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Late Mesozoic-Cenozoic Evolution of the Barents Sea and Kara Sea Continental Margins

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THEME 14: Circum-Arctic Margins: The Search for Fits and Matches

Summary: The most remarkable tectonic feature of Barents Sea and Kara Sea continental margins is a Cenozoic system of deep troughs and grabens which follow Devonian-Jurassic paleorifts. These depressions are divided by a number of major domes and uplifts. The dominating tectonic process in the Barents-Kara shelf was the successive degradation of an uplifted land within Svalbard-Franz Josef Land-Severnaya Zemlya zone, which served as a terrigenic source for sedimentary basins of southern and central parts of the continental margin. The general neotectonic regime of the continental margin has caused strong uplift of orogens and shields as well as shelfic archipelagos Svalbard, Franz Josef Land and Severnaya Zemlya and predominantly subsidence of intracontinental and marginal shelf basins. In general, Cenozoic tectonics were favourable for preservation and re-forming of oil & gas resources on the shelf. Late Cretaceous-Danian regressive, Paleocene-Eocene transgressive, Oligocene-Miocene regressive, Pliocene-Pleistocene regressive-transgressive and Holocene transgressive epochs of continental margin evolution are recognized. Cenozoic development of Arctic was controlled by progressive penetration of processes of riftogenesis and spreading from North Atlantic into the Norwegian-Greenland and Eurasian basins, which constrained the contrasting character and circum-oceanic zoning of tectonic movements at continental margins.

INTRODUCTION

Theis paper is largely based on multi-channel seismic data published in Russia (BATURIN 1988, BEZMATERNYCH et al. 1993, SENIN et al.1989) and Norway (FALEIDE et al.1984, JOSEHANS et al. 1993, SATTEM et al. 1994, SUNDVOR & AUSTEGARD 1990, VAGNES et al 1992) and single channel high resolution acoustic profiling (Fig. 1) carried out by Russian (MUSATOV 1996) and Norwegian expeditions (ANTONSEN et al. 1991, KNUTSEN et al. 1993, SOLHEIM et al. 1998, VORREN et al. 1990). Ground evidence of the geological structure included gravity and piston coring (ELVERHOI & SOLHEIM 1987, GUREVICH 1995, STEIN et al. 1996), shallow drillings (GRITSENKO & BONDAREV 1994, KRAPIVNER 1986) and materials of deep wells on the shelf and adjacent islands (ARMISHEV et al. 1988, GRAMBERG et al. 1985). Moreover, the tectonic zoning provide evidence on tectonic settings in adjacent islands (DIBNER 1998) and mainland areas (KUZIN 1983, VARLAMOV 1983).

The Barents Sea and Kara Sea shelves occupy the main part of the extended transitional zone between its continental frame (Baltic crystalline shield, Timan-Kanin and northern Taimyr Baikalian inliers, Scandinavian - West Spitsbergen epi-Caledonian, Polar Ural - Pai-Khoi, Novaya Zemlya and Byrranga epi-Hercynian - Early Kimmerian orogens) and continental slopes and rises of Norwegian-Greenland (NGB) and Eurasian (EB) basins. Young epicontinental Barents - northern Kara shelf marginal and Pechora, West Siberian intracontinental basins occur on the continental margin. Each structure of this morphostructural assemblage is characterised by its own specific features of Cenozoic tectonic and geodynamic regime.

The giant oil and gas fields discovered in the Barents and Kara Seas shelves yield evidence for huge reserves of hydrocarbons. In this context, studies of Cenozoic structures on the continental margin are important for the reconstruction of crustal motion and recent geodynamics. The geological structure of the shelf shows three main units: folded basement, relics of Paleozoic carbonaceous-terrigenous cover and Upper Paleozoic-Cenozoic terrigenous unit of epicontinental shelf basins (GRAMBERG & POGREBITSKIJ 1984). Four major subunits are recognized in the composition of the upper terrigenous unit: Upper Paleozoic-Triassic (from 1-2 to 8-10 km in thickness), Jurassic-Lower Cretaceous (0.5-3 km), Upper Cretaceous-Eocene (0-1 km) and Oligocene-Quaternary (0-0.5 km). A seismic section of Cenozoic cover of the southern Kara Sea shelf is shown in Figure 2; regional reflectors D_1 and D_2 correspond to the base of Pliocene and Quaternary sequences respectively. High industrial oil & gas prospectivity is proved (OSTISTY & FEDOROVSKY 1993) for both Paleozoic carbonaceous-terrigenous (large Prirazlomnoe oil field and Severo-Gulyaevskoe oil-gas field) and Upper Permian-Mesozoic terrigenous units. The Upper Permian-Triassic sequence contains the large Murmanskoe, medium Severo-Kildinskoe and other gas fields; Jurassic-Lower Cretaceous rocks contain the uniqe Shtockmanovskoe and Ledovoe gas condensate fields and large Ludlovskoe, Rusanovskoe, Leningradskoe gas & gas condensate fields.

Barents and Kara Seas margins exhibit the following anomalous features:

- a unique extension (up to 750-1500 km); extremely dissected and contrasting relief (Fig. 3);
- higher thicknesses of sedimentary cover (up to 18-20 km and even more in the southern Barents depression);
- peripheral shelf domes of archipelagos, exposing Hercynian, Caledonian and Precambrian folded basement; wide occurrence (GRAMBERG 1988, ELDHOLM & TALWANI 1977) of deep-sea rift grabens uncompensated by sedimentation;

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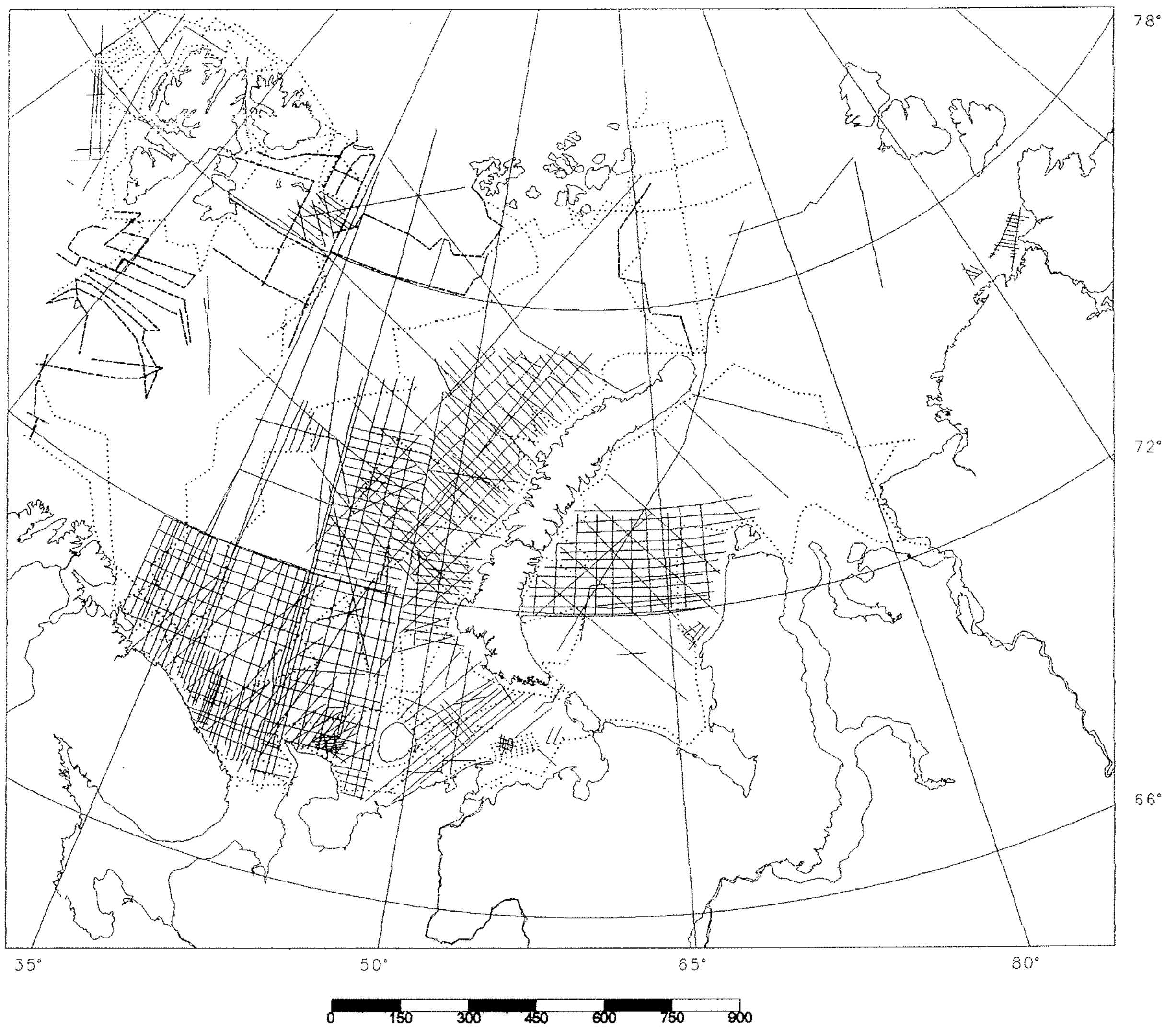
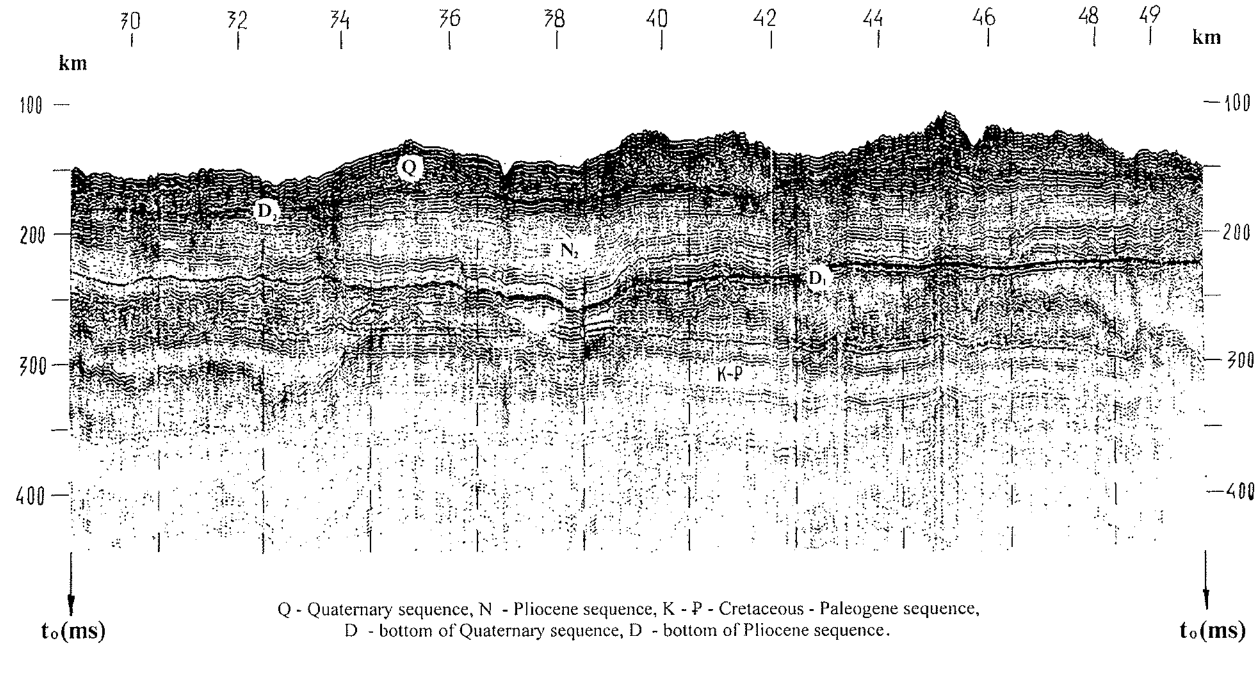


Fig. 1: Seismic data map showing seismic acoustic lines available for this study area



Q - Quaternary sequence, N - Pliocene sequence, K - P - Cretaceous - Paleogene sequence,
D - bottom of Quaternary sequence, D - bottom of Pliocene sequence.

Fig. 2: Sparker records on the southern Kara Sea shelf. Q = Quaternary sequence, N = pliocene sequence, K-P = Cretaceous-Paleogene sequence, D_1 = bottom of Quaternary sequence, D_2 = bottom of Pliocene sequence

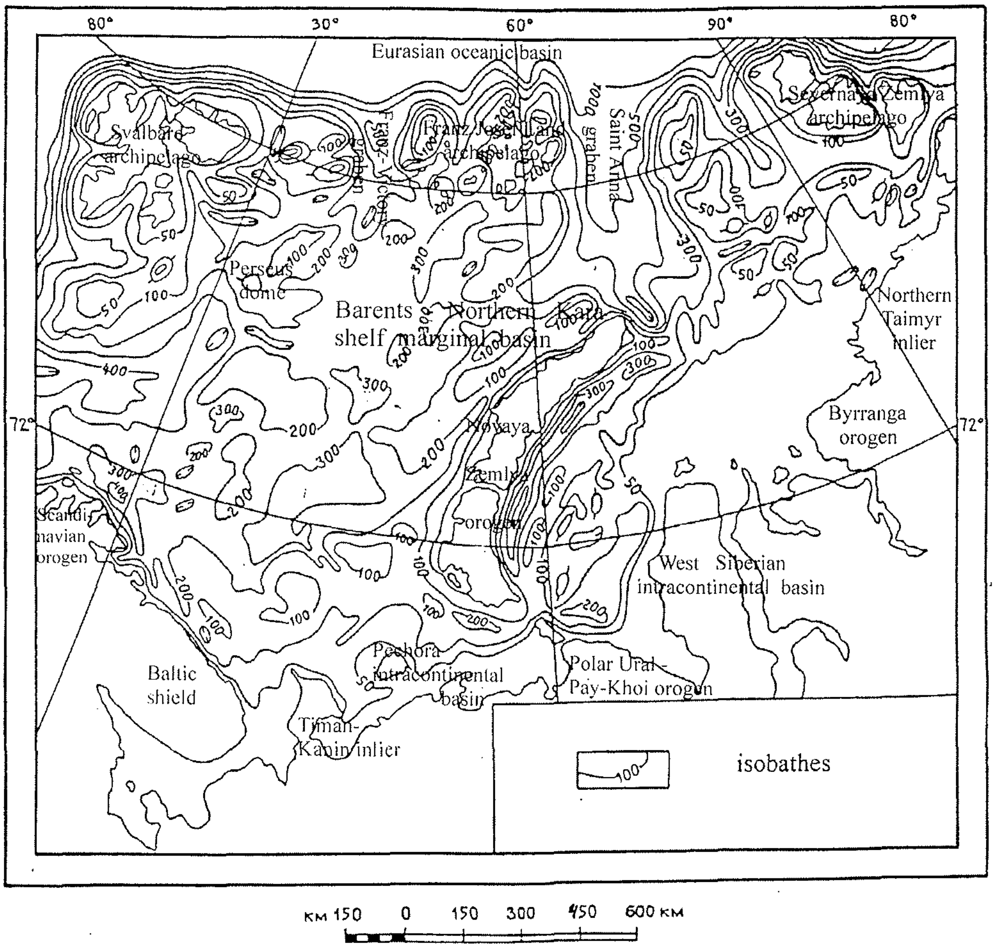


Fig. 3: Bathymetry of the Barents Sea and Kara Sea shelves

- nongranitic crust inliers;
- higher seismicity (magnitudes up to 5-7), particularly near continental slopes and flanks of deep-sea grabens);
- manifestations of the Late Mesozoic (Franz Josef Land Archipelago and the northernmost Barents Sea Shelf), Late Cenozoic (Novaya Zemlya Archipelago) and recent (West Spitsbergen) basic magmatism;
- and abundant normal and normal-lateral faults controlling fjord grabens and deep-sea grabens edges (Musatov & Musatov 1992).

THE LATE MESOZOIC-CENOZOIC EVOLUTION

The Early/Late Cretaceous boundary was a turning point (Pogrebitskyi 1976) in the geological history of the Arctic. At that time vast denudation areas that existed in the present location of the Arctic deep-sea basins were affected by rift-related destruction. The Late Cretaceous-Danian phase was characterised by the largest regional uplift of Arctic continental margins, particularly along the periphery of the EB and NGB spreading basins. The top of Jurassic and sometimes Triassic (e.g., Perseus in the Barents Sea) sedimentary sequences were exposed by intensive erosion at major anticlines and domes. Apparently, this epoch of regional uplifts was controlled by the crustal responce of the North Eurasian continental margins to intense compression produced by initial spreading in the NGB and EB. The main phase of regional uplift took place during the end of the Late Cretaceous (Campanian-Maastrichtian) epoch. Figure 4 demonstrates the character of the pre-Late Cenozoic erosion on the northern Kara Sea Shelf; reflector D (the bottom of Upper Cenozoic veneer) forms a regional unconformity on single channel seismic data.

The Paleocene-Eocene time was characterised by peneplanation of relief and local marine transgressions. The Arctic Paleocene-Eocene were characterised by seafloor spreading (Kristoffersen 1990) in NGB and vast basaltic flows in the Brito-Arctic Thule Province. At that time, the continental margins were tectonically passive and experienced moderate oscillatory movements, which were the reason of shallow marine (under transgressive conditions) and deltaic sedimentation. Crusts of weathering are recognized for this time in the Baltic shield, Kanin-Timan inlier of folded basement and Polar Ural - Pai-Khoi orogen. The epoch of peneplanation of relief spanned most of Paleocene time, when continental margin was dominated by denudation-accumulation plains, and marine transgressions developed there in the Eocene. Due to high sea-level stand in the Eocene, the transgression, which propagated from the actively developed NGB to the Bear and Nordcap trenches, involved also the Barents-

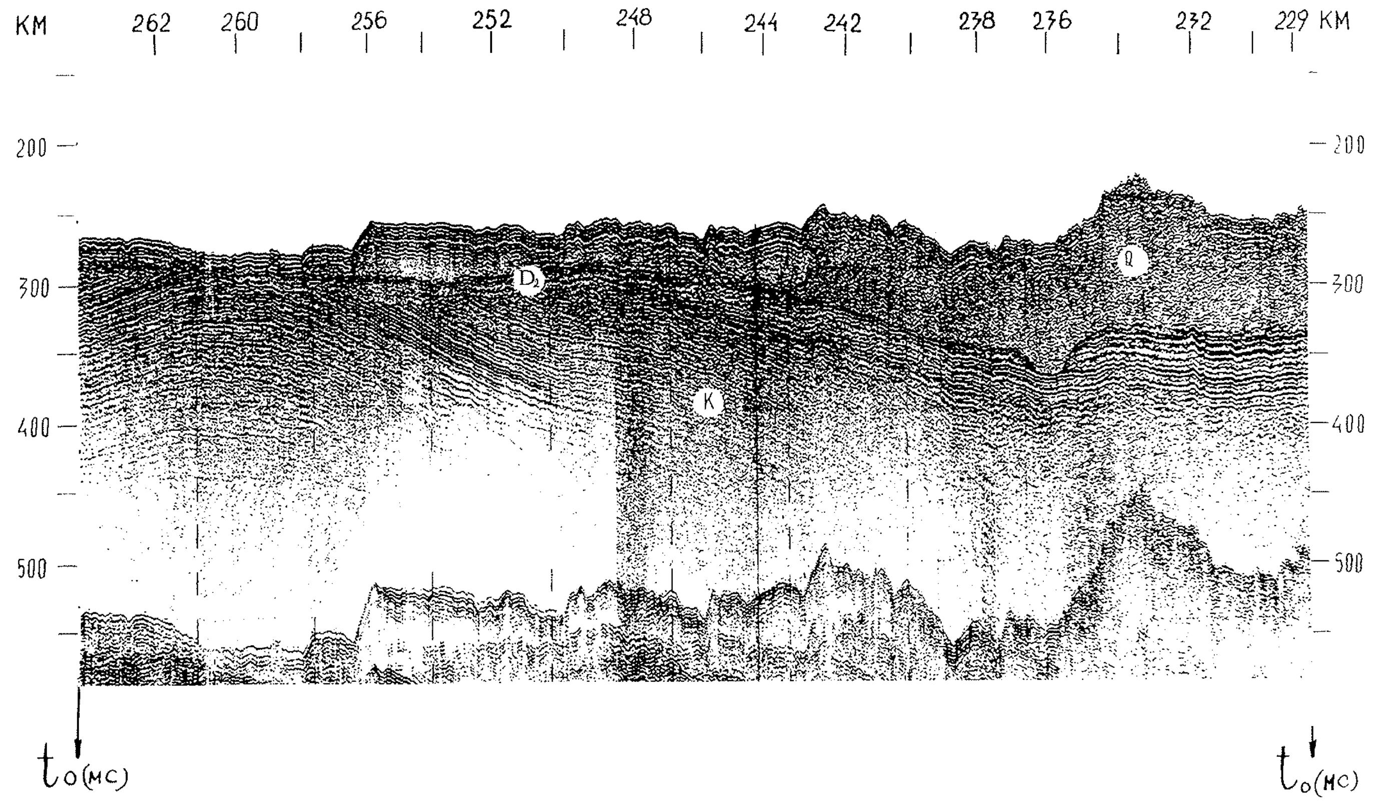


Fig. 4: Sparker records on the northern Kara Sea shelf. Note unconformities (toplap and erosion truncation) at the reflector D_2

Kara shelf; however, unlike the East Arctic shelf, its sediments were nearly all denudated there as a result of Oligocene-Miocene uplift. The Central and Forlandsundet peri-oceanic basins of Svalbard Archipelago, parallel to NGB continental slope, are unique in thicknesses of their Paleogene clastic sediments exceeding 2.5-3 km (DOWDESWELL 1988, DOWLING 1988). The thickness of Paleocene-Eocene siliceous-argillaceous deposits accumulated in the Western Siberian intracontinental plate amounts to 1 km and more. However, the transgression here propagated from the south through the Turgay basin and Western Siberia was a shelf of Tethys oceanic basins.

In the Arctic the Oligocene-Miocene stage is characterized by a drastic change in paleogeographic settings. Spreading processes took place in the whole EB (JOKAT et al. 1995). Intensive uplifts of epiplatform orogens and shields, started in the Oligocene, revived low mountain relief. They were accompanied by first glaciations related to mountain growth. The West Siberian marine basin shoaled and gradually dried up, accumulating lignite-bearing alluvial-lacustrine deposits. Oligocene-Miocene coarse-grained alluvial deposits on the shelf occur in deep erosional valleys (Fig. 5). Perioceanic Svalbard basins closed and experienced compressional inversion, and the next stage of uplifting and development of tectonic deformations (ZARCHIDZE et al. 1991) is the most active in the whole platform history of Svalbard Archipelago. At the western coast a Caledonian horst was thrusted over marginal shelf basin in the post-Oligocene time. An uplifted land that afterwards became a source area of sedimentary basins began to develope in peripheral zone of the Barents-Kara basin (Svalbard - Franz Josef Land - Severnaya Zemlya dome) under alternating conditions of extension and compression. By their tectonic regime, the uplifting areas along the Spitsbergen-Severnaya Zemlya continental slope corresponded to a rift shoulder relative to EB. Major Cenozoic regressions (up to 300 m below modern sea level) are fixed in Late Oligocene and in the end of Late Miocene (Fig. 6) epochs.

Active EB development and destruction of continental rock masses at the Pliocene-Pleistocene stage led to degradation of adjacent source areas near the Eurasian Basin continental slope dissected by Franz-Victoria, Saint Anna, and Voronin deep-sea grabens, where widespread predominantly glacial-marine sediments were deposited. Several regressive-transgressive cycles during Pliocene and Pleistocene influenced to the interaction of marine transgressions and ground glaciations (SOLHEIM & KRISTOFFERSEN 1984) of highlands and adjacent shelves and islands. The Holocene epoch is characterised by general subsidence and marine transgression. Fragments of Paleogene peneplain broken up into separate blocks by younger tectonic dislocations were partially buried on shelves in periods of transgression, and denudation of the surface occurred at regressions and glaciations. The Pliocene-Quaternary cover is represented by arenaceous-argillaceous, mostly glacial-marine deposits, sparker records, single channel seismic data, coring and shallow drillings suggest that its thickness is commonly 5-150 m on the Barents and Kara Seas shelf (Fig. 7). In the Late Cenozoic period continental slopes experienced progradation due to intensive activity of suspension flows and forming of fan deposits (EIDVIN et al. 1988) up to 1-2 km in thickness.

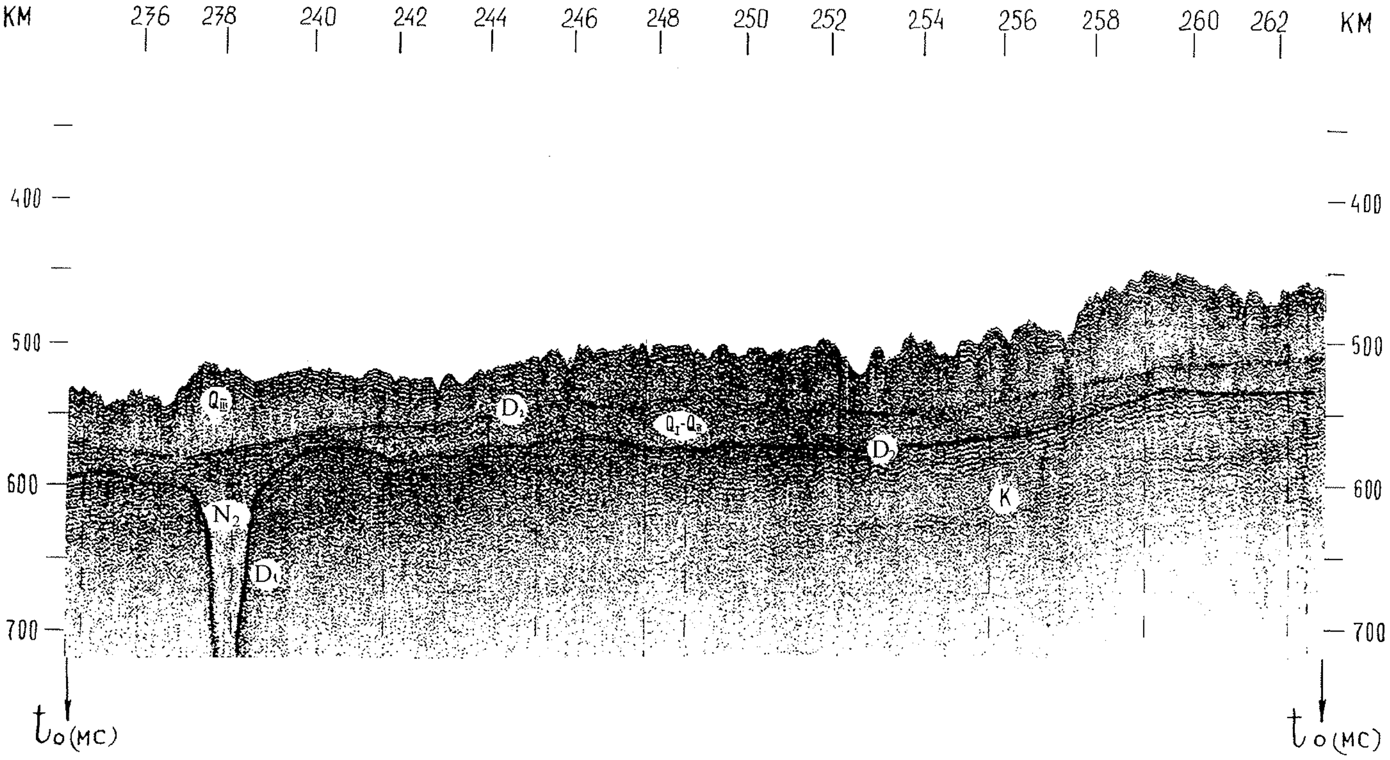


Fig. 5: Seismic section of the upper Cenozoic cover in the St. Anna Trough. See deeply cut acient valley in the top of the Cretaceous rocks (N_2).

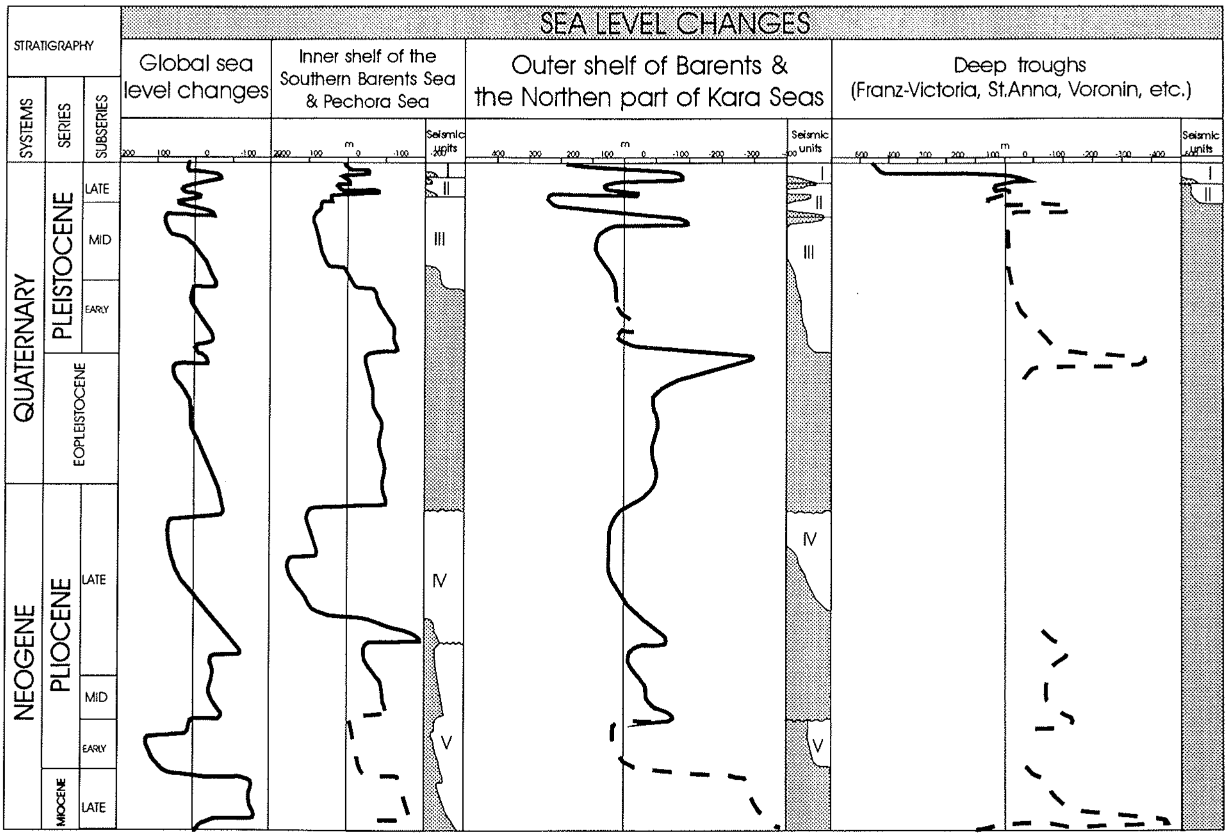


Fig. 6: Sea level changes during the Late Cenozoic compiled from various sources.

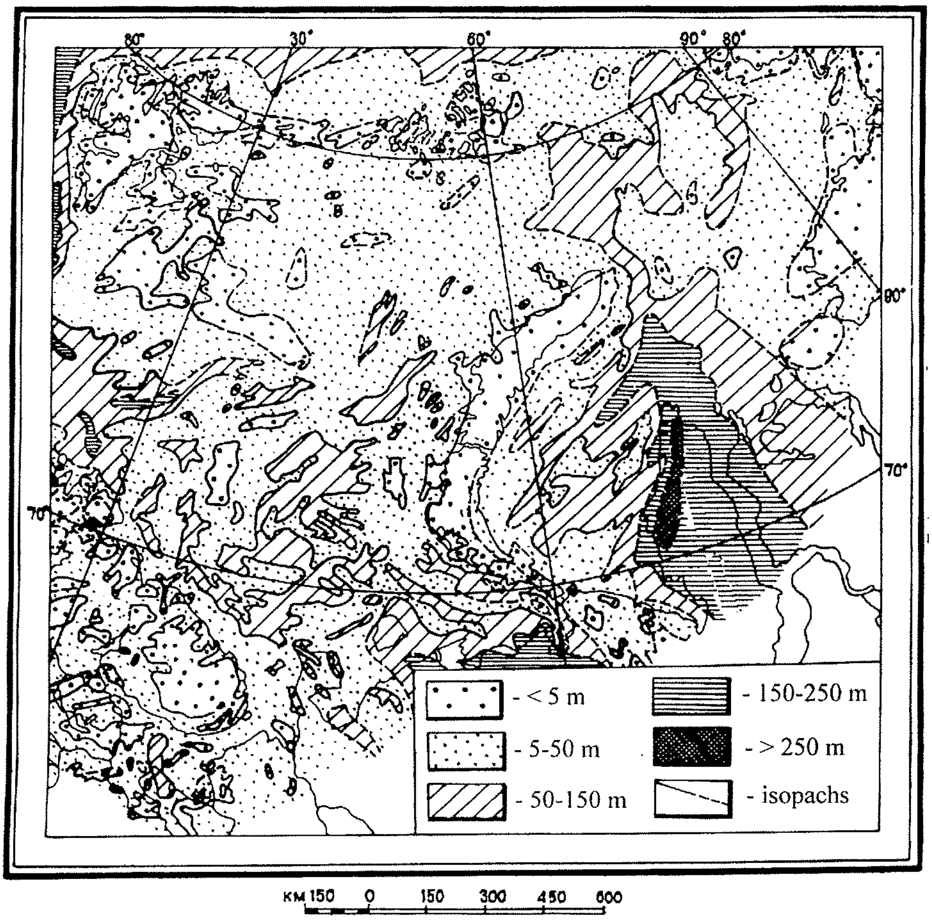


Fig. 7: The thickness of Pliocene-Quaternary sediments of the Barents Sea and Kara Sea shelves

The last neotectonic rearrangement of Arctic margins occurred at the end of Late Pleistocene, marking the onset of a new paleogeographic stage. Neotectonic activation was accompanied by a glacio-eustatic regression and the last glaciation (Late Wurmian in Alps, Late Weichselian in Europe, Late Valdai on the Russian platform, and Sartan in Western Siberia). Its extent, estimated by different authors, is either different from or wholly incompatible (Krapivner 1986, Kuzin 1983) with the model of a pan-Arctic glacier covering all Arctic shelves (Grosvald 1983) in Russia. Elevations of marine terraces in Russian Arctic indicate that glacio-isostatic movements die out towards the east of the region, where the last glaciation was minimal. At the Late Pleistocene-Holocene stage, intense crustal subsidences in peripheral deep-sea grabens and glacio-isostatic coastal uplifts accomplished the formation of the present-day morphostructural pattern in Arctic transition zones. The contemporary seismicity of continental slopes, fjord coasts, and some of rift grabens is the evidence for persisting tectonic activity of the transition zone.

Late Cretaceous-Cenozoic tectonic activity was the reason of the growth up of perspective structures, strong denudation and sometimes forming of new hydrocarbon (HC) resources or their destroying. Positive neotectonic movements as well as strong (up to 1-2 km) denudation of the top of Mesozoic rocks (Skagen 1993) had caused decreasing rock pressure and HC migration from ancient reservoires. Re-forming of HC was also influenced by Cenozoic sea level changes. Major regressions were positive depressive factors, but Quaternary sheet glaciations increased pressures due to ice weight. Pressures were maximally decreased in neotectonic faults zones and in ancient paleovalleys of fluvial origin (Kuzin 1983). Prospective oil and gas factors are an inherity of structural features (Varlamov 1983), activation of perspective structures, moderate neotectonic movements and their gradients. Negative factors are crucial changes of structural assemblages (Riis & Jensen 1992, Theis et al. 1993) and high gradients of neotectonic movements. At the activated peripheral shelf uplifts adjacent to Spitsbergen, Franz Josef Land and Severnaya Zemlya archipelagos and in rift grabens Franz-Victoria, St. Anna and Voronin numerous neotectonic predominantly normal faults as well as strike-slip faults and thrusts were the reason of HC fields disturbance. This fact is the barrier for oil & gas search (Knutsen et al. 1993, Loseth et al. 1993) at the edge of continental-margin plate.

CONCLUSIONS

Late Cretaceous-Cenozoic spreading of the sea floor in Norwegian-Greenland and Eurasian oceanic basins was the reason for neotectonics and geodynamics of Barents and Kara Seas shelf (Fig. 8). The results of these processes were a complicated alteration of compression and extension conditions on the continental margin. Five major stages of the Barents and Kara Seas margins evolution are recognized:

- Late Cretaceous-Danian regressive,

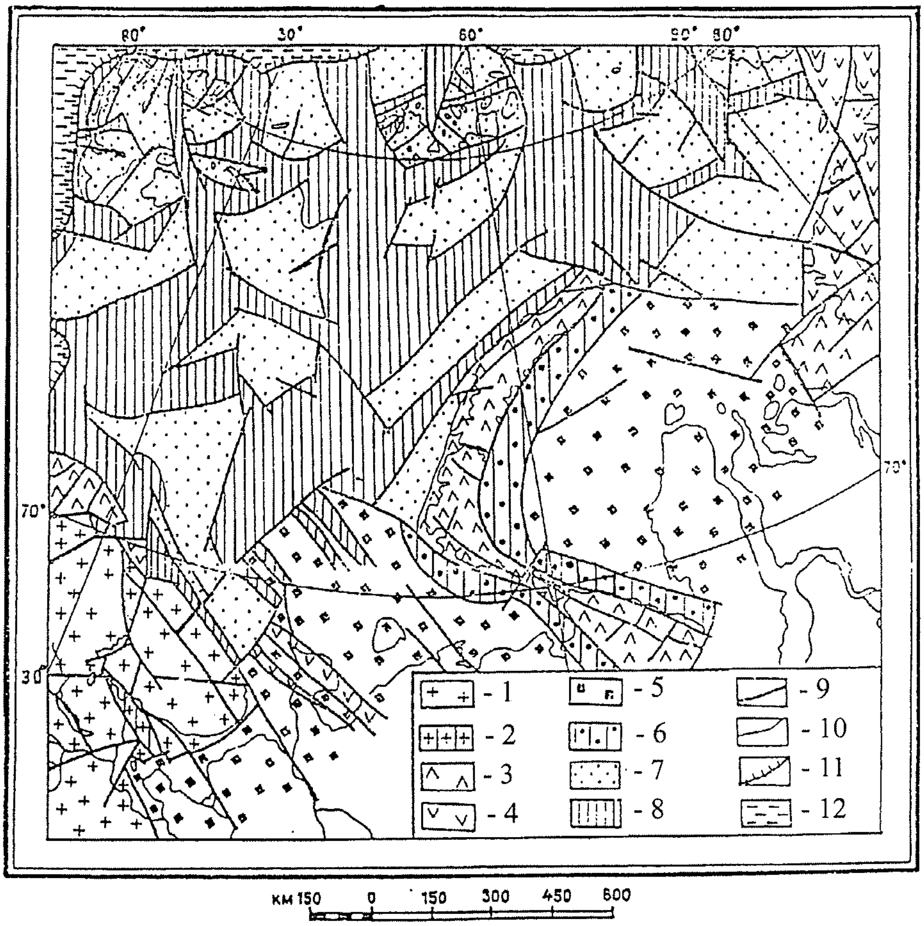


Fig. 8: Neotectonics of the Barents Sea, Kara Sea and White Sea shelves and adjacent areas. 1 = crystalline shields; 2 = Cenozoic grabens within shields; 3 = Caldonian, Hercynian and Kimmerian orogens; 4 = inliers of folded plate basement; 5 = intracontinental basins; 6 = depressions within intracontinental basins; 7 = domes and horsts of shelf marginal basins; 8 = uncompensated grabens of continental margin; 9 = faults; 10 = boundaries of structures; 11 = flexure zones of the shelf break; 12 = continental slopes.

- Paleocene-Eocene transgressive,
- Oligocene-Miocene regressive,
- Pliocene-Pleistocene regressive-transgressive and
- Holocene transgressive epochs. The NGB-EB transition zones characterise the earlier stage of the development of an Atlantic-type margin.

Cenozoic tectonics was dominated by sharp uncompensated subsidences of shelf basins reviving the intricate graben-rift systems of the Barents-northern Kara basin. The maximum of tectonic activity of the Barents-Kara Seas continental margin was confined to the coastal belt, where uplifting involved Scandinavia, the Kola Peninsula, Timan-Kanin inlier, Polar Ural - Pai-Khoi - Novaya Zemlya and Byrranga orogens and the peripheral shelf uplift along the Spitsbergen - Severnaya Zemlya continental slope. The highest oil and gas perspective zones are recognised in central parts of intracontinental and marginal basins, i.e. on slopes of horsts and grabens and local positive structures of anticline and non-anticline type.

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