of China. Novosibirsk : SO RAN, 1992. 32 p.
2. Rapatskaya L. A., Buglov N. A., Egorova N. E. On Some Factors of Hydrocarbon Ontogenesis in North China Petroleum Basin. *Proceedings of Irkutsk State Technical University*. 2013. No. 10. pp. 95–104.
3. Levitan M. A., Antonova T. A., Gelvi T. N. et al. The facial structure and quantitative parameters of the Pleistocene deposits of the China seas. *Bulletin of Commission for Study of the Quarternary.* 2018. No. 76. pp. 143–156.
4. Liu G., Fu J., Yang H., et al. Application of structural characteristics research in Chezhen sag of Jiyang depression of Bohai Bay Basin in oil and gas exploration. *China Science and Technology Review*. 2013. No. 21. pp. 29.
5. Wang Ya., Lin H., Feng J. et al. Quantitative evaluation of provenance supply capacity for sandy conglomerates: A case study of Guojuzi subsag in Chezhen Sag. *Oil and Gas Geology*. 2018. Vol. 39, No. 6. pp. 1154–1163.
6. Liu B., Wang Y., Qian X. The Two Ordovician Uncomformities in North China. Their Origins and Related Regional Reservoirs' Prediction. *Acta Sedim-Entologica Sinica*. 1997. Vol. 15, No. 1. pp. 25–36.
7. Xu Ch., Wang Y., Yang G. The genesis and influential factors of layered reservoir of Yeli-Liangjiashan formation in the Jiyang depression of the Bohai Bay Basin. *Petroleum Geology and Experiment*. 2009. Vol. 31, No. 4. pp. 362–365.
8. Lin X., Li J., Yang T. et al. Oil-Gas Exploration Status and Future Targets in Bohai Bay Basin. *Xinjiang Petroleum Geology*. 2013. Vol. 34, No. 2. pp. 140–144.
9. Luo Q. Concept, principle, model and significance of the fault controlling hydrocarbon theory. *Petroleum Exploration and Development*. 2010. Vol. 37, No. 3. pp. 316–324.
10. Chen H., Yu J., Shu L. et al. The Structural Styles and Their Relation with Petroleum-Gas Resources of the Jiyang Depression, Shandong Province, China. *Geological Journal of China Universities.* 2005. Vol. 11, No. 4. pp. 622–632.
11. Zhang B. The Sequence Stratigraphy and Petroleum Geology in Chezhen Depression. Beijing : Petroleum Industry Press, 2004. 170 p.
12. Zhu G., Jin Q., Zhang S. et al. Hydrocarbon-generating system of Eogene Shahejie formation in Chezhen Sag. *Natural Gas Industry*. 2006. Vol. 26, No. 3. pp. 19–22.
13. Qiu Sh. The geological and geodynamic features of the formation and the regularities of oil fields location within the Davanchzhuan area of the Chezhen block of the Shenli field (Bohai Bay Basin, China). *XXVIII International Scientific Conference Lomonosov-2021. Lomonosov Moscow State University*. Moscow : MAKS Press, 2021.
14. Qiu Sh. The features of geological structure of Shenli oil field (within the Chezhen sag). *The Young to the Earth Science: IX International Scientific Conference of Young Researchers.* Moscow : Sergo Ordzhonikidze Russian State University of Geological Prospecting. 2020. Vol. 1. pp. 38–39.
15. Yang Q. Early Paleozoic Stratigraphic Distribution and Tectonic Evolution of the Northern Margin of the North China Platform. *Inner Mongolia Coal Economy*. 2014. No. 6. pp. 118–121.
16. Milanovsky E. E. The main stages of riftogenesis in China. Moscow : Interdepartmental Geophysical Committee, 1991. 148 p.
17. Bormotov V. A., Merkulova T. V. Cenozoic stage in the evolution of the northern branch of the Tan-Lu-Okhotsk rift system: deep structure and seismogeodynamics. *Tikhookeanskaya Geologiya*. 2012. Vol. 31, No. 1. pp. 26–41.
18. Ma H. The characters and control of tectonics on sequence stratigraphy of the lower tertiary in Jiyang basin. Guangzhou Institute of Geochemistry. Chinese Academy of Sciences. 2005. 108 p.
19. Huang J., Ren J., Jiang Ch. et al. An outline of the tectonic characteristics of China. *Acta Geologica Sinica.* 1977. Vol. 51, No. 2. pp. 117–135.
20. Ji Sh., Yan Z., Jiang N. Discuss on tectonic and sedimentary evolutions of Bohaiwan basin—taking Jiyang sag as an example. *Petroleum Geology and Engineering*. 2008. Vol. 22, No. 3. pp. 21–25.
21. Li L., Zhao L., Liu H. et al. Late Mesozoic to Cenozoic extension and strike slip structures and deep background of Bohai Bay Basin. *Scientia Geologica Sinica*. 2015. Vol. 50, No. 2. pp. 446–472.
22. Zhao L., Li L. The extensional pattern and dynamics of Bohai Bay in Late Mesozoic-Cenozoic. *Geology in China*. 2016. Vol. 43, No. 2. pp. 470–485.
23. Lin H., Liu P., Wang T. et al. Diagenetic evolution mechanism of deep glutenite reservoirs based on differences in parent rock types: a case study of lower submember of Member 3 of Shahejie Formation in Chezhen sag, Bohai Bay Basin. *Acta Petrolei Sinica*. 2019. Vol. 40, No. 10. pp. 1180–1191.
24. Guo X., Liu K., He Sh. et al. Petroleum generation and charge history of the northern Dongying depression, Bohai Bay Basin, China: insight from integrated fluid inclusion analysis and basin modelling. *Marine and Petroleum Geology*. 2012. Vol. 32, No.1. pp. 21–35.
25. Lysak S. V. Thermal history, geodynamics, and current thermal activity of lithosphere in China. *Geology and geophysics*. 2009. Vol. 50, No. 9. pp. 1058–1071.
26. Hu Q., Zhang Y., Meng X. et al. Characterization of micro-nano pore networks in shale oil reservoirs of Paleogene Shahejie Formation in Dongying Sag of Bohai Bay Basin, East China. *Petroleum Exploration and Development*. 2017. Vol. 44, No. 5. pp. 720–730.
27. Rodnikova. G., Zabarinskaya L. P., Rashidov V. A. et al. Geodynamic Models of the Deep Structure Beneath the Natural Disaster Regions of Active Continental Margins. Moscow : Nauchnyi Mir, 2014. 172 p.
28. Gatinsky Yu. G., Prokhorova T. V., Runquist D. V. Central Asian Geodynamic Regimes West and East 102–104° Geodivider. *Geodynamic and Tectonophysics*. 2020. Vol. 11, No. 2. pp. 334–351.
29. Zhuo Ya. Q., Guo Ya., Bornyakov S. A. et al. A Test of the oblique-rifting model for transfer zone deformation in the north Fen-Wei rift: implications from the 1989 m 6.1 Datong-Yanggao earthquake swarm. *Geodynamic and Tectonophysics*. 2019. Vol. 10, No. 1. pp. 43–51.
30. Liu L., Lin Ch. The Control Effect of Sedimentary Filling Patterns and Fault Slope Zones of Sea 3 Member of Shahejie Formation in Chezhen Sag, Jiyang Depression. *Journal of Yangtze University*. 2020. Vol. 17, No. 5. pp. 10–17.
31. Wu W., Gao X., Li L., Zhang D., Liu B. Favorable conditions formed in large-scale buried-hill reservoir in Bohai Bay Basin. *Special Oil and Gas Reservoirs*. 2015. Vol. 22, No. 2. pp. 22–26.
32. Jin Q., He Sh., Lu M. Relationship between Overpressures Characteristics and Hydrocarbon Enrichment in the Chechen Depression of Bohai Bay Basin. *Geological Science and Technology Information*. 2015. Vol. 34, No. 3. pp. 113–119.
33. Wu F. Study on the evolution regularity of Chengnan fault. *Inner Mongolia Petrochemical Industry*. 2014. No. 16. pp. 119–120.
34. Kasyanova N. A. The role of young fracturing in the formation and spatial distribution of hydrocarbon deposits in the North-Western Caspian Sea. *Neftyanoe khozyaystvo*. 2018. No. 5. pp. 36–39. EM