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# Seismoacoustic studies within Wijdefjorden, Spitsbergen

ABSTRACT: On the ground of results obtained by the seismoacoustic profiling carried out in 1985 and primary examination of core samples the following main seismoacoustic units are distinguished and characterized: unit A — bedrock, unit B — till and/or compacted glaciomarine deposit, unit C — glaciomarine ice-front deposit, unit D — glaciomarine mud. These results enabled to present the distribution of seismoacoustic units along the fiord and its extension on the shelf, as well as to determine a relation of bottom structures to Late Vistulian(?) deglaciation and the action of Holocene tributary glaciers, probably during the Little Ice Age. The position of marginal structures corresponding to local retreat stages of the glacier front is also presented.

Key words: Arctic, Spitsbergen, bottom sediments, geophysics.

## Introduction

Studies of Spitsbergen fiord were improved after application of the seismoacoustic methods. Such investigation in Spitsbergen area have been initiated of the end of the seventies. The seismoacoustic profiles were done in all round the Spitsbergen shelf (Elverhøi *et al.* 1983, Elverhøi and Solheim 1983, 1987) and within fiords, most of all on the west coast especially in the Kongsfjorden and Hornsund (Elverhøi *et al.* 1983, 1987, Elverhøi 1984, Elverhøi and Solheim 1987, Kowalewski *et. al.* 1987).

During the summer 1985 ice and weather conditions enabled to perform investigation in Wijdefjorden (Fig. 1). This paper presents results of investigations carried out during the Second Marine Geodynamic Expedition of the Institute of Geophysics of the Polish Academy of Sciences to the Spitsbergen region. Expedition was supervised by Professor A. Guterch, the bottom investigations were conducted by Dr. S. M. Zalewski.

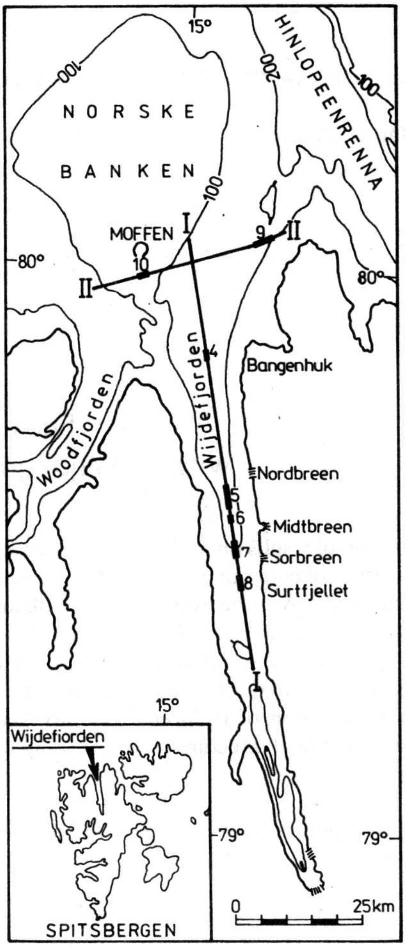


Fig. 1. Location of the cross-section (I—I and II—II) based on CSP (boomer records) and piston corer samples. Numered sections 4—10 show the positions of the boomer record examples (*see* Pls. 1—8). Ice cliffs are marked.

Wijdefjorden is different distinctly from the other fiords of Spitsbergen by its shape, dimensions, position with regard to geological structures, and contemporaneous delivery of the glacial material. A great length of the fiord, its elongated, subsequent and narrow outline, lack of side basins, comparatively even coast line and absence of the threshold closing the fiord, provide for making the trial to determine the course of the Late Pleistocene deglaciation of the main glacier and to determine the role of contemporaneous influence of tributary valley glaciers together with determination of the bottom structures development and distribution related to these processes. Due to that it was possible to collect the essentional material and compare it to other Spitsbergen fiords — usually with more complicated shores, with separated large side basins and feeded (today or in the past) by relatively equivalent in size polar and subpolar glaciers.

The first primary results of investigations carried out by the authors in Wijdefjorden were presented previously (Kowalewski *et al.* 1987, 1989; Kowalewski and Rudziński 1988). Some results of primary studies of superficial bottom sediments from Wijdefjorden together with a comparative analysis of fine grained clastic sediments from Spitsbergen fiords were presented by Görlich (1988).

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## Data acquisition

Seismoacoustic investigations by CSP (continuous seismic profilling) method were carried out with a use of the *EG* and *G* made apparatus — Uniboom 230. Good penetration was obtained at resolution about 1 m to the top of the bedrock (to 40 — 60 m under the bottom level) and going deeper — to some scores of meters into the bedrock. One profile was carried out along the fiord and the other on the shelf, outside the fiord (Figs. 1—3).

Samples were collected with a core sampler (of gravitational-piston type) with the inner diameter of plastic tube of 80 mm. The inner tube with a core was removed from the sampler on the ship board every time, and after protection by plastic leaf was transported in the cooling box (in temperature 2—4°C) to Poland. Tubes were cut in a laboratory and macroscopic description of cores as well as Ph and Eh measurements and X-ray examinations were done. Several dozen of samples for analytical investigations (lithologic, mineralogic, chemical, content of organic remants, *etc.*) were collected. Analytical data put a good use for seismoacoustic profiles interpretation and the results will be published in the other paper (Kowalewski *et al., in press*). Types of sediments were distinguistished according to Holtedal eliminations (*after* Solheim and Kristoffersen 1984). During protection of cores on the ship board some samples from the lower and upper part of cores, approachable without cutting of the tube, were rendered accessible to Dr. K. Görlich. In exchange some samples, from grab-sampler taken by Dr. Görlich were obtained.

Places of samples collection and situation of profiles were located by radar bearings on characteristic objects on a coast.

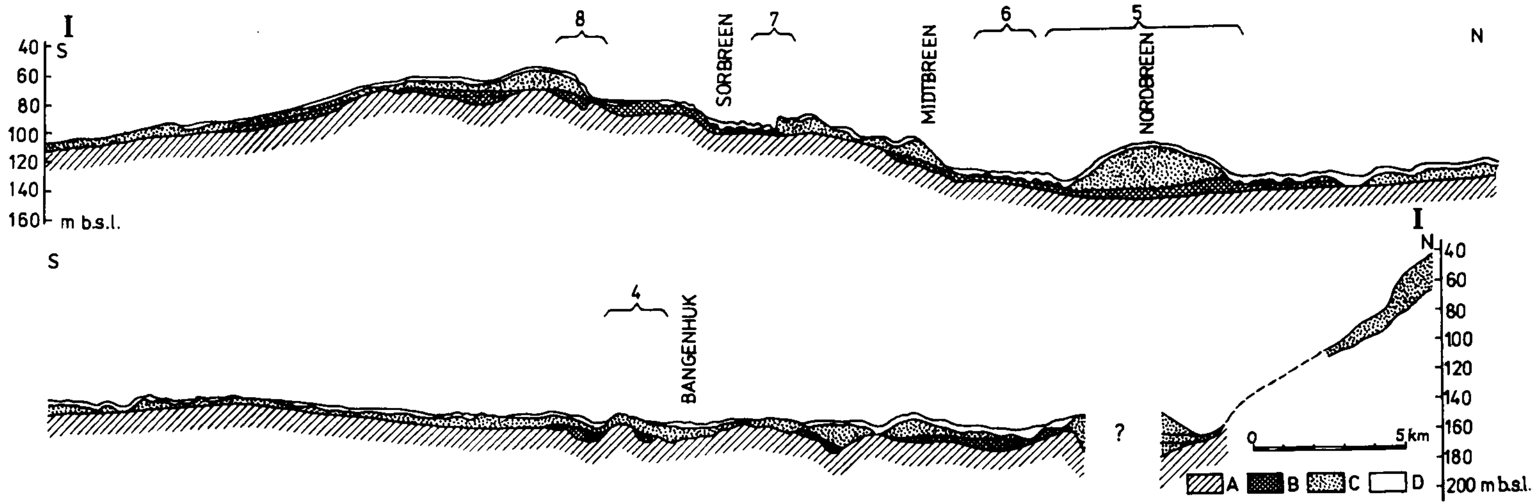


Fig. 2. Synthetical cross-section along Wijdefjorden (location on Fig. 1). Seismoacoustic units: A bedrock, B till and/or compacted glaciomarine deposit, C glaciomarine ice –front deposit, D glaciomarine mud.

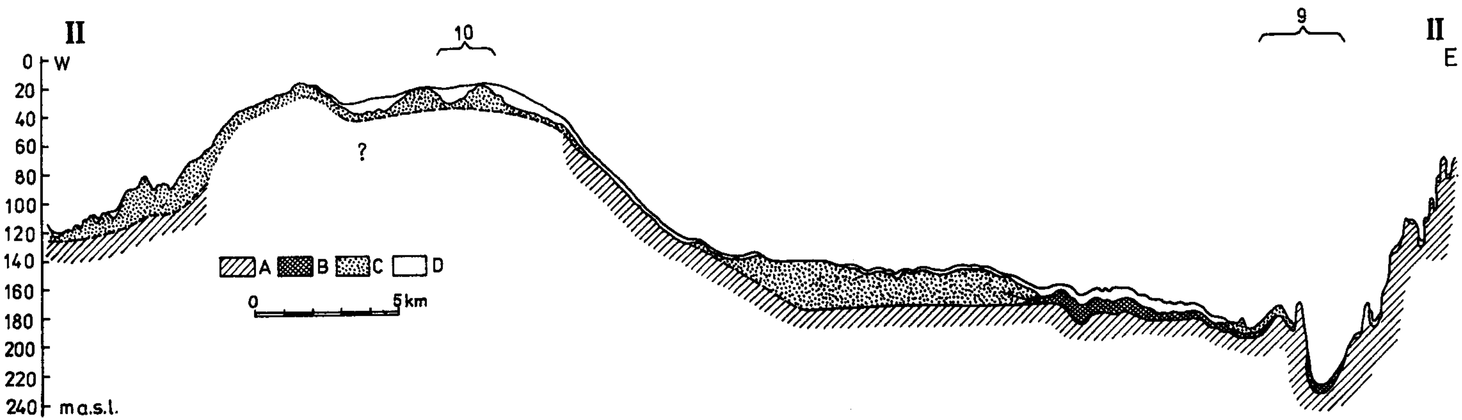


Fig. 3. Synthetical cross-section on the shelf north to Wijdefjorden (location on Fig. 1). Probable position of the Billefjorden Fault Zone is marked. Next explanations on Fig. 2.

## Background

Wijdefjorden extends along the Billefjorden Fault Zone. This zone divides the Precambrian-Lower Silurian Hecla Hoek Formation (mainly gneisses and feldspar or micaceous schists) — outcropping along the coast from the Upper Silurian-Devonian Old Red Formation — exposed on the west coast (Hjelle and Lauritzen 1982, Gjelsvik *et al.* 1985).

The fiord is more than 110 km long and its width is changing from some kilometers in initial part to 20 km near the fiord mouth. A fiord valley has its prolongation (without threshold) as a wide depression on the shelf. In the bottom of the final part of depression a narrow furrow is cut which joins the Hinloppenrynna at the depth above two hundred and scores meters (Fig. 1). A distinct threshold occurs only in the upper part of the fiord near Sturfjellet, erected to the depth of 60 m bellow sea level. This threshold divides the inner fiord basin with narrow depression depth above 240 m (Navigational Map). In the outer basin longitudinal profile is relatively plane. Gentle bottom slope gradually deeps to the fiord mouth where the depth exceeds 120 m bellow sea level. Near the tributary glaciers of Sörbreen, Midtbreen and especially Nordbreen hummocky sculpture of the bottom with denivelation about a dozen or so meters was as certain (close to Nordbreen 20—30 m). Inclination of slopes is changing from some to a dozen or so degrees. Similar morphology was also found on the bottom near Bangenhuken and to the north of it as well as at the foot of Norske Banken. The Norske Banken represents a shelf limited by depressional prolongations of Wijdefjorden and Woodfjorden on both sides.

The coast line of Wijdefjorden is relatively even. There is only one lateral bay (Vestfjorden in inner basin). Ice-cliffs are here of second-rate type now. In the inner basin only two ice cliffs of Mittag-Lefflerbreen glacier (which is a remnant of main glacier) and neighbouring tributary Stubendorfbreen glacier appear. In the outer basin, in the middle part of the fiord, three valley glaciers step in. Due to that the direct contribution of glacial meltwater in the transportation of glacial debris has the limited importance in the fiord now. Supply from suspension cloud prevails together with ice-rafting and waters flown down from the land. In the mouth fiord part and on the shelf ice-rifting is mainly connected with ice flues and icebergs coming over from the open sea.

The influence of the open sea agents (waving, influence of oceanic water, tidal currents, and so forth) is limited to the outer basin and especially to its outlet. This proceeds from the fiord configuration as well as from the long endurance period of the ice cover in the fiord mouth and adjacent sea (Vinje 1985). The lack of threshold in the mouth favours the winnowing the suspension from the fiord.

## Seismoacoustic units

Four main seismoacoustic units were distinguished and characterized on the grounds of detailed analysis of the seismoacoustic profiles and results of bottom sediments samples investigations. These units were interpreted (Pls. 1—8) with reference to knowledge of bottom and land geomorphology and taking advantage of investigation data from the other fiords (Elverhøi *et al.* 1983, 1987, Elverhøi and Solheim 1983, 1987, Kowalewski *et al.* 1985, 1987). A bedrock (unit A) was distinguished covered by young glacigene (unit B) and glaciomarine (units C and D) deposits. The marine muds (thickness to 1 m) appear in the fiord mouth and on the shelf. These muds were not separated by the authors from the unit D.

**Unit A. Bedrock.** The top surface of the bedrock is even, due to its exarational character. Within the fiord the bedrock is covered by young sediments with thickness changing from some to some scores of meters (Fig. 2), maximum up to 40 m (Pl. 2). Sturfjellet threshold, which divides inner basin from outer one, has a distinct rocky-accumulational character with structural foundations (Pl. 5). Here the top of the bedrock uplifts to the most high level within the fiord. The bedrock appears along the profile and undoubtedly corresponds to Devonian formations in Old Red facies (upper units of Devonian Red Sandstones *after* Reed *et al.* 1987). They are cut by numerous faults and *cut and fill* structures (the most probably associated with periodic action of Devonian seasonal rivers). Several faults reach the bottom surface what suggests the vital tectonic processes taking place in the Billefjorden Fault Zone (of Upper Devonian foundation) to the present days. On the profile carried along the fiord (Fig. 2) any deposits which could be interpreted as rocks corresponding to Hecla Hoek formation were confirmed. This formation is undoubtedly represented in the eastern part of the fiord bottom, on other side of Billefjorden Fault Zone ranging to the east from the line of profile I—I. Strongly overfolded and cut by faults Hecla Hoek formation deposits occur in the eastern part of profile II—II (Fig. 3). A morphology of this part of shelf bottom is diversified by ridges, rocky spurs and furrows (Pls 6—7). The bottom surface is covered only by thin (thickness about some meters and even less than 1 m) sheet of young sediments. The thick cover of young sediments (up to 60 m) was discovered within Norske Banken (Fig. 3) in the eastern part of profile II—II, where they overlay the Old Red deposits, folded into blunt folds.

The studies of the bedrock lithology and tectonics will constitute the subject of the further works of the authors.

**Unit B. Till and/or glaciomarine compacted deposit.** This unit forms a discontinuous sedimentary cover which pads the bottom (Pl. 4) especially filling the depressions in a top surface of the bedrock (Pls 1 and 5). The maximum thickness do not exceed 10 m. The absence of this formation even on large distances of the profile should be considered as an eresional efect.

From the lithological point of view these deposits are composed of stiff pebbly muds with varying, sometimes abuundant content of coarser graines. These muddy diamictons are undoubtedly corresponding with the basal till (lodgement til *sensu* Boulton and Deynoux 1981) deposited during recession of the glacier front in the active flow stage and/or melt-out till deposited during stagnation of the glacier front. It cannot be excluded, that some parts of these sediments are represented by compacted glaciomarine ice-front deposits. Here and there in fillings of the bedrock depressions distinct limitation of separate parts of unit D was established what may correspond to some sedimantary acts.

**Unit C. Glaciomarine ice-front deposit.** The unit C overlaps the lower units A and B. Here and there, the unit C sediments are locally interbedded by unit D sediments. Unit C deposited in the bedrock depressions fills them up giving more or less homogenous cover. More frequently it is included in hummocky structures with a relative height up to max 20—30 m (Pl. 2). The thickness of unit C is variable, changing from some meters to 40—50 m in Norske Banken and at its foot (Fig. 3).

Most of all there are unsorted sediments composed of disorderly disposed components (massive, unsorted diamictons) with abundant content of coarser graines and local concentrates of stones and boulders. The distribution of graining is at least bimodal but more often polymodal. First of all there are sandy gravelly muds with changeable ratio of separate fine fractions.

Locally within the unit C, especially on the thresholds, some differentiations occur which correspond to separate sedimentary acts (Pls 4—5) probably related to glacier front oscillations (annual and seasonal). There are structures of push moraines type as well.(Pl. 5). Here and there on seismic pattern some structures connected with flowage and creeping can be distinguished — mainly encountered on the distal slopes of „hummockies". There are also some structures interpreted by the authors as melting structures connected from buried dead ice or to under-water permafrost (Pls. 3—4). It cannot be excluded that some part of these structures were formed due to gas migration from the bedrock to the surface. Similar „gas pockets" were distinguished on the bottom of southern Baltic Sea. Authors feel deeply grateful to W. Rossa for discussions and giving facilities of unpublished data from this region. Very seldom weakly expressed structures were encountered which in our opinion may correspond with the bedding od mega-cross type.

Sediments of the unit C described in this paper as glaciomarine ice-front deposits correspond with deposits defined (Elverhøi *at al.* 1983) as surge or ice-front deposit. Sediments of this unit have been originated on the bottom (just close to the ice-front) due to rapid deposition of glacial debris supplied by meltwater, dumping and debris flow from ice front. Within the fiord, besides sediments of the unit C corresponding with the main deglaciation during the Late Vistulian, sediments originated from the tributary glaciers during the Little Ice Age occur. These sediments are distinctly superimposed on the previously deposited formations (Pl. 2).

Deposits of the unit C are widespread on the shelf in the Norske Banken region (Fig. 3, Pl. 8) where they formed the relatively thick cover. In places where the unit C reaches the sea bottom muddy pebbly sands occur. It may be considered that bottom wash-out by waves and currents has been taking place here.

In the eastern part of the profile II—II (Fig. 3, Pl. 6) the bottom has a very differentiated relief and the cover of sediments is very thin. Hence the thickness of the unit C deposits is very small, maximum several meters, and in places they are absent.

**Unit D. Glaciomarine mud.** This unit is widespread and deposited all along the profiles I—I and II—II forming the cover smoothing the irregularities of the surface bottom or overlapping the relatively large elevations (Pl. 4). Therefore its thickness is variable and amounts from some score centimeters to almost 10 m (Pl. 8). In places, especially in the eastern part of the profile II—II (Pls. 6—7), this unit was not ascertained.

A seismic pattern of this unit is composed of the complex of distinct horizontal reflexes traces on the long distances. In places disturbations are observed which can be connected to sliding and creeping of sediments as well as with buried dead ice melting (thow structures), and/or gas migration. The latest, for example, is very good visible in depressions between hummocks located near the Midtbreen and Nordbreen (Pl. 3).

These highly reflective and acousticly transparent sediments are composed of muds and muddy sands with dropstones. In detailed description those are muds with intercalations of distinct higher content of the sandy fraction, homogeneous muds and homogeneous bioturbated muds. The colour of sediments changes from brown-gray to mahogany. The brown colour is a result of the great content of material from the Old Red formations. Black laminae, streaks and stains ferrous-organic compounds are frequently inherent. In the fiord mouth and on the shelf olive-green silts were formed, usually bioturbated with intact and crushed shells. These sediments correspond with contemporaneous marine muds.

Glaciomarine deposits of the unit D are formed due to gravitational waterlain sedimentation from the surface suspension plume washed out by glacial meltwater into the fiord with contribution of melt-out material from the drifting ice. According to the position towards glacial front and bottom sculpture these muds indicate some differentiations most of all connected to the quantity and rate of material fall on the bottom with surface sediment plume. On the slopes and elevations sandy muds or/and muddy sands occur which have been deposited due to bottom wash out or scouring by the currents.

## Discussion

Seismoacoustic units distinguished by the authors in the Wijdefjorden, similary to those defined in the other fiords (*cf.* Elverhøi *et al.* 1983, Kowalewski *et al.* 1987) are first of all interpreted as facial units connected to the definite model of sedimentation environment and its development. It depends on the rate and manner of deglaciation and described units could be different in the lithological content. Additionally, glacier oscillations and surges caused the complicated structure with units of the different age but similar facial shape and with the frequent lateral and vertical mutual transitions. Therefore it is impossible to make use of the seismoacoustic units distinguished in the Wijdefjorden as informal stratigraphic units.

In this region chronostratigraphical considerations are very difficult due to poor recognition of the Quaternary deposits stratigraphy on the land and lack of the sediment or forms dating. However on the grounds of our investigations and actual state of knowledge of the Spitsbergen evolution during the Late Quaternary (Ohta 1982, 1987, Elverhøi et al. 1983, Solheim and Kristoffersen 1984, Troitsky 1985, Troitsky *et al.* 1985, Landvik *et al.* 1987) one can consider that last time infilling of the Wijdefjorden by the glacier took place during the Late Pleistocene. Deglaciation occurred in several local stages with annual and seasonal glacier-front oscillations, also surge type. According to progressing deglaciation sediments of our unit B were deposited, composed of the lodgement tills and/or melt-out tills, and of unit C which comprises pebbly-muddy-sandy diamictons. In the bottom of the Wijdefjorden preserved forms indicate several local stationary phases of the glacier with the „morainic hummocks". They occur (Figs. 2—3) in turn from the north: on the surface and at foothills of the Norske Banken as well as within the fiord — near the Bangenhuken, near the Sturfjellet (where they form an extensive rocky-accumulative threshold), and undoubtedly in the inner basin in places of visible bathymetric shallow — the threshold. Oscillations of the glacier front made possible the occurrence of displacement in the units system creating the push forms. On the bottom surface beyond the zone directly situated near the glacier (marginal zone *after* Kowalewski *et al.* 1987, jet-zone *after* Görlich 1988) the glaciomarine muds were deposited — with different phases depending on the distance to the glacier front. All these sediments create our seismoacoustic unit D.

In the fiord bottom, after retreat of the glacier a relict ice remained covered by the sediments (ice-blocks, ice lences, and permafrost as well). Gradual melting of this ice caused the creation of thow structures. It should be also considered, suggested by the authors, the possibility of gas influence migrating from the bedrock. This gas was accumulated in the sediments below glacier foot and released after its melting. Release of air bubles from being melted buried dead ice should have some influence too.

Renewed development of the Spitsbergen glaciation during the Little Ice Age caused the expansion of the main glacier into the Wijdefjorden, limited to the inner basin by the authors opinion. In the outer basin glaciers flowing from the Asgarfonna generally reached the fiord in that time when they created the marginal forms on the bottom. These forms placed transversely the fiord and composed our seismoacoustic unit C of muddy diamictons type. Moreover the obvious increase of the glacial material supply took place at that time which was transported in suspension state as well as by the ice-rafting and this sedimentation of various glaciomarine muds was increased. So within the different parts of the Wijdefjorden the seismoacoustic units C and D are of various age — changing from the Late Pleistocene to the Early Holocene.

Differentiation of forms in the Wijdefjorden bottom can be as well connected to the various rate and manner of deglaciation. Some of these forms might be created in the frontal deglaciation and the other in the areal deglaciation conditions.

With the frontal deglaciation the deposits corresponding to the tills of lodgement type (*sensu* Boulton and Deynoux 1981) should occur in glacier basement — when the actively flowing glacier retreat took place, or of melt-out tills type — when the glacier stagnates (Anderson *et al.* 1985). Then on the glacier foreland a distinct underwater rampart of end moraines is formed (generally glaciofluvial, *sensu* Ruszczyńska-Szenajch 1982) usually pushed due to the glacier front oscillations, often with the outwash fans (sandurs) cover on the foreland. On the fast recession of the glacier front sets of ridges and hummock remain on its subsidiaries — corresponding with the previous system of fractures in the glacier (Solheim and Pfirman 1985, Solheim 1986). Such interpretation can be considered for the forms within the Sturfjellet threshold.

With the areal deglaciation active flow of the ice does not occur. Then the glacier front is gently sloping down and is covered by the morainic material. Besides the activity of englacial and/or supraglacial meltwater processes connected to the surface debris flow are of a very great importance. In such a case the complex of forms consisting of indistinct relief dome — composed of interbeddings of melt-out and flow-tills with glaciofluvial material and buried dead ice can come to existence. On the foreland the cover of the outwash fans (sandurs) with numerous pitted sandur can preserve at that time. On the subsidearies, on the fast rate of deglaciatory hummocks with ice core (*see* Pl. 3) can remain the ones which are elevated about several meters above melt-out or flow-till moraines.

Locally observed relatively large thickness of the unit C indicate the rapid sedimentation with abundant material supply. Such conditions are most of all connected to the front of retreating glacier after its surge. The unit D deposits are rare in the fiord, and are connected to poor glacial supply at a certain distance to the front of the main glacier in the narrow fiord and to limited contribution of tributary glaciers.

## Conclusions

Application of the seismoacoustic method performed in the Wijdefjorden enabled to ascertain the occurrence of the young sedimentary cover on the uneven bedrock surface. Thickness of the cover changes from several to dozen meters. Seismoacoustic units were distinguished within it, interpreted as glacial and glaciomarine deposits connected to the main deglaciation and the activity of tributary glaciers. Deglaciation after the main glacier, extended in the maximum range on to the shelf, at last near the Moffen Island (in the Late Vistulian?) took place in several stages. Terminal moraines have remained on the bottom corresponding with several phases. The facial content and the distribution of described units were additionally affected by variable conditions of deglaciation process — taking place in the frontal deglaciation environment changing gradually into areal deglaciation.

Renewed development of the Spitsbergen glaciation during the Little Ice Age caused the limited surging of the main glacier and strong influence of tributary glaciers. Complexes of marginal forms were formed at that time connected to the glacier tongues entrance to the fiord, transversely to its axis.

Within the seismoacoustic units distinguished by the authors facial differentiation of sediments is observed. Detailed analysis of collected core samples enabled to prepare the model distinguishing mark and characterization of the lithofacies. This will constitute the subject of the further works of the authors. Individual elaboration is necessary as well to solve the problems connected to gas migration, neotectonics and buried dead ice which were mentioned only in this paper.

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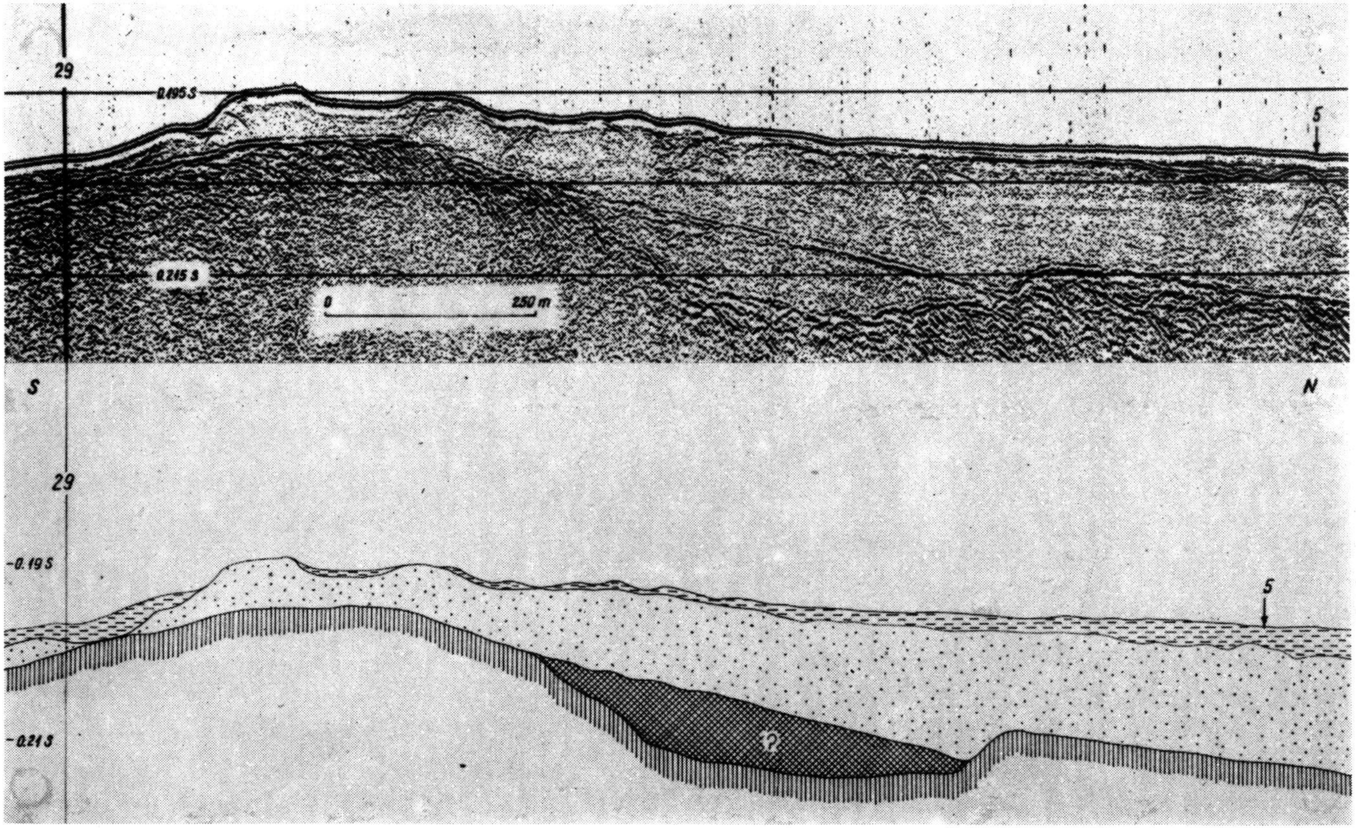
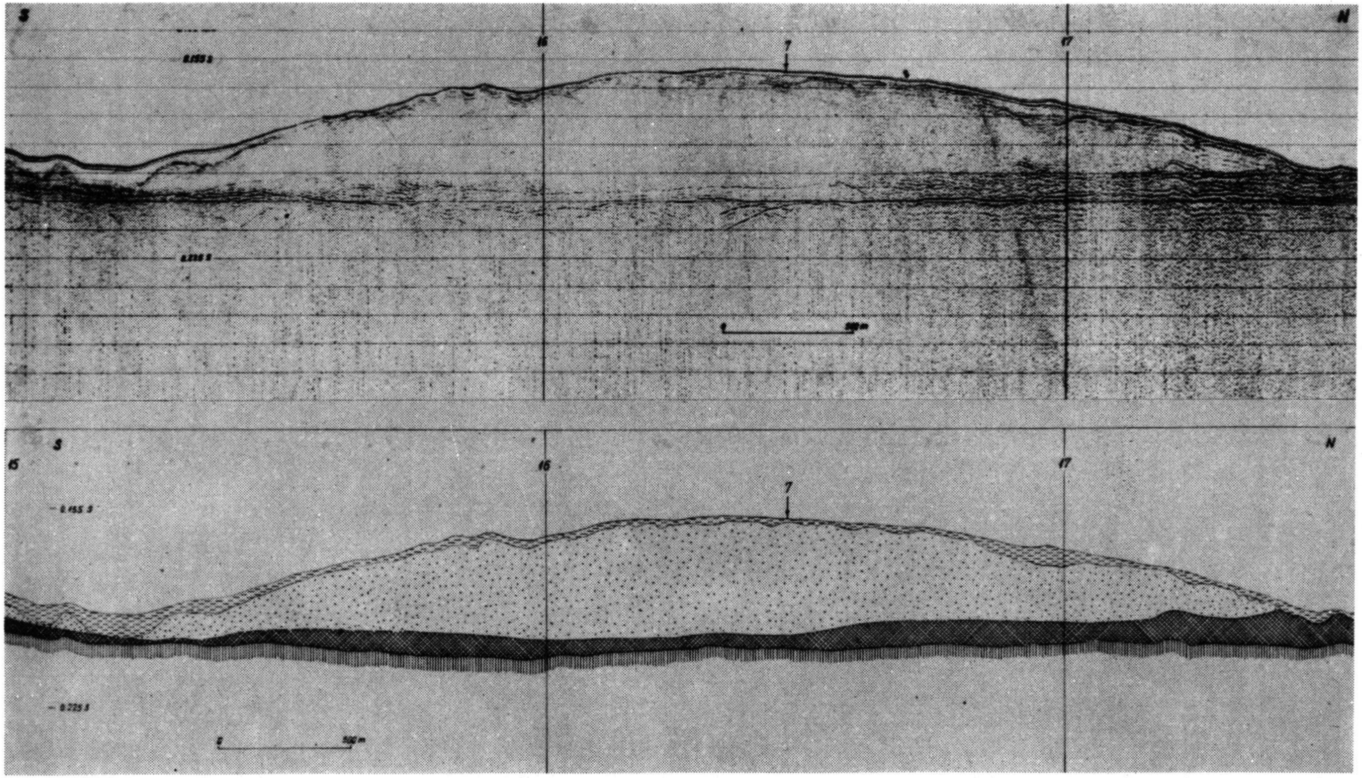
# Streszczenie

Na podstawie wyników profilowania sejsmoakustycznego (CSP) z 1985 r. (fig. 1—3) oraz wstępnych wyników analiz rdzeni osadów pobranych z dna, wyróżniono i scharakteryzowano następujące, główne jednostki sejsmoakustyczne (pl. 1—8): jednostka A — podłoże skalne, jednostka B — glina zwałowa lub zwięzłe osady glacjalnomorskie, jednostka C — glacjalnomorskie przylodowe osady, jednostka D — glacjalnomorskie muły. Przedstawiono rozkład jednostek sejsmoakustycznych wzdłuż osi fiordu i w jego przedłużeniu na szelfie, wraz z określeniem związku form dna z deglacjacją późno-Vistuliańskiego (?) lodowca głównego oraz z holoceńską działalnością lodowców bocznych, zapewne podczas tzw. Małej Epoki Lodowej. Przedstawiono położenie form marginalnych, odpowiadających recesyjnym etapom postojowym czoła lodowca.

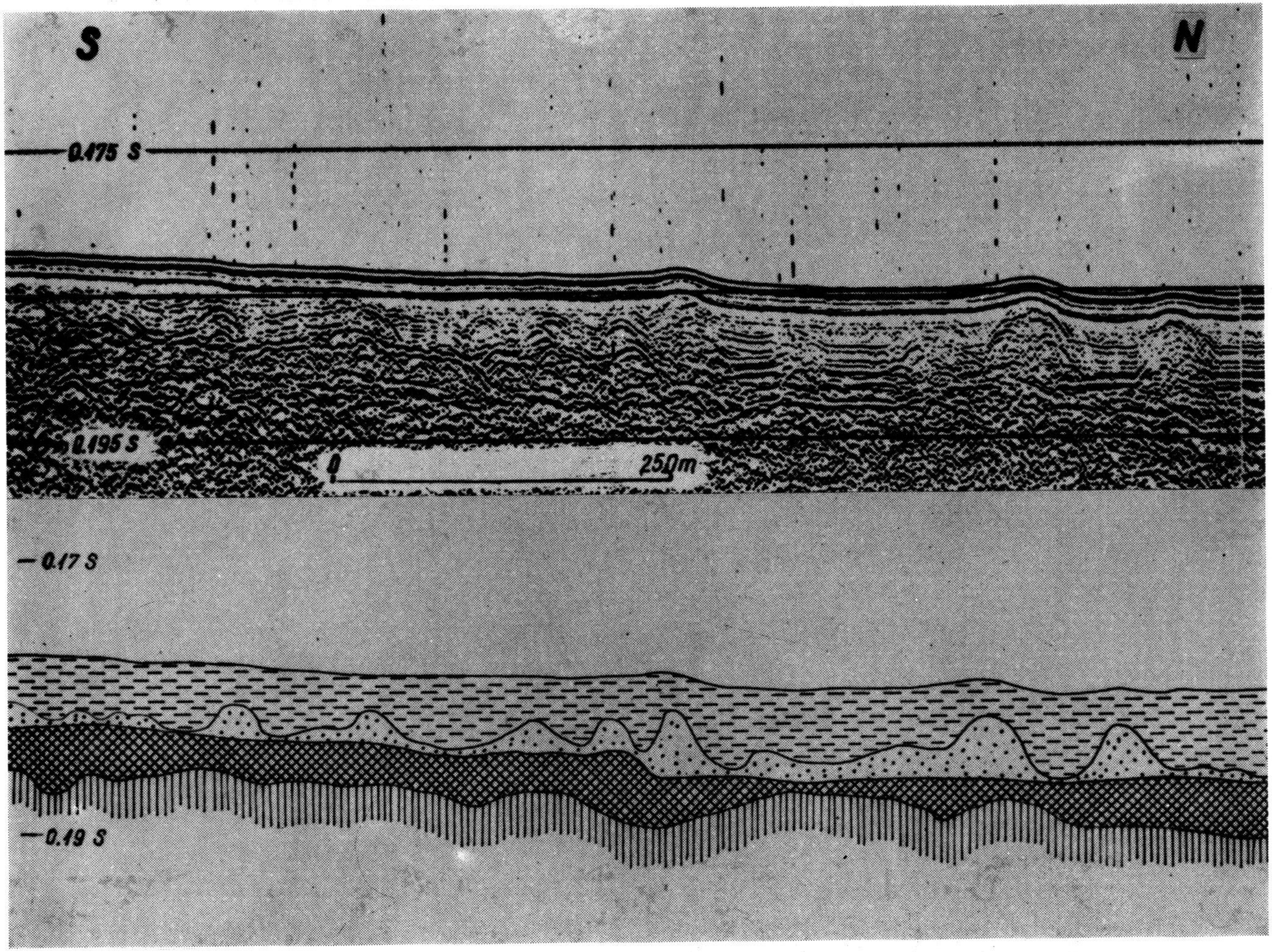
Prace były wykonywane w ramach programu Badań Polarnych CPBP 03.03. Polskiej Akademii Nauk.



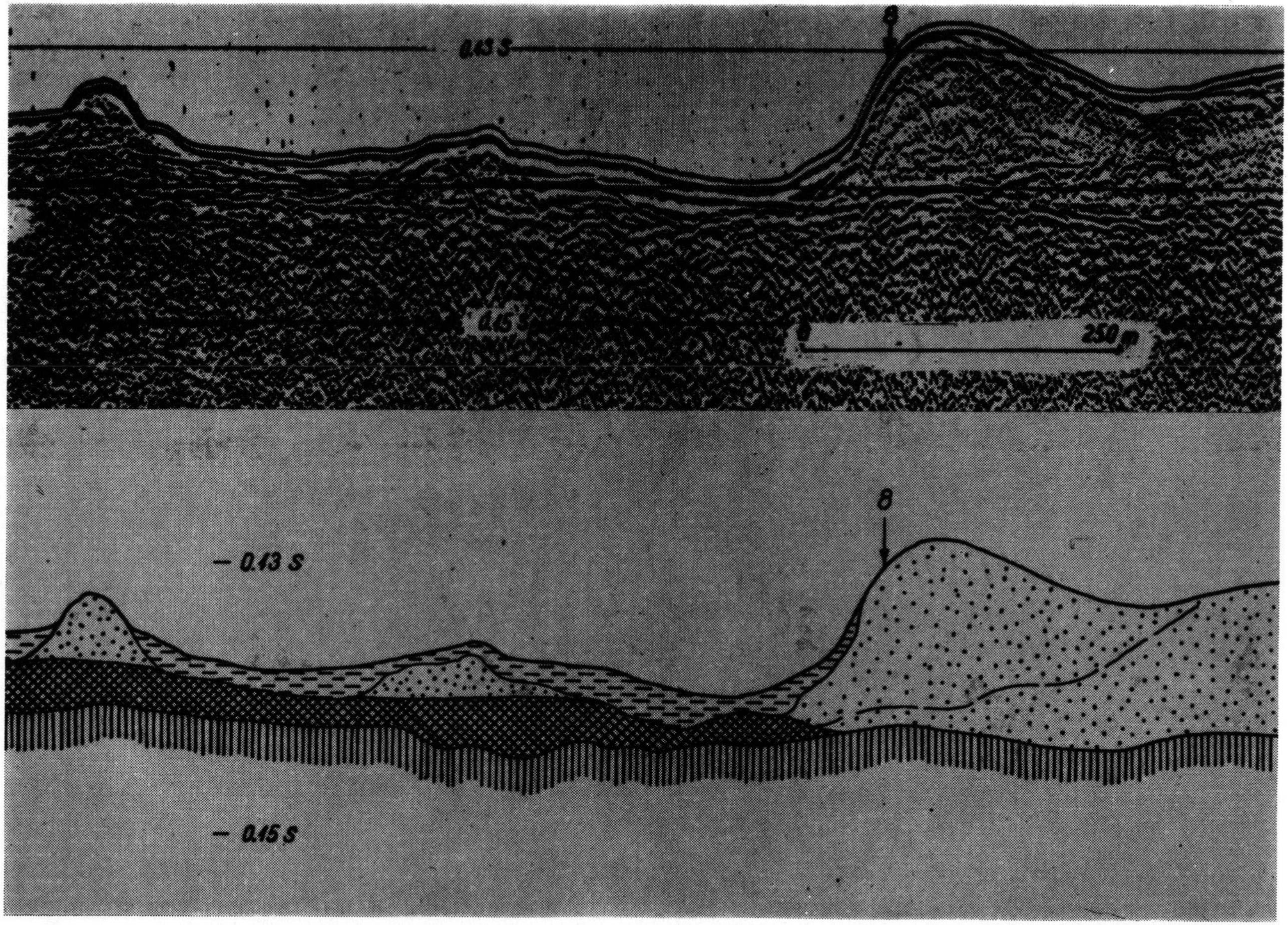

Selected section (4) of the boomar record and interpretation from Wijdefjorden. Location on the Figs. 1 and 2 (section 4). Horizontal lines mark time travels. Bedrock (unit A) vertical dashed, till (unit B) chequered, glaciomarine ice front deposit (unit C) dotted, glaciomarine mud (unit D) white.



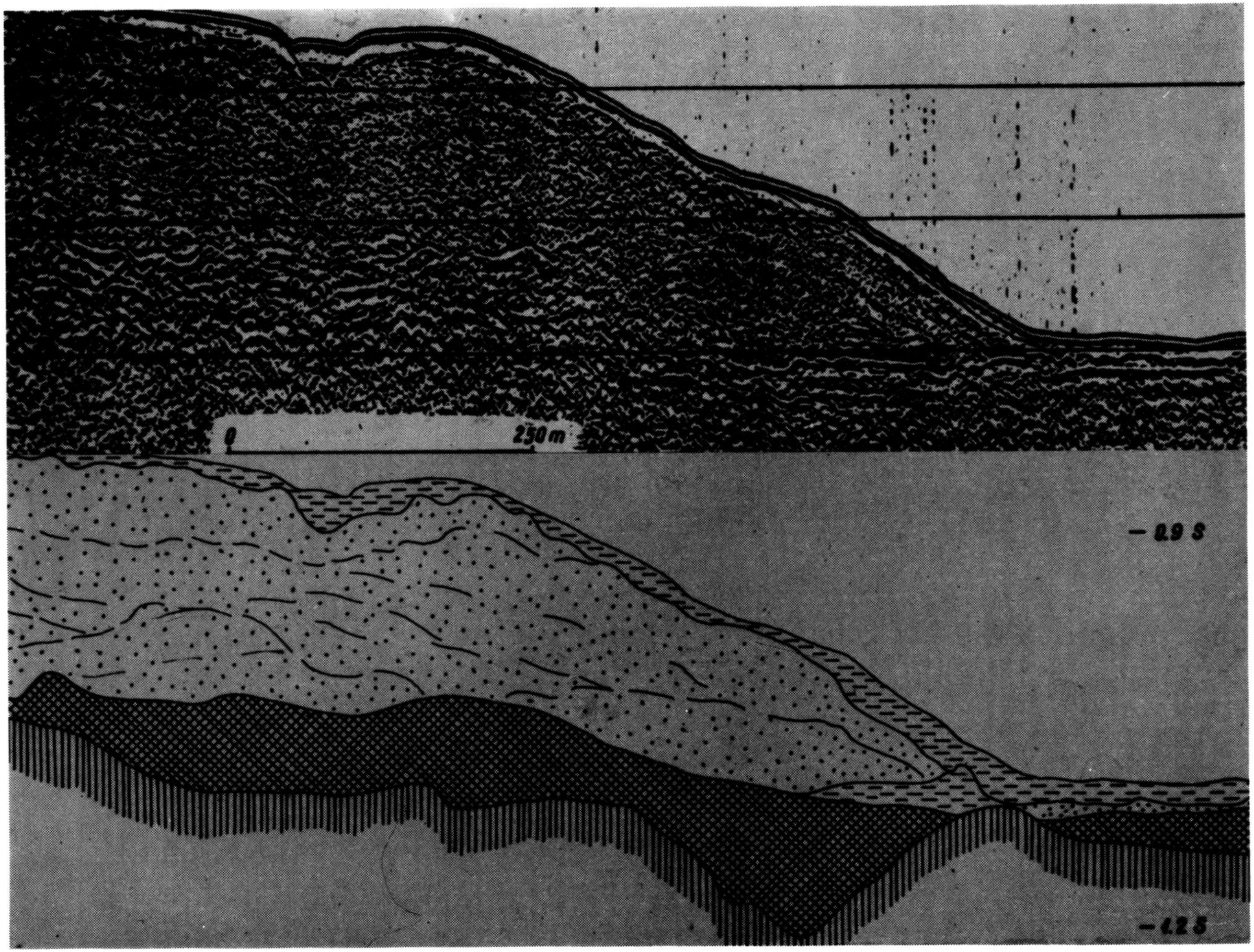

Selected section (5) of the boomar record and interpretation from Wijdefjorden. Arrow shows position of the piston corer samples. Next explanations on Pl. 1.



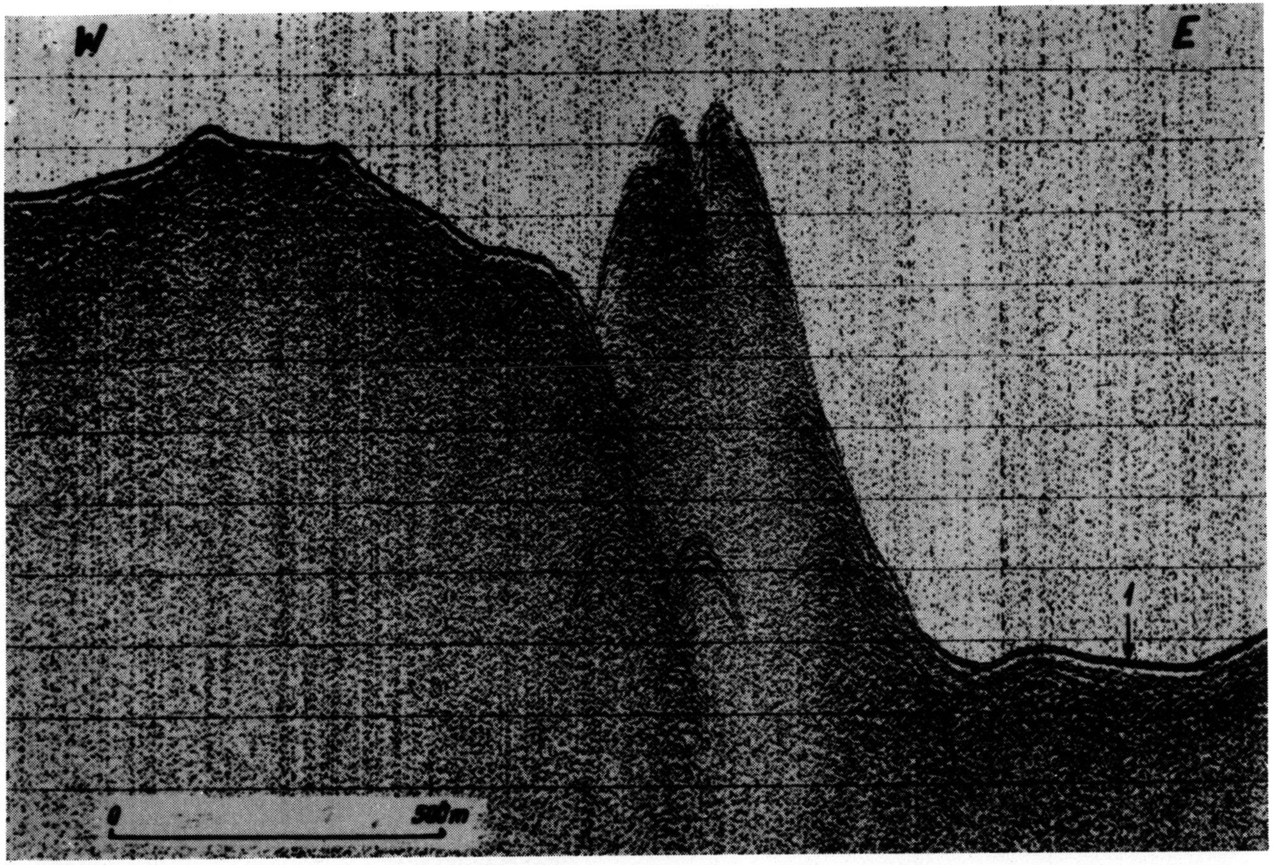

Selected section (6) of the boomar record and interpretation from Wijdefjorden. Explanations on Pl. 1.



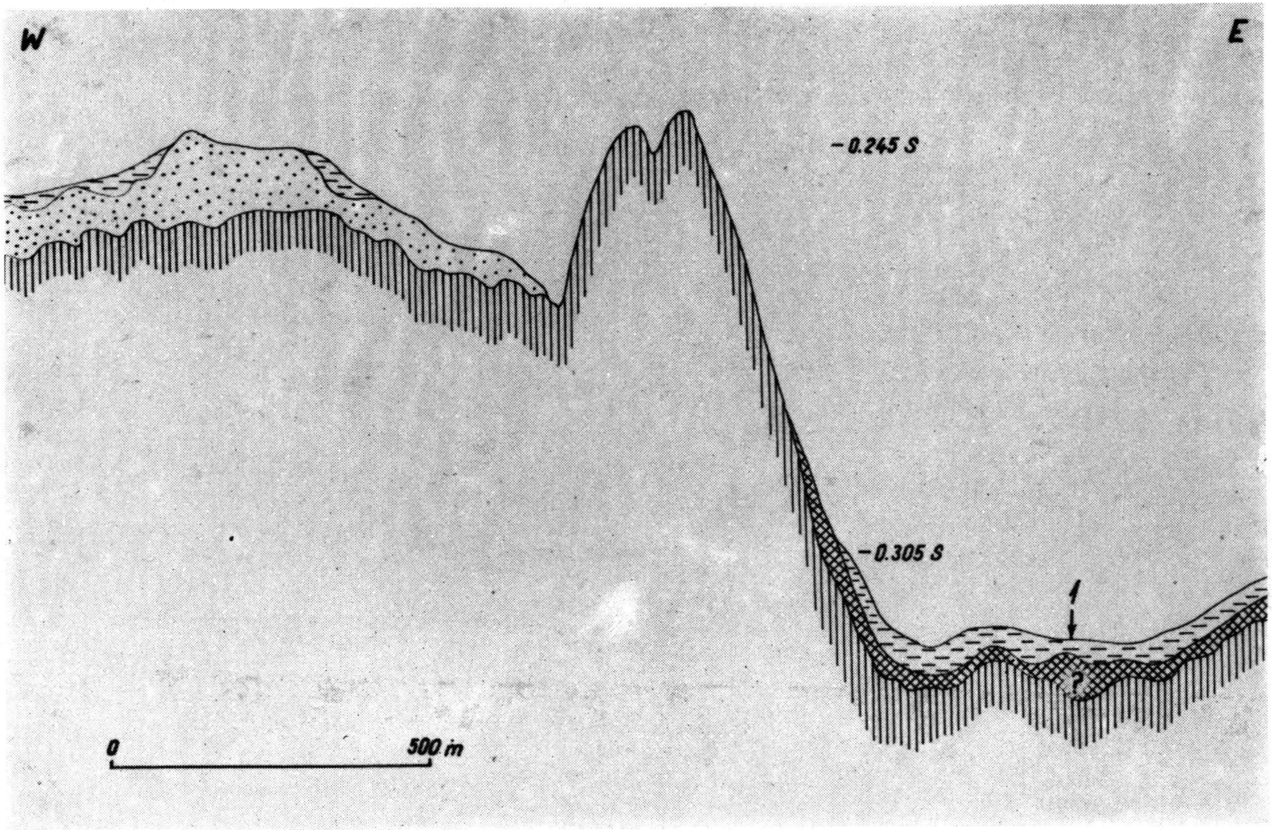

Selected section (7) of the boomar record and interpretation from Wijdefjorden. Arrow shows position of piston corer sample. Next explanations on Pl. 1.



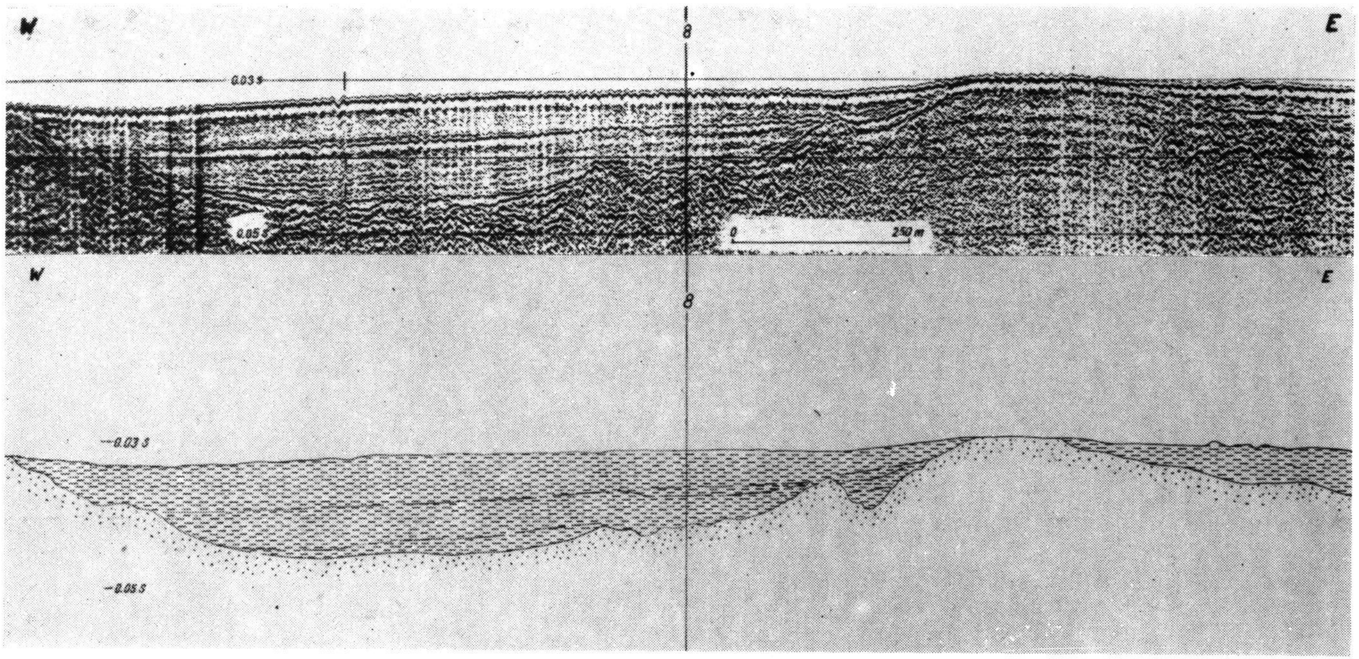

Selected section (8) of the boomar record and interpretation from Wijdefjorden. Explanations on Pl. 1.




Selected section (9) of the boomar record on the shelf, east side of the cross-section II—II. Location on Figs. 1 and 3. Arrow shows the position of the piston corer sample.




Interpretation of the section of the boomar record presented on Pl. 6. Explanations on Pl. 1.




Selected section (10) of the boomar record on the shelf, west side of the cross-section II—II. Location on Figs. 1 and 3. Explanations on Pl. 1.