TECTONICS AND PETROLEUM POTENTIAL OF THE BERING SEA BOTTOM

Vadim M. Golubev, All-Russian Research Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologiya), 1 Maklin Prospect, 190121 St.Petersburg, Russia.

ABSTRACT

A single sedimentary megabasin, with all of the characteristics of an oil- and gas-bearing province, is distinguished within the Bering Sea and adjacent land. Potential oil- and gas-bearing parts of the megabasin are located in the Northern, Central, and Southern areas. Formation of these areas was mainly related to the circum-zonal orogenic developmental stages of the Late Mesozoic to Cenozoic Koryak-Western Kamchatka and southern Alaska fold systems, the Cenozoic Olyutor-Kamchatka and Aleutian fold systems, and median massifs separated by the Chukotka-central Alaska, Aleutian, Komandor, and Bowers systems. Regional oil and gas accumulations may have formed in structural zones by the linking of originally isolated sedimentary basins of similar tectonotype. Estimates of undiscovered hydrocarbon resources show high potential for the province, 16.1 x 10^9 t, with an average density of about 12.1 x 10^3 t/km^3, and generally similar oil to gas ratios. One-third of the resources are concentrated on the shelf; the rest are confined to abyssal zones. Estimates are determined by evaluating the main bulk of sedimentary cover within the abyssal zones and the shallow-water origin of potential oil- and gas-bearing terrigenous complexes. The complexes were submerged during the formation of abyssal basins in the Late Miocene and Pliocene.

INTRODUCTION

Geological and geophysical investigations over the years by Russian geological organizations, in particular NPO "Sevmorgeologiya," and the U.S. Geological Survey provided data on the structure of nearly all regions of the Bering Sea. These data are presented in recent publications (Yegiazerov, 1985; Scholl, 1987; Ivanov, 1985; Burlin, 1991). However, the complicated geologic structure of the region, insufficient and nonintergrated structural data, and the lack of a definitive model of both the region's evolution and the entire estimation of its petroleum potential--all made it necessary to employ a complex integration of geological, geophysical, and petroleum geology data (Golubev, 1992a).

GEOLOGY AND GEODYNAMICS

In the Bering Sea region, there are two connected Late Mesozoic to Cenozoic Alpine-folded areas, the Koryak-Kamchatka and Alaska-Aleutian fold systems, which inherited geosynclinal structures of the Paleozoic to Early Mesozoic (Caledonian to Hercynian) geotectonic cycles (Figs. 1 and 2). The folded areas are linked from the Bering Sea to the Pacific mobile belt and consist of the late Mesozoic to Cenozoic Koryak-Western Kamchatka and Olyutor-Kamchatka and the Cenozoic southern Alaska and Aleutian fold systems. Late Mesozoic to Cenozoic fold systems form the marginal part of the eastern Bering Sea and Cis-Koryak part of the western Bering Sea shelf. The Cenozoic fold systems form the Cis-Kamchatka part of the western Bering Sea shelf, Aleutian Island arc, and the Shirshov and Bowers submarine ridges.

These fold systems separate Precambrian median massifs; the uplifted continental Chukotka-central Alaska and the subsided oceanized Aleutian, Komandor, and Bowers. The massifs are overlapped differently by Paleozoic to early Mesozoic fragmental intermediate sedimentary cover. The late Mesozoic to Cenozoic Okhotsk-Chukotsk volcanic belt, the analogue of the "oceanic" layer-2 in the Aleutian massif, overlaps fold structures on the continental platform side and created an inner boundary of the continent-to-ocean transition zone. The Cenozoic Kamchatka-Koryak and Aleutian volcanic belts, the analogues of "oceanic" layer-2 in the Komandor and Bowers massifs, overlie axial zones of Cenozoic fold systems, whose foredeeps were deep-water trenches, and form an outer boundary of the transition zone.

The sedimentary cover of the Bering Sea megabasin ranges in thickness from 0.5 to over 9 km and generally comprises two structural-stratigraphic complexes: (1) Eocene to Early Miocene and (2) Late Miocene to Quaternary. These complexes are divided into numerous subcomplexes along the coast (as fragments), on the shelf, in deep-water basins, and (with less thickness) in the northern Pacific Ocean. The megabasin unites three circum-zonal sedimentation areas; Eocene to Quaternary sequences in the Central area (shelf to deep-water), thin (1-3 km) Miocene to Quaternary sequences in the Northern area (shelf), and Southern area (shelf to deep-water).

The type of zoning in the sedimentation areas is determined by their position with respect to back, intermontane, fore late-orogenic, and post-orogenic sedimentary troughs of the late Mesozoic to Cenozoic and Cenozoic fold systems around the arches of uplifted and subsided median massifs and the disposition of overlying late-orogenic and post-orogenic sedimentary cover. Early orogenic complexes of Late Cretaceous to Eocene and Eocene to Oligocene age compliment the sedimentary sequence in axial parts of the troughs. Predominantly terrigenous orogenic, late-orogenic, and post-orogenic complexes were deposited in basins, which subsided under the weight of the growing sedimentary section formed under compensating sedimentation conditions in a shallow sea. Post-orogenic turbidite and diatomaceous subcomplexes of the Central and Southern areas were deposited during Late Miocene and Pliocene to Quaternary developmental phases of the Aleutian, Komandor, and Bowers deep-water basins.

In the neighbouring Pacific Ocean, oceanized Precambrian platform rocks can be distinguished. These are represented by oceanic marginal swells, ridges, and basins that also show evidence of Late Miocene and Pliocene stepwise subsidence.

The morphology and structural pattern of the sedimentary cover and basement of these regional structures suggest their analogy to the triad of the transition zone tectonic fabric: fold systems, volcanic belts, and ancient massifs and the interrelated development of the continents and ocean.

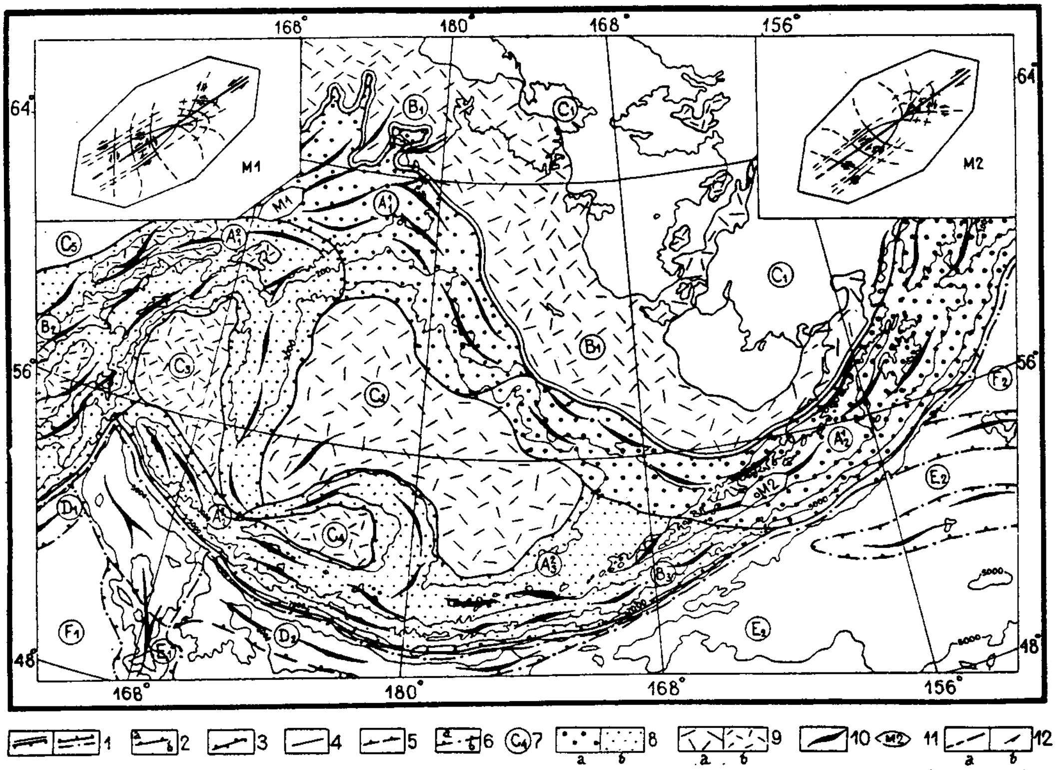

Fig.1. Map of tectonic zones and geodynamics of the Bering Sea region. Limits of structures: 1-Continent to Pacific Ocean transition zone: (a) off continental platforms, (b) off oceanic platforms; 2-(a) between fold areas and (b) median massifs; 3-between fold systems; 4-volcanic belts; 5-(a) between marginal oceanic swells and (b) oceanic plates; 6-(a) between oceanic ridges and (b) oceanic plates; 7-symbols of structures (see below); Age of structures; 8-fold systems; (a-late Mesozoic to Cenozoic, b-Cenozoic); 9-volcanic belts and "oceanic" layer-2 of oceanized Precambrian massifs; Dynamics of structures: 10-axes of anticlinorium and horst-anticlinorium zones of fold systems and volcanogene-block-faulted ridges; 11- superposition places and orientation of tectono-physical models; 12-deformation models: a-faults, b-shift orientations. Tectonic structures: Bering Sea segment of continent-to-ocean transition zone: Fold areas (late Mesozoic to Cenozoic): A_1-Koryak-Kamchatka, A_2-Alaska-Aleutian; Fold systems: late Mesozoic to Cenozoic: A_1^1- Koryak-Western Kamchatka, A_2^1-Southern Alaska; Cenozoic: A_1^2-Olyutor-Kamchatka, A_2^2-Aleutian; Volcanic belts: B_1- Okhotsk-Chukotsk (late Mesozoic to Cenozoic), B_2-Kamchatka-Koryak and B_3-Aleutian (Cenozoic); Median massifs (Precambrian with Paleozoic to early Mesozoic metacover): C_1-Chukotka-Central Alaska (late Mesozoic to Cenozoic activation), C_2-Aleutian (late Mesozoic to Cenozoic oceanization), C_3-Komandor and C_4-Bowers (Cenozoic oceanization), C_5-Okhotsk Sea (late Mesozoic to Cenozoic activation and oceanization); Northern segment of Pacific Ocean platform: Marginal oceanic swells (late Mesozoic to Cenozoic): D_1-Zenkevich, D_2-Aleutian; Volcanogene-block-faulted oceanic ridges (Cenozoic): E_1-North- Western, E_2-East-Aleutian; Oceanic plates: F_1-Northwestern (late Mesozoic to Cenozoic oceanization), F_2-Northeastern (Cenozoic oceanization).

The original unity is also supported by a trans-regional crustal fault network that is related to the planetary network of georotary stresses. This fault network controlled the regional structure of the basement and sedimentary cover in the Bering Sea. The structural pattern of fold areas matches tectonophysical models of near-shear stresses (Fig.1) and portrays fold systems as the surface expression of global deep-shear zones. The East-Asian and West-American deep-shear zones form deformational belts between the Eurasian, North-American, and Pacific Ocean platforms. Reciprocating angular movement of the platforms, related to the variable rotation rate of the Earth, regulate sinusoidal change of deformation types in the two major shear zones of the region. The relaxation of deformation is responsible for phased and connected development of geosynclinal systems, volcanic belts, and thermodynamic overcompaction (oceanization) of the median massifs, which are separated by the orogenic belts. Tectonophysical reconstruction of the alpine evolution of the region correlates with coeval oceanization of the Pacific Ocean platform caused by the chemical and substantial differentiation of deep crust at the expense of interplanetary gravitational effects and Earth core replacement (Golubev, 1992b).

PETROLEUM POTENTIAL

The structure, geological history, and petroleum geology of the Bering Sea sedimentary megabasin identify it as a potential oil and gas province whose prospective areas correspond to paleobasins (Fig.3). Regional oil and gas accumulations may occur within structural zones of the paleobasins that consist of chains of originally isolated sedimentary basins of similar tectonotype. These chains may form regional hydrocarbon accumulation zones in orogenic and post-orogenic sedimentary basins and troughs in back, intermontane and fore zones of fold systems as well as by late-orogenic and postorogenic sedimentary structures of median massif arches. Potential regional oil and gas accumulation zones are bounded by the axial lines of marginal anticlinal uplifts of fold systems and median massifs, and they are divided into regions along the axes of interbasin transverse basement uplifts.

Assessment of the hydrocarbon resources of the

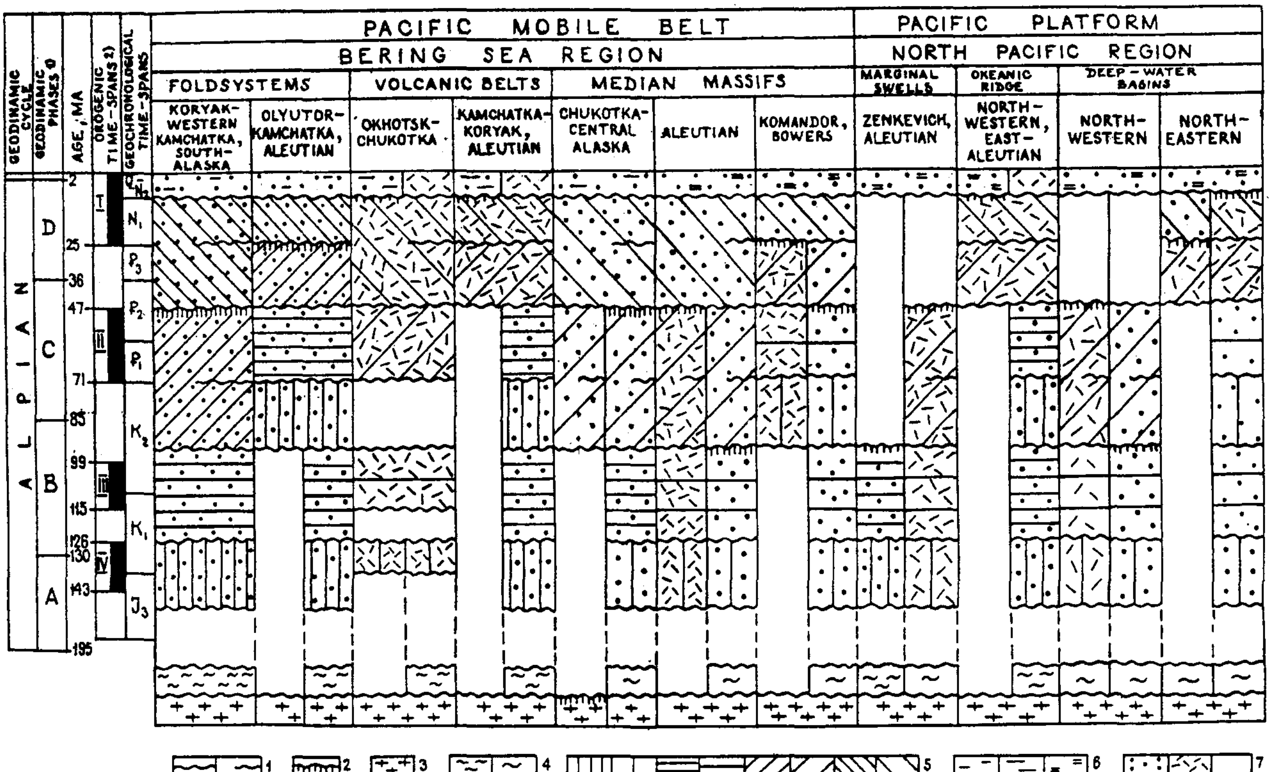

Fig.2. Principal correlation scheme of structural-stratigraphic complexes of the Bering Sea and North-Pacific regions. 1- regional structural and sedimentological unconformities: a-between complexes, b-between subcomplexes; 2-base of sedimentary cover; 3-Precambrian crystalline megacomplex; 4-Paleozoic to Early Mesozoic (Caledonian to Hercynian) metasedimentary mesocomplex: a-geosynclinal, b-syngeosynclinal; 5-late Mesozoic to Cenozoic (Alpine) complexes: a-early-geosynclinal, b-syn-early-geosynclinal, c-late-geosynclinal, d-syn-late-geosynclinal, e-early-orogenic, f-syn-early-orogenic, g-late-orogenic, h-syn-late-orogenic; 6-late Cenozoic (neotectonic) complexes: a-post-orogenic, b-syn-post-orogenic, c-proper oceanic; 7-dominant composition of late Mesozoic to Cenozoic complexes: a-terrigenous, b-volcanogenic, c-gap. 1) A-initial, B-middle, C-late, D-terminal phases; 2) I-Late Alpine, II-Laramie, III-Austrian, IV-Late Kimmeridgian phases after A.A. Pronin; 3) absolute age after S.P. Romanovsky.

Bering Sea province is based upon a combination of geologic analogues and statistical technique. Petroleum geological analogues to the regions of the Bering Sea province are found within or near the Pacific oil- and gas-bearing belt. Due to their general similarity, the basin analogues are proposed to compare with each tectonotype in the regions of the Bering Sea province. Average resource densities and oil to gas ratios from the Pacific province are used for calculation in the Bering Sea province. Therefore, the assessment of undiscovered hydrocarbon resources is made as a probability, with a possible deviation from actual resources in the range of ± 50 percent of the calculated values. The assessment reliability applies to all of the province subdivisions and estimates the maximum and minimum possible hydrocarbon resources for each region.

Based on these assumptions and using an oil to gas ratio of 55/45 (%), we estimate the in-place resources of the Bering Sea province to be 16.1 x 10^9 t of hydrocarbons in an area of 1.33 x 10^2 km. The continental shelf, covering an area of 413,300 km^2, is estimated to contain 5.23 x 10^9 t of hydrocarbons and abyssal zones, covering an area of 917,800 km^2, is estimated to contain 10.8 x 10^9 t. Calculated hydrocarbon-resource densities average 12,700 t/km^3 on the shelf and 11,800 t/km^3 in abyssal zones. The highest calculated resource density (18,000 t/km^3) in the province is characteristic of the intermontane and foredeep tectonotype of the late Mesozoic to Cenozoic fold systems, which is supported by the general confinement of the world's largest oil fields to alpine foredeeps.

The highest probability for large oil and gas accumulations lies in the Central area, which is represented by intermontane and marginal sedimentary troughs of the Late Mesozoic to Cenozoic Koryak-Western Kamchatka and Southern Alaska fold systems and also by late-orogenic and postorogenic sedimentary basins on the arch of the Aleutian oceanized Precambrian massif. Estimated hydrocarbon resources in the Central area, covering 1,060,200 km^2, are 14.7 x 10^9 t (91% of the province resource) with an average density 13,900 t/km^3 using an oil to gas ratio of 55/45 (%).

Especially prospective on the shelf of the Central area are the Navarin and St.George regions (basin analogues: Cook Inlet, USA, and Simanto, Japan) with estimated hydrocarbon resources of 1.19 x 10^9 and 8.60 x 10^8 t at a density of 18,000 t/km^3 and an oil to gas ratio of 60/40 (%). Under-slope regions of the deep-water Aleutian Basin (Koryak-Aleutian, Alaska-Aleutian, and Bowers-Aleutian) have the same density but an oil to gas ratio of 70/30 (%), resulting in potential hydrocarbon resources for each region (8.24 x 10^8 t, 3.33 x 10^8 t, and 8.32 x 10^8

t, respectively). The other shelf regions, Anadyr, Bristol (basin analogues: Ishikari and Sendai, Japan), Khatyr, and Unimak (basin analogues: Saint Elias and northern California, USA), have a lower resource density (13,000 t/km^3), but relatively high potential: 7.86 x 10^8 t, 9.75 x 10^8 t, 3.77 x 10^8 t, and 2.80 x 10^8 t, respectively, with an oil to gas ratio of 60/40 (%). However, incomparably higher potential hydrocarbon resources with the same densities occur in the West-Aleutian and East-Aleutian regions of the central deep-water basin: 3.63 x 10^9 and 4.62 x 10^9 t, using an oil to gas ratio of 50/50 (%) (basin analogues: Gulf of Mexico and Hudson Bays, USA). Medium-sized and large, predominantly gas, accumulations in Neogene deposits and mostly oil- and gas-condensate deposits in Eocene to Oligocene rocks may be expected in the Central area.

Of considerably less potential are late-orogenic and postorogenic sedimentary basins of the Northern prospective area (basin analogues: continental Yukon Flats-Kandik and East-Bering Sea, USA). They are situated on the arch of the Chukotka-Central Alaska Precambrian massif and have a thinner (1 to 1.5 km) sedimentary sequence. Hydrocarbon resources of this shelf area, covering 84,500 km^2, are estimated to be 6.14 x 10^8 t with an average density of 7,300 t/km^3 and average oil to gas ratio of 65/35 (%). The most promising region, Norton Basin, may contain 2.12 x 10^8 t of hydrocarbon resources with a density of 8,000 t/km^3 and an oil to gas ratio of 70/30 (%). Medium-size and small oil and gas fields may be expected in the Northern area.

The Southern area, covering 186,400 km^2, is regarded as a late Cenozoic analogue of the Central area but may have potential hydrocarbon resources as low as 7.16 x 10^8 t with an average density 3,800 t/km^3 and an average oil to gas ratio 35/65 (%). The lower potential is a result of small-sized structural and stratigraphic hydrocarbon traps, thinner sedimentary section (1-1.5 km), the predominantly volcanogenic composition of potential reservoir complexes, the narrow stratigraphic range (predominantly Late Miocene) of sedimentary cover, and the deposition of potential hydrocarbon reservoir and source rocks in an abyssal sedimentary environment. Frequent seismic and volcanic activity in the Southern area also created unfavourable conditions for the accumulation of hydrocarbons by degrading the quality of reservoir rocks. The Karagin-Korf shelf sedimentary basin (basin analogues: Akita and Ryukyu, Japan) is a relatively

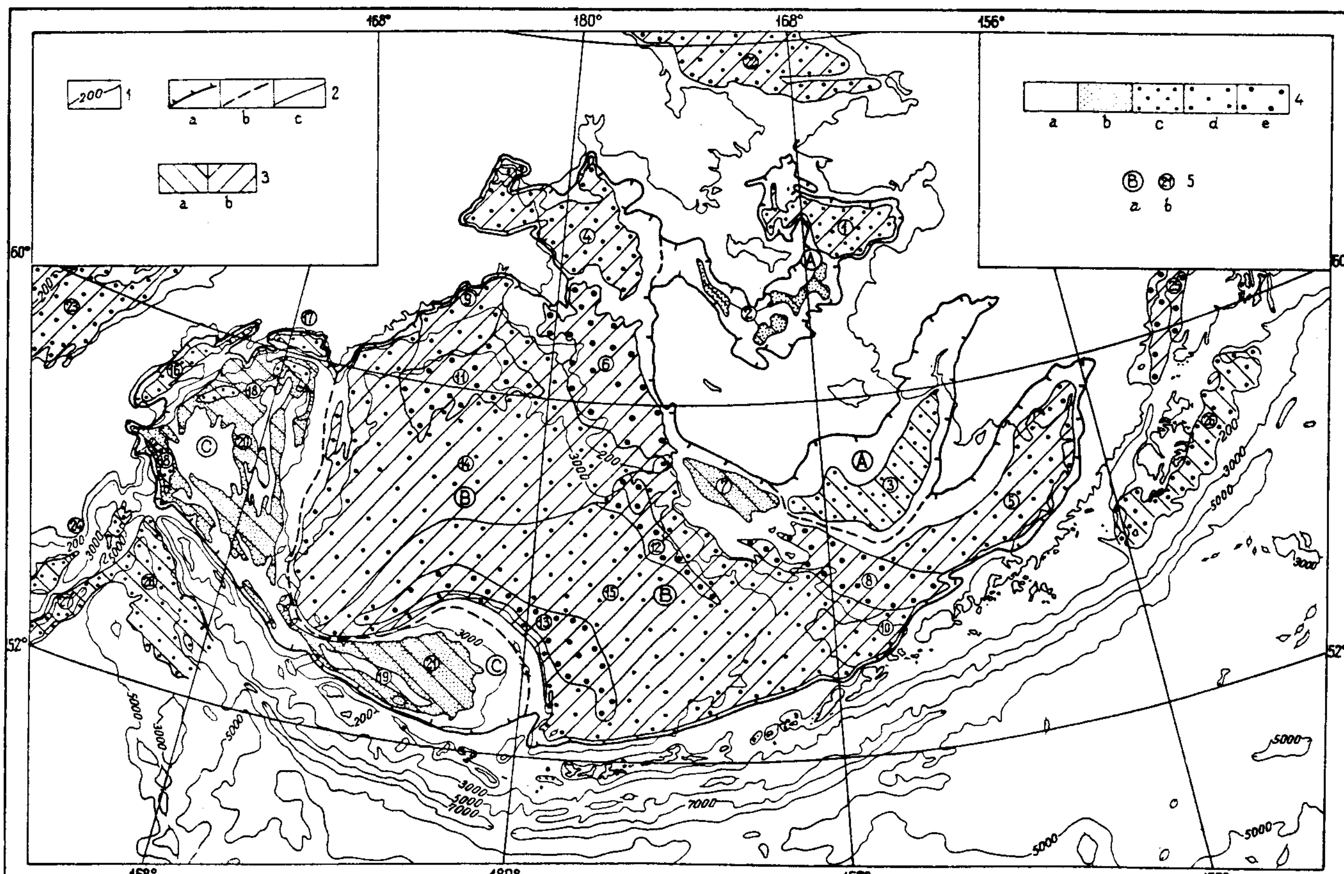

Fig.3. Map of petroleum potential in the Bering Sea region. 1-isodepths (m); 2-limits of petroleum geological structures: a-provinces, b-areas, c-regions; 3-distribution of major potentially hydrocarbon-bearing sedimentary complexes: a-Neogene, b-Paleogene to Neogene; 4-distribution of specific density of predicted hydrocarbon resources, x 10^3 t/km^3: a-barren territories, b-to 5, c-5 to 10, d-10 to 15, e-15 to 20; 5-symbols of petroleum geological structures: a-areas, b-regions. Hydrocarbon-bearing (known) and possible hydrocarbon-bearing structures: Bering Sea oil- and gas-bearing province: A-Northern area-regions: 1-Norton, 2-St. Lawrence, 3- Kuskokwim; B-Central area-regions: 4-Anadyr hydrocarbon-bearing, 5-Bristol, 6-Navarin, 7-St. Paul, 8-St. George, 9-Khatyr hydrocarbon-bearing, 10-Unimak, 11-Koryak-Aleutian, 12-Alaska-Aleutian, 13- Bowers-Aleutian, 14-West-Aleutian, 15-East-Aleutian; C-Southern area-regions: 16-Karagin-Korf, 17-Olyutor, 18- Kamchatka-Komandor, 19-Aleutian-Bowers, 20-Central-Komandor, 21-Central-Bowers; Neighbouring provinces- regions: 22-Hope, 23-Shelikof, 24-East-Kamchatka group, 25-Cook Inlet hydrocarbon-bearing, 26-Kodiak, 27-Kuril- Kamchatka group, 28-Aleutian group.

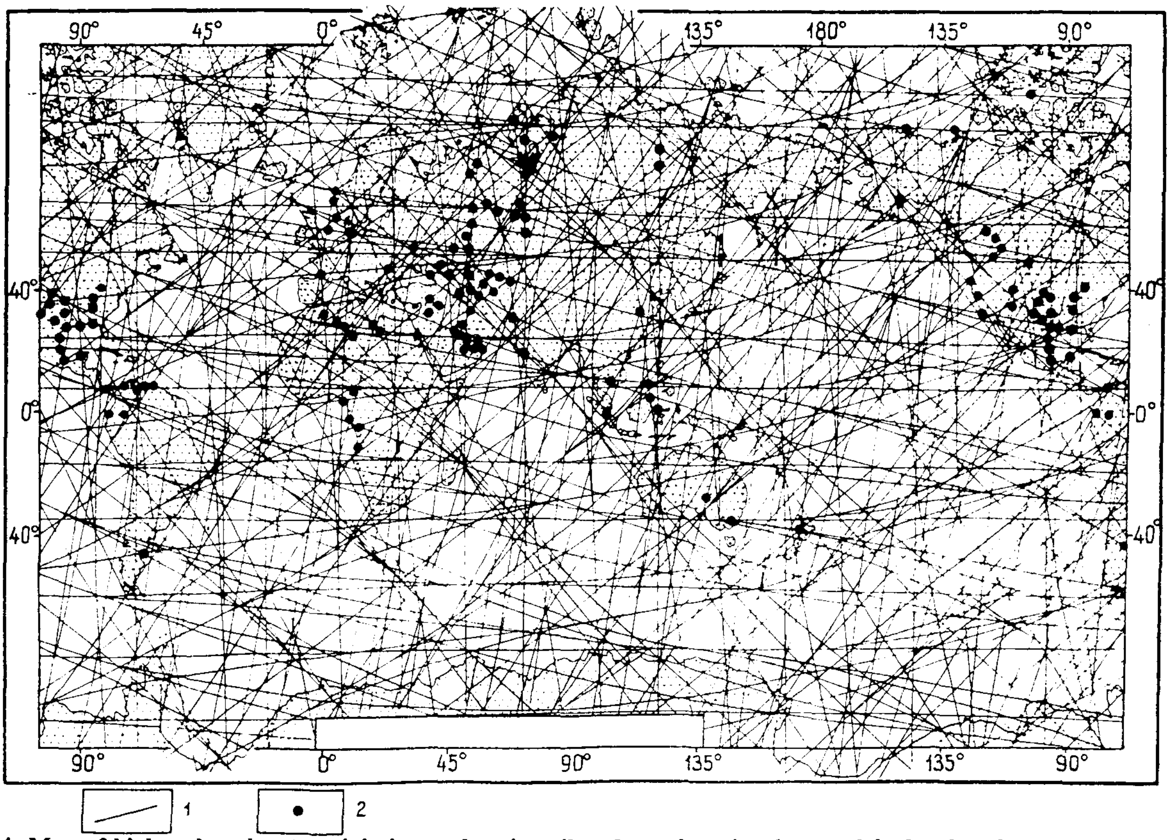

Fig.4. Map of high-order planetary jointing and major oil and gas deposits. 1-crustal faults, 2-hydrocarbon deposits, after P.F. Burollet.

prospective area that may contain 7.6 x 10^7 t of hydrocarbons with a resource density of 8,000 t/km^3 and the oil-gas ratio 60/40 (%). The Kamchatka-Komandor and Aleutian-Bowers under-slope, deep-water basins (basin analogues: Kanto and Kuril, Japan) have the same parameters: 5.8 and 8.4 x 10^7 t of hydrocarbons. Small oil and gas fields may occur in these regions of the Southern area.

Eocene to Oligocene and Early Miocene mainly terrigenous complexes may be predominantly oil-bearing. The Upper Miocene to Pliocene complex is already known to be predominantly gas-bearing. Some prospects of the Central area are contained in the fragmental and deeply buried Late Cretaceous to Eocene complex. This complex contains up to 5 percent of the areas resources and is regarded as its smallest reserve.

The petroleum potential of sedimentary basins in the Bering Sea megabasin is produced by the Cenozoic subcycle of global hydrocarbon accumulation activated by the late-orogenic stage of Alpine geodynamic cycle and the initial stage of neotectonic geodynamic cycle. The oil- and gas-generation potential of the two above complexes may be controlled by the Eocene and (at a lesser scale) Miocene climatic optimums that, with the addition of simultaneous geodynamic activation, may have stimulated the abrupt increase in bioproduction (Golubev, 1989).

The highest potential for hydrocarbon accumulation (especially oil) in the province are areas located near axial parts of sedimentary basins and their intersection nodes with transverse and diagonal faults. This prediction is supported by the distribution pattern of most major proven accumulations in world petroleum basins, especially in orogenic troughs of foldsystems. Over the nodes of fault intersections there are oil and gas fields of the exact basin analogue of the most prospective regions of the province--the intermontane Cook Inlet basin.

The occurrence of major oil and gas fields at nodes of the network of planetary jointing (Fig.4) may be explained by activation of bioproduction and subsequent hydrocarbon generation in geodynamically active places of the Earth's surface (Golubev, 1989). Arched uplifts of sedimentary cover formed at fault intersection nodes develop mainly as syndeposition structures and form hydrocarbon traps of the most common types: lithologic, stratigraphic, and structural. Fractures over local structures improve reservoir properties of rocks and enable hydrocarbons to migrate and accumulate. Especially effective oil-migration paths are formed by listric faults that frame local structures and drain virtually whole sedimentary basins. The moderately high seismic activity of the sedimentary basin, cyclically renewing its drainage network, is another positive factor for the formation of large hydrocarbon accumulation.

CONCLUSIONS

The occurrence of oil and gas accumulations at nodes of crustal syndepositional faults may become an important factor in exploring sedimentary basins in ocean-to-continent transition zones that are geodynamically active and originally prospective for petroleum. The occurrence of these nodes in the Bering Sea region add to its high petroleum potential and make it one of the most prospective in the search for maritime petroleum areas. However, the region's climate and limits on technological and economic capability restrict near-term development and assign the Bering Sea megabasin the role of the largest commercial petroleum region in the 21st century.

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