

# "Submerged Shorelines" on Glaciated Continental Shelves: Solving the Puzzle?

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## ABSTRACT

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A hypothesis is proposed which has been based upon an analysis of physical processes operating at the grounding line of the Ross Ice Shelf, Antarctica. It suggests that the submarine terrace-shaped benches of glaciated shelves were formed at the grounding lines of the Pleistocene marine ice sheets, well below the former sea levels. Consequently, present-day depths of the benches cannot indicate the sea levels of the past.

**ADDITIONAL INDEX WORDS:** *Submarine terraces, ice shelves, grounding line, tidal pump, glacial erosion, marine ice sheet, glacioeustasy, sea level changes.*

## INTRODUCTION

Submarine terrace-shaped benches that broadly occur on the continental shelves and continental slopes of the world keep attracting interest of geologists and oceanographers who believe that the depths and ages of the landforms may give insight into the history of sea level changes and vertical movements of the earth's crust. Such benches are characteristic of all shelves and slopes, they are known on both "normal" and glaciated continental shelves being everywhere considered as features of the same origin. The latter, however, has never been proved and seems extremely doubtful.

While the submarine benches of "normal" shelves, e.g. those of Caribbean islands, are real wave-cut platforms formed during sea level lowerings caused by former glaciations (which was extensively confirmed by uniformity of their depths as well as by numerous finds of submerged subaerial materials on the platforms and by their age determinations), the origin of similar features occurring on glaciated shelves and adjacent continental slopes contin-

ues to be a puzzling problem. In this context, the problem of origin of the former and latter benches must be treated separately. In fact, this separation should be the starting point of the present analysis.

There is little doubt that all submarine benches of "normal" shelves were worked out by waves at the ancient shores during glacioeustatic lowerings of sea level, but we must leave this out and focus on similar benches of glaciated shelves which are our subject. Practically all high-latitude shelves of both Northern and Southern Hemispheres fall into this latter group. As it was pointed out, the benches of glaciated shelves were also regarded as former shorelines that became submerged by the postglacial glacioeustatic transgression of the ocean. On the other hand, nearly all the shelves in question were definitely inaccessible for wave erosion and other subaerial geomorphological processes during cold epochs of the Pleistocene, in particular during Weichselian, or Wisconsinan time, since they were covered by extensive ice sheets and downwarped by ice loads. Hence, it is hard to believe that the glaciated shelves could bear any traces of ice-age or preglacial sea levels, so that for the terrace-like benches of the shelves one must look for some more appropriate, and non-controversial, explanation.

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## PRESENT STATE OF THE PROBLEM, HISTORY OF RESEARCH

Judging by publications, the submarine terraces and similar forms of the sea bottom have been most extensively studied in the North Atlantic region and adjacent parts of the Arctic Ocean. The discovery of the terraces is traditionally connected to works by NANSEN (1904, 1924), although, to the best of my knowledge, the earlier paper on the subject (describing submerged benches of the submarine outskirts of the British Isles) dated back to the last decade of XIX century (HULL, 1898).

As for Soviet students of the problem, the earliest and most significant contribution was made by KLIONOVA (1938, 1948, 1960). Various aspects of the submarine-bench problem were examined and discussed by SAKS (1953), LISITSYN and USINTSEV (1953), VINOGRADOVA *et al.* (1959), KULIKOV and MARTYNOV (1961), GRABOVSKY (1968), RVACHEV (1968), STRELKOV (1968), SHCHUKIN (1969), LINDBERG (1972), MATISHOV (1972), MYSLIVETS (1973), KOTENIOV *et al.* (1976). Also, a number of foreign publications on the problem should be considered, and among them the papers by RIGG (1960), STANLEY *et al.* (1968) and FILLON *et al.* (1978).

The above authors presented data on areal extent and depths of terrace-shaped benches occurring in the North, Norwegian, Greenland, Barents, Kara and Labrador Seas. Judging from available information, the landforms are broadly developed within a considerable range of depths—from moderate (less than 200 m) and significant (400 to 600 m) down to quite great (1500 m and deeper). In particular, according to RVACHEV (1968), seven submarine benches occur on the western edge of the Barents continental shelf in the vicinity of Bjornoya, having depths ranging from 50-70 m to 320-330 and 370-380 m, while on the bottoms of Bjornoyrenna and Sorkapprenna their depths reach 450-510 m. For the island shelf of Newfoundland Rvachev pointed out submarine benches with depths of 260-280 m, 290-330 m and 350-380 m. According to FILLON *et al.* (1978), such landforms off the shores of the northern Labrador Peninsula occur at the depths of 130 to 400 m, some of them being tilted due north.

Detailed surveys by KOTENIOV *et al.* (1976) have confirmed that a set of pronounced sub-

marine benches exist in the vicinity of Bjornoya; their soundings yielded depths of 70-80 m, 160-200 m and 250-350 m. The benches, 5 to 50 km wide, are separated from one another by several (at least two) parallel submarine moraine belts that extend continuously between the shores of northern Norway and Sorkapp, Svalbard, along the western margin of the Barents shelf (Figure 1). Individual morainic ridges of the belts are up to 40 or 50 km long, their sides slope very gently, and widths (2 to 8 km) are strikingly large relative to heights (10 to 15, sometimes 30 to 50 m). The ridges are built up chiefly by aquatic till. The outermost morainic belt appears to be a direct extension of the Egga moraine of the Norwegian shelf and, like the Egga, likely was formed during the late Weichselian glaciation. As for the outermost benches, they have been worked out in the continental slope making its profile stepped. Such shape of profile is characteristic of the Norwegian continental slope too: according to KOTENIOV *et al.*, the slope profile has been complicated by benches, having average widths of 5 km, at the depths of 350-300 m, 600-800 m, 1150-1300 m, and 1650-1800 m.

Geographical position of the most pronounced submarine terrace-shaped benches in the Eurasian Arctic was shown on the "Map of Quaternary Deposits of the Arctic and Sub-Arctic" (1965). There, and in the majority of other places, "submarine terraces" were identified on the basis of purely morphological evidence, though in a few sites their occurrence was also confirmed by specific data on the lithology of bottom sediments associated with the benches.

Several hypotheses were advanced in order to account for the origin of the submarine forms: the eustatic, neotectonic, and "astronomic", as well as certain explanations based on their different combinations. Klionova who paid particular attention to submarine benches of the Barents continental shelf adhered to the first hypothesis, being sure that the benches had been formed during the planetary sea-level lowerings of the Pleistocene ice ages: "The occurrence of two main submarine terraces on the floor of the Barents Sea should be considered as a reflection of two latest glaciations of the Pleistocene whose traces are so clearly imprinted upon landscapes of the Russian Plain", she wrote in 1938 (p. 78). Klionova believed that the upper terrace having the depth of 60-70 m

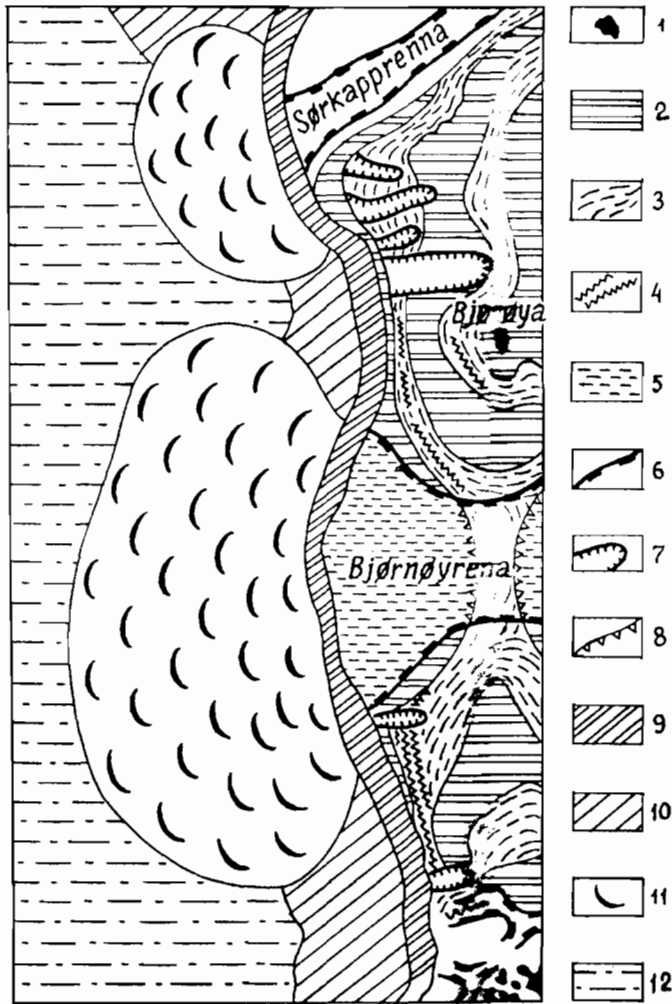


Figure 1. Submarine geomorphic features, western margin of the Barents continental shelf and adjacent continental slope. Simplified after Koteniov *et al.*, 1976. Legend: (1) land; (2) submarine terrace-shaped benches; (3) seabed zones of ridge-and-hill topography; (4) individual morainic ridges; (5) surface of marine and glaciomarine deposition within submarine troughs; (6) outline of trough bottom; (7) smaller troughs; (8) boundaries of largest riegels; (9) continental slope; (10) continental rise, upper part; (11) submarine outwash fans; and (12) continental rise, lower part.

was connected with the Valdai, or Weichselian, glaciation, while the deeper one having the depth of about 200 m dated back to the epoch of Dnieper, or Saale, glaciation (KLIONOVA, 1948, 1960).

Klionova's views were shared by SAKS (1953) who, however, deemed more appropriate to associate the two aforementioned benches not with the Valdai and Dnieper glaciations but rather with two—the late and early—stages of

the last (the Valdai) glaciation which he called the Sartan and Zyrianka glacial stades. This (glacioeustatic) concept was further elaborated by STRELKOV (1968) who examined all the available results of hydrographical surveys in the Barents and Kara Seas and concluded that the topography of their floors suggests not two, but three submarine terraces with the depths of 70-100 m, 200-300 m and 400-500 m which he thought proper to associate with the late and

early stades of the Valdai and the main stage of the Dnieper glaciation, respectively.

The glacioeustatic hypothesis remains popular for the North Atlantic shelves till now, and all the evidence attesting to their Weichselian ice-sheet glaciation are practically ignored. For instance, MYSLIVETS *et al.* (1976) hold that two sets of the "submerged shorelines" occurring in the North Atlantic within the depth range of 100-150 m must be connected with the late and early stages of the last glaciation, while the deeper shorelines recorded at the depths of 200-300 m belong to older ice ages, hence are also of glacioeustatic nature and good for calculations of volumetric changes of the world's ocean. Two authors, LASTOCHKIN AND FIODOROV (1978), believe that the Barents and Kara shelves bear several "surfaces of marine accumulation and abrasion" and judge them to be vast submarine terraces which have recorded different stages of former, relatively stable, levels of the Arctic Ocean; they even attempted to date the surfaces by comparing their depth with the curves of eustatic changes in sea level. Meanwhile, according to STANLEY *et al.* (1968), submarine benches of the Nova Scotian shelf occurring at the depths of 145-155 m were worked out during the Illinoian (Saalean) low stand of sea level, whereas similar forms of the same shelf that are at the depth of about 120 m, during another low stand which was associated with Wisconsinan (Weichselian) cold time.

The deepest submarine benches are commonly thought to be of pre-Quaternary age. For instance, FILLON *et al.* (1978) held that the terrace-shaped benches of the North-Labrador continental slope lying as deep as about 400 m had been formed approximately two million years ago. Similarly, RVACHEV (1968) believed that all submarine benches of the North Atlantic with the depths in excess of 200 m must be considered as Pliocene formations; in particular, the benches of such far-away shelves as the Barents and Newfoundland shelves with the same depths of 300-330 m had been formed synchronously, during a hypothetical pre-Quaternary regression of the World's Ocean. In other words, Rvaches, like so many other geologists, adhered to the concept that the benches of glaciated shelves were real coastal terraces which originated at former sea levels and subsequently submerged; hence, he consid-

ered the data on their depths to have been an adequate basis for their long-distance, even trans-oceanic, correlations.

The tectonic hypothesis that explains the submarine forms in question by regional and local crustal subsidence within continental margins has been mostly applied to account for the benches which either lie at exceptionally great depths or have irregular—sloping, undulating or "broken"—longitudinal profiles. This hypothesis was particularly often resorted to by NANSEN (1904), VINOGRADOVA *et al.* (1959), RIGG (1960) and others. Global neo-tectonism was presumed to be a cause of the "submerged shorelines" by LINDBERG (1972), too, who hypothesized about huge worldwide Pleistocene changes in sea level that had resulted from the "geo-hydrocratic processes", *i.e.* changes in volume of the oceanic basins.

Some researchers argue that the submarine benches can be adequately explained only on the basis of an "astronomic" theory, the theory connecting the origin of these forms with changes in the motion parameters of the Earth as a space body. Thus, according to certain calculations by G. D. KHIZANASHVILI (1960) and G. G. KHIZANASHVILI (1963), main levels of marine terraces, both submerged and emerged, have been formed as a result of "skewing" the ocean surface caused by abrupt increases in the tilt of the Earth's axis.

It is necessary to emphasize once more that all the above-mentioned hypotheses, despite their differences, have one feature in common: they all stem from the assumption that the submarine terrace-shaped benches of the discussed North-Atlantic shelves were formed by seawave activity operating at the former sea levels, and the present-day position of the benches relative to sea level is a result of subsequent submergence. However, this assumption looks most implausible now, since the recent research has demonstrated the following (HUGHES *et al.*, 1977; GROSSWALD, 1980, 1983; DENTON and HUGHES, 1981; GROSSWALD and VOZOVIK, 1984):

(a) The North-Atlantic (as well as North-Pacific) continental shelves were repeatedly glaciated by extensive Pleistocene ice sheets, and it seems probable that the ice-sheet margins extended far into adjacent deep basins producing ice shelves in the Arctic Ocean, the

Greenland, Norwegian, Labrador and even Bering Seas;

(b) The latest ice-sheet glaciation of the continental shelves occurred during Weichselian (Wisconsinan) time, reaching its maximum some 17-21 thousand years ago;

(c) The weight of the marine ice sheets was sufficient to depress underlying continental shelves by hundreds meters, *i.e.* by vertical distance that considerably surpassed the range of glacioeustatic lowerings in sea level.

With all this taken into account, it is but logical to conclude that during the eustatic regressions of ice ages the shelves in question were beyond reach of the coastal processes, so that no real marine terraces could form on them. Besides, the shelves underwent glacial erosion, while the adjacent continental slopes were repeatedly buried by the masses of glaciomarine sediments. For this reason, it would be illogical to assume that there are real marine terraces of different ice ages or of pre-glacial age preserved on glaciated shelves or nearby continental slopes. Also the great amplitude of glacioisostatic movements of the North Atlantic continental margins, ensuing from calculations and evidence, invites failure to all the attempts of trans-oceanic correlations of submarine "terraces" based on their depths.

Thus, we have to state that the eustatic hypothesis is not applicable for an explanation of the submarine terrace-shaped benches of the North Atlantic. The same is true of the tectonic and "astronomical" hypotheses: once the glaciated shelves can possibly bear only the terraces formed after the last deglaciation, all the dramatic events suggested by the hypotheses must date from the Holocene, *i.e.* from last 9 to 13 thousand years. But this appears quite improbable since the crustal movements related to internal processes of the Earth take much longer time, and no significant wandering of the poles has been tracked down for the last 90 million years (KERR, 1987). All in all, it seems clear that the whole set of above-mentioned explanations of the North Atlantic submarine terrace-shaped benches is incompatible with the concept of ice-sheet glaciations of the polar continental shelves.

#### ATTEMPT TO SOLVE THE PROBLEM

The new hypothesis explaining the benches has been presented below which does not con-

tradict to the concept of the continental shelves glaciations. Contrary to all other explanation, it suggests direct cause-and-effect relations of the benches to the geomorphological processes operating at the grounding lines of former marine ice sheets.

Grounding lines are the boundaries delimiting the internal (*i.e.* grounded upon bedrock) from the external (*i.e.* floating) parts of marine ice sheets. The latter are the ice sheets that ground on bedrock lying well below sea level, their ice being in energy- and mass-exchange with sea-water masses. Actual positions of the grounding lines result from interactions of several factors, such as sea level, bedrock depth, mass balance and velocity of ice sheet—and they change (advance or retreat) in response to variations of the factors. It is noteworthy that even the tidal fluctuations of sea level cause quite perceptible diurnal displacements of grounding lines, so that attempting to determine their positions one should speak either about zones of their daily migrations or about certain averaged situations. Judging by data of theoretical research, a grounding line of a marine ice sheet can be stable only on a bed, *i.e.* on a shelf or continental slope, which is inclined in a distal (offshore) direction; and the variability of its position is strongly dependent on the angle of bed inclination, decreasing on steep bed and increasing on gentle.

During maximum stages of each of the North Atlantic and North Pacific glaciations, including the last of them, grounding lines of marine ice sheets were positioned on the edges of continental shelves or on upper parts of adjacent slopes. Waning of the ice sheets and eustatic rise in sea level during late glacial periods meant a retreat of the grounding lines—the retreat that always proceeded in a step-by-step way, so that the intervals of abrupt changes alternated with intervals of temporary stabilizations. We may infer therefore that there were several, sometimes many, stages in stabilization of grounding lines, corresponding to a single glaciation, the last glaciation included; that those different positions of grounding lines may range within a rather wide spectrum of depths; and that the difference of ages between extreme members of such spectra may be rather short—not in excess of a few thousand years.

We propose that the terrace-shaped benches of the discussed glaciated shelves and slopes

were formed not by surficial waves at former sea levels, but in submarine-subglacial environments at the temporarily stabilized grounding lines of the marine ice sheets that covered the shelves.

An insight into the mechanisms of formation of the benches was first gained from HUGHES' (1977) discussion of the present-day processes operating on seabed at the junction of the marine West Antarctic Ice Sheet and the floating Ross Ice Shelf. Basing upon a theoretical analysis of the processes, Hughes pointed out (1) that this junction is the boundary at which bed erosion exerted by the grounded ice sheet gives way to glaciomarine deposition; (2) that the water mass underlying the ice shelf in the vicinity of the grounding line consists of two distinct layers—the lower one which is relatively saline and warm and the upper one which is relatively fresh and cold; thus, being stratified, that water mass should be susceptible to formation of internal gravity waves; (3) that the tidal pumping produced by the ice shelf may be considered an adequate generator of the internal waves, and (4) that shoaling of the waves can result in turbulence which, in turn, may lead to bottom-sediment transport and sorting.

Presently, these suggestions were confirmed by the data of physical modeling, laboratory experiments and field observations. In particular, an extensive program of drilling and geophysical research in the Ross Sea, Antarctica, demonstrated that during the Pleistocene expansions of ice the floor of the sea was repeatedly subjected to glacial erosion while after deglaciations it turned into an area of continuous glaciomarine deposition, and that the boundary between the two seabed environments coincided and moved back and forth with the grounding line of the Ross Ice Shelf (DENTON and HUGHES, 1981; KELLOGG *et al.*, 1979). Also, the thermophysical investigations and radio echosounding in Antarctica suggest that basal melting takes place there over considerable areas of the ice sheet, which produces annually, according to ZOTIKOV (1977), rather a great masses of meltwater of which some 30 to 50 km<sup>3</sup> comes out beneath the Antarctic ice shelves. In addition, direct measurements of temperature and salinity distribution in water under the Ross Ice Shelf near the J-9 borehole confirmed the double-layered structure of the

water mass (CLOUGH and HANSEN, 1979; ZOTIKOV *et al.*, 1980), whilst observations on the periodic level fluctuations of that ice shelf proved the operation of tidal pumping (ROBINSON *et al.*, 1974). Reality of internal gravity waves being generated beneath the floating ice shelves is clear from the data of special theoretical and experimental research (CACCIONE and SOUTHARD, 1974; MIROPOL'SKY, 1975, 1977), whilst a layer of winnowed and sorted sand (so called "transitional horizon") which, according to KELLOGG *et al.* (1979), immediately overlies the late Pleistocene lodgement till of the Ross Sea bed being, in turn, overlain by marine silts of the Holocene, suggests rather high efficacy of the submarine reworking of the till surface.

Thus, the proposed hypothesis not only permits to reconcile the fact of occurrence of submarine terrace-shaped forms on the polar continental shelves with the evidence suggesting their ice-sheet glaciations, but also points to a possibility of another explanation of the forms—of considering them as glacier-erosional benches which were also subjected to impact of internal gravity waves. Judging by the depths of the grounding line of the present-day West Antarctic Ice Sheet, such benches could be formed some 500-900 meters below sea level, and in certain cases, *e.g.* in the mouths of subglacial trough-valleys, even much deeper—down to 1200-1800 m. As for the submarine zones of irregular ridge-and-hill topography adjoining to outward margins of the benches, they seem to be the products of glaciomarine deposition which operated on the distal (external) side of the grounding line at the same time as the abutting benches were being formed on the proximal (internal) side of the line (Figure 2). Hence, the typical occurrence of "terrace-staircases" on the polar shelves with the steps lying at wide ranges of depths may suggest not repeated lowerings of sea level during different Pleistocene and pre-Pleistocene glaciations, as it is broadly believed, but rather a step-by-step retreat of grounding lines of former marine ice sheets in the course of a single (most probably the latest) deglaciation hemicycle. Likewise, the other features of submarine benches in question and zones of irregular (morainic) topography, such as their reciprocal parallelism clearly visible in Figure 1, an unusual for land moraines—broad and flat—profiles of sub-

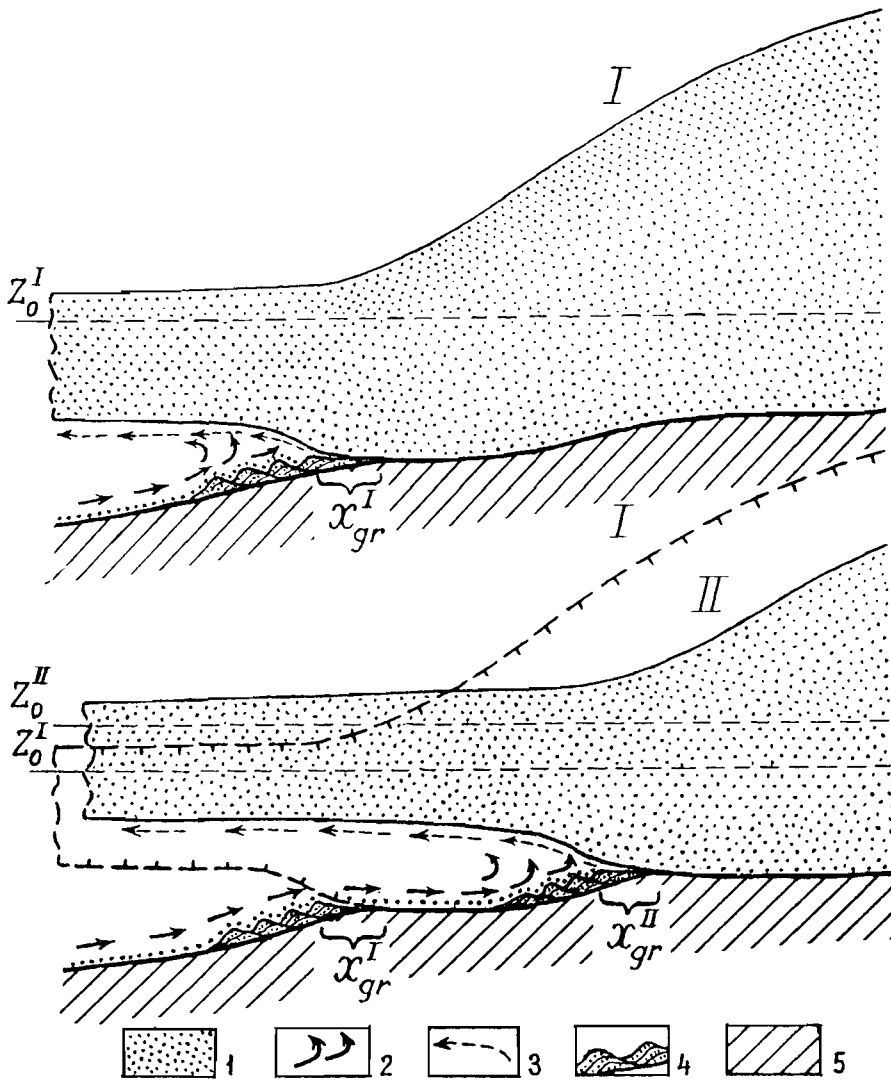


Figure 2. Formation of ice-erosional benches and abutting zones of ridge-and-hill moraines associated with rise in sea level and step-like retreat of an ice shelf grounding line.  $Z_0^I$  and  $Z_0^{II}$ , consecutive positions of sea level;  $X_{gr}^I$  and  $X_{gr}^{II}$ , zones of diurnal migrations of grounding lines; I and II, consecutive stages of ice-sheet retreat. Legend: (1) glacier ice; (2) water circulation beneath the ice shelf (relatively warm and saline water); (3) the same (relatively cold and fresh water); (4) submarine accumulations of glaciomarine sediments; and (5) bedrock.

marine ridges and hills, and geochemical affinity of the sediments the ridges and hills are made up of to the Holocene marine deposits, reported by KOTENIOV *et al.*, (1976), are all in good agreement with the hypothesis suggesting formation of both the beaches and ridge-and-hill zones in submarine and subglacier environ-

ments at the grounding lines of the past ice sheets.

This attempt at solving the puzzle of submarine terrace-shaped benches occurring on polar shelves was first made by the author several years ago (GROSSWALD, 1980), and it is encouraging for the hypothesis that in follow-

ing years some marine geologists arrived independently at the same conclusion (FILLON and HARMES, 1982).

Hence, the depths of the terrace-shaped benches of the polar glaciated shelves provide evidence neither on former sea levels nor on the range of the vertical movements of the Earth's crust. Instead, the forms, being the traces of temporally stable positions of the marine ice sheet grounding lines, shed light on the former geography of the boundary between grounded and floating portions of the ice sheets at different stages of their history. More generally, this all suggest that a specific, the deepest on the Earth, "denudation level" appears to be associated with grounding lines of the marine ice sheets, both former and existing, at which a specific complex of geomorphological processes operated or operate.

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□ RESUMEN □

Se propone una hipótesis basada en el análisis de los procesos físicos que tienen lugar en la línea de base de la plataforma de hielos Ross en la Antártida. A partir de ella se sugiere que las terrazas submarinas de las plataformas glaciares se formaron sobre la línea de base de las placas de hielo marino del Pleistoceno bastante por debajo del nivel del mar primario. Consecuentemente, la profundidad actual de las terrazas no puede indicar el nivel del mar pasado.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ RÉSUMÉ □

On propose une hypothèse basée sur l'analyse des processus physiques qui agissent là où la banquise de Ross, dans l'Antarctique, touche le fond de la mer. Elle suggère que les terrasses sous-marines des plateformes continentales qui ont été englacées se sont formées là où les glaces marines du Pléistocène touchaient le fond, bien en dessous des anciens niveaux de la mer. Aussi, la profondeur actuelle de ces terrasses n'est-elle pas un indicateur des niveaux de la mer dans le passé.—*Roland Paskoff, Université Lumière de Lyon, France.*

□ ZUSAMMENFASSUNG □

Es wird eine Hypothese zur Lösung des Problems der "untergetauchten Küstenlinien" des glazial überformten kontinentalen Schelfes vorgeschlagen. Diese Hypothese beruht auf der Analyse physikalischer Prozesse, die an der Basis des Ross-Ice-Schelfregion der Antarktis wirksam sind. Diese Analysen lassen den Schluß zu, daß die submarinen terrassenförmigen Stufen des glazial überformten Schelfes an der Basis des pleistozänen marinen Eisschildes geformt wurden, und zwar deutlich unterhalb des früheren Meeresspiegels. Konsequenterweise kann die heutige Tiefenlage der Stufen kein Indikator für die Lage des Paläomeeresspiegel sein.—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, F.R.G.*