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GEOLOGY

Deep-Water Glacial Plow Marks in the Western Margin of the Barents Sea

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Abstract—Data obtained from high-resolution multibeam echo sounding during the 26th cruise of R/V *Akademik Nikolai Strakhov*, maps of the Western Arctic bathymetry, the glaciomorphological characteristics of the last Eurasian Ice Sheet, and isobases of the seafloor uplift have been used for multi-layered cartographic compilation on the western margin of the Barents Sea shelf. Glacial plow marks at depths of 350–400 m were identified on the basis of detailed bathymetry data collected in the transition zone. The glacial plow marks are relict and correspond to the lines of the ice flow of the ancient Eurasian sheet. The seafloor relief, the position of the outlet paths of surges, and the thickness of the shelf glacier morphologically determine the orientation and depth of the plow marks.

Keywords: multibeam echo sounding, glacial plow marks, Eurasian Ice Sheet, ice flow lines

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Traces of plowing of the deep-sea floor by the lower parts (keels) of shelf glaciers or icebergs remain in the form of glacial plow marks, exaration scour marks, which are widespread in the areas of ancient glaciation. These traces are ditches with a rectilinear, winding, and sometimes, spiral shape. Their length can reach many kilometers, ranging from 200 to 300 m or more in width and exceeding 10 m in depth. They are usually encountered on the shelves with a seafloor depth of about 200 m. At the same time, in both the southern and northern hemispheres, there are cases known when the exaration scour marks are located at significantly greater depths. For example, on Chatham Rise, east of New Zealand, scour marks were established [13] at depths of 450–470 m; in the North Falkland Basin [9], they were observed at depths of 280–470 m. In the Arctic, plow marks were established [8] at a depth of 1200 m on the flat-topped Hovgaard Ridge, which is located south of Fram Strait between 78°45′N and 78°5′N. We consider that these plow marks were formed by icebergs with a keel depth of up to 1090 m.

During the 26th cruise of R/V *Akademik Nikolai Strakhov* (Geological Institute, Russian Academy of Sciences, 2009), multibeam echo sounding (MBES) was conducted in the ocean–continent transition zone from the deep abyssal depths to the shelf depths in the western margin of the Barents Sea, southwest of the Spitsbergen archipelago in the trough mouth of Stur-Fjord (Fig. 1). The MBES results presented, selected for this work, indicate the distinct northeast-striking plow marks located at depths ranging from 330 to 400 m. It is known [6] that the modern iceberg draft in the Barents Sea is up to 137 m, and a maximum draft of 180 m was registered in the Franz Josef Land archipelago (FJL). According to the data obtained during of the 38th cruise of R/V *Akademik Nikolai Strakhov* (Shirhov Institute of Oceanology, Russian Academy of Sceinces; Geological Institute, Russian Academy of Sciences, 2018), the tracing of plow marks in the central part of the Barents Sea shelf ceases at depths of 205 m.

The morphology of the plow marks, demonstrated in Fig. 1, was interpreted in [5] as an object of tectonic origin. This hypothesis was based on the presence of an uncompensated isostatic loading in the zone of avalanche sedimentation behind the shelf edge. This isostatic loading led to vertical movements of the crystalline substrate and resulted in the formation of the observed fracturing. Analysis of the geophysical data showed that there are no similar structures in the seafloor relief in the analogous boundary maximums of isostasy in other transition zones located outside the zone of the recent glacier development.

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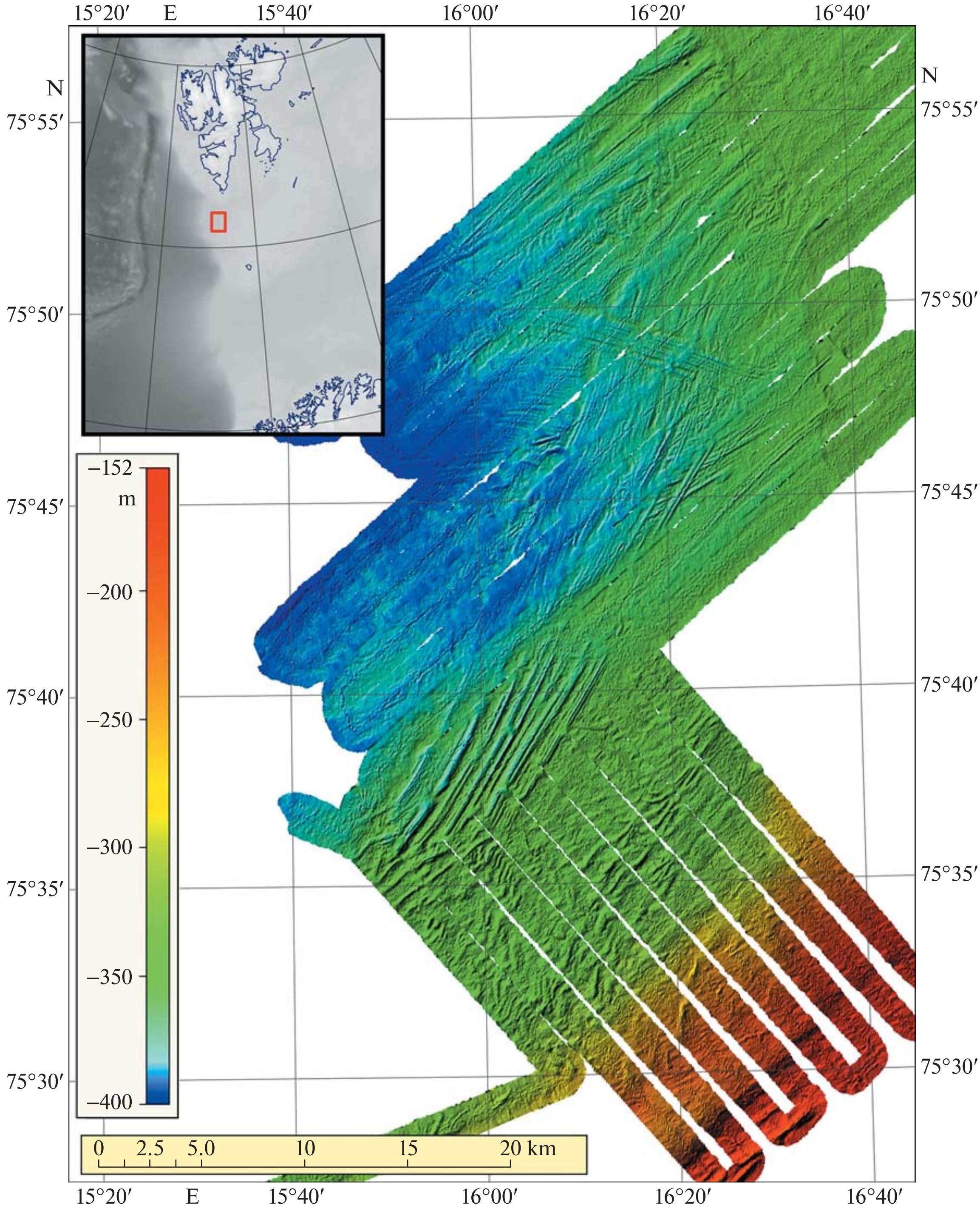

Fig. 1. The shaded relief of the seafloor at the mouth of the Stur-Fjord trough according to data obtained from multibeam echo sounding during the 26th cruise of R/V *Akademik Nikolai Strakhov* (Geological Institute, Russian Academy of Sciences, 2009). The location of the polygon in the western margin of the Barents Sea is shown in the inset.

It is most likely that these objects are mega-scale ice plow marks (mega-scale glacial lineation) [2]. Such landforms are established in many areas of the Antarctic and Norwegian shelves. They are associated with the rapid advance of the part of the ice cover or dome with an increased velocity (surge, ice flow). These subglacial landforms are straight-lined with considerable length (up to the maximum length of 37 km), but usually 80% of plow marks are less than 9 km in length.

According to the data summarized in [6], the glacial plow marks, the depths of which are more than

200 m at the seafloor of the Barents Sea and its margins, are relict. They may have been formed not by individual modern icebergs, produced on the FJL and Spitsbergen archipelagos, but by powerful shelf glaciers during the glaciation epochs, at the minimum sea level in relation to the modern level (about −100 m).

The origin of the identified plow marks (Fig. 1) can be rationally interpretated by comparing their spatial position with the glaciomorphological data of the last glaciation in the area.

Compilation of the glaciomorphological data with the relief of the Barents Sea shelf and its margins is demonstrated on a map (Fig. 2). To compile the map, we used the topographic materials according to [7], the relief of the last Pan-Arctic Ice Sheet (PAIS) according to [3], and the isobases of the isostatic uplift of the Earth's crust in the northwestern part of the Barents Shelf over the last 6500 years according to [11].

The southern boundary of the last glacial sheet of Northern Eurasia [2, 4] has been indicated by the formations of glacial-dammed lakes and ancient marginal valleys (Fig. 3). This boundary stretched from southwestern Ireland through the Irish Sea and North Sea to Central Europe, then across the Russian Plain and Western Siberia to the northeastern edge of Taimyr. In northwestern Europe, the boundary of this sheet either coincided with the external edges of the Hebrides, North Sea, and Norwegian shelves or descended to the neighboring continental slopes. According to materials from Knipovich Polar Branch of the Russian Federal Institute of Fisheries and Oceanography and Norwegian studies [10, 14], the western edge of the Barents–Kara part of the ice sheet between Northern Norway and Spitsbergen also reached the shelf edge. There is very little direct data on the northern boundary of the ice sheet. It is known [4] that the troughs of the northern part of the Barents–Kara shelf dissect it to the very edge and extend to the continental slope. The zones of marginal shallows are morphologically similar to moraine banks of the Norwegian shelf and Medvezhinskaya bank, as well as to the banks on the submarine plateau to the north of Spitsbergen.

Similar submarine plateaus are also common north of Belyi Island, Victoria Island, Franz Josef Land, Vise Island, and Severnaya Zemlya. Moraine–ridge relief is typical on the banks of all glacial shelves (Antarctic, Norwegian, Icelandic, North Sea, and others) [3]. Within the aforementioned boundaries (Fig. 3), the glacial sheet of Northern Eurasia had an area of 8 370 000 km^2, a half of which (4 150 000 km^2) corresponded to the modern shelves, including 170000 km^2 to the Hebrides and the Irish Sea, 460 000 km^2 to the North Sea, 160000 km^2 to the Norwegian Sea, 1810000 km^2 to the Barents Sea, and 880 000 km^2 to the Kara shelf [3, 4].

The isohypses of the surface of the ancient ice sheet (Fig. 2) were plotted taking into consideration the relief of the modern Antarctic and Greenland ice sheets. On the maps of these modern ice sheets, there were areas where combinations of the morphological features of ice covers, the directions of ice motion, and the relief of the seafloor were similar to the same characteristics of the reconstructed ice sheets and ice streams. This technique provided a reliable image of the slopes of the ancient glacial sheet. The basic elements of the Eurasian Ice Sheet were the British, Scandinavian, Barents, and Kara ice sheets, with elevations of 1900, 3000, 2450, and 2400 m, respectively. The Svalbard dome, about 2100 m high, was distinguished within the Barents sheet (Fig. 2).

The British, Scandinavian, and Barents sheets were separated by wide saddles (600 and 1500 km), the watersheds of which did not descend lower than 1300–1500 m. The saddle between the Barents and Kara sheets had an elevation of 2000 m. The latter two sheets overlapped the same shelf and can be considered as a single Barents–Kara subsheet. The centers of the glacial sheets of Northern Eurasia were located above the lowlands or modern seas, and the bed beneath them had a concave shape (Fig. 3). This concavity was most clearly manifested in the beds of the Scandinavian, Barents, and Kara sheets. The main saddles occurred on the continuation of troughs of the largest ice streams— Medvezhinskaya, Franz Victoria, and St. Anne (Figs. 2, 3).

The map of the relief of the Eurasian Ice Sheet allowed us to reconstruct the thickness of its ice. For this purpose, the elevations of the bed, taken from the map of the modern Eurasian relief, were subtracted from the elevations of the cover surface. Corrections for the glacioisostatic deflection of the Earth's crust were introduced into the values obtained in this way. When determining these corrections, the isostatic approach was used. According to this estimation, the value of this deflection is proportional to the thickness of the ice cover and to the ratio of the ice density (0.88 g/cm^3) and the asthenosphere substance of the Earth (3.3 g/cm^3). Accordingly, the differences obtained increased by 33%, or 25% of the thickness of the reconstructed cover.

The measurements and calculations [1] showed that the Eurasian Ice Sheet had a volume of 14 million km^3 with the Scandinavian sheet accounting for 6.1 million km^3, i.e., less than half. The Barents and Kara ice sheets contained 4 and 2.4 million km^3 of ice, respectively, and more than 7 million km^3 of ice was accumulated on all the sheets of Northern Eurasia [2]. According to the same measurements, the average thickness was 1400 m for the British sheet, 1870 m for the Barents sheet, and 1500 m for the Kara sheet. The isostatic deflection beneath them was 400–600 m, the average shelf depths increased to 700–900 m, and

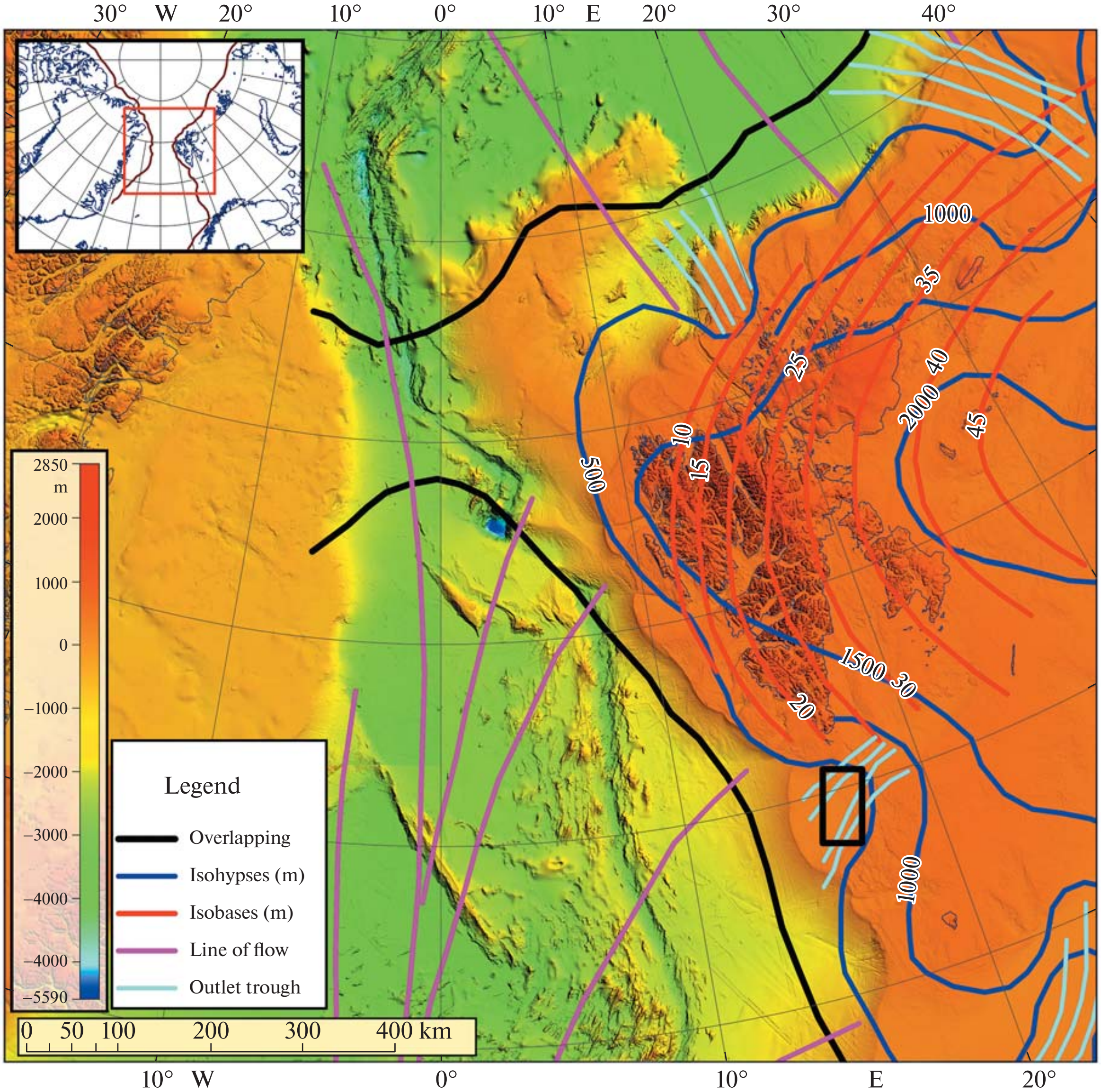

Fig. 2. The scheme of the characteristics of the ice sheet in the northwestern part of the Barents Sea. A black square shows the polygon of the detailed bathymetric survey of the 26th cruise of R/V *Akademik Nikolai Strakhov* (Fig. 1). The seafloor relief is shown according to the data of the International Bathymetric Chart of the Arctic Ocean 4.0 (IBCAO 4.0). The lines show the overlapping of the ice sheet on the trough bed (black); isohypses of the surface of the Pan-Arctic Ice Sheet (PAIS) (blue); isobases (red); lines of the surface ice flow of the ancient shelf glacier (pink); and lines of the ice flow of the outlet glacier in the PAIS area of the subglacial trough (turquoise). The location of the basic plot of the map in the Arctic is shown in the inset.

their areas increased significantly (by 1.7 million km^2) by means of coastal lowlands.

From the above calculations, the following statements hold.

(1) About 70% of the bed of the Eurasian Ice Sheet was submerged below sea level. This ice sheet should be considered as predominantly “marine.”

(2) More than half of the ice sheet mass, or 8–9 million km^3 of ice, was in a state of structural instability. This mass of ice could reach stationarity only if the ice streams of this cover were dammed by floating glaciers—shelves of an inner type.

(3) In the northern and western parts, the ice cover did not end with cliffs, coinciding with the shelf edges, but transited into floating glaciers—shelves of the Arctic and North European (Norwegian–Greenland) basins [3]. These glaciers, during their transition from the covering to the floating state, formed plow marks (Fig. 1), which were located deeper than 200–250 m and had a relict origin. The plow marks are located in the area of outlet troughs, and their orientation coin-

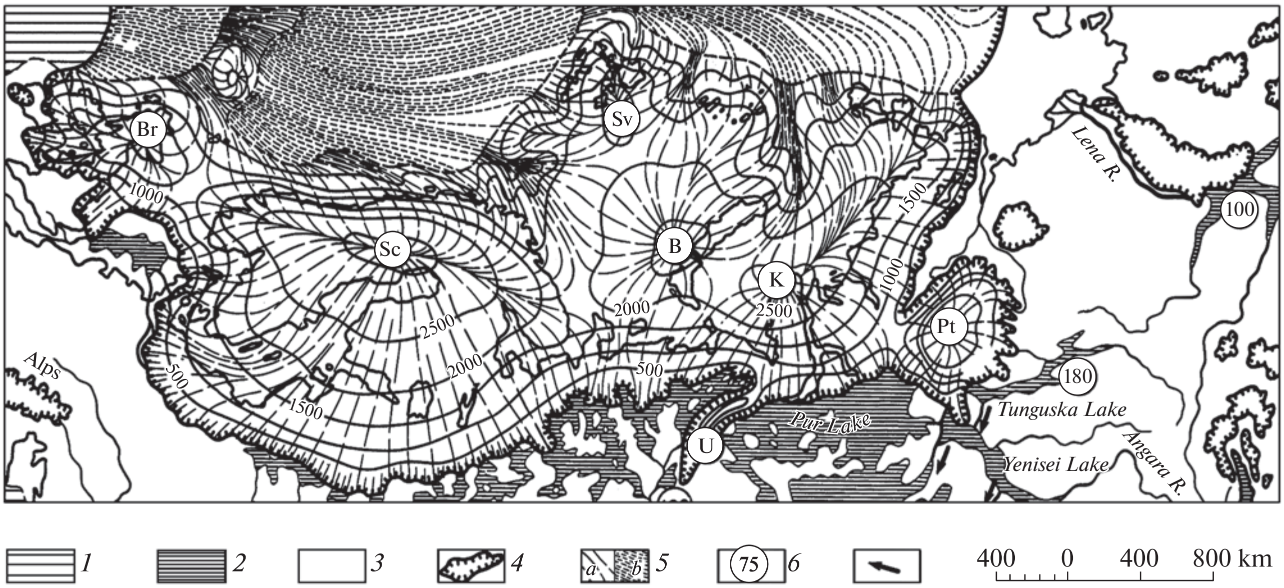

Fig. 3. The last Eurasian Ice Sheet (according to [2], with modifications). (1) Glacier-free ocean, (2) freshwater basins, (3) ice-free land, (4) glacier boundaries; (5) lines of motion of glaciers: overlapping (a) on the bed and (b) floating, (6) levels of intracontinental basins (relative to the modern ocean), (7) runoff of glacial waters. Glacial sheets: Br, British; Sc, Scandinavian; B, Barents with Svalbard Dome (Sv); K, Kara; Pt, Putorana.

cides with the reconstructed flow lines of glaciers (Fig. 2).

Waning of the last ice sheet began about 13 ka BP. It was followed by deglaciation of the Norwegian shelf, which ended at 11 ka BP. By the same time, surges (dramatic increases in the velocity) of ice flows in the western segment of the Barents Ice Sheet should have begun. It is likely that the deep-water bays had already cut into the sheet edge by the Late Dryas and, thereby, cleared ice from the lower segments of the troughs of the western Barents Sea shelf and the fjords of Spitsbergen. This segment began to lose mass rapidly, and the saddles between the Scandinavian, Barents, and Svalbard sheets began to descend [3]. Around 9000 BP, the northern ice flows also became more active. Their surges were followed by deglaciation of the remaining troughs, including the Franz-Victoria, St. Anne, and Voronin troughs. As a result, the Barents–Kara subcontinent was dissected into a system of fragments, the mechanical instability of which resulted in new surges. Following this, the basic areas of the Barents–Kara shelf were cleared of ice. The residual ice sheets remained for some time only in the Kola and Medvezhinskaya banks, over the Spitsbergen and other Arctic archipelagos.

Not all stages of the destruction of the Eurasian Ice Sheet have been dated reliably; however, it is now clear that the disintegration of its "marine" parts was not simultaneous, but occurred during several stages and continued over 6000 years, beginning on the North Sea shelf 14–13 ka BP and ending on the Barents–Kara shelf later than 9 ka BP.

Due to the fact that the main factor preventing surges of the "marine" parts of the ice sheet was the dammed effect of floating glaciers–shelves, we can conclude that the stage-by-stage deglaciation directly reflects the chronological sequence of the destruction of the glaciers–shelves, which was accompanied by the formation of the specific deep-water plow marks. The southern part of the North European glacier–shelf disappeared about 14 ka BP and its northern part, about 12 ka BP, while disintegration of the glacier–shelf of the Arctic Basin occurred 9.5–9 ka BP [3].

In mapping the seafloor relief during the 26th cruise of R/V *Akademik Nikolai Strakhov*, we obtained MBES data (Fig. 1) with the seafloor plow marks coinciding with glaciomorphological reconstructions of the surface lines of the ice flow in the western margin of the last Eurasian Ice Sheet (Fig. 2), which were initiated by the deglaciation of shelf glaciers described above. On the basis of the MBES data, obtained in the area of the western margin of the Barents Sea, and the maps of relief of the last Pan-Arctic Ice Sheet and its Eurasian part, we built a multilayer compilation of the data of the seafloor relief with the plow marks and the surface lines of the cover ice flow that agree well with them (Fig. 2). The site studied is located near the line where the glacial sheet overlaps the bed and ice of the outlet glacier transits to floating, forming the ancient Arctic shelf glacier.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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