Cenozoic sedimentary structure and neotectonics of the Barents–Kara shelf from reflection profiling data

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Abstract. The Cenozoic sediments of the Barents–Kara shelf were investigated by running thousands of kilometers of continuous reflection profiles (CRP) and one-channel zero-offset ray reflection surveys. The seismic data were verified by drilling engineering-geological holes and stratigraphic wells on the shelf and islands; impact cores as long as 5–7 m were recovered for this purpose from the bottom sediments. Five structural units were identified in the Upper Cenozoic sediments: a Paleocene–Eocene marine, an Oligocene-Miocene limnoalluvial, Pliocene-Pleistocene marine, glaciomarine, and glacial units, and a late Pleistocene-Holocene marine unit. These units correlate with four periods in the paleogeographic history of the continental margin: transgression (Ꝑ$_{1-2}$), regression (Ꝑ$_3$–N$_1$), regression–transgression ($N_2 - Q_{\rm III}$), and transgression ($Q_{\rm III-IV}$). Neotectonic criteria of the shelf oil and gas potential were established, which must have been favorable for the preservation and reconfiguration of hydrocarbon pools and for the growth of structures' reliefs.

Introduction

The importance of the problem discussed in this paper is defined by the intensive industrial development of the Russian Northern Territories and Arctic shelf, known to be promising for oil and gas discoveries. Evidence in support of these high prospects [*Josehans et al.,* 1993] are the following discoveries: the Shtokmanovskoe and Ledovoe fields with their unique gas-condensate reserves, the large Murmanskoe gas field in the Upper Permian–Triassic clastic rocks, and the large Prirazlomnoe and Severo-Gulyaevskoe oil and gas-condensate fields in the Paleozoic clastic and carbonate rocks. These and a number of other fields discovered in the Barents Sea, as well as the unique Rusanovskoe and Leningradskoe gas-condensate fields located in the Lower Cretaceous deposits of the Kara Sea, prove the occurrence of huge hydrocarbon resources in the shelf. Although the Cenozoic period of the shelf history did not result in the formation of new hydrocarbon pools (except for potential hydrocarbon accumulations in the prograding wedges of the continental slopes and in perioceanic basins), it had a decisive effect [*Knitsen et al.,* 1993; *Musatov,* 1997; *Skagen,* 1993] on the preservation and reconfiguration of hydrocarbon pools and on the growth of the reliefs of the existing petroliferous structures by two or three orders of magnitude. In some areas Cenozoic substantially muddy deposits act as regional caprocks. For these reasons the studies of the Cenozoic sediments by geological and geophysical methods were important to provide knowledge of the neotectonic conditions of the region and its oil and gas potential, in addition to improving the knowledge of the shelf's engineering-geological properties, necessary for drilling stratigraphic wells, laying pipelines, and building various engineering structures.

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Database

This study was carried out using the results of continuous reflection profiling (CRP) with radiation sources ranging between 200 and 1000 Hz and of one-channel zero-offset reflection surveys at frequencies between 70 and 200 Hz, which had been accomplished in various years by the teams of the following institutes: VNIIOkeangeologiya [*Barents Shelf Platform,* 1988; *Druzhinina and Musatov,* 1992; *Geology of the USSR...,* 1984; *Lopatin and Musatov,* 1992; *Map of Recent Tectonics...,* 1998; *Musatov,* 1996; *Musatov and Musatov,* 1992; *Zarkhidze and Musatov,* 1989; *Zarkhidze et al.,* 1991; *Zarkhidze,* 1991], Marine Arctic Geological Exploration Expedition [*Baturin,* 1988], Institute of Oceanography, Russian Academy of Sciences [*Aksenov et al.,* 1988; *Dunaev et al.,* 1990; *Pavlidis,* 1992], All-Russia Institute of Geology (VSEGEI) [*Spiridonov et al.,* 1980],

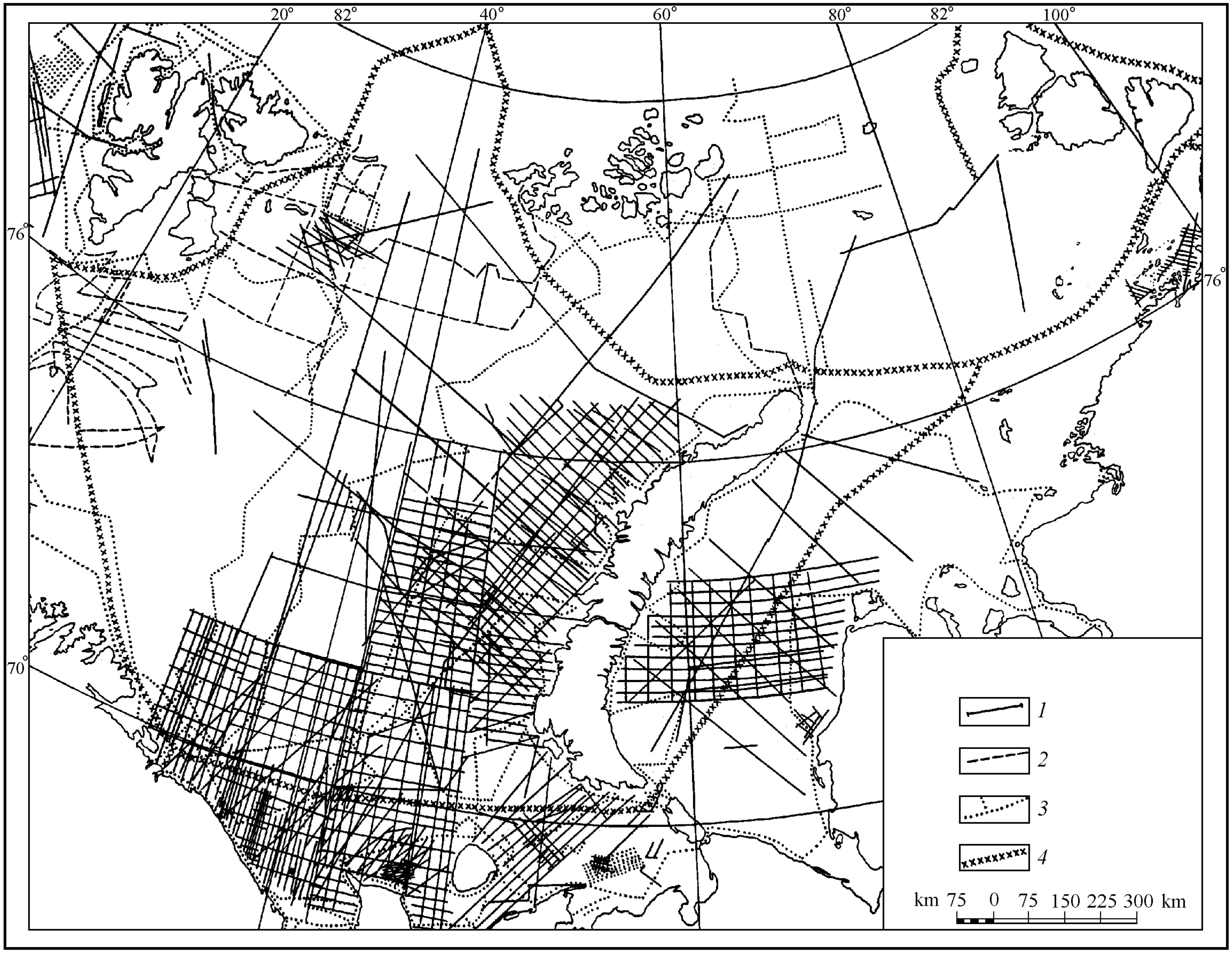

Figure 1. Index map of continuous reflection and zero-offset ray reflection profiles.
1 – low-frequency continuous and zero-offset ray reflection profiles surveyed by Russian vessels; 2 – profiles surveyed by Norwegian vessels; 3 – high-frequency Russian profiles; 4 – high-frequency German profiles.

Institute of Marine Geophysics (NIIMorgeofizika) [*Senin et al.,* 1989], Murmansk Institute of Marine Biology, Kola Research Center, Russian Academy of Sciences [*Matishov,* 1988; *Samoilovich et al.,* 1993], Norwegian Polar Institute [*Antonsen et al.,* 1991; *Elverhoi and Solheim,* 1987; *Elverhoi and Lauritzen,* 1984; *Elverhoi et al.,* 1988; *Gustavsen et al.,* 1997; *Musatov,* 1996, 1997; *Solheim and Kristoffersen,* 1984; *Solheim et al.,* 1990; *The Geology...,* 1998], University of Bergen [*Kristoffersen et al.,* 1984], University of Tromse [*Vorren et al.,* 1988], and other organizations. The index map of the seismic materials available is shown in Figure 1. One can see that the coverage varies greatly from place to place. Better known are the southern, western, and central parts of the shelf because of a dense network of regional and local geological survey profiles (Sheets R-36-38 and S-38-41). The northern and northeastern areas of the Barents and Kara seas were investigated by reflection profiling and zero-offset reflection survey to a lesser extent because of hard ice conditions.

Russian [*Armishev et al.,* 1988; *Pogrebitskii,* 1997; *Senin et al.,* 1989; *Verba et al.,* 1987] and Norwegian [*Eldholm et al.,* 1987; *Skagen,* 1993] CDP reflection data were used to correlate deep reflection markers in the sediments and to investigate deep-seated sources of neotectonic processes. Sea-floor topographic maps of various scales prepared by Russian [*Matishov,* 1988; *Musatov,* 1997], Norwegian [*Elverhoi and Solheim,* 1987; *Elverhoi et al.,* 1988; *Solheim et al.,* 1990; *Vorren et al.,* 1988], and American [*Cherkis et al.,* 1991; *Matishov et al.,* 1995] researchers were used as a bathymetric basis for neotectonic maps. The geological interpretation of the geophysical data was supported by the sections of stratigraphic wells drilled on the shelf [*Armishev et al.,* 1988] and on islands [*Gramberg et al.,* 1985], and also of engineering-geological holes [*Gritsenko and Krapivner,* 1989; *Krapivner,* 1986; *Onishchenko and Bondarev,* 1988; *Samoilovich et al.,* 1993] (Figure 2). Where these were not available (in the northern areas of the Barents and Kara seas), use was made of 4–5-meter and longer corer samples (comparable with reflection profiling resolution). Many cores of this type were recovered in the last decades during the cruises of Russian [*Aksenov et al.,* 1988; *Barents Shelf Platform,* 1988; *Druzhinina and Musatov,* 1992; *Gurevich and Musatov,* 1992; *Lopatin and Musatov,* 1992; *Musatov,* 1997; *Musatov and Musatov,* 1992; *Pavlidis,* 1992; *Spiridonov et al.,* 1980; *The Geology...,* 1998; *Zarkhidze and Musatov,* 1989; *Zarkhidze et al.,* 1991] and Norwegian [*Antonsen et al.,* 1991; *Elverhoi and Lauritzen,* 1984; *Elverhoi and Solheim,* 1987; *Elverhoi et al.,* 1988; *Solheim and Kristoffersen,* 1984; *Solheim et al.,* 1990; *Vorren et al.,* 1988] research vessels. Biostratigraphic differentiation charts of the Cenozoic sediments from the Timan–Ural and West-Siberian regions [*Chochia and Evdokimov,* 1993; *Danilov,* 1978; *Geology of the USSR...,* 1984; *Yakhimovich and Zarkhidze,* 1990; *Zarkhidze and Musatov,* 1989; *Zarkhidze et al.,* 1991] and local seismostratigraphic charts of the shelf [*Antonsen et al.,* 1991; *Baturin,* 1988; *Eldholm et al.,* 1987; *Gritsenko and Krapivner,* 1989; *Gustavsen et al.,* 1997; *Musatov,* 1996; *Senin et al.,* 1989; *Shipelkevich et al.,* 1994] were used as a regional basis for correlating seismic bodies outcropping on the sea floor with the respective units on land.

Method of study

During the early stage of our study, the seismic stratigraphic analysis of the reflection profiler, zero-offset ray reflection, and CDP data [*Gritsenko and Krapivner,* 1989; *Lopatin and Musatov,* 1992; *Musatov,* 1996; *Zarkhidze et al.,* 1991] was carried out in three steps: (1) the Cenozoic sedimentary sequence was divided into depositional sequences separated by regional erosion unconformities; (2) seismic facies were analyzed to reconstruct the conditions of sedimentation in a basin; (3) appropriate curves were plotted to reconstruct relative tectono- and/or glacio-eustatic changes of sea level in the region. The lithology and stratigraphic control of seismic bodies were determined from boreholes available (not many) [*Armishev et al.,* 1988; *Gramberg et al.,* 1985; *Gritsenko and Krapivner,* 1989; *Krapivner,* 1986; *Onishchenko and Bondarev,* 1988; *Samoilovich et al.,* 1993] and corer samples [*Aksenov et al.,* 1988; *Antonsen et al.,* 1991; *Barents Shelf Platform,* 1988; *Druzhinina and Musatov,* 1992; *Elverhoi and Lauritzen,* 1984; *Elverhoi and Solheim,* 1987; *Elverhoi et al.,* 1988; *Gurevich and Musatov,* 1992; *Gustavsen et al.,* 1997; *Lopatin and Musatov,* 1992; *Musatov,* 1997; *Musatov and Musatov,* 1992; *Pavlidis,* 1992; *Solheim and Kristoffersen,* 1984; *Solheim et al.,* 1990; *Spiridonov et al.,* 1980; *The Geology...,* 1998; *Vorren et al.,* 1988; *Zarkhidze and Musatov,* 1989; *Zarkhidze et al.,* 1991], collected from the shelf, with the subsequent correlations and interpolations along the entire length of the seismic horizon. We identified seven seismic stratigraphic units (SSU) which were separated by unconformities caused by lateral terminations of strata usually of the toplap or erosional truncation types, less commonly of the downlap or onlap types.

The seismic stratigraphic analysis of the Cenozoic sediments was followed by the reconstruction of the magnitudes of neotectonic movements on the shelf. The Paleogene peneplanation surface marked by kaolinite and hydromica weathering crusts along the fringe of the shelf on the Baltic Shield and the Timan–Kanin and Polar Urals horst-megasynclinoria was used as a reference surface. In addition to the incorporation of the modern

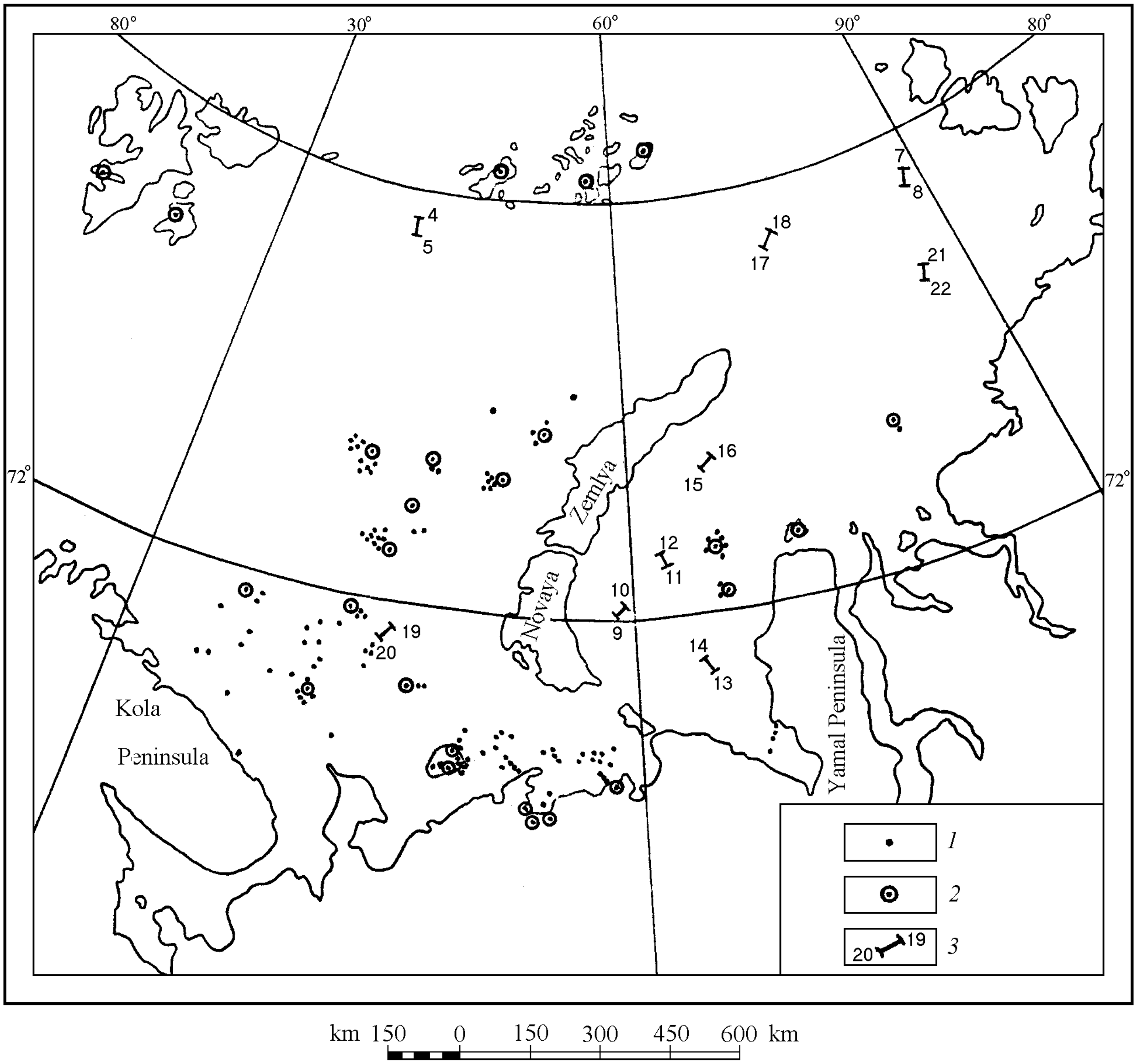

Figure 2. Location map of drill holes and fragments of reflection profiles.
1 – engineering-geological holes; 2 – stratigraphic wells; 3 – location of reflection profiles whose seismic sections are displayed in Figures 4–5 and 7–22.

topography (Figure 3), the following corrections were introduced while calculating the magnitudes of recent tectonic movements:

(1) correction for sedimentation. The fragments of the original peneplanation surface on the shelf are buried under the uneven mantle of Neogene–Quaternary clastic sandy-muddy deposits that rest with a high angular unconformity on the deeply eroded bedrock (Figures 4 and 5). Based on the reflection profiler and zero-offset reflection data, an isopach map of these sediments was plotted (Figure 6). The thicknesses of the Upper Cenozoic sediments were subtracted from the absolute elevations of the modern sea floor to reconstruct the depths of the primary pre-Neogene surface and plot a structural map on the Upper Cenozoic base;

(2) correction for denudation. The amount of the material eroded during the neotectonic period was evaluated using the seismic records available: the eroded portion of the sequence was reconstructed from reflectors in the underlying Mesozoic strata. The thickness of the material eroded near the archipelagos, on the tops of the Percej, South Kara, and North Kara banks, was found to be as great as 250–300 m (Figures 7 and 8). When plotting the contour lines of recent movements,

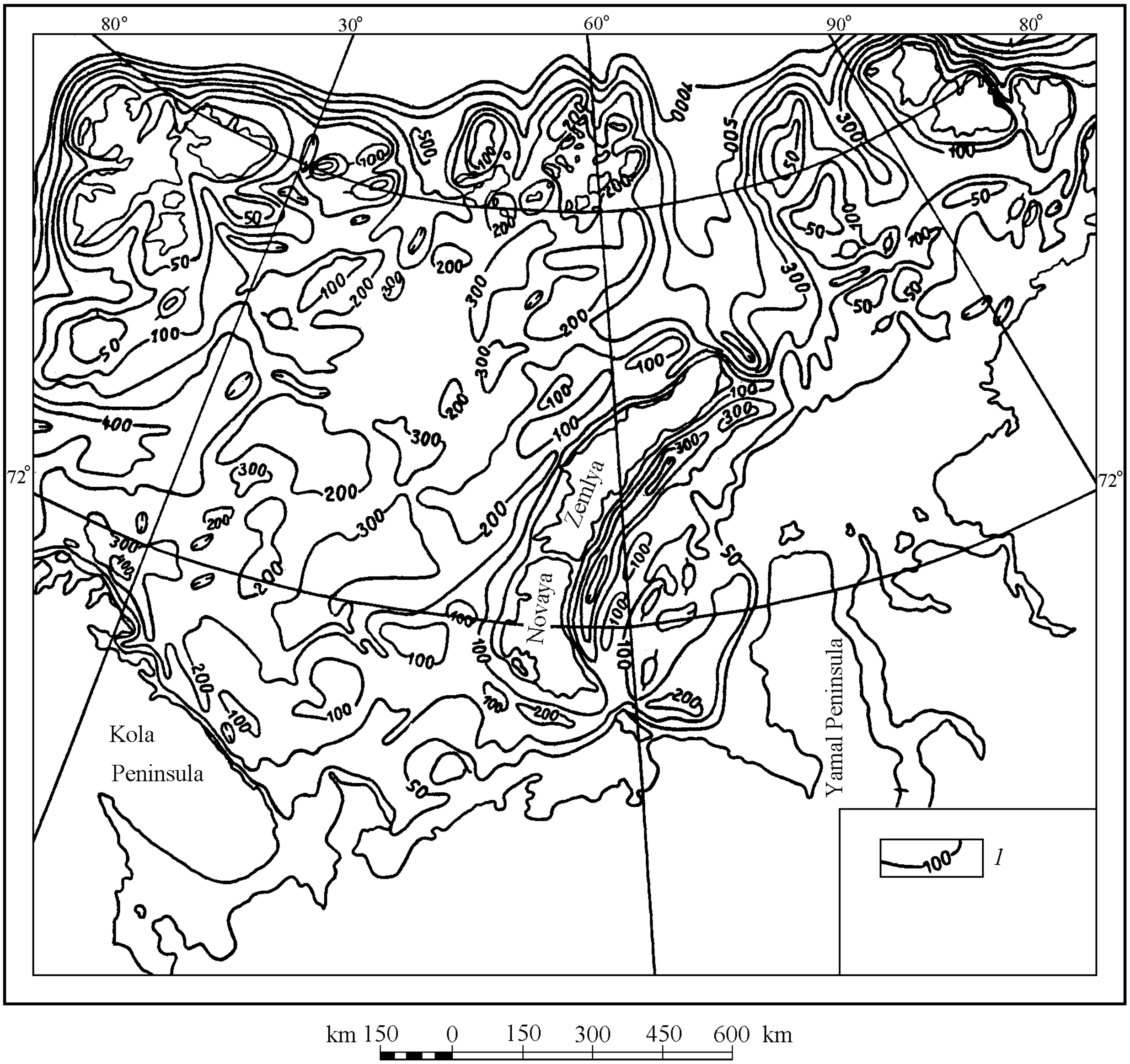

Figure 3. Bathymetric map. 1 – isobath.

the effect of erosion channels (ramified network of paleovalleys) was incorporated by smoothing the contours of the isohypses on the base of the Upper Cenozoic base;

(3) correction for eustasy. According to the recent estimates [*Chochia and Evdokimov,* 1993; *Geology of the USSR...,* 1984; *Gurevich and Musatov,* 1992; *Musatov and Musatov,* 1992; *Skagen,* 1993; *Zarkhidze and Musatov,* 1989], the sea level dropped at the end of the Oligocene to elevations ranging between −250 and −350 m. These values were used for the estimation of the magnitudes of Neogene–Quaternary crustal movements. This was done using a so-called bathygraphic method [*Map of Neotectonics...,* 1998] which implies that the topography (and paleotopography) of the outer shelf zone reflects tectonic movements that occurred during the entire recent period, and that the topography in the inner shelf represents Late Pleistocene–Holocene movements that took place during the last transgression–regression cycle with the magnitude of the Late Würmian (Late Vistulan, Late Valdaian, Late Wisconsinian, Sartanian) regression being as great as –120 m;

(4) correction for glacio-isostasy. This correction was introduced during calculations for the regions of the last (Late Würmian) glaciation, where the growth of the magnitudes of recent uplifts was generally associated [*Map of Recent Tectonics...,* 1998; *Musatov and Musatov,* 1992] with the isostatic rebound (uplifting)

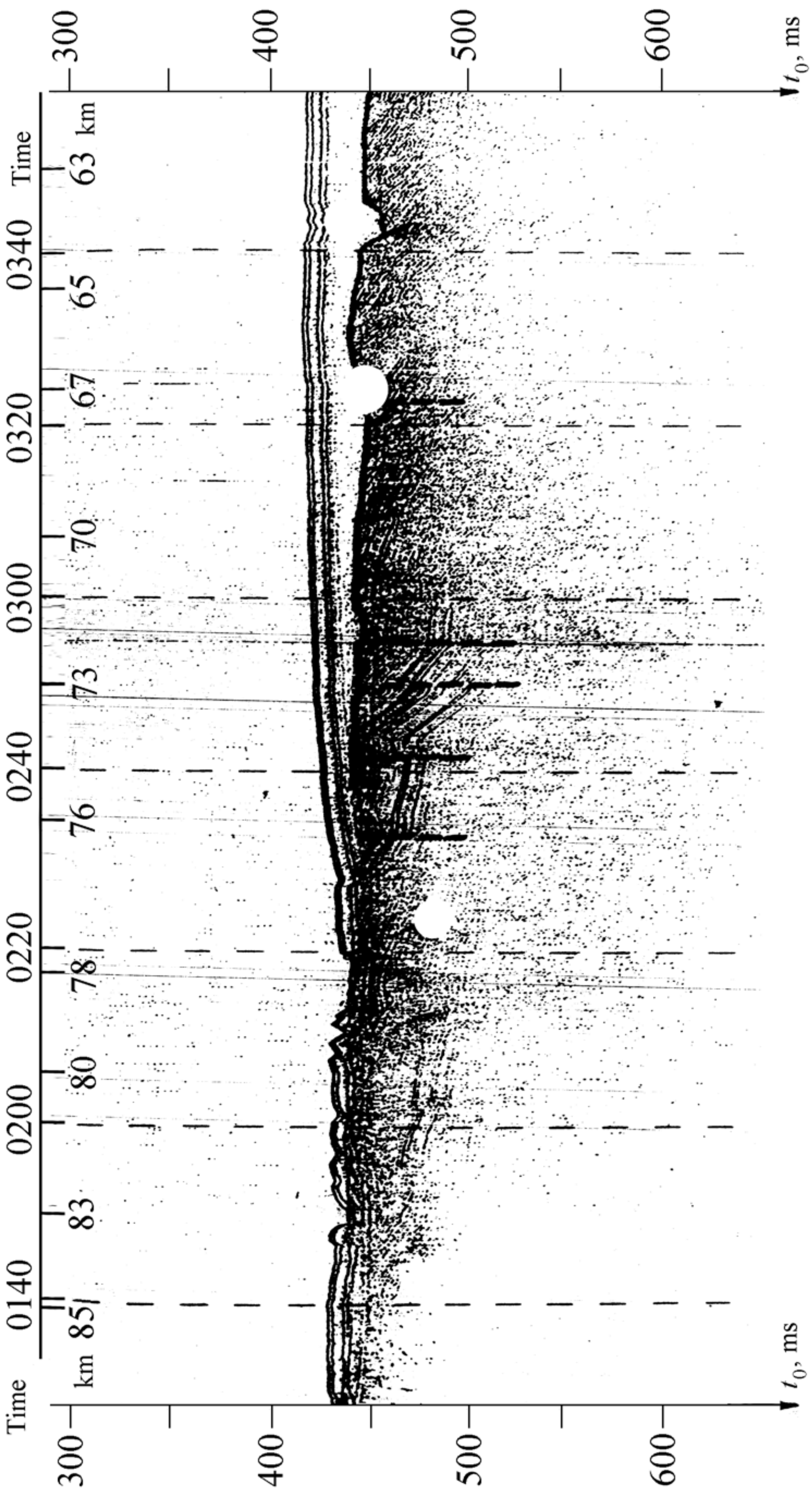

Figure 4. Example of seismic record of Jurassic and Quaternary deposits in the Franz-Victoria Trough.

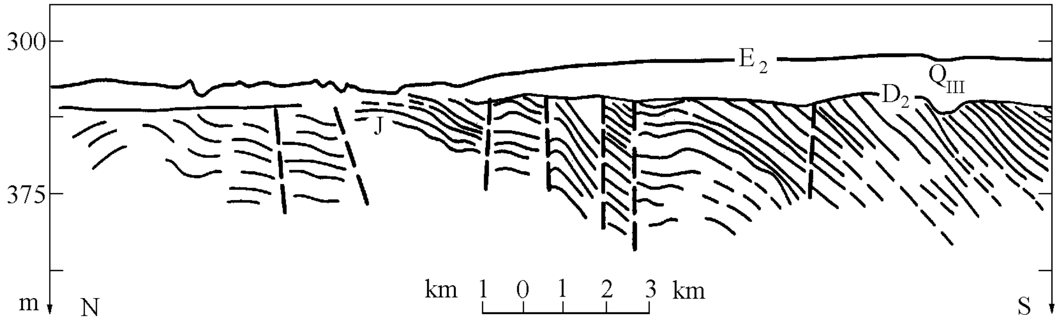

Figure 5. Interpretation of the record displayed in Figure 4 showing post-Jurassic faults and toplap at the Quaternary base.

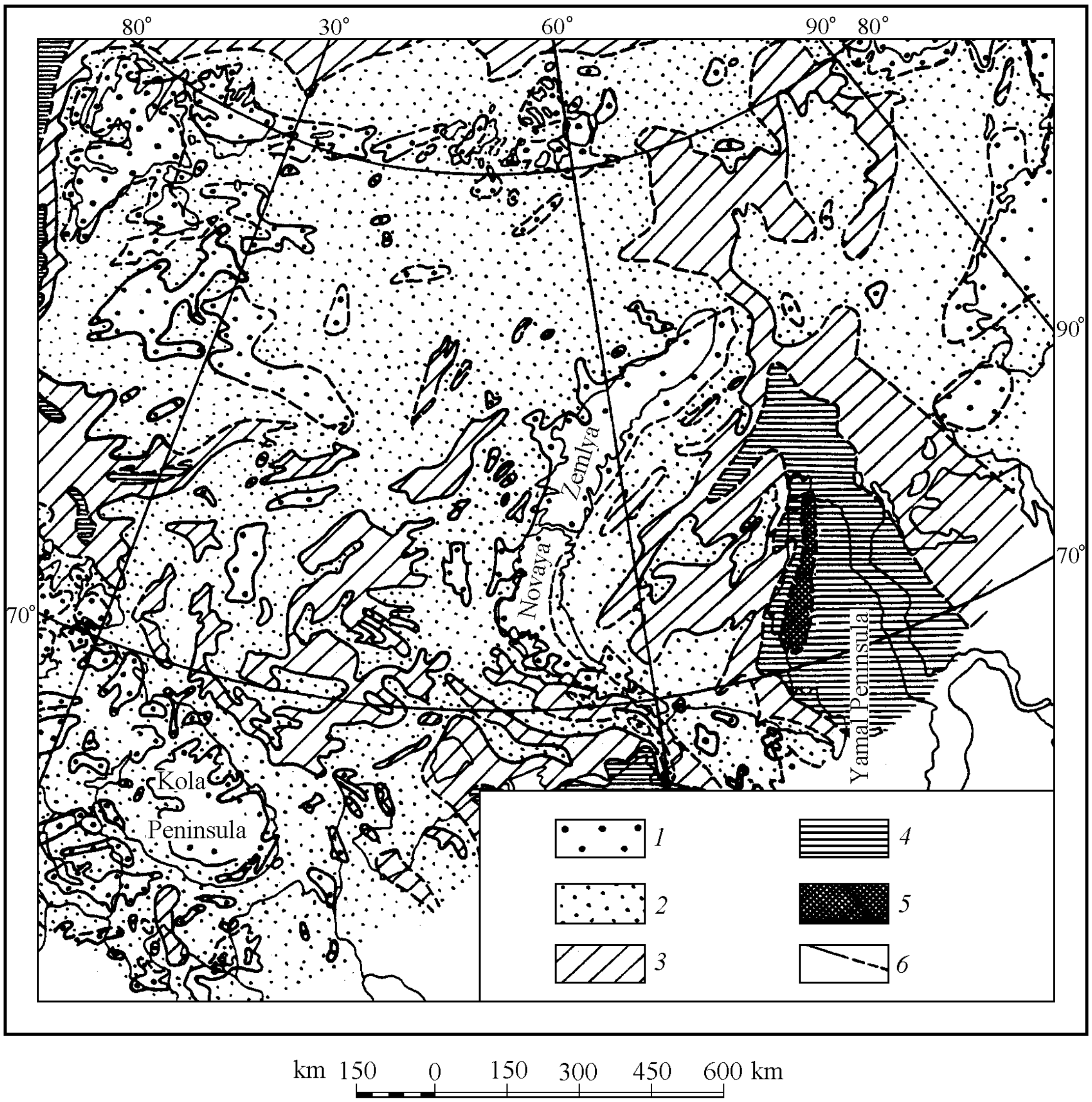

Figure 6. Isopach map of Pliocene–Quaternary deposits in the Barents–Kara region.
1 – < 5 m; 2 – 5 to 50 m; 3 – 50 to 150 m; 4 – 150 to 250 m; 5 – > 250 m; 6 – isopachs proved and inferred.

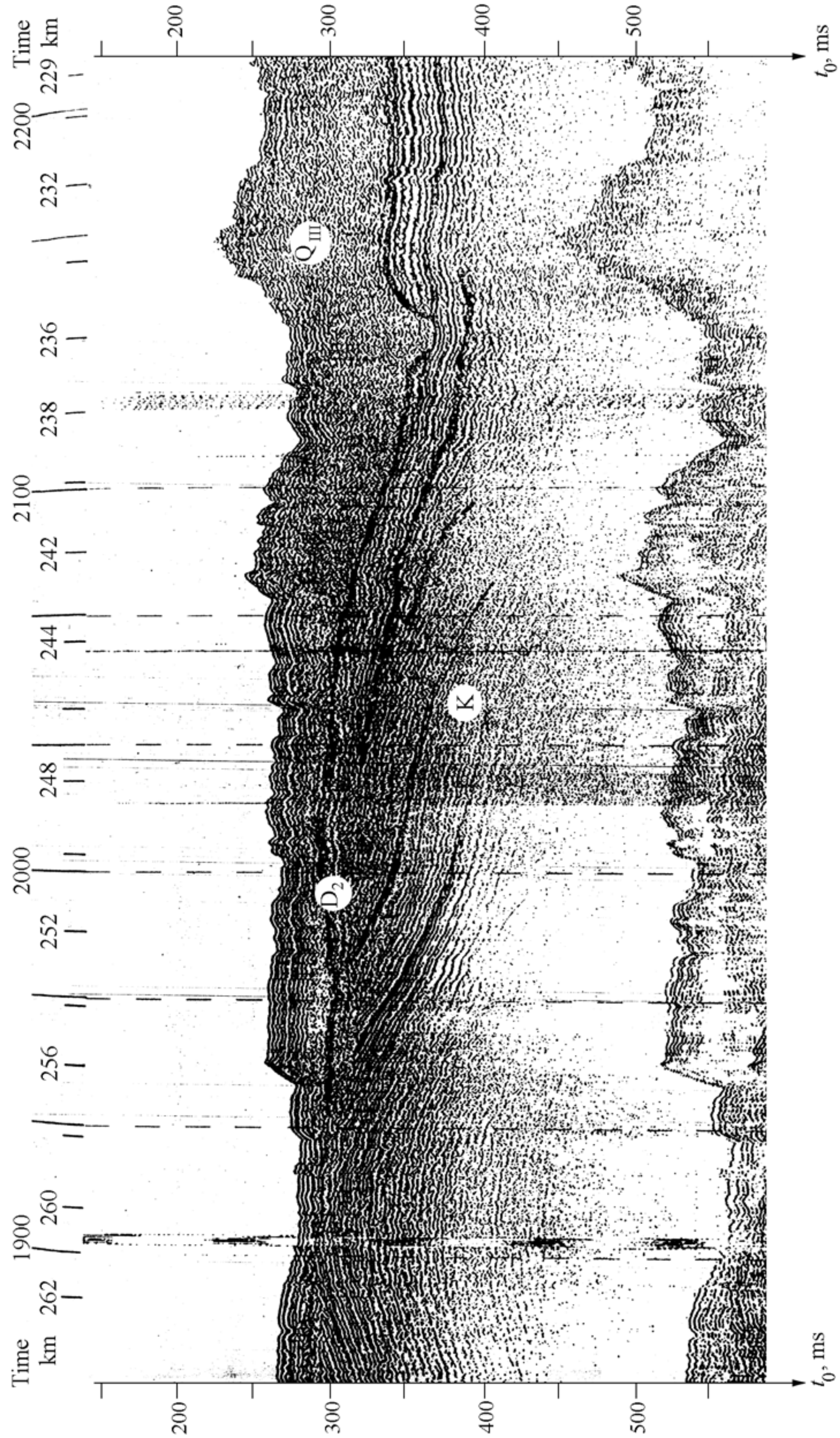

Figure 7. Example of seismic record of Lower Cretaceous and Quaternary deposits in the northern Kara Sea.

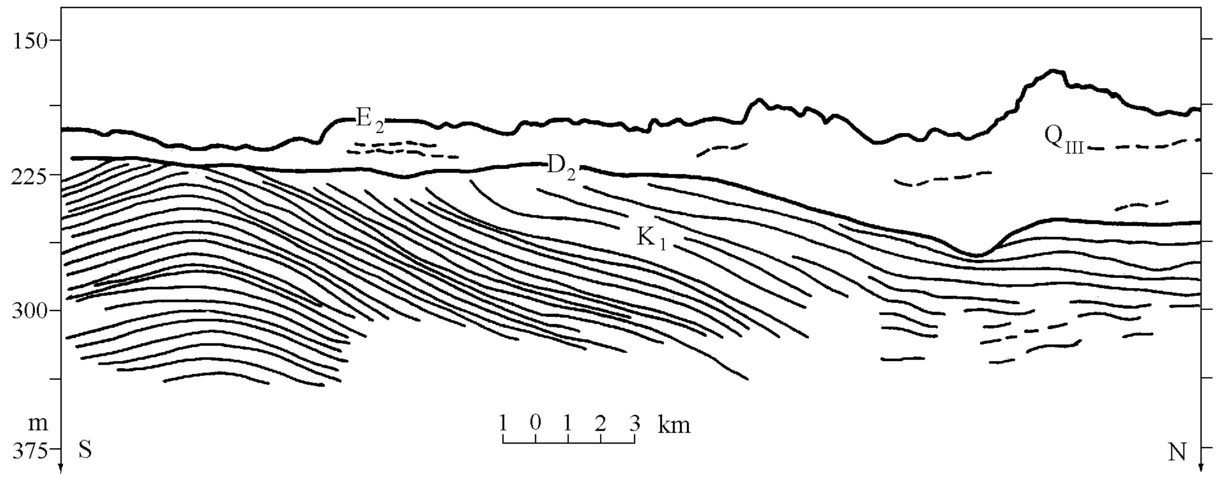

Figure 8. Interpretation of the record displayed in Figure 7 showing pre-Quaternary erosional truncation.

of the crust after the ice load had been removed. In view of the fact that the estimates of the size of the Late Würmian glacial in the Arctic region vary greatly from the model of a single Panarctic glacier [*Grosvald,* 1983; *Solheim and Kristoffersen,* 1984] over the entire area of the Barents and Kara seas to its ultimate denial [*Chochia and Evdokimov,* 1993; *Danilov,* 1978; *Gritsenko and Krapivner,* 1989; *Krapivner,* 1986], we used a compromise model of the moderate spreading of continental ice onto the shelf [*Dunaev et al.,* 1990; *Samoilovich et al.,* 1993; *Spiridonov et al.,* 1980]. And even then, with the thicknesses of the Late Würmian glaciers as great as 2–2.5 km on the Fennoscandian coast, Spitsbergen, Franz-Josef Land, and in the Barents Sea [*Elverhoi et al.,* 1988; *Kristoffersen et al.,* 1984; *Solheim and Kristoffersen,* 1984; *Solheim et al.,* 1990; *The Geology...,* 1998; *Vorren et al.,* 1988], the magnitudes of glacio-isostatic uplifts were as great as 50–200 m [*Avetisov,* 1996; *Map of Recent Tectonics...,* 1998] as was found from the radiocarbon datings of sediments from post-glacial marine terraces (-5 to -115 m high) [*Musatov,* 1997; *Pavlidis,* 1992; *Zarkhidze and Musatov,* 1989; *Zarkhidze et al.,* 1991]. In that case their values were subtracted from the total magnitudes of recent movements.

Having determined the directions and magnitudes of recent movements on the Barents–Kara shelf, we evaluated the neotectonic criteria of its petroleum potential. The evaluation was based on the most important elements of hydrocarbon potential prediction: the tectonic type of the basin, the total thickness of sediments, the volume of deposits below the depth of 2 km, the amount of deep-sea sediments in the sequence, the intensity of Mesozoic–Cenozoic subsidences, etc. Regarded as the positive factors of oil and gas potential were the direct inheritance of the recent structural style, the activation of structures of the 1st, 2nd, and higher orders, the medium-size ($<$ 300 m) magnitudes of neotectonic movements and their gradients, and substantial volumes of Cenozoic erosion that resulted in a perceptible formation pressure decline and hydrocarbon migration. Taken as the negative factors of oil and gas accumulation were the recent rearrangements of the old structural style, the poor preservation of local structures, the great range and high gradients of tectonic movements, a dense network of recent faults and fractures, which might have removed parts of hydrocarbon accumulations, and ice sheets that increased formation pressures.

This work was done in tree main steps: (1) seismic stratigraphic analysis of reflection profiler and zero-offset reflection data to reconstruct the structure of the Cenozoic sedimentary cover, (2) study of reflection horizons at its top and base to reconstruct the recent tectonics of the shelf, and (3) interpretation of the neotectonic criteria of the shelf's petroleum potential using all geological and geophysical data available.

Discussion of results

The lower seismic stratigraphic unit SSU-VII occurs on the Barents–Kara shelf in a sporadic manner obviously because of a great regional uplift that took place on the continental margin [*Musatov,* 1996; *Zarkhidze et al.,* 1991] during the Late Cretaceous–Oligocene epoch. The Paleogene deposits of this unit have velocities of 1.79–1.82 km/s [*Eldholm et al.,* 1987; *Elverhoi and Lauritzen,* 1984; *Geology of the USSR...,* 1984], are $>$ 500 m thick, and occur in the Norwegian sector of the Barents Sea in the Medvezhinsky and Nordkapp

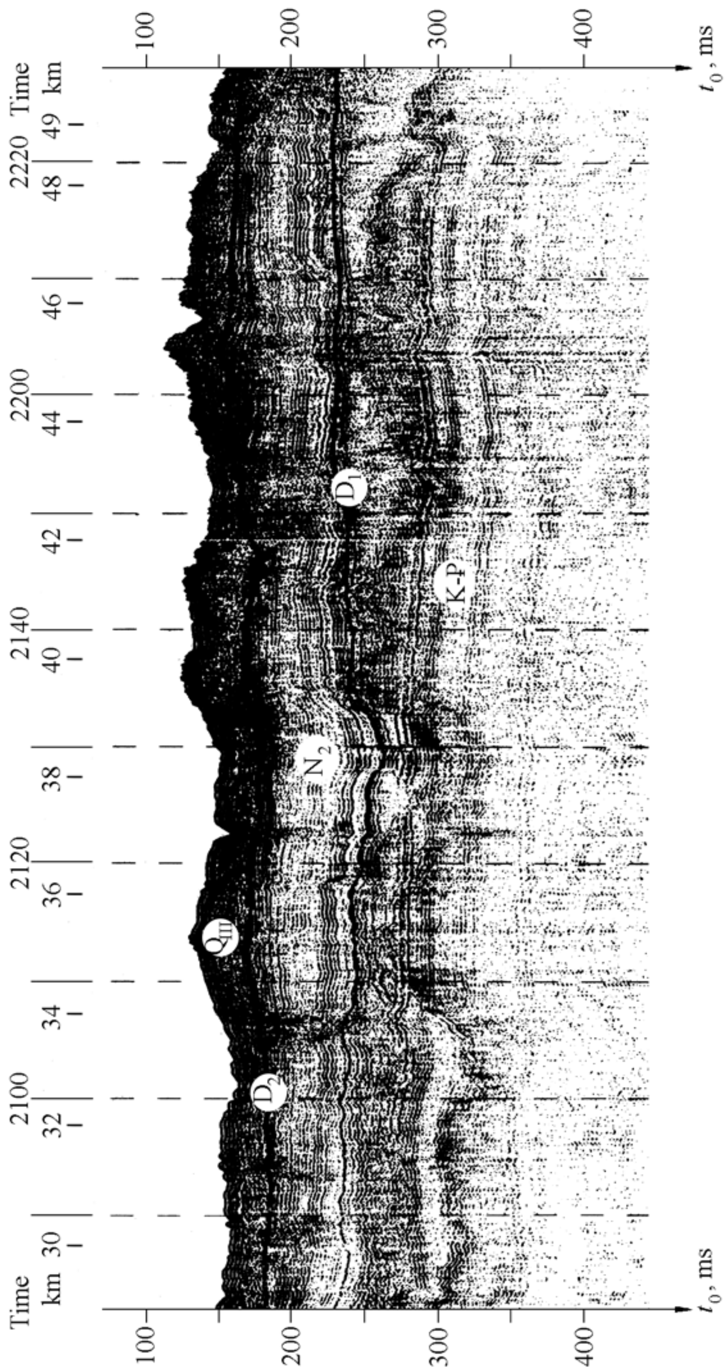

Figure 9. Example of seismic record of Cenozoic sediments in the South-Kara Syneclise.

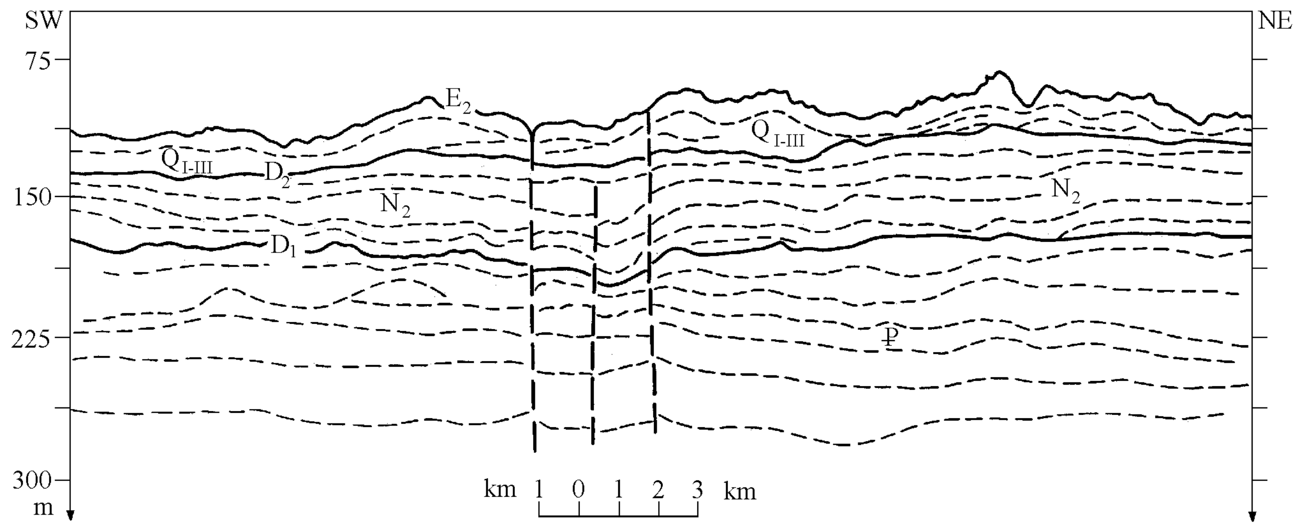

Figure 10. Interpretation of the record displayed in Figure 9 showing horizontally bedded Paleogene and Neogene deposits.

troughs. The sediments grow thicker toward the western edge of the shelf and are as thick as 2.5 km on the continental rise where an area of maximum deposition (depocenter) was located. Apparently, during rifting and spreading in the Norway–Greenland oceanic basin, the sea advanced onto the shelf from the west [*Eldholm et al.,* 1987; *Musatov and Musatov,* 1992; *Yakhimovich and Zarkhidze,* 1990]. The SSU-VII unit rests on eroded Cretaceous rocks and is overlain unconformably in the onlap manner by Quaternary sediments. The modern shelf does not contain any analogs of the unique West Spitsbergen or Forlansunnet troughs from the west of the Swalbard Archipelago, which are filled with Paleocene–Eocene interbedded mudstones, siltstones, sandstones, and conglomerates as thick as 2.5 km [*Armishev et al.,* 1988; *Zarkhidze et al.,* 1991], this sequence being crowned with the Oligocene lake and swamp sandy deposits, interbedded with mudstones, gravelstones, and coals, of the Sturvol Formation [*Barents Shelf Platform,* 1988]. A continental period began at the end of the Oligocene over the entire continental margin including the shelf, coasts, and archipelagos.

In the Russian sector of the shelf, the SSU-VII unit, as thick as 1 km, was established in the South-Kara Syneclise of the West-Siberian Platform (Figures 9–12). The sediments have velocities of 1.9–2.1 km/s [*Barents Shelf Platform,* 1988; *Geology of the USSR...,* 1984] and show reflection patterns of parallel bedding with distinct double reflection wavetrains. The seismic records show that this unit rests, conformably or with a stratigraphic break, on the Upper Cretaceous strata and is overlain unconformably (in erosional truncation manner) by Neogene–Quaternary deposits. A hole drilled on Sverdrup Island penetrated Paleogene clays and silts with sand interbeds, which rest, with a stratigraphic unconformity, on Turonian rocks and are overlain, with an erosion, by Upper Cenozoic sediments. Generally the Paleogene rocks of the West-Siberian Platform decrease in thickness northward, coastal facies appearing in the same direction. This evidence suggests that the sea advanced into the Arctic region through the Turgai Trough from the side of the Tethyan basins.

Table 1 presents a general seismic stratigraphic chart of the Cenozoic sediments, which lists the seismic stratigraphic units established in the shelf areas with their average thicknesses and reflection patterns (in the parentheses). The table also shows the stratigraphic analogs of these units from the adjacent shelf and land areas of the Pechora and West-Siberian platforms [*Zarkhidze and Musatov,* 1989; *Zarkhidze et al.,* 1991], where in addition to the average thicknesses and reflection patterns, their stratigraphic units and lithologies are indicated. The hatched intervals denote breaks in sedimentation.

The base of the Neogene–Quaternary sequence is marked in all seismic records by an angular unconformity of the erosional truncation type. This unconformity correlates with a D reflector package from the regional Cenozoic seismic stratigraphic chart [*Barents Shelf Platform,* 1988; *Druzhinina and Musatov,* 1992; *Lopatin and Musatov,* 1992; *Musatov,* 1996; *Zarkhidze et al.,* 1991] and separates, in seismic records, into reflectors D_0 (base of the Miocene SSU-VI unit), D_1 (base of the Pliocene SSU-V unit), and D_2 (base of the Pleistocene SSU-II, III units). Velocities vary from 1.5 to 1.7 km/s [*Lopatin and Musatov,* 1992] above this regional unconformity surface.

Table 1. Seismic stratigraphic chart of Cenozoic sediments on the Barents–Kara shelf

Age: Period	Age: Epoch	Barents–Kara Platform (shelf)	Pechora Platform: shelf	Pechora Platform: land	West-Siberian Platform: shelf	West-Siberian Platform: land
1	2	3	4	5	6	7
QUATERNARY	Holocene	SSU-I : 0–5 m (flat-bedded, acoustically transparent)	SSU-I : 1–40 m (acoustically transparent)	Marine terraces 3–5 m (sand, silt)	SSU-I : 1–15 m (acoustically transparent)	Marine terraces, max. 14–20 m (sand, silt, clay)
	Neopleistocene	SSU-II : 5–50 m (bedded, speckled)	///////////////	///////////////	///////////////	///////////////
			SSU-II : 5–40 m (discontinuously bedded)	Marine terraces 20–25 and 35–45 m (clay, silt, sand)	SSU-II : 2–60 m (vaguely bedded)	Marine terraces 22–35 и 45–65 m (clay, sand, silt)
		SSU-III : 5–75 m (discontinuously bedded, chaotic)	///////////////	///////////////	///////////////	///////////////
			SSU-III : 5–100 m (flat-bedded, speckled)	Marine terraces 80–100 and 180–220 m; Rogovskaya Group : 200–250 m (sand, silt, diamicton)	SSU-III : 5–70 m (bedded,discontinuously bedded)	Marine terraces 65–80 and 160–180 m; Salekhard Formation : 30–80 m (diamicton, silt, sand)
						Kazym Formation : 10–80 m (sand, silt, clay)
Eopleistocene	Eopleistocene	///////////////	///////////////	///////////////	SSU-IV : 10–75 m (speckled, bedded)	
		SSU-IV: 0–50 m (bedded, cross-bedded)	SSU-IV : 25–125 m (bedded, acoustically transparent)	Padimeiskaya Group: 60–240 m (diamicton, clay, sand)		Polui Formation : 40–60 m (clay, silt, sand)
		/////////////// ///////////////				
NEOGENE	Pliocene	/////////////// ///////////////	///////////////	///////////////	SSU-V : 20–50 m (cross- and flat-bedded)	Yar-Sale Group : 70–100 m (silt, sand)
			SSU-V : 30–60 m (flat- and cross-bedded	Kolva Group: 80–250 m (clay, silt, sand)		
		SSU-V: 0–30 m (cross-bedded)				Shuryshkar Formation : 50–100 m (clay, sand)
		/////////////// ///////////////		Prosundui Formation 80–200 m (clay, silt, sand)		

Table 1. Continued

1	2	3	4	5	6	7
NEOGENE	**Miocene**	///////////////	///////////////	///////////////	///////////////	///////////////
		///////////////	///////////////	///////////////	SSU-VI : 10–150 m (cross-bedded)	Tavolzhan Formation : 10–80 m (sand)
		///////////////	///////////////	Vangurei Suite : 40–80 m (clay, sand)		Pelym Formation : 110 m (silt, sand)
		///////////////	///////////////			Abrosimovskaya Formation : 100 m (sand)
PALEOGENE	**Oligocene**	///////////////	///////////////	///////////////	///////////////	///////////////
		SSU-VII : 0–600 m (flat- bedded)	///////////////	///////////////	SSU-VII : 100–1000 m (flat- bedded)	Turtas Formation : 65–200 m (silt, clay)
	Eocene		///////////////	///////////////		Tavda Formation : 100–150 m (silt, sand, clay)
			///////////////	///////////////		Irbit Formation : 80–265 m (silt, clay, sand)
			///////////////	///////////////		Serov Formation : 50–100 m (silt, sand, clay)
	Paleocene	///////////////	///////////////	///////////////		Tibei-Sale Formation : 25–140 m (clay, silt)

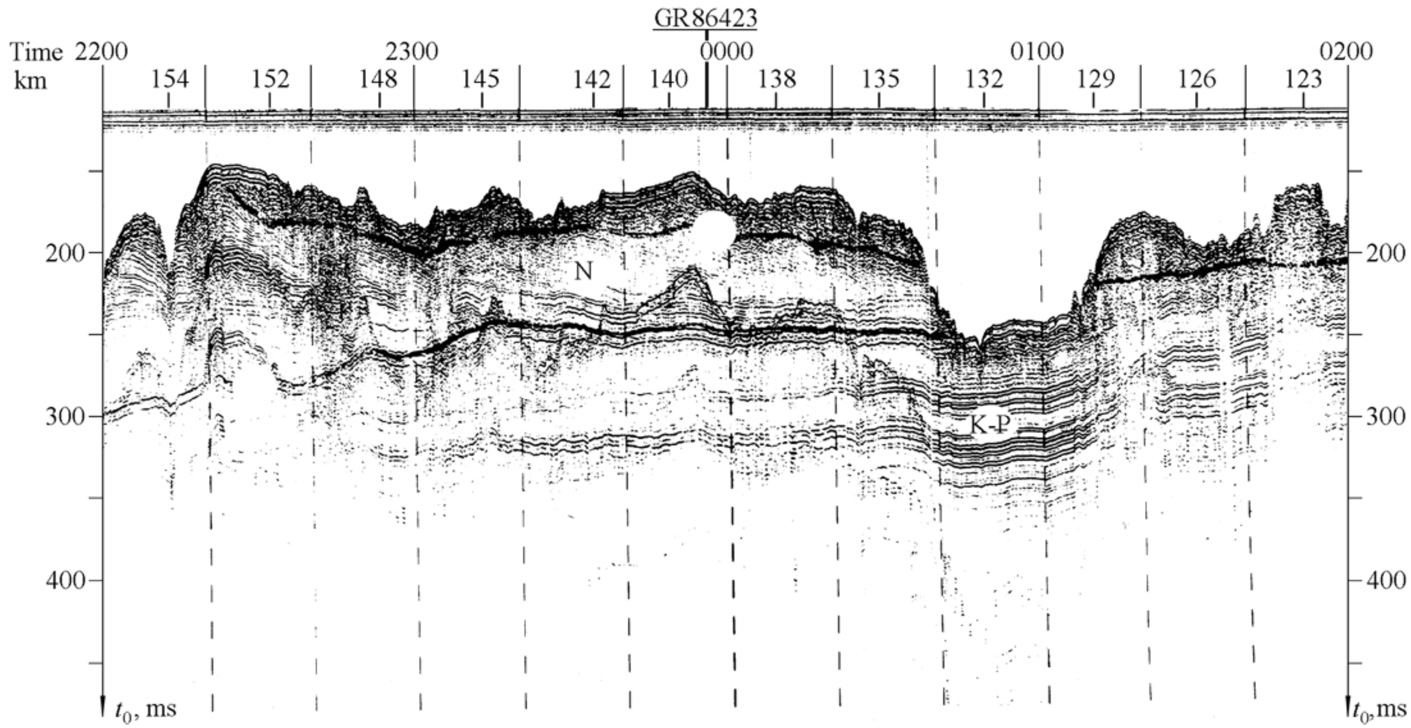

Figure 11. Example of seismic record of Paleogene and Neogene–Quaternary deposits in the South-Kara Syneclise.

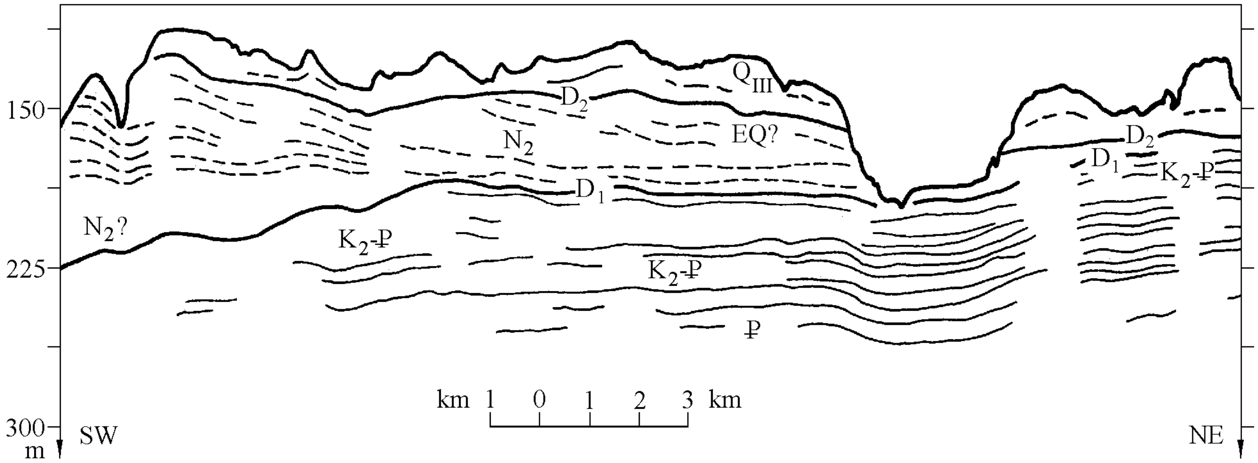

Figure 12. Interpretation of the record displayed in Figure 11 showing pre-Pliocene and recent erosional truncations.

The SSU-VI unit occurs in the deep hollows and valleys of the pre-Neogene topography in the South-Kara syneclise: its lower contact is a baselap unconformity, the upper contact being an erosional truncation. In seismic records this unit looks as a cross-bedded sequence, as thick as 150 m, with inclined reflections inside. These sediments fill broad paleovalleys open toward the middle of the basin. Based on their position between the Paleogene and Pliocene strata and on their analogy with the continental deposits of the Abrosimovskaya, Pelym, and Tavolzhan formations of West Siberia [*Zarkhidze et al.,* 1991], the SSU-VI sediments were interpreted as Miocene alluvial and deltaic deposits (Figures 13 and 14). By the end of this epoch the sea level dropped by 300–350 m [*Danilov,* 1978; *Musatov,* 1996], the Barents–Kara shelf got dry again, and new deep paleochannels were produced by rivers (Figures 15–18).

The SSU-V unit rests, with an erosional truncation unconformity, on the Mesozoic and Paleogene rocks in the Pechora and West-Siberian platforms. In seismic records its rocks occur as extensive sheets, up to 50–60 m thick, with horizontal or cross-bedded reflection patterns. In the Barents–North Kara Platform, the sediments of this unit fill very deeply incised paleovalleys and have nowhere been found as basin facies. According to the results of engineering-geological drilling [*Gritsenko and Krapivner,* 1989; *Onishchenko and Bondarev,* 1988], the SSU-V unit is correlatable with the marine and deltaic sediments of the Prosundui and Kolva formations [*Yakhimovich and Zarkhidze,* 1990; *Zarkhidze and Musatov,* 1989] from the Timan–Urals land region.

The SSU-IV unit rests on the underlying SSU-V unit with a toplap unconformity and is characterized by a great diversity of reflection patterns varying from irregular to acoustically transparent ones. In the Pechora and West-Siberian platforms the rocks of this unit occur as wedge-shaped bodies or sheet drapes, ranging between 75 and 125 m in thickness; in the Barents–North Kara Platform they occur as paleochannel fills having a maximum thickness of 50 m. Based on drilling data [*Gritsenko and Krapivner,* 1989; *Krapivner,* 1986; *Onishchenko and Bondarev,* 1988] and on the correlation of SSU-IV with land stratigraphic units, this unit was dated Eopleistocene and correlated with the deposits known as the Padimeiskaya Group [*Yakhimovich and Zarkhidze,* 1990; *Zarkhidze et al.,* 1991] in the Timan–Urals region, in which unsorted sand-, clay-, and silt-size diamictons, containing larger size material, appeared for the first time in the Cenozoic sequence [*Barents Shelf Platform,* 1988; *Zarkhidze and Musatov,* 1989], the latter circumstance being indicative of cooling and first glaciations.

The SSU-III unit rests on numerous erosion channels at its base and in seismic records looks as extensive sheets as thick as 75–100 m throughout the shelf area. Judging by its reflection configurations (chaotic to parallel stratified), this sequence includes both fine sorted and coarse moraine-like deposits. The SSU-III sediments were dated Early–Middle Pleistocene on the basis of the microfossil assemblages found in the drill cores [*Gritsenko and Krapivner,* 1989; *Onishchenko and Bondarev,* 1988]. On the shelf of the Pechora Platform, the upper sediments of this unit are deformed to flowage folds [*Krapivner,* 1986], where the bends in the top repeat the bends of the internal reflections, this pattern suggesting the rise of shale diapirs. On the shelf of the Barents–Kara Platform, near the glaciation centers on the archipelagos, these sediments show glaciotectonic features: sheet-ice glaciation took place there at the end of the middle Pleistocene, where the sea retreated to elevations of −200 m [*Dunaev et al.,* 1990; *Musatov,* 1997; *Pavlidis,* 1992], known as the third glacial stage

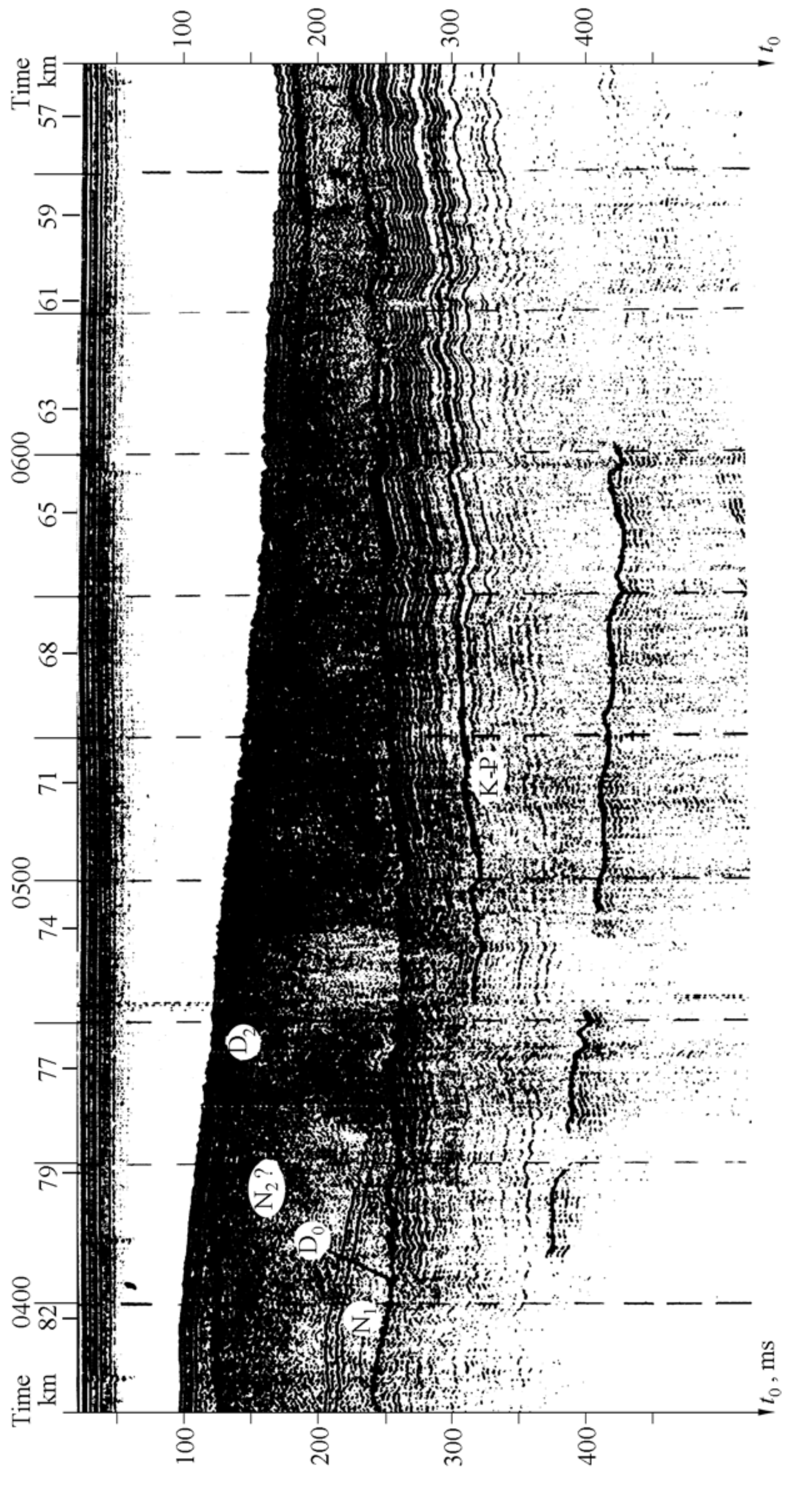

Figure 13. Example of seismic record of Upper Cretaceous–Cenozoic deposits in the South-Kara Syneclise.

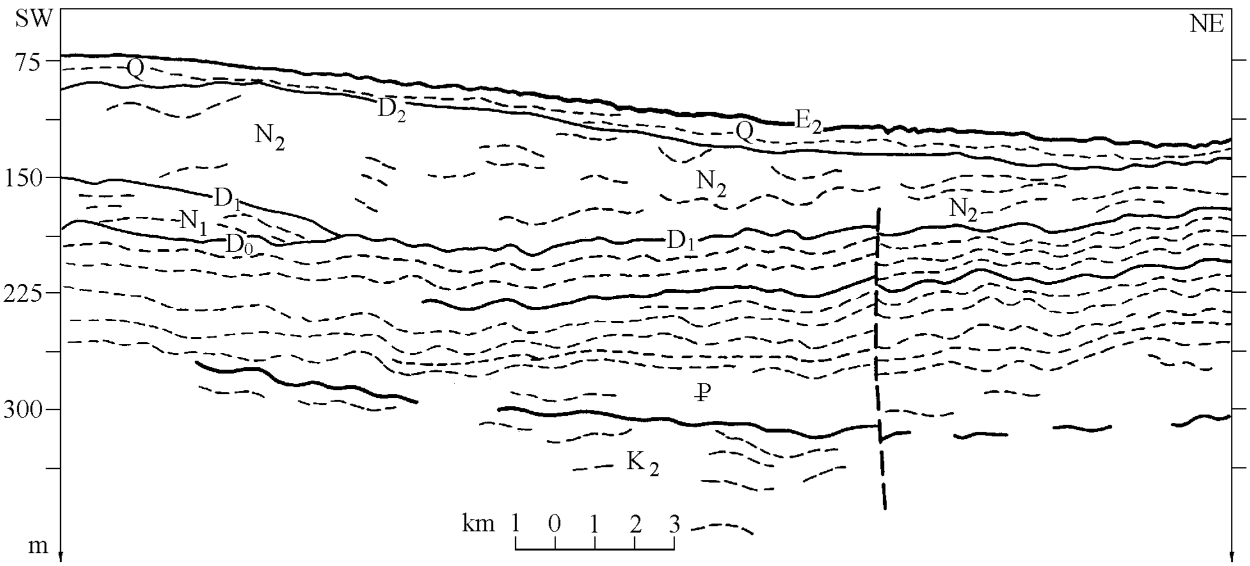

Figure 14. Interpretation of the seismic record displayed in Figure 13 showing the geometries of the tops and bottoms of the Paleogene, Miocene, Pliocene, and Quaternary sequences.

(Riss) of the Pleistocene Epoch in the Alps and as the Illinoian glacial stage in North America.

The base of the overlying SSU-II unit is marked, at this depth, by an erosional truncation which is covered, at a greater depth, by the underlying SSU-III sediments conformably or as a baselap. At the coasts of the Pechora and West-Siberian platforms, the sand–clay sediments of marine terraces extend onto the shelf as SSU-II sheets and sheet drapes, as thick as 50–60 m (Figures 19 and 20). The irregular reflection patterns recorded in the SSU-II top suggest the occurrence of tills of the last glacial stage (Würm or classical Wisconsin). The tills are displayed in seismic records as chaotic short events (Figures 7 and 8) and occur, in the underwater topography, as terminal moraine bars, as high as 30–40 m, extending to depths of 120 m, the magnitude of the last glacio-eustatic regression.

The uppermost SSU-I unit shows horizontally stratified or acoustically transparent reflection patterns and consists of blanket marine sediments of the post-glaciation transgression. An erosional truncation was established at its base as far as a depth of -120 m; at greater depths its sediments overlap the underlying SSU-II unit conformably. The SSU-I thickness ranges usually between 1 and 5 m and is as great as 40 m in some depocenters of lagoonal sediment accumulation, e. g., off the northeastern coast of Kolguev Island [*Gritsenko and Krapivner,* 1989; *Samoilovich et al.,* 1993]. This unit was recorded only at high frequencies ($>$ 3.5 kHz); where lower frequencies ($<$ 1 kHz) were used, the noise of the transmitted signal often exceeded its thickness.

Conclusion

The seismic stratigraphic units described in this paper characterize four periods in the Cenozoic history of the Barents–Kara shelf: Paleocene–Eocene sedimentation (SSU-VII), Oligocene–Miocene denudation (SSU-VI), Pliocene–Pleistocene denudation–sedimentation (SSU-III–V), and Late Pleistocene–Holocene sedimentation (SSU-I, II). The major Late Oligocene and Late Miocene regressions, as well as lesser regressions at the Plio/Pleistocene and Eo/Neopleistocene boundaries, represented by erosion channels incised at the contacts of the seismic stratigraphic units (Figures 21 and 22), resulted in the deposition of a large volume of denudation material on the shelf. Norwegian researchers estimated the magnitude of the Tertiary erosion on the Svalis Bank as 1750–2050 m [*Skagen,* 1993]. Somewhat lower magnitudes were established for some banks and rises in the Russian sector of the shelf: 200–300 m on the Admiralty Rise, 150–200 m near the Kola Peninsula, 300–500 m in the South Kara Syneclise, and 500–1000 m near the archipelagos and on the Percej Bank. Cenozoic erosion exposed Jurassic and even Triassic rocks in the cores of large anticlines.

Figure 23 shows a neotectonic map of the Barenz–Kara shelf area. Figure 24 displays the magnitudes of Neogene–Quaternary movements reconstructed using the technique described in this paper. The maximum magnitudes of upward movements (+200 to +500 and 1000 m) were found for the shields surrounding the shelf, for the post-Caledonian and post-Hercynian–early

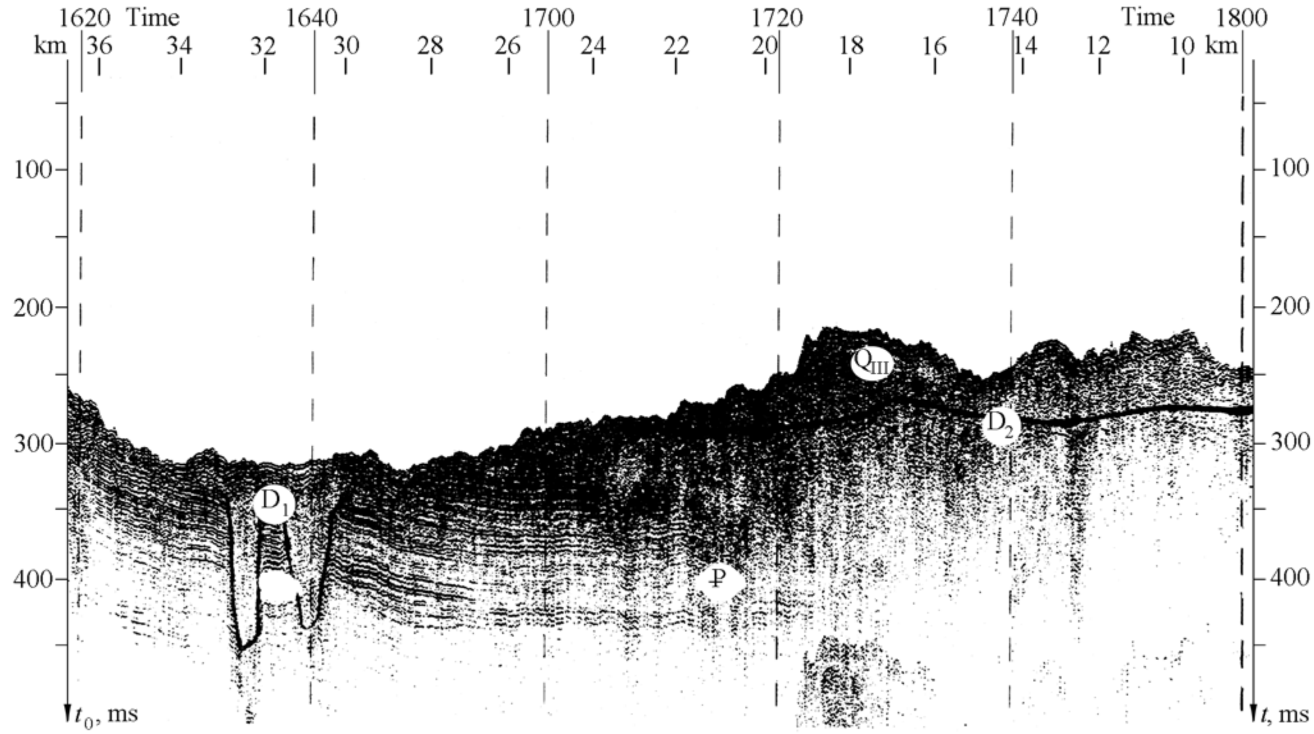

Figure 15. Example of seismic record of Cretaceous–Cenozoic deposits in the Kara Sea.

Kimmerian orogenic belts, and also for the marginal shelf archipelagos. The highest magnitudes of downward movements (−400 to −500 and −750 m) were established for the graben-shaped troughs: Medvezhinsky, Nordkapp, Franz-Victoria, Saint Anna, and Voronin. The basins of the Barentz–Kara megadepression experienced inherited recent subsidences with magnitudes of −200 to −400 m. The shelf of the intracontinental Pechora and West-Siberian platforms underwent both upward and downward movements ranging between +50 and −250 m. The regional background neotectonic subsidence of the Barents–Kara margin was −200 m.

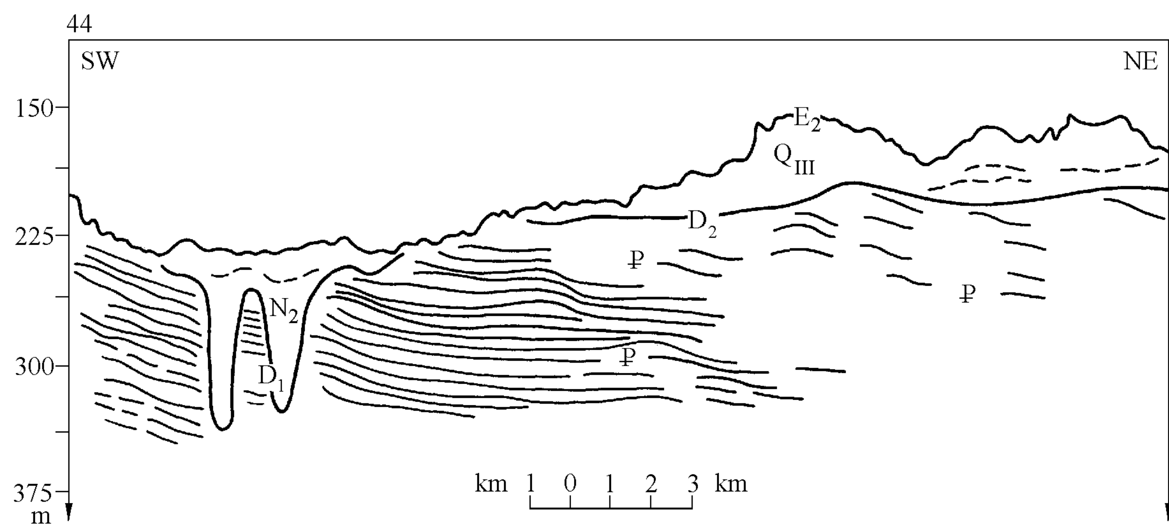

Figure 16. Interpretation of the seismic record displayed in Figure 15 showing Neogene erosion paleochannels.

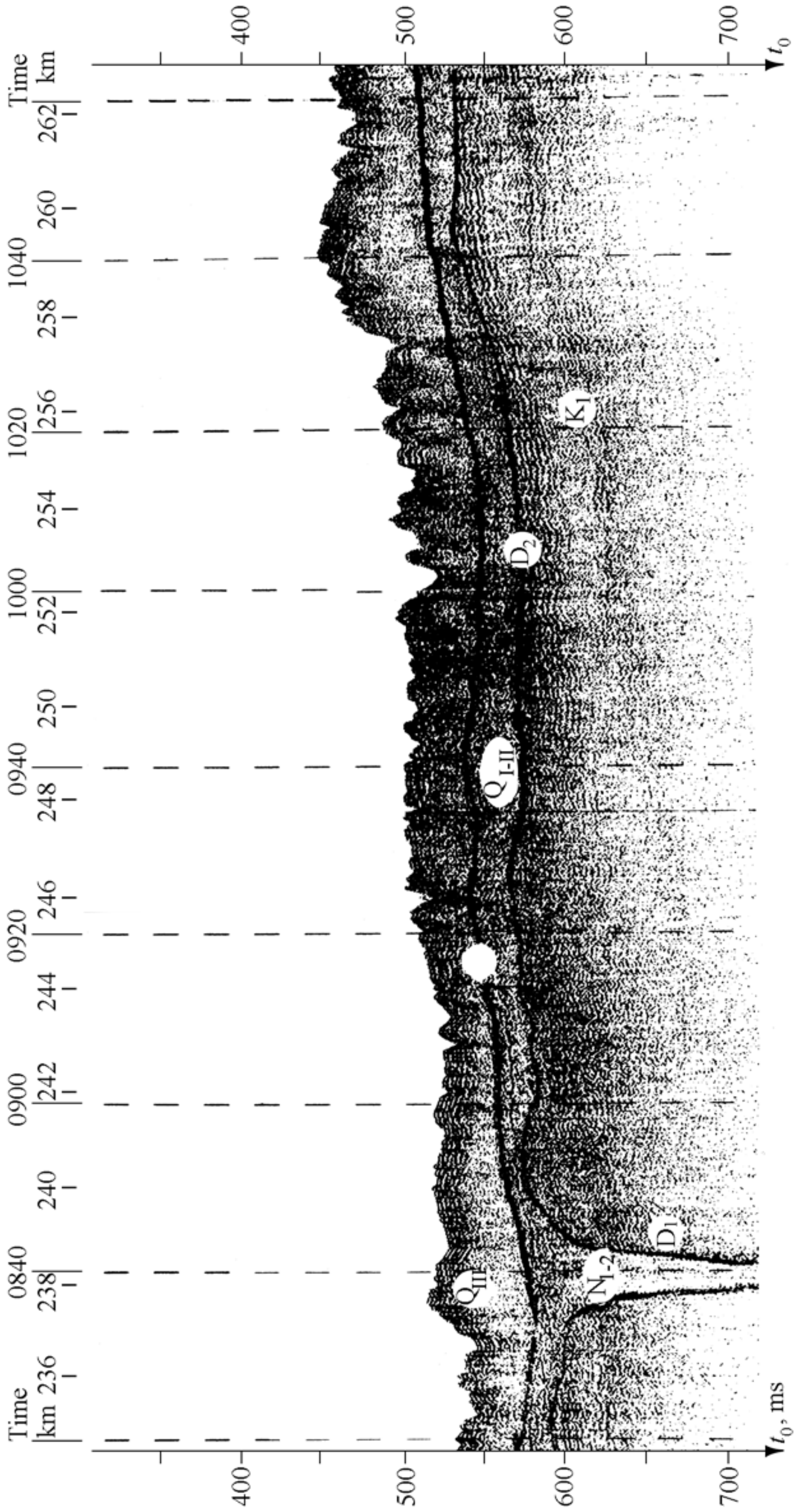

Figure 17. Example of seismic record of Lower Cretaceous and Quaternary deposits in the Saint Anna Trough.

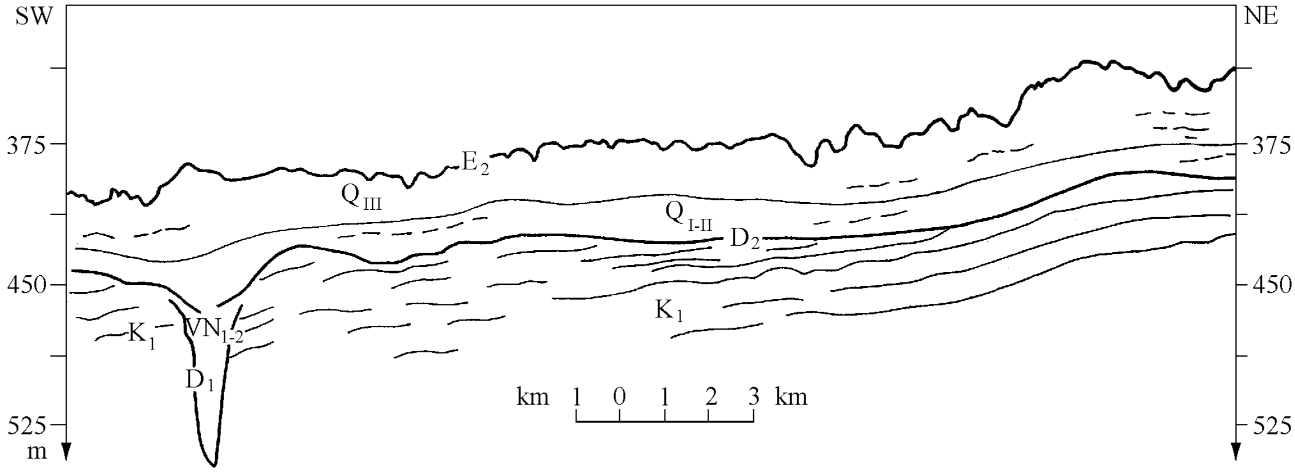

Figure 18. Interpretation of the record displayed in Figure 17 showing Neogene paleochannels.

The Cenozoic regressions (removal of huge water masses), recent oscillatory crustal movements, glacio-isostatic uplifts, and great volumes of eroded material resulted in a formation pressure decline, the reconfiguration of hydrocarbon accumulations, and the migration of hydrocarbons from old reservoirs. Contributive to gas accumulation were muddy sediments that accumulated on the shelf during the Cenozoic to attain a thickness of a few hundred meters and served as caps impermeable for fluids. Most of hydrocarbon accumulations are contained in structural, anticline-type traps in the sediments, which were formed mainly during the Late Cretaceous–Cenozoic epoch [*Musatov,* 1996, 1997].

Figure 25 shows a map of the neotectonic factors favorable for oil and gas accumulation: highly promising areas are concentrated in the central parts of the West-Siberian and Pechora intracontinental platforms and of the Barents–Kara continental-margin platform with the maximum thicknesses of sediments (14–18 km), a moderate range (200–300 m) of recent crustal movements, and maximum increments (100–200 m) of the reliefs of second-order structures. Of particular value are local recent highs in the Barents–Kara megadepression, where the unique Shtokmanovskoe gas-condensate field is restricted to a boundary zone between the Central Barents Bank and the South-Barents Basin. Also promising are the zones of prograding continental slopes with thick (> 2 km) Cenozoic wedges.

The comparatively mild recent tectonic activity and the attenuation of faults in the upper horizons of the sedimentary cover were favorable for the reconfiguration of gas accumulations in the southern and central parts of the shelf. At the same time, normal and oblique-slip faults, inherited in the marginal shelf rise near the archipelagos and in the marginal graben-shaped troughs, experienced strong reactivation during the Cenozoic. Some of them were newly formed during the recent period and penetrated throughout the sediments. The outer shelf periphery along the Spitsbergen–Severnaya Zemlya continental slope suffered a radial neotectonic rearrangement with high-gradient recent movements attaining a total range of 2–3 km. This region is estimated as low-promising because old hydrocarbon pools must have been destroyed by intense fault tectonics. In all other regions of the Barents–Kara shelf, neotectonic conditions were favorable for the preservation and reconfiguration of oil and gas accumulations.

During the Cenozoic the Barents–Kara shelf was part of the continental margin of the Norway–Greenland and Eurasian deep-sea basins, two of the youngest segments of the world ocean, where the oldest magnetic anomaly (24) is as young as Middle Paleocene. The geological and geophysical characteristics of the shelf are unique for the passive Atlantic-type continental margin: the broad (750–1500 km) and deep (500–600 m) shelf, thick sediments (up to 18 km in the South-Barents Basin), a wide development of marginal graben-shaped troughs expressed in the top of the acoustic basement, the occurrence of granite-free crustal windows, elevated seismicity ($M = 4$–6), especially near the continental slope and trough sides [*Avetisov,* 1996], Miocene (on Novaya Zemlya) and recent (on western Spitsbergen) basaltic volcanism, etc. These processes were accompanied by high-magnitude, differential, primarily downward crustal movements that occurred during the early stage of the continental margin evolution and were caused by the dependence of neotectonic condi-

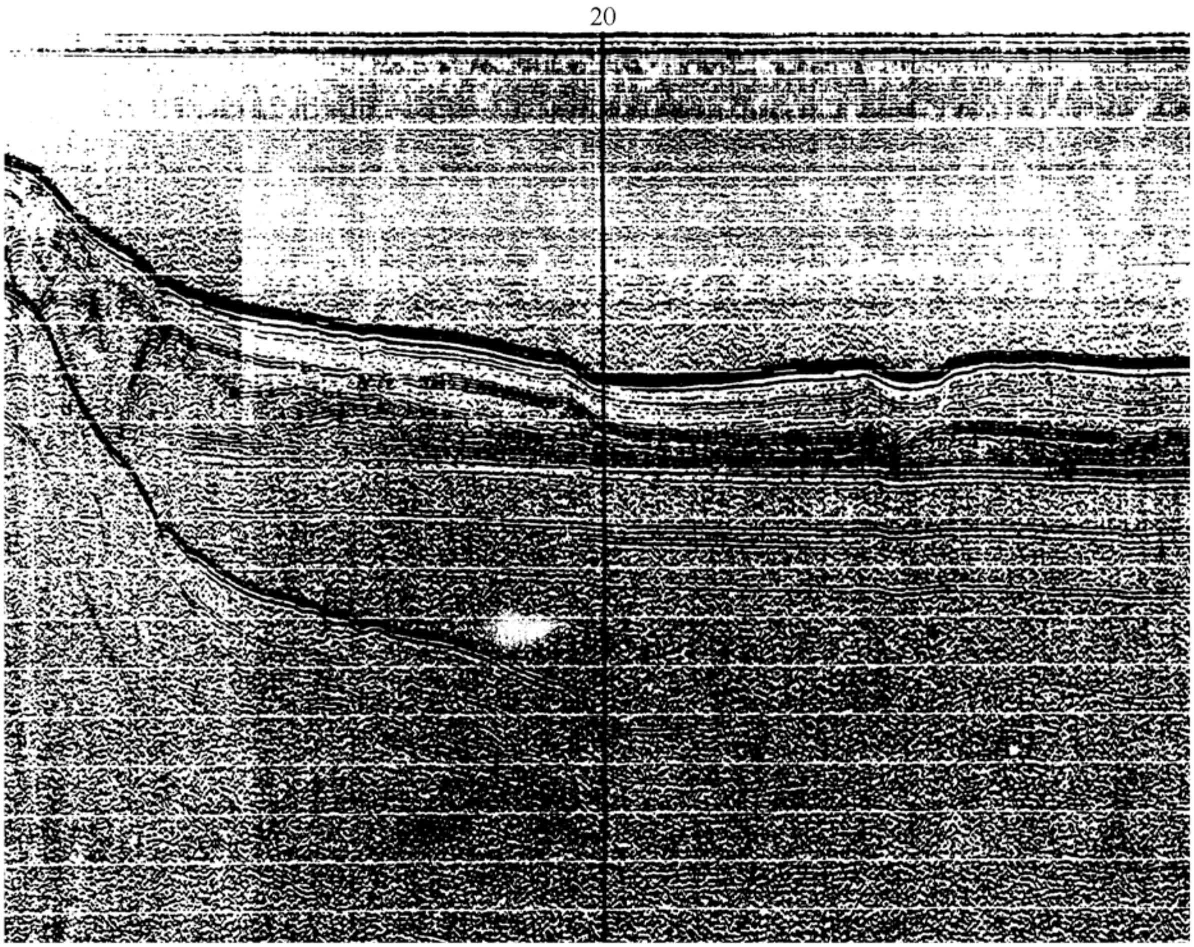

Figure 19. Example of seismic record of Lower Cretaceous and Neogene–Quaternary deposits in the Gusinyi Trough.

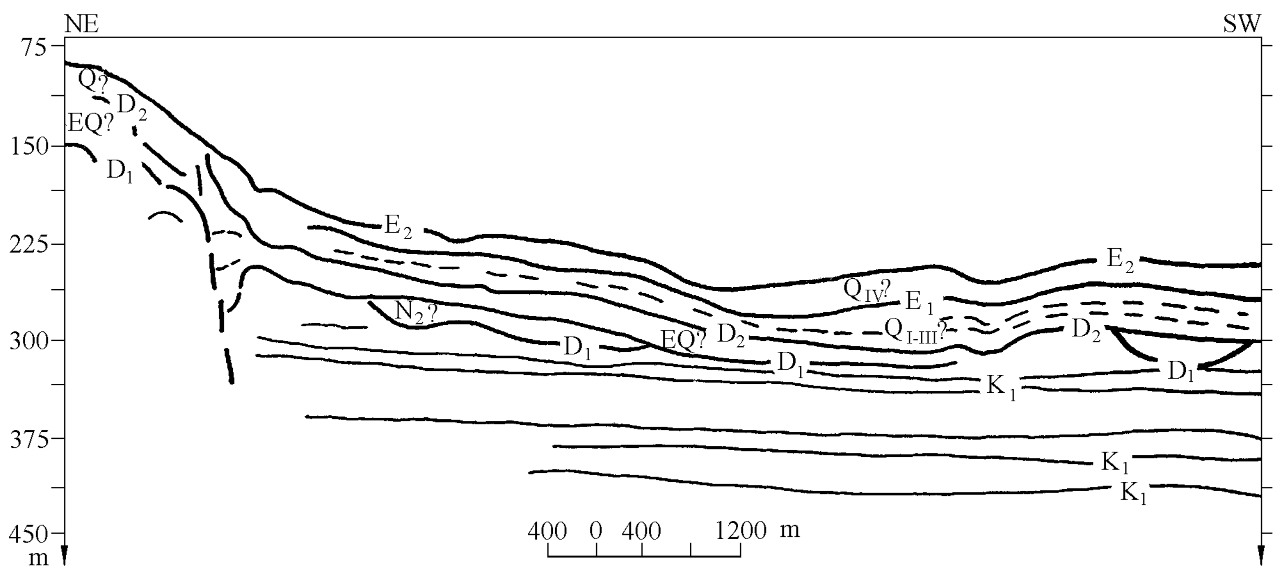

Figure 20. Interpretation of the record displayed in Figure 19 showing drape sheets of Quaternary seismic units.

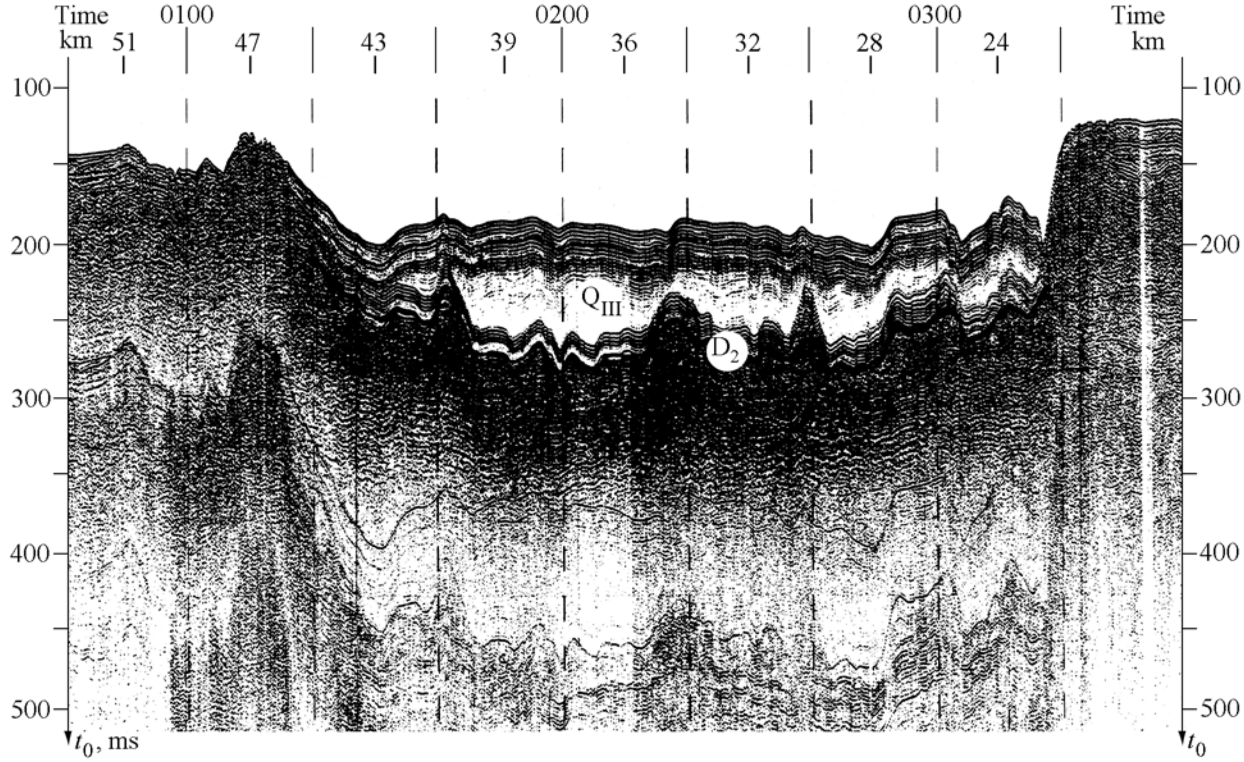

Figure 21. Example of seismic record of Cretaceous and Quaternary seismic units.

tions in the transition zone on the processes of rifting and spreading in the Norway–Greenland and Eurasian basins. The leading process in the whole of the Western Arctic region was the progressive intrusion of the Gakkel Ridge from the North Atlantic into the Arctic Ocean toward the Laptev Sea shelf, near which the oldest magnetic anomaly identified is anomaly 5 (Miocene). The spreading-related oscillatory movements of the Barents–

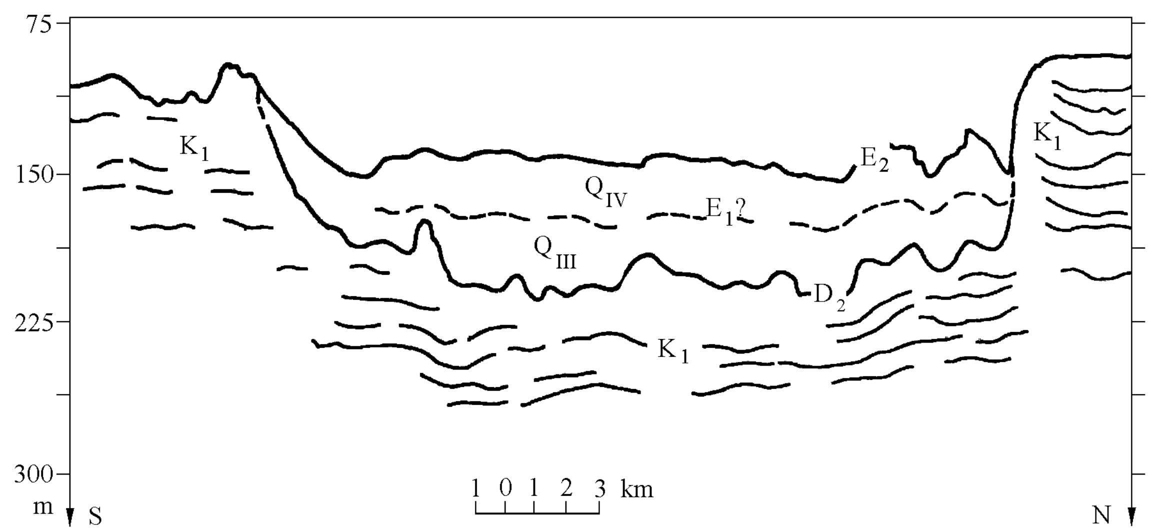

Figure 22. Interpretation of the record displayed in Figure 21 showing a Late Quaternary paleovalley.

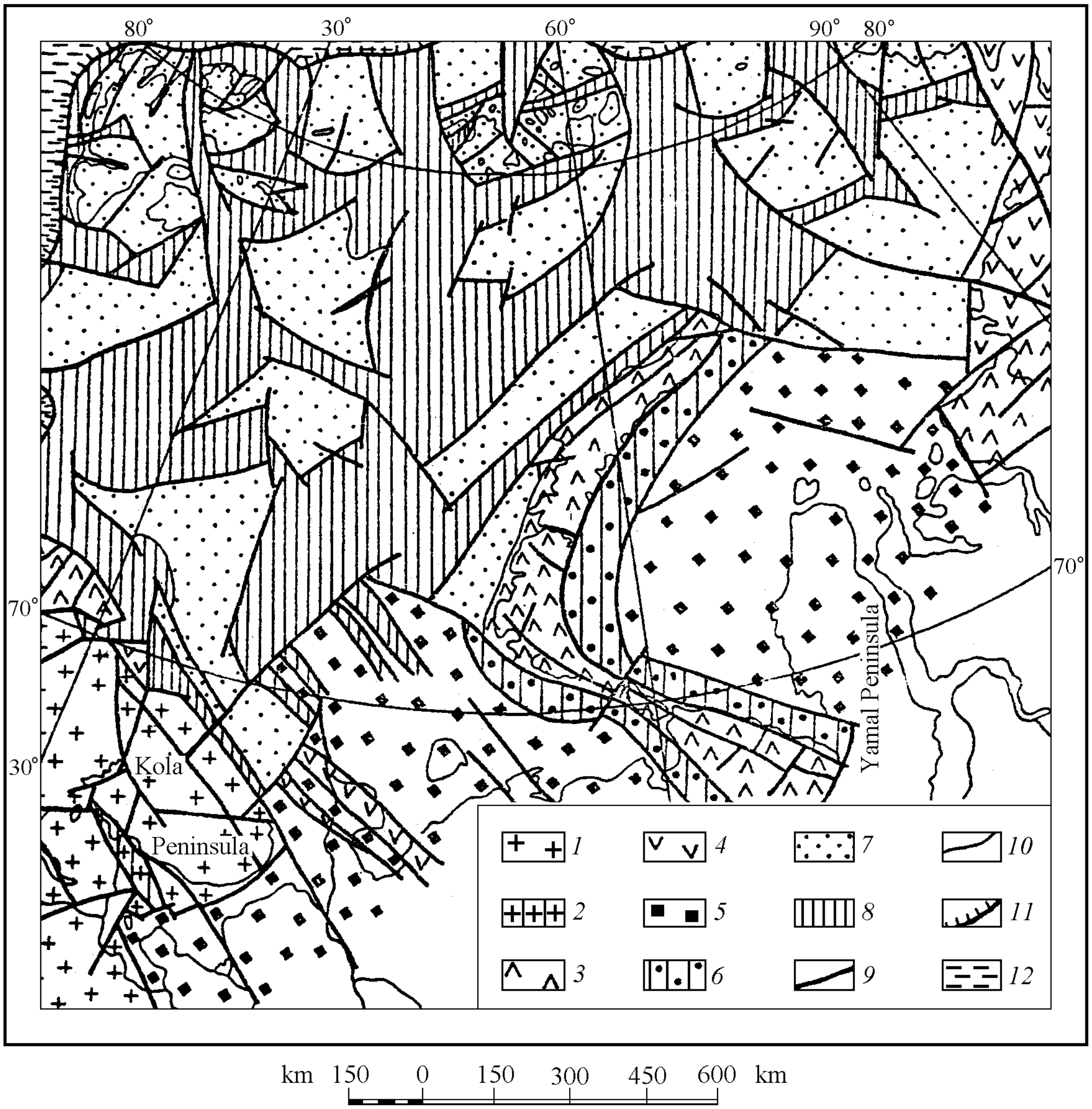

Figure 23. Neotectonic map of the Barents–Kara region.
1 – crystalline shields; 2 – graben-shaped troughs in crystalline shields; 3 – post-platform orogenic belts; 4 – outcrops of platform folded basement; 6 – pre-orogenic troughs; 7 – rises and knolls of continental-margin platform; 8 – trenches and troughs in continental-margin platform; 9 – active recent faults; 10 – plicated boundaries of newly formed structures; 11 – flexure-fault zone at the shelf edge; 12 – continental slope.

Kara margin occurred under alternating extension and compression conditions and terminated by the general subsidence during the Pliocene–Pleistocene.

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References

Aksenov, A. A., Dunaev, N. N., Ionin, A. S., et al., *Eurasian Arctic Shelf in Late Quaternary Time,* (in Russian), Nauka, Moscow, 1988.

Antonsen, P., Elverhoi, A., Dypvik, H., and Solheim, A., Shallow Bedrock Geology of the Olga Basin Area, North-Western Barents Sea, *Amer. Ass. Petrol. Geol. Bull., 75,* (7), 1178–1194, 1991.

Armishev, A. M., Borisov, A. V., Bro, E. G., et al., Geologic Structure of the Western Arctic Continental Margin

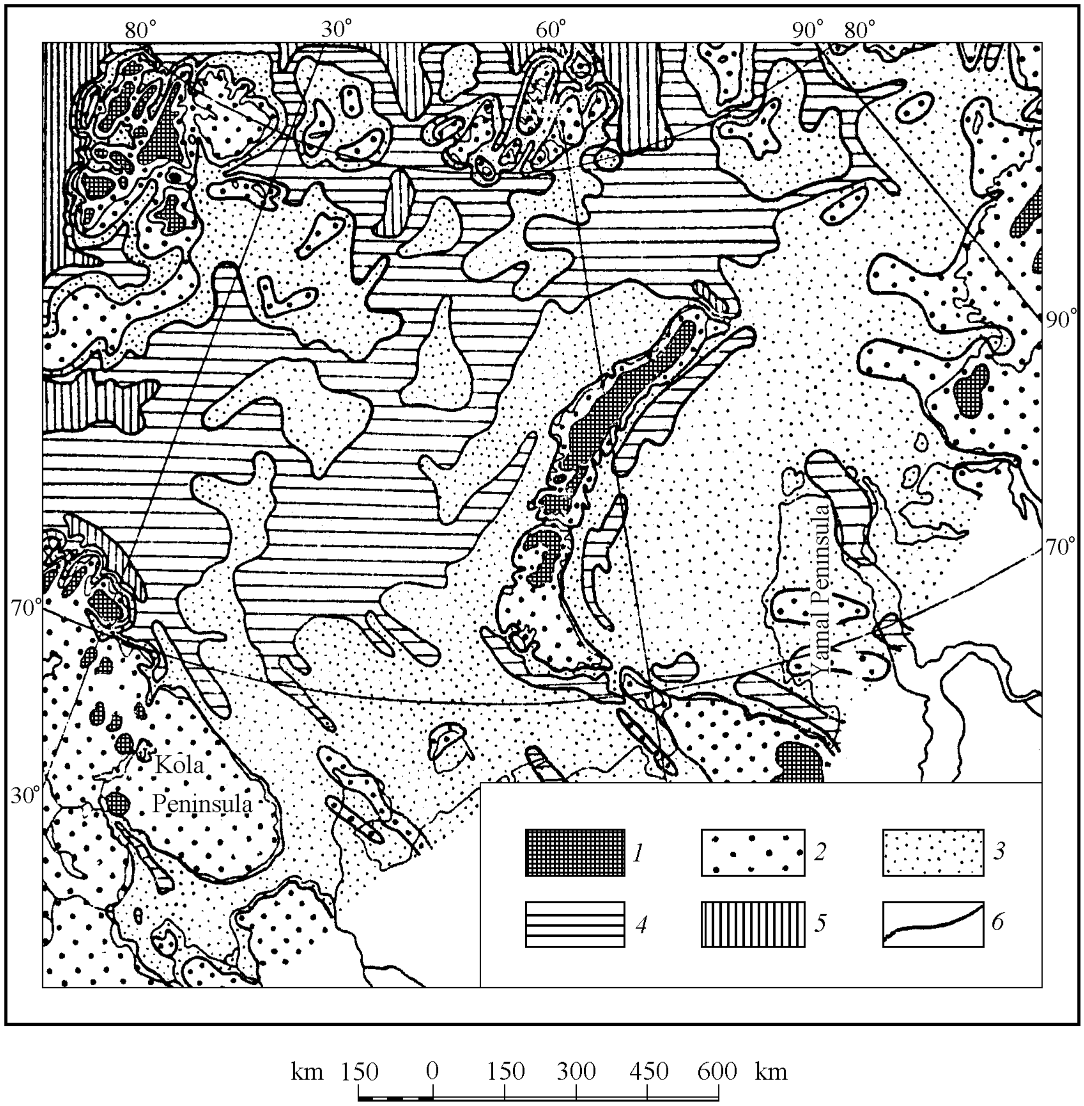

Figure 24. Magnitudes of neotectonic movements in the Barents–Kara region.
1 – > 500 m; 2 – 500 to 0 m; 3 – 0 to −250 m; 4 – −250 to −500 m; 5 – < −500 m; 6 – isobases of recent movements.

from Geophysical and Deep-Drilling Data, in: *Geology of Seas and Oceans, Papers of Soviet Geologists, 28th International Geological Congress,* (in Russian), pp. 195–204, PGO Sevmorgeologiya, Leningrad, 1988.

Avetisov, G. P., *Zones of Seismic Activity in the Arctic Region,* (in Russian), VNIIOkeangeologiya, St. Petersburg, 1996.

Barents Shelf Platform, (in Russian), Ed. I. S. Gramberg, Nedra, Leningrad, 1988.

Baturin, D. G., Structure and Evolution of the Continental Margin of the Eurasian Basin between Spitsbergen and Franz-Josef Land, *Dokl. Akad. Nauk SSSR, 299,* (2), 419–423, 1988.

Cherkis, N. Z., Fleming, H. S., Max, M. D., et al., *Bathymetry of the Barents and Kara Seas,* Naval Research Laboratory, Washington, 1991.

Chochia, N. G., and Evdokimov, S. P., *Late Cenozoic Paleogeography of East Europe and West Siberia,* (in Russian), Mord. Univ., Saransk, 1993.

Danilov, I. D., *Arctic Lithogenesis,* (in Russian), Moscow, 1978.

Druzhinina, N. I., and Musatov, E. E., New Evidence on the Micropaleontology and Seismic Stratigraphy of Bottom Sediments in the Barents Sea, *Geol. Zhurn. Akad. Nauk Ukrainy,* (9), 76–85, 1992.

Dunaev, N. N, Ionin, A. S., Nikiforov, S. L., and Pavlidis, Yu. A., The Structure and Development of Novaya Zemlya Bays in Context of Late Valdaian Glaciation, in:

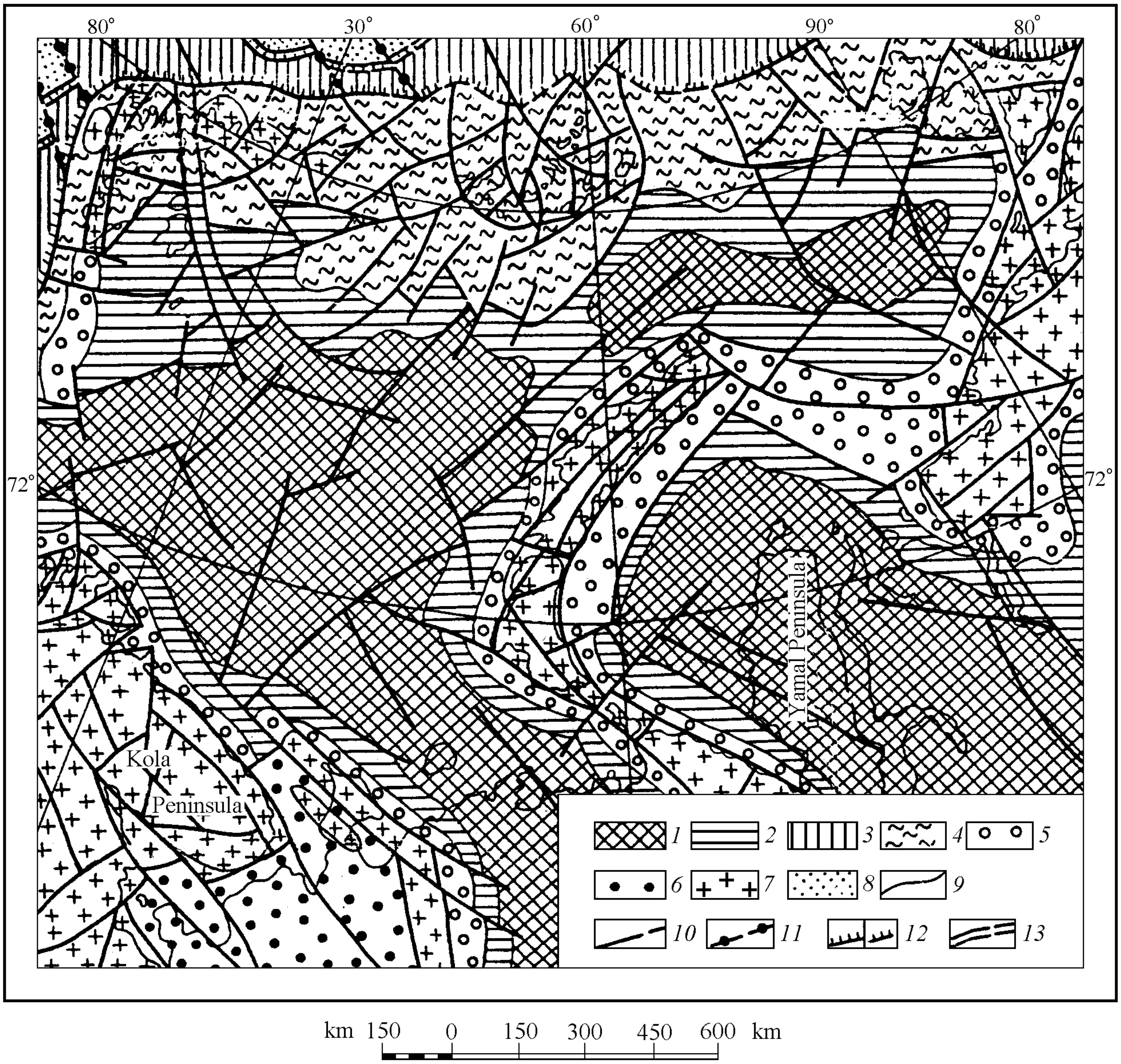

Figure 25. Schematic map of petroleum potential in the Barents–Kara shelf based on the results of neotectonic analysis.
1 – highly promising areas of the neotectonically inherited continental-margin and intracontinental platforms with maximum sedimentary thicknesses; 2 – promising areas of marginal and intracontinental platforms with thick sediments that were moderately lowered during recent time; 3 – promising areas of prograding continental slopes with thick Cenozoic clinoforms; 4 – low-promising areas of the reactivated outer periphery of the continental-margin platform, where differential crustal movements and recent faults might have destroyed hydrocarbon accumulations; 5 – low-promising areas of marginal and intracontinental platforms with thin sediments; 6 – low-promising areas of old platforms unaffected by neotectonics; 7 – nonpromising areas of neotectonically raised shields, orogens, and ridges of platform folded basements; 8 – nonpromising areas of Cenozoic spreading-type oceanic platforms; 9 – boundaries of areas with varying petroleum prospects; 10 – Late Mesozoic–Cenozoic faults controlling hydrocarbon accumulations; 11 – transform faults; 12 – shelf-edge flexure-fault zone (a), same reworked by recent graben-shaped rifts; 13 – contact between the oceanic and the continental crust.

Modern Sedimentation on World Ocean Shelves, (in Russian), pp. 94–103, Nauka, Moscow, 1990.

Eldholm, O., Faleide, J. L., and Myhre, A. M., Continent–Ocean Transition at the Western Barents Sea/Svalbard Continental Margin, *Geology,* (15), 1118–1122, 1987.

Elverhoi, A., and Solheim, A., *Shallow Bedrock Geology and Geophysics of the Barents Sea,* vol. 37, Norsk Polarinstitutt Skrifter, 1987.

Elverhoi, A., and Lauritzen, O., *Berdrock Geology of the Northern Barents Sea (West of 35 degrees) as Inferred from Overlying Quaternary Deposits,* vol. 180, pp. 5–16, Norsk Polarinstitutt Skrifter, 1984.

Elverhoi, A., Antonsen, P., Flood, S. B., Solheim, A., and Vullstad, A. A., *The Physical Environment of the Western Barents Sea, 1: 500 000, Shallow Bedrock Geology, Structure, Litho- and Biostratigraphy,* vol. 179D, Norsk Polarinstitutt Skrifter, 1988.

Geology of the USSR and the Distribution of Mineral Resources, Russian Arctic Seas, vol. 9, (Eds. I. S. Gramberg and Yu. E. Pogrebitskii), Nedra, Leningrad, 1984.

Gramberg, I. S., Shkola, I. V., Bro, E. G., et al., Stratigraphic Wells on Barents and Kara Sea Islands, *Sov. Geol.,* (1), 95–98, 1985.

Gritsenko, I. I., and Krapivner, R. B., Recent Deposits in the Southern Barents Sea Region: Sedimentary Seismic Stratigraphic Units and Their Lithology, in: *Recent Deposits and Paleogeography of Arctic Seas,* (in Russian), pp. 28–45, KF AN SSSR, Apatity, 1989.

Grosvald, M. G., *Continental Shelf Ice Sheets,* (in Russian), Nauka, Moscow, 1983.

Gurevich, V. I. and Musatov, E. E., Recent Sediment Accumulation and Phanerozoic Consedimentation on the West-Arctic Shelf, in: *Problems of the Cenozoic Paleoecology and Paleogeoraphy of Arctic Seas,* (in Russian), pp. 47–53, Nauka, Moscow, 1992.

Gustavsen, F. B., Dypvik, H., and Solheim, A., Shallow Geology of the Northern Barents Sea: Implications for Petroleum Potential, *Amer. Ass. Petrol. Geol. Bull., 81,* (11), 1827–1842, 1997.

Josehans, S. E., Ostisty, B. K., Birkeland, O., et al., Hydrocarbon Potential in the Barents Sea Region: Distribution and Potential, in: *Arctic Geology and Petroleum Potential,* (Eds. T. O. Vorren, et al.), pp. 273–320, Elsevier, Norweg. Petrol. Soc., Amsterdam, 1993.

Knitsen, S. M., Richardsen, G., and Vorren, T. O., Late Miocene–Pleistocene Sequence Stratigraphy and Mass Movements on the Western Barents Sea Margin, in: *Arctic Geology and Petroleum Potential,* (Eds. T. O. Vorren, et al.), pp. 573–606, Elsevier, Norweg. Petrol. Soc., Amsterdam, 1993.

Krapivner, R. B., *Rootless Neotectonic Structures,* (in Russian), Nedra, Moscow, 1986.

Kristoffersen, Y., Milliman, J. D., and Ellis, J. P., *Unconsolidated Sediments and Shallow Structure of the Northern Barents Sea,* vol. 180, pp. 25–39, Norsk Polarinstitutt Skrifter, 1984.

Lopatin, B. G., and Musatov, E. E., Seismic Stratigraphy of Neogene–Quaternary Deposits on the Western Arctic Shelf, *Sov. Geol.,* (6), 56–61, 1992.

Map of Neotectonics of North Eurasia, 1:5 000 000, 12 sheets and Explanatory Notes, (Chief Editor A. F. Grachev), (in Russian), OIFZ RAN, Moscow, 1998.

Matishov, G. G., *Evolution Approach to the Study of Arctic Marine Ecosystems (with Reference to the Barents Sea),* (in Russian), KNTs AN SSSR, Apatity, 1988.

Matishov, G. G., Cherkis, N. Z., Vermillion, M. S., and Forman, S. L., *Bathymetric Map of the Franz-Josef Land Area,* Sheet 1, Boulder, Colorado, Geol. Soc. Amer., 1995.

Musatov, E. E., Distribution of Cenozoic Sediments on the Barents Sea Shelf between Spitsbergen and Franz-Josef Land, *Okeanologiya, 36,* (3), 444–450, 1996.

Musatov, E. E., Recent Tectonics of Arctic Continental Margins, *Fizika Zemli,* (12), 72–78, 1996

Musatov, E. E., The Geomorphology of the Northern Barents Sea Shelf Margin between Spitsbergen and Franz-Josef Land, *Geomorfologiya,* (1), 43–51, 1997.

Musatov, E. E., Neotectonic Indications of Petroleum Potential in the Barents–Kara Shelf, *Izv. VUZov. Geologiya i Razvedka,* (3), 43–51, 1997.

Musatov, E. E., and Musatov, Yu. E., On the Origin of Fjords with Reference to the Western Arctic Region, *Byul. MOIP. Otd. Geol., 67,* iss. 3, 28–33, 1992.

Onishchenko, S. V., and Bondarev, V. N., Stratigraphy and Paleogeographic Patterns of the Pechora Shallow Marine Sequences, in: *Quaternary Paleoecology and Paleogeography of the Arctic Seas,* (in Russian), pp. 142–150, Nauka, Moscow, 1988.

Pavlidis, Yu. A., *World Ocean Shelf in Late Quaternary Time,* (in Russian), Nauka, Moscow, 1992.

Pogrebitskii, Yu. E., Arctic Ocean Opening and Associated Geologic Processes on the Surrounding Continents, *Reg. Geol. i Metallogeniya,* (7), 129–136, 1997.

Samoilovich, Yu. G., Kagan, L. Ya., and Ivanova, l. V., *Quaternary Deposits of the Barents Sea,* (in Russian), KNTs RAN, Apatity, 1993.

Senin, B. V., Shipilov, E. V., and Yunov, A. Yu., *Tectonics of the Arctic Ocean–Continent Transition Zone,* (in Russian), Murm. Kn. Izd., Murmansk, 1989.

Shipelkevich, Yu. V., et al., *Atlas of East Barents Shelf Geology,* VNIIOkeangeologiya, St. Petersburg, 1994.

Skagen, J. I., Effect on Hydrocarbon Potential Caused by Tertiary Uplift and Erosion in the Barents Sea, in: *Arctic Geology and Petroleum Potential,* (Eds. T. O. Vorren, et al.), pp. 711–719, Elsevier, Norweg. Petrol. Soc., Amsterdam, 1993.

Solheim, A., and Kristoffersen, Y., *Sediments above the Upper Regional Unconformity: Thickness, Seismic Stratigraphy and Outline of Glacial History,* vol. 179D, pp. 3–36, Norsk Polarinstitutt Skrifter, 1984.

Solheim, A., Russwurm, L., Elverhoi, A., and Berg, M. N., Glacial Geomorphic Features in the Northern Barents Sea: Direct Evidence for Grounded Ice and Implications for the Pattern of Deglaciation and Late Glacial Sedimentation, in: *Glaciomarine Environments: Processes and Sediments,* (Eds. J. A. Dowdeswell and J. D. Scource), Geol Soc. London Spec. Publ. 53, pp. 253–268, 1990.

Spiridonov, M. A., Devdariani, N. A., Kalinin, A. V., et al., *Sov. Geologiya,* (4), 43–55, 1980.

The Geology of Franz-Josef Land and the Northernmost Barents Sea, (Co-eds. A. Solheim, E. Musatov, and

N. Heintz), Norsk Polarinstitutt Meddelelser, 1998 (in press).

Ustritskii, V. I., On the Geotectonic Origin of Lomonosov Ridge, *Geotektonika,* (1), 77–89, 1990.

Verba, M. L., Pavlenkin, A. D., and Tulina, Yu. V., Crustal Structure under the Barents Sea Shelf, in: *Geological and Geophysical Investigations in the World Ocean,* (in Russian), pp. 40–46, PGO Sevmorgeologiya, Leningrad, 1987.

Vorren, T. O., Hald, M., and Lebesbue, E., Late Cenozoic Environments in the Barents Sea, *Paleogeography, 3,* (5), 601–612, 1988.

Yakhimovich, V. L., and Zarkhidze, V. S., *Neogene Stratigraphy of the Timan–Ural Region,* (in Russian), IG BNTs UrO AN SSSR and VUChK, Ufa, 1990.

Zarkhidze, V. S., and Musatov, E. E., Major Stages in the Late Cenozoic Paleogeographic Evolution of the Western Arctic Region, in: *Predictive Evaluation of Mineral Resources in the Nearsurface Formations of West Siberia and the Urals,* (in Russian), pp. 123–140, ZapSibNIGNI, Tyumen, 1989.

Zarkhidze, V. S., Musatov, E. E., and Generalov, P. P., Norwegian, Barents and Kara Seas: Cenozoic, in: *Paleogeographic Atlas of the Shelf Regions of Eurasia for the Mesozoic and Cenozoic,* vol. 2, pp. 1318–1335, (Eds. M. N. Alekseev, I. S. Gramberg, and Yu. M. Pushcharovsky), G. B. Robertson Group Publ., 1991

Zarkhidze, V. S., Fulton, R. G., Mudie, P. J., et al., *Circumpolar Map of Quaternary Deposits of the Arctic,* Map 1818A, Sheet 1, Geol. Surv. Canada, 1991.

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