Tectonics of the sedimentary basins in the Russian sector of the Chuckchi Sea

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ABSTRACT

The integrated analysis of geological and geophysical, primarily seismic data, resulted in new interpretations of the stratigraphy of the Chukchi Sea shelf in its southern and northern parts (Russian sector) and tectonics of the South and the North Chukchi basins. It is demonstrated that the sedimentary cover in the northern part of the Russian Chukchi Sea sector shares similarities with the U.S. sector but important differences are also identified. In the Russian sector, the westward extension of the Colville foredeep is reduced in thickness due to subdued scale of subsidence and deeper erosion. The sub-latitudinal marginal uplift near the hinge line along the south margin of the North Chukchi trough (analog to the Barrow Arch) is less significant. In the South Chukchi basin rift-fault structures are prominent in the earliest strata that floor the basin. Transtension structures (extension accompanied by strike-slip displacements) are widely developed. Transtensional displacements occurred in the Oligocene-Early Miocene time and are well correlated with similar features in other Eastern Arctic sedimentary basins.

INTRODUCTION

After recent (1990-2009) seismic data acquisitions, exploration interest has sharply increased in the sedimentary basins in Russian offshore sector of the Eastern Arctic, including South and North Chukchi basins. This region, in our opinion, has a number of challenges and principal problems to be addressed. Some of them are listed below:

- Absence of wells in the north and south parts of the Russian sector in the Chukchi Sea that causes an ambiguous interpretation of the sedimentary cover in the North and South Chukchi basins.
- Seismic sequence comparison with the Alaska part of the Chukchi Sea and tracking of seismic reflector horizons are challenging, since the Hanna Trough, expressed in the sedimentary cover in the U.S. sector and described by drilling data, is separated from the North Chukchi Basin in the Russian sector by a big horst-and-graben zone with a reduced stratigraphic interval.
- The South Chukchi and North Chukchi sedimentary basins are separated by the Wrangel-Herald fold-thrust zone, which frustrates correlations of seismic reflections along submeridional lines crossing the two basins.
- Insufficient characterization of similarities and differences in the basin structure in front of the Brooks-Herald-Wrangel fold-thrust belt in Russian and American offshore sectors.
- Insufficient studies of hydrocarbon systems, regarding distribution and characterization of oil source rocks, main reservoir rocks and seals.

METHODS

The Rosneft Arctic Research team has conducted seismic mapping in the Russian sector of the Chukchi Sea in support of a hydrocarbon potential assessment. The assessment incorporates evaluations of the presence and distribution of oil source and reservoir rocks, and the impact of tectonic events and major unconformities to hydrocarbon reservoir integrity. The study results are based on traditional basin analysis using only the latest data set, which includes:

- Seismic data, acquired by Dalmorneftegeofizika (DMNG), TGS Nopec and WesternGeco in 1990-2006 in the amount of 13,400 linear km;
- Drilling data both onshore and offshore Alaska (VSP, well logs, stratigraphic tops, etc.);
- Geological information on adjacent land and islands, including the Alaska State Geological Survey reports for 2008-2009.
- Reports of DMNG, VNIIOkeangeologia and other organizations and institutes;

- Numerous publications on the U.S. and Russian sectors of the Chukchi Sea and adjacent land (i.e. Filatova and Khain, 2007; Kim et al., 2009; Kosko and Ushakov, 2003; Malyshev, et al., 2010; Orudzheva, et al., 1999; Vierzhbitsky, et al., 2009; Brown, 2009; Sherwood, et al., 1998; and Tolson, 1987).

RESULTS OF SEISMIC INTERPRETATIONS

Our stratigraphic organization of the reflecting horizons in the Russian waters was based on character matches to reflecting horizons in seismic time sections in the U.S. sector of the Chukchi Sea. The U.S. sector seismic interpretations are controlled by well and outcrop data and document major unconformities as shown in Figure 1. As a reference horizon for the seismic-stratigraphic correlation, we selected the reflecting horizon at the Cenozoic base (mBU) controlling the top of the complex, which is clearly expressed and well-defined from the seismic signature. In the Paleozoic-Early Cenozoic section of various parts in the Novosibirsk-Chukchi-Brooks fold zone and on the Chukchi Sea shelf, five regional unconformities are clearly identified: Late Devonian?-Early Carboniferous (Ellesmerian, EU), pre-Late Permian (PU), pre-Late Jurassic (JU), pre-Aptian (BU) and Early Paleocene (mBU).

NORTH CHUKCHI BASIN

Based on seismic ties to the Crackerjack and Klondike wells in the U.S. Chukchi Sea, five tectonostratigraphic complexes were identified and mapped in the Russian sector of the North Chukchi basin: 1) Upper Devonian-Lower Carboniferous syn-rift; 2) Middle Carboniferous-Middle Jurassic post-rift; 3) Upper Jurassic-Neocomian syn-rift; 4) Aptian-Upper Cretaceous post-rift (syn-collision); and 5) Cenozoic complex of passive continental margins. As used here, the term "North Chukchi basin" refers to a composite basin that includes the "Wrangel-Herald ledge" on the south and the "North Chukchi trough" on the north.

The sedimentary cover in the northern part of the Russian sector shares some similarities with the

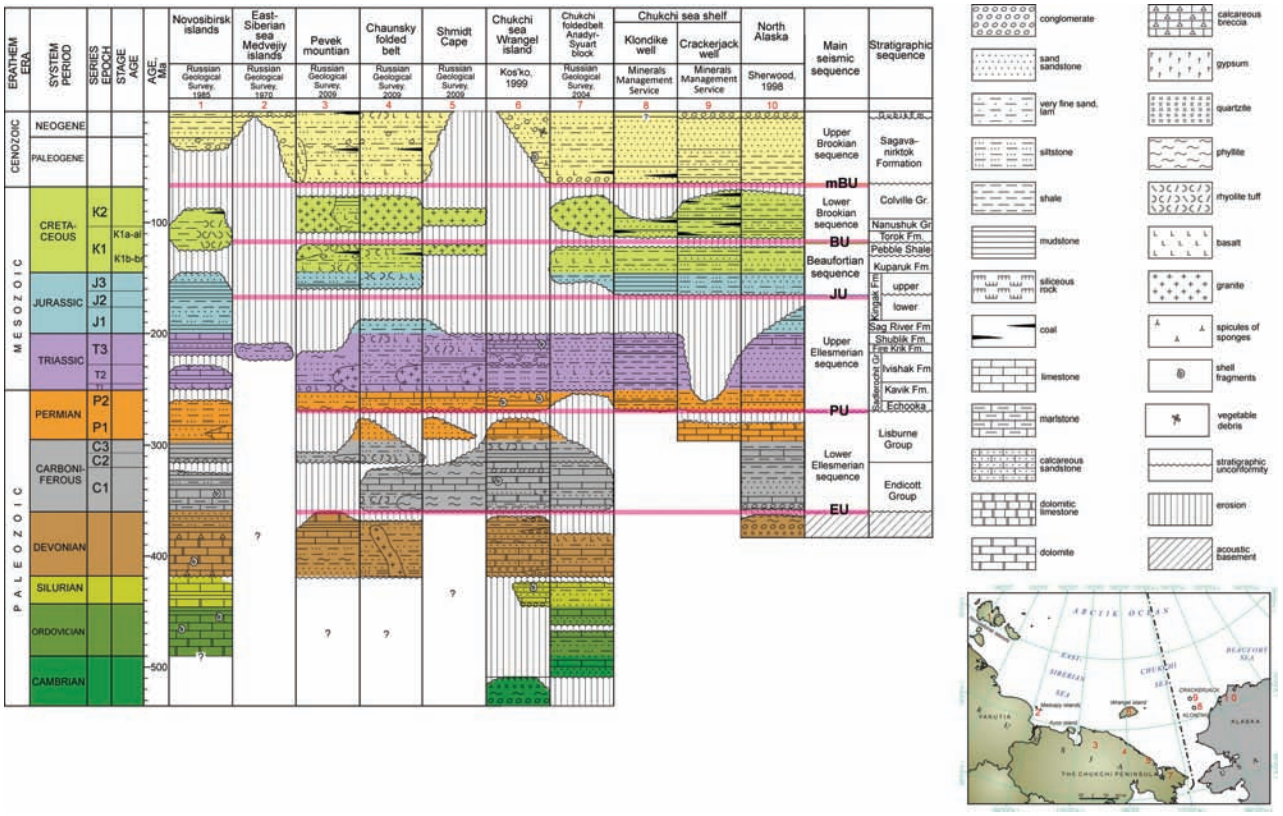

Fig. 1. Correlation through the Novosibirsk and Wrangel-Chukchi-Brooks fold zones, the Russian and U.S. sectors of the Chukchi Sea shelf, and the western North Slope of Alaska.

U.S. Chukchi Sea sector but also differs in some important aspects.

As shown in Figures 2 and 3, the North Chukchi basin is located north of the Wrangel-Herald fold-thrust zone. Its northern boundary is associated with the Andrianov uplift. The Wrangel-Herald Ledge underlies the southern part of the North Chukchi basin between the Wrangel-Herald fold-thrust zone and the North Chukchi trough. The Hinge zone separates the Wrangel-Herald ledge from the North Chukchi trough.

In the southeastern and southwestern parts of the North Chukchi basin along the Wrangel-Herald fold-thrust zone, the Russian-sector extension of the Colville foredeep of Alaska is fragmented into isolated outliers that preserve relatively thin foredeep fill sequences. The Colville foredeep outliers are isolated by large uplifts along the Wrangel-Herald ledge in the Russian sector as mapped in Figure 2. These uplifts were elevated during foredeep subsidence and blocked the establishment of a continuous basin linked to the Colville foredeep. The Wrangel-Herald ledge was also broadly elevated in Early Paleocene time, which resulted in the foredeep sediments exposure to the surface with their full denudation in the central part.

Formed contemporary to foredeep subsidence, the sub-latitudinal marginal uplift, similar to the Barrow Arch (Alaska) in the Russian sector of the Chukchi shelf, is observed only north of the foredeep outliers. Elsewhere, the sub-latitudinal marginal uplift merges with the hinge zone along the south margin of the North Chukchi trough and does not form a distinct mappable feature.

At the base of the Ellesmerian complex of the North Chukchi basin, a rift-like trough is identified between the paleo-uplifts just north of the Wrangel-Herald-Brooks fold zone (located in Figure 2). The rift-like trough is characterized by submeridional extension and is interpreted as filled by the Early Carboniferous formations, similar to the Endicott Group. The trough has a structure similar to the Hanna Trough and the sedimentary cover of the U.S western sector of the Chukchi Sea (Fig. 2).

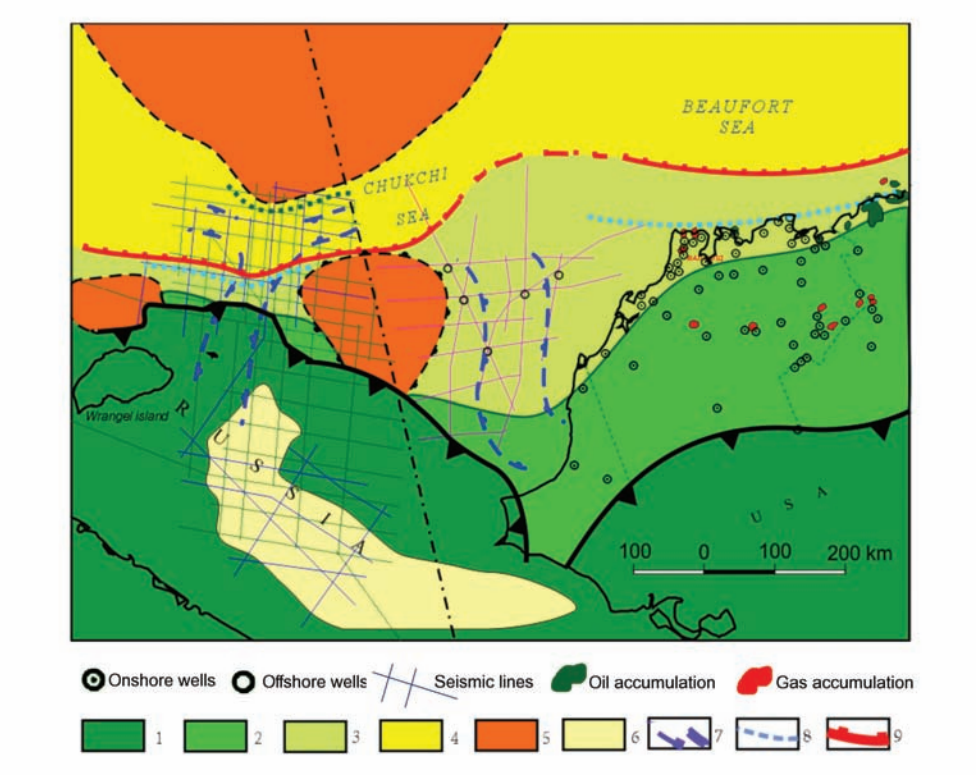

Fig. 2. Tectonic scheme of Russian and U.S. sectors of the Chukchi Sea: 1 - Wrangel-Herald Brooks fold zone, 2 - foredeep, 3 – platform, 4 - Jurassic-Cenozoic troughs, 5 – paleo-uplifts (a – Mamontov uplift, b - North Chukchi graben-and-horst zone, c – Andrianov uplift), 6 - South Chukchi-Hope basin, 7 – Early Ellesmerian rift-like troughs, 8 - Barrow Arch (Alaska), Andrianov uplift (Russia) and similar marginal uplifts, 9 – Hinge zone, 10 – wells, 11 – oil and gas fields.

SOUTH CHUKCHI BASIN

The South Chukchi sedimentary basin is located south of the north-vergent Wrangel-Herald fold-thrust zone. The South Chukchi basin is the northwest extension of the Kotzebue and Hope basins of the U.S. sector of the Chukchi Sea. Its geological history has three main phases. At the initial phase (Albian-Late Cretaceous), subsidence was driven by rift faulting, possibly during a collapse of the Wrangel-Herald-Brooks fold zone. In the Late Oligocene-Early Miocene phase, extension continued with a significant strike-slip component. Similar transtension processes took place at that time over the whole Eastern Arctic, which is expressed in widespread development of extensional incipient strike-slip structures on the shelves of the Laptev, East Siberian, and Chukchi Seas and on adjacent lands. Obviously, these events were associated with the Eurasian Basin opening and, apparently, with the plate-tectonic rearrangements during general geodynamic evolution in the Arctic region. At the final or third phase during Pliocene-Quaternary time, the South Chukchi basin experienced a regional subsidence not accompanied by faulting.

The above-described events are reflected in the sedimentary cover as major stratigraphic unconformities that can be observed on regional seismic lines. These unconformities divide the sedimentary section into three structural complexes:

- Lower - syn-rift complex (Albian-Late Cretaceous), developed in grabens and semi-grabens and absent on the separating uplifts,
- Middle - post-rift complex Late Oligocene-Early Miocene) with development of northwest-trending transtensional structures, and
- Upper - syniclise complex (Pliocene-Quaternary) of sub-horizontal strata draped upon the lower complexes and basement rocks.

In the central part of the South Chukchi basin along the main fault zone that divides the basin into two large troughs - Schmidt on the southeast and Sredinny on the northwest, there is the Ushakov anticline zone with pop-up structures. Moving away from this fault zone, the amplitudes and sizes of positive structures diminish. Fault tectonics become less prominent towards the Hope and Kotzebue troughs (Malyshev, et al., 2010). Strike-slip displacements occurred along reactivated faults in the lower structural complex and the basement, but in some cases the strike-slip faults are newly formed, characterized by different orientation and cross the older faults.

SOURCE ROCK DATA FOR THE RUSSIAN SECTOR OF THE CHUKCHI SHELF

As regards to hydrocarbon potential, the North Chukchi basin has the highest oil prospective, established from similarity with the Arctic Alaska basin of the Alaska North Slope, where currently more than two dozen oil and gas fields were discovered, including the unique Prudhoe Bay field with 3 to 5 billion tons of oil reserves (Orudzheva, et al., 1999).

The source rock prediction was based on public data on geochemical studies over Wrangel Island, the Chukotka Peninsula, the U.S. sector of the Chukchi Shelf, and Alaska North Slope. Oil source rocks were identified in the entire sedimentary interval from Carboniferous to Paleocene. The Lower Carboniferous section (Kekiktuk formation) contains mudstone layers of 0.5-1% TOC. Kerogen is of mixed humus-sapropel and humus types. In Alaska, the Upper Carboniferous-Lower Permian Lisburne Group contains mudstones and clayey limestones of 0.5-1% TOC and kerogen of type II. On Wrangel Island, the Upper Permian interval includes numerous layers of black shales and marls (Kosko and Ushakov, 2003). Geochemical studies of these rocks were not conducted; however, accounting for the preferential basin facies development, we can predict high TOC content of sapropelic type. The Ivishak mudstones are fairly rich in sapropelic and humic-sapropelic organic matter (TOC varies from 0.5 to 3%).

The Shublik clayey limestones and mudstones are the main oil source rocks in the region. TOC in these rocks reaches 8% with kerogen of mainly sapropelic type. The Lower Cretaceous Pebble Shale mudstones also have good oil potential. TOC in them varies from 1.6% to 5.5%, and the kerogen type is II-III. In the Middle-Upper Jurassic Kingak mudstones, TOC varies from 0.5% to 6.47%, with the kerogen type of II-III. The youngest oil source rocks recognized in the region are the Lower Cretaceous Torok mudstones (Aptian-Albian). TOC in these

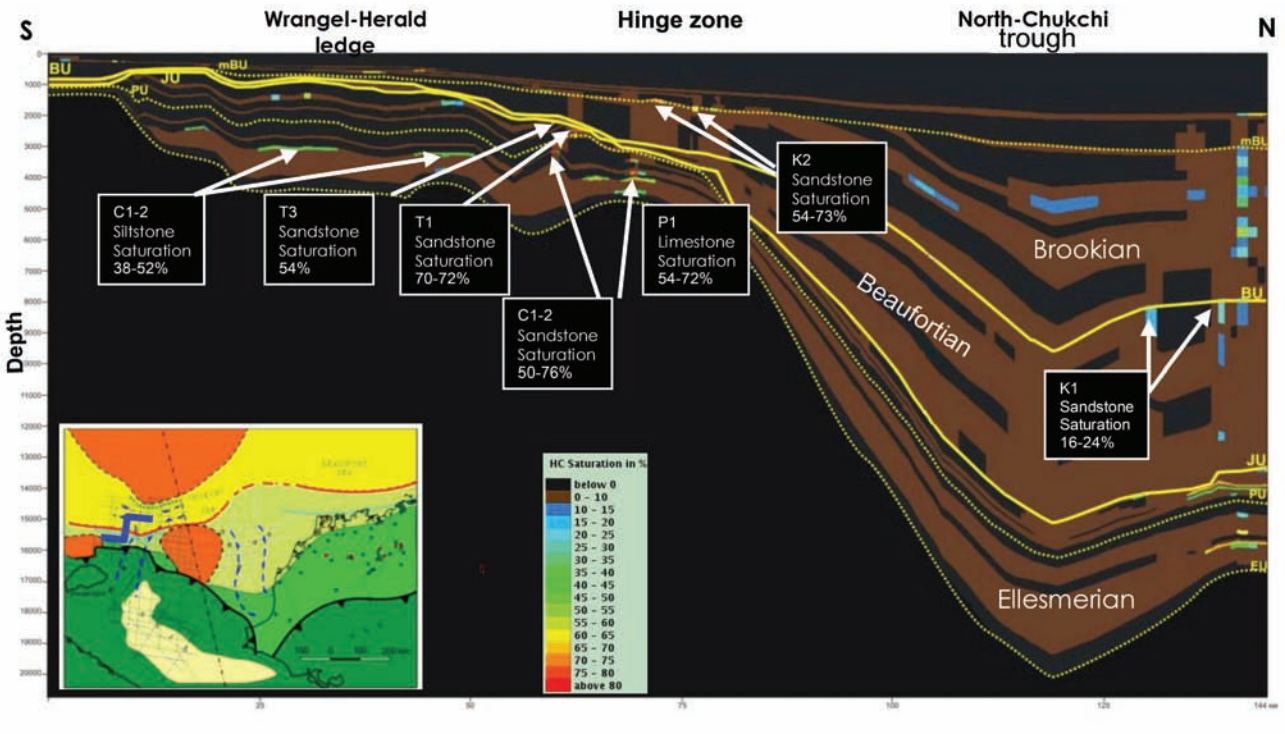

Fig. 3. Present-day hydrocarbon saturation across the North Chukchi basin (south to north cross-section – TemisSuite basin modeling)

rocks is 0.6-2.2% with kerogen of the mixed humus-sapropel type. The overlying Paleogene section includes primarily gas prone rocks. TOC there is up to 5-6% (in some samples - up to 12.3%) mainly due to the humus component.

The distribution of oil source rocks, reservoirs and seals through the section in the offshore region is predicted from the depositional reconstruction and seismic facies analysis. The analysis of the outcrops on the Wrangel Island and Chukchi Sea coast indicated the general facies zoning for the most of the sedimentary section. The main source rock – the Shublik Formation - is predicted over the majority of the North Chukchi basin, except for its depocenter and a part of the southern flank, where Shublik was eroded in Jurassic time. Seismic mapping in the U.S. sector shows that the Shublik Formation in Hanna trough is truncated by unconformities west of 166º west longitude due to erosion over the western Chukchi platform and related isolation from Hanna trough (Sherwood, et al., 1998). However, we believe that the Shublik Formation is preserved in isolated correlative basins in the Russian sector of the Chukchi shelf west of the Chukchi platform uplift where the Shublik Formation is lost to erosion.

MODELING OF PETROLEUM GENERATION, MIGRATION, AND ENTRAPMENT

Our mapping of the present-day geological structure and history of sedimentary basins in the Russian sector of the Chukchi Sea form the basis of two-dimensional hydrocarbon system modeling using the software package TemisSuite. In the absence of actual geochemical data for the Russian offshore sector, we conducted multivariate modeling using reasonable ranges of geochemical parameters (sources rock presence, distribution, thickness, kerogen type, and total organic carbon) consistent with U.S. sector data for correlative source rocks. The heat flow was assigned as the average from existing measurements (50-60 mW/m2). The heat flow was calibrated with the Klondike well data in the U.S. sector of the Chukchi Sea.

The results of 2D-modeling showed that within the Wrangel-Herald Ledge the oil source rocks within the sequence of Upper Paleozoic and older rocks were completely expended for oil prior to Late Jurassic time. The Mesozoic source rocks experienced thermal exposures sufficient for oil generation in Cenozoic time and remain in the oil window at present. Cretaceous-Paleogene source

rocks remain thermally immature.

In the sedimentary section of the North Chukchi basin in the Wrangel-Herald Ledge, the highest oil potential is associated with the Permian, Triassic and Jurassic and Lower Cretaceous intervals (Fig. 3).

Gas accumulations are forecast for the Cretaceous-Paleogene section in the depocenters and on the flanks of the North Chukchi trough. The main risks here are related to the Permian-Triassic clastic reservoirs presence (erosional events could have removed the reservoirs at some of the prospects) and trap integrity in the periods of the Cretaceous and Early Paleozoic erosion events.

In geological hydrocarbon prospects, the North Chukchi basin includes the Andrianov gas prospective zone and Academic oil prospective zone, divided into the Lineiny, Mamontov and West Mamontov prospective regions. The highest oil and gas potential in this case is related to the Academic hydrocarbon-prospective region with eight identified prospects.

CONCLUSIONS: UNDISCOVERED PETROLEUM POTENTIAL

A total of about 20 prospects are mapped in the northern shelf of the Chukchi Sea. The estimated hydrocarbon resources are slightly higher than the volumes of the RF Ministry of Natural Resources (2.2 bln ton OE). Despite the estimated higher hydrocarbon potential of the basin, the region is characterized by a very high risk of hydrocarbon accumulation destruction from numerous faults and erosion events. In this regard, further study of the North Chukchi basin is required to assess the erosion magnitude. We recommend the drilling of wells along the Wrangel-Herald fold zone, where the Pre-Upper Cretaceous formations are shallow.

The South Chukchi sedimentary basin seems to be less prospective than the North Chukchi. It includes the Nadezhdin, Onman and Ushakov hydrocarbon-prospective regions (Fig. 5) and is predicted as mainly gas-bearing in the Upper Cretaceous-Paleogene section on structures adjoined

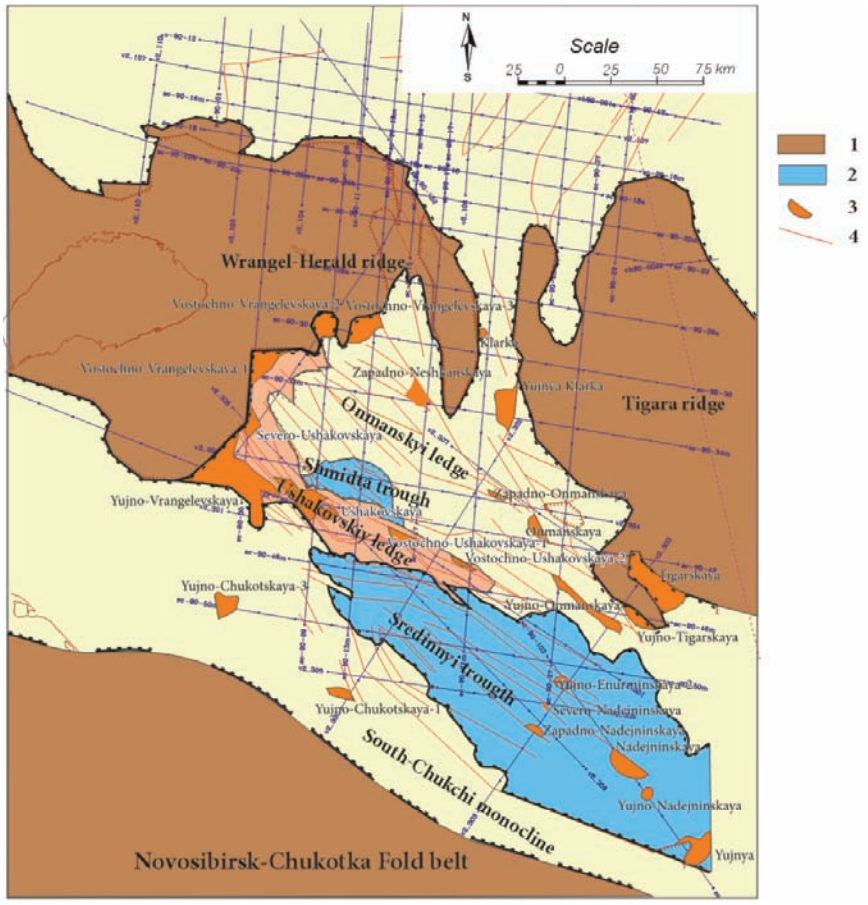

Fig. 4. Tectonic scheme of the South Chukchi basin: 1 – Basement high; 2 – Depressions; 3 - Local structures; 4 – faults.

to subsidence depocenters – particularly the Schmidt and Sredinny troughs. The key risks here are related to the potential for trap destruction in the period of the Pre-Middle Miocene erosion.

REFERENCES

Brown, David, 2009. Arctic Holds Huge Resource Promise, American Association of Petroleum Geologists AAPG Explorer V. 30, No.7. pp. 6-9.

Filatova, N.I and Khain, V.E., 2007, Eastern Arctic Tectonics, in Geotectonics,. No. 3, pp. 3-29 (in Russian).

Kim, B.I., Evdokimova, N.K., Kharitonova, L.Ya., 2009, Geology and petroleum potential of the East Arctic shelf of Russia, in Geology of Polar Regions. Materials of the XLII Tectonic Meeting. V.1. Moscow. GEOS, pp. 266-271 (in Russian).

Kosko, M.K. and Ushakov, V.I, 2003. Wrangel Island: Geology, Minerageny, Geoecology, VNIIOkeangeologia, St. Petersburg, pp. 137 (in Russian).

Malyshev, N.A., Nikishin, A.M., Drachev S.S., 2010, The tectonic history of sedimentary basins in the Russian Arctic shelf and adjacent land, in Tectonics and geodynamics of fold belts and Phanerozoic platforms. V.2. Moscow. GEOS, pp. 19-23 (in Russian).

Orudzheva, D.S., Obukhov A.N., Agapitov D.D., 1999, Prospects for oil and gas exploration in the Chukchi Sea, in Petroleum Geology. No 3, pp. 28-33 (in Russian).

Sherwood, K.W., Craig, J.D., Lothamer, R.T., Johnson, P.P., and Zerwick, S., 1998, 13. Chukchi Shelf assessment province: in: Undiscovered Oil and Gas Resources, Alaska Federal Offshore (As of January 1995): Sherwood, K.W., (ed.), U.S. Minerals Management Service, OCS Monograph MMS 98-0054, p. 115-196. A map that shows the extent of the preserved Shublik Formation west of Hanna trough is shown in figure 13.22 on file page 187 in the downloaded document. Available online at Bureau of Ocean Energy Management website at http://www.boem.gov/uploadedFiles/BOEM/Oil_and_Gas_Energy_Program/Resource_Evaluation/Resource_Assessment/1995AlaskaResourcesMMS98_0054.pdf.

Tolson R.B., 1987, Structure and stratigraphy of the Hope Basin, southern Chukchi Seas, Alaska // Geology and resource potential of the continental margin of western North America and adjacent ocean basins: Beaufort Sea to Baja California / D.W. Scholl, A. Grantz, J.G. Vedder (Eds.). Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series. V. 6. pp. 59-71.

Vierzhbitsky, V.E., Sokolov, S.D., Tuchkova, M.I., 2009, Tectonics, structural evolution stages and hydrocarbon potential of the Chukchi Sea shelf (Russian Arctic), in Geology of Polar Regions. Materials of the XLII Tectonic Meeting. V.1. Moscow. GEOS, pp. 85-89 (in Russian).