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Research Report No 24

PRESENTATION OF SEA ICE RIDGES IN GENERAL
AND PHYSICAL CHARACTERISTICS OF BALTIC RIDGES
FOR SHIP RESISTANCE CALCULATIONS

BY ARNO KEINONEN

Sjöfartsstyrelsen
Finland

Finnish Board of Navigation

Sjöfartsverket
Sverige

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Arno Keinonen

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F O R E W O R D

The Winter Navigation Research Board presents its research report no 24. In this report the present knowledge of the Baltic sea ice ridges is given with the principal aim to provide besic data for the design of ships intended for winter traffic in the Baltic.

The Winter Navigation Research Board wishes to express its appreciation to the author and its thanks to Wärtsilä, to Proffessor Palosuo and to all others who have assisted in preparing the report.

Helsinki and Norrköping April 1978

Jan-Erik Jansson   Lennart Johansson

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PRESENTATION OF SEA ICE RIDGES IN GENERAL AND PHYSICAL CHARACTERISTICS OF BALTIC RIDGES FOR SHIP RESISTANCE CALCULATIONS

Arno Keinonen
Research Assistant
The Academy of Finland

A brief general presentation of sea ice ridges is given on the basis of the literature published on the subject.

The physical characteristics of a normal Baltic type ridge are researched in order to produce a basis of ridge data for calculations of the ice resistance encountering ships in sea ice ridges of the Baltic, first winter, type.

1 Introduction

To give the reader a wide view of the ridges, a general presentation about them is first given with a state of art review to Baltic ridge statistics.

The main objective of this paper is, however, to introduce the physical characteristics of a Baltic ridge type, a first year ridge. The set of data should be as a representative and in convenient form to be used as input data for ship resistance calculations in Baltic type ridges.

All ice-covered waters show a wide variety of ice formations. From the navigational point of view the most difficult obstacle is formed by ice ridges. The limits to the capability of a ship to navigate through ice-bound waters is generally determined by the ridges. In winter, the merchant ships in the Gulf of Bothnia are often stopped by these. In the Arctic heavy multi-year ridges form an obstacle still unpenetrable by any ship.

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A great amount of measurements of sea ice ridges have been made for determining the Arctic ice mass and its balance and in order to use the data for the development of dynamic ice model in the Arctic. This kind of data is got from Refs. 6, 7, 8, 16, 19 and 21. The loads caused by ridges on engineering structures have been one reason for determining the characteristics of ice ridges, too. Refs. 1, 7, 8, 14, 15, 17 and 18 give this kind of data. Some attention has also been paid to the top roughness as an obstacle to surface vehicles and the sub-surface roughness which is of importance for example when determining the possibilities of spreading contaminant under ice.

Not much interest has been shown in sea ice ridges in connection with the ship's navigation through ridged ice, even though some researchers have measured also more exact physical characteristics of first-year and multi-year ridges, Refs. 1, 2, 4, 7, 8, 14, 15, 18, 21. Available to the author there are data of ridges penetrated by a ship, Refs. 3, 9, 10, 11, 12.

In ship tests where ridge profiles have been measured the most important thing at an early stage has been the comparison of the ridges and the test results with each other. The measurement of the top profiles has been made and the entire profiles have been predicted by means of mass balance calculation, which have given the sizes and possible shapes of the parts of the ridges below the water level. The absolute physical properties have been assumed to be the same in all ridges because the tests have been made in the same sea area at the same time of the year at approximately the same air temperature. This assumption has proved satisfactory, see Ref. 5.

The determination of the physical properties of the ice in the ridges and the structure of the ridges is important when the ice resistance of ships in ridges is to be approached theoretically.

A study was made for the purposes of this paper for the determination of ridge characteristics, Ref. 4. The part of two ridges above the water level was investigated carefully. Based on Ref. 4 and other data, Refs. 5, 7, 8, 9, 10, 11, 12, 13, 14, 17, 18, the configuration and physical characteristics of a Baltic type ridge will be determined and described.

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2 Ridge

2.1 General

In the Sea Ice Nomenclature of the World Meteorological Organization, Ref. 20, a ridge is determined to be a line or wall of broken ice forced up by pressure. The submerged volume of the broken ice under a ridge forced downwards by pressure is termed an ice keel. The ice pile above the water level is termed a sail. Figure 1 shows a schematic ridge. In Fig. 2 a Baltic type ridge is shown from above.

A ridge may be fresh or weathered. Weathering means rounding of the ice blocks due to melting and filling of voids of the visible top part, and covering with snow (see Fig. 3, a weathered Baltic ridge field).

When ridging takes place in ice of a constant thickness it may be continued in a wide area. Then the ice formation is called hummocking. Fig. 4 shows a hummocked Baltic ice field. According to Ref. 20 a hummock is a hillock of broken ice which has been forced upwards by pressure. The submerged volume of broken ice under the hummock, forced down by pressure, is termed a bummock.

As can be deduced from the above, ridges and hummocks are closely related to each other because the formation of both of them takes place through the pushing of ice blocks in a pile both above and below the water surface. The difference between them is that a ridge is a line, whereas a hummocked ice field is wider and not necessarily long.

In this work an ice formation where ice fragments are piled both above and below the water surface will be called a ridge. A ridge field is determined to contain several sails and keels in immediate contact with each other (corresponds to a hummocked ice field). A ridged ice field is an ice field with ice ridges and/or ridge fields and with fast level ice between them. An ice field where the distance between two individual ridges or two successive ridge fields exceeds one kilometer is however not called a ridged ice field.

2.2 Formation and Life Cycle of Ridges

The formation of ridges is generally a natural consequence of a movement between two ice fields when they meet each other. Another way in which ridges are formed is pressure inside one ice field, which may lead to ridging.

The movement or pressure in ice is caused by a combination of different environmental factors, i.e. wind stress, water stress, temperature stresses, tidal forces and the coriolis force. The primary and secondary of these are wind and water stresses.

The formation of ridges and its mechanism has been described by several researchers. A selection of them is listed here: Zubov (21), Kovacs (7), Weeks et al. (18), Fukutomi & Kusunoki (2), Palosuo (15), Parmerter & Coon (16). Their observations can be summed up as follows:

The ridges can be divided into two main types on the basis of the mechanism of their formation. One main type of ridges, the more frequent one, is a pressure ridge. It is formed when two large adjacent ice fields are in relative movement towards each other. When the ice fields meet each other ice blocks are broken mainly by a bending mechanism, and these broken ice blocks are pushed above and below the water surface. The proportion of ice pushed above and below is determined approximately by the balanced flotation of ice. This generally means that about one eighth of the ice is pushed above the water level. The rest of the ice forms the major part, the keel, of the ridge below the water level. A ridge which is formed this way will contain ice from the channel between the parent ice fields, if there was any, and ice broken from the parent ice fields or at least one of them. Furthermore, inside the ridge there is snow from the surface of the ice blocks.

A shear ridge is the other main type of ridge. It is formed when two large adjacent ice fields move nearly parallel to each other. The mechanism of breaking is then assumed to be crushing and shearing of

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the ice.

The difference between the two major types of ridges is that the ice blocks in pressure ridges are oriented more at random, while in shear ridges the ice blocks generally seem to prefer a nearly vertical orientation near the water level.

The appearance of fresh ridges is sharp-edged, and fragments are visible from a near distance, at for example a low flying altitude. Gradually a ridge gets weathered and the sharp edges disappear, and the top part gets generally snow-covered. Weathering, when continued for a long time, alters the ridge considerably.

As in the Baltic no ice is left over summer, the Baltic ridges do not survive the melting season, the summer. A Baltic type of ridge is thus a first-year ridge made of ice of a thickness below one meter. The age of ridges in the Baltic area may vary between zero and six months.

In the arctic areas where the ice does not melt completely during summer, the ridges melt only partially, and the major part of ridges still remains until the next winter. Ridges that have survived one melting period are called multi-year ridges. According to Ref. 18 at least two melting periods are needed to fill the voids between the ice blocks in a ridge. Then the ridge gets solid. At the same time the ridge gradually becomes smaller as both the top and the bottom melt, mainly during melting periods.

3 Amount and Size of Ridges in the Baltic

3.1 General

In the Baltic Palosuo (5) has studied the formation and structure of ridges and measured the profiles of more than 20 separate ridges, from above and below the water level. Palosuo has apparently found the practical upper limit for the size of a free floating ridge in this sea area.

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The amount and distribution of ridges has recently been studied, Ref. 17, by Wärtsilä staff in connection with a study of winter traffic in the Gulf of Bothnia.

The top profiles of 39 ridge fields were measured in connection with ship tests in the Gulf of Bothnia, Refs. 3, 9, 10, 11, 12, during the years 1974-1977. These fields contained one or several ridges each. These ridges do not represent the average ridge size, but they contain mainly ridges above the average size.

3.2
Amount of Ridges

From a collection of data of ridges in connection with the study in Ref. 17 the amount of ridges that an icebreaker penetrated during its assistance work in the winter of 1976 has been counted. A ridge was registered when in the channel behind the icebreaker a visible increase of the amount of ice was observed. This has been estimated to correspond to a minimum ridge keel depth of 1.5 metres. In Fig. 5 this distribution is drawn. The distribution is not to be understood to be comparable with pure statistical ridge distributions made by ice researchers, because the officers of the icebreaker had a good knowledge of ice conditions and they have intentionally avoided an unknown number of the heaviest ridges. Instead, this ridge distribution is a good first approximation of the amount of ridges that any ship will meet on her way to Kemi or Oulu (a great yearly variation may be expected). In Fig. 6 the observed proportion of different ice types in the northern part of the Gulf of Bothnia during 1976 is drawn in accordance with Ref. 17. The observed distance of ridges+) is 3...10 % of the possible distance i.e. the distance of level ice,

+) The distance of ridges means the part of a route covered with ridges. The distance is calculated from the evaluated maximum thickness of each ridge. The maximum thickness is multiplied by a coefficient 2.5 to get the corresponding distance of the ridge along the route. The coefficient is based on the experience obtained by the author of simulated ridges in an ice model basin. (See Fig. 1, CL.)

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broken ice and ridges. In an old channel to a harbour no ridges are registered because the ice channel is gradually homogenized. The old channel is in practice surrounded by a great amount of ridges. The heaviest ridged ice conditions were met at the end of February.

3.3 Size of Ridges

The maximum keel depth reported by Palosuo (15) is 28 meters and the corresponding total thickness 31.4 meters. This is the biggest free floating ridge observed during the years 1965 to 1977 and can be considered, according to Palosuo, the practical maximum that can be expected to be formed in the Baltic.

The mean total thickness of ridges in the Baltic is, on the basis of observations reported in Ref. 17, 4 metres. The mean thickness of ridges where ships have been tested in the Baltic during the years 1974...1977 is 10 metres. The actual mean thickness lies somewhere between these. In the near future more accurate data are expected.

4 Structure of Ridges in the Baltic

4.1 General

The ships' ice resistances in ridges during the full scale tests in the northern part of the Gulf of Bothnia, Refs. 9, 10, 11, and in the Azov Sea+), Ref. 12, have been explained by calculated ice mass thickness of ridges with a surprisingly good correlation and small distribution, except for in a few cases. Thus a major part of the ridges has most probably been of equal structure type and the outlying resistance results are understood to belong to some other ridge type, and have got their physical explanations accordingly.

The major part of the ridges are of normal pressure type. The other general ridge type, shear ridges, is far less common than pressure ridges. Furthermore, the icebreaker officers know the type of ridges

+) The Azov sea has no multi-year ice. It is comparable with the Baltic in this respect.

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where very thin ice (less than c. 0.1 m) has formed a thick ice ridge practically without any porosity, and they know ridges which stand on the sea floor. The last two are special ridge types which will not be dealt with in this work.

In the following a ridge is divided into three parts, also presented in Fig. 1, where a ridge nomenclature is presented.

- sail, including all ice and snow above the top of the fast level ice
- frozen ice layer, including the fast ice fields around and inside the ridge, mainly of the original parent ice fields of the ridge
- keel, including all ice, snow and slush below the bottom of the frozen ice layer

The ridge characteristics considered here are:

- the amount and density of ice and snow
- the configuration of the sail and the keel
- the strength of the ice in different parts of the ridge
- the thickness profile of the frozen ice layer
- the shape and size of the ice blocks
- the locations and directions of ice blocks inside the structures of the sail and the keel

Only first-year ridges are considered because the Baltic ridges belong to that category only. The characteristics considered here are important either to the ice resistance of a ship directly or to the mass balance calculations for determining the characteristics of the whole ridge on the basis of the measurements of the top part only.

Primarily the characteristics determined here will be used for the calculations of the ship resistance and the assumptions and generalizations will be made accordingly. If these results are used for other purposes, the basic assumptions must be investigated with care.

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On the basis of the limited knowledge of today no accurate model for a ridge can be presented. In the following the general physical characteristics are determined and discussed as far as it is possible.

4.2 Sail

The shape of the sail has been studied by determining the slope angles of the ice pile formed above the water level. The slope angle is an apparent friction angle for a structure formed of ice blocks. Owing to the great variation in environmental conditions during ridge formation it seems evident that a wide parametric study would be needed for setting down rules for determining the slope angle of the sail. Thus the following values based on non-systematic observations are only of a direction-giving character, and their great variation is thus also natural. In Ref. 19 Wittman & Schule give a slope angle of 50 degrees for the sail, in Ref. 7 Kovacs gives 24 degrees. The latter seems to the author to be nearer the values of Baltic ridges.

The porosity of the ice block structure of the sail is in two ridges of Ref. 4, 36 and 43 per cent. These may be regarded as representatives of the limit values at this stage of knowledge.

The density of the ice in the sail is in Ref. 4 871 kg/m^3 on an average, which means a deteriorated stage of the ice. In Ref. 8 the density of the ice in the sail of a multi-year ridge is approximately the same as in Ref. 4 in the top part of the sail. The topmost ice has in both cases become least dense owing to the open interaction with the atmosphere. The inner parts of the sail have a practically constant density. Thus the kind of density profile of the sail that is given in Refs. 4 and 8 can be tentatively assumed to be characteristic of ridges, except the totally new ridges where no decrease in ice density has taken place.

For the mass balance calculations the relative amount of snow and its density vary much more than those of the ice below the levelled line. Incorrect values of density and amount of snow cause bigger errors in the total mass of a ridge than a wrong value for ice density, because the ice density may deviate only slightly from a standard value compared with the corresponding variation of snow density and amount. The

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density of snow measured in Ref. 4, 371 kg/m^3, is felt to be the practical maximum mean density of a snow cover in the Baltic. The accumulation of snow happens as shown in Ref. 4, on both sides of the sail and snow seems to fill the majority of the voids inside the sail.

The positions of ice blocks have not been random, Ref. 4. The low sails seem to have ice blocks oriented in the direction of the ice movement, Ref. 4, Figs. 3 and 4. Anyhow, when a greater sail is met the priority for any particular direction of the ice blocks seems to disappear, see e.g. Figs. 4 and 9.

The thickness of the ice blocks in the Baltic ridges vary in accordance with Fig. 7, in which all the ridges measured during ship tests in the northern part of the Gulf of Bothnia in 1974...1977 are plotted. One ridge has normally contained ice blocks of one or two thicknesses. More common is one thickness only, according to experience.

The distribution of block size versus thickness is shown in Fig. 8. The maximum dimension of the ice block is plotted. The analysis is based on the pictures of the ridges during the above-mentioned ship tests. Thus only the topmost ice blocks are considered. The majority of the results fall between length to thickness ratios 3 and 5. Fig. 9 shows a typical average ridge in this respect.

In Ref. 1 two arctic ridges of the first-year class are analyzed and the shape ratio for ice blocks of these were 3.8 and 6.2, the latter being assumed by the authors to be a shear ridge. This agrees well with the values for Baltic ridges.

The strength of ice in the sail is a variable dependant on the ice temperature and brine volume. During the measurements of Ref. 4 the temperature was above zero degrees centigrade all the time, thus only one type of temperature profile was achieved. Ref. 18 presents the investigations of a 10 metre thick arctic ridge in a temperature of approximately -12^{o}C. This ridge consisted of 15...20 cm and 50...60 cm thick ice blocks, and the surrounding level ice was

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c. one metre thick. Thus it is near the Baltic type of ridges, except the different level of salinity which is in the arctic ridge about 4 o/oo and in the Baltic ridges 0.35 o/oo. From Ref. 18 it can be concluded that the temperature in the sail increases almost linearly when going deeper, until the freezing temperature of sea water is reached just below the frozen ice layer below the sail.

The average strength of ice in a ridge sail vs. ice temperature in the Baltic is shown in Fig. 10. The temperature change in the sail is assumed to be linear. The bending strength of the ice is calculated on the basis of the brine volume for different ice temperatures.

4.3
Frozen Ice Layer

Around a ridge there may be level ice of one or two thicknesses. The average level ice thickness around ridges measured in connection with the icebreaker tests in the northern part of the Gulf of Bothnia has been 0.51 metres. The growth of the level ice after ridge formation was at the end of March 0.2 metres on an average, which is the difference between the thicknesses of the level ice fields around the ridge and the ice blocks in the sail. In Fig. 11 all registered thicknesses are plotted. 30 ridges were measured. The level ice thickness was approximately equal on both sides of the ridge in 23 ridges and in 7 ridges the thicknesses on the different sides of the ridge field were not equal. Equal here means falling into the same 10 cm category. In six ridge fields the level ice thickness was measured on one side of the ridge field only.

The results in Ref. 4 indicate that in the Baltic the frozen ice layer is thicker below the sail than around the ridge. The average additional thickness is 50...72 % of the sail ice block thickness. The frozen ice layer can be said to contain also some adjoining ice blocks that are frozen to it. These probably partly explain the additional thickness below the sail. It must be noted that these indications have been got from measurements during the late March and are not so evident during earlier winter months.

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In the ship tests exceptionally high resistance was encountered in a few ridges. This has turned out to be due to a rafted frozen ice layer in the ridge. This rafted ice has frozen to the bottom of the frozen ice layer and it has appeared when frozen ice blocks have turned up when penetrating ridges with ships. Only two out of 36 ridges turned out to be rafted this heavily. In Fig. 12 one example of such a rafted frozen ice layer in a ridge is shown. The thickness of the ice blocks in the sail was 0.15 m. The surrounding level ice field and the frozen ice layer were 0.41 and 0.8 m thick.

High salinity in the topmost part of the frozen ice layer below the sail - as indicated in Ref. 4 and as may be deduced from Ref. 8 as well - makes this layer weaker than the surrounding level fast ice. Also the isolating sail causes a temperature decrease in the frozen ice layer which has the same kind of effect on the strength. An example of the weakening is calculated and shown in Fig. 13. If the salinity of the surrounding level ice is 0.7 o/oo and in the topmost part of the frozen layer 1.4 o/oo, as in Ref. 4, the bending strength of the frozen layer and surrounding level ice versus air temperature are as in Fig. 13. Then a linear temperature change in the vertical direction is assumed and the bending strength is assumed to be determined by the topmost third of the ice.

The density of ice in the frozen ice layer can be approximated to be the same as that of the surrounding level ice field, Ref. 4, 915 kg/m^3.

4.4 Keel

The shape of the keel has been investigated by determining the slope angles, as for the sail, and the following values are reported: In Ref. 20, Wittman & Schule give 32 degrees, Kovacs reports values between 32 and 38 degrees in different sources, Refs. 7, 18. These are average values. From the divings in the Baltic, Ref. 14, slope angles of up to 60 degrees can be measured. Thus a wide range of angles seems possible. The method for mass balance calculation of a ridge profile

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in Ref. 5 has no standards included in this respect but the keels drawn by means of the method have unbounded slope angles for the keel.

The ice blocks below the water surface seem to be very corroded especially in the deepest parts of the keel, Refs. 14, 18. The ice is thus partly in the melting stage. Its density is assumed to be the same as in the middle part of the sail. From Ref. 8 an indication can be got of this to support the assumption.

The strength of the ice in the keel is low, as it stays near the melting stage constantly. In Ref. 18 results of the coring of an arctic ridge indicate that the strength decreases down to two metres below the water surface, and below that the strength was less than 2 x $10^5 N/m^2$. In principle, the same kind of behaviour can be expected in the Baltic ridges as well.

If a ridge is born in very cold weather, the ice blocks in the keel may freeze together immediately after the ridge formation. According to Ref. 20 this happens in the Baltic only down to 1...1.5 metres' depth, generally.

The thickness of the ice blocks in the keel is the same as that in the sail. Because of melting and corrosion the edges of the ice blocks will be more rounded in the keel than in the sail. Until more accurate facts are available, the same ice block size will be assumed in the keel as that registered above the water level. No present data indicate any other values. The block dimensions of the keel have been registered in connection with divings, Refs. 14 and 15. At times the blocks showed a clear tendency to grow smaller towards the bottom, but there were also instances of the biggest ice flake lying at the bottom of the keel. Some ridges had a thick layer of ice blocks that had glided on each other horizontally or slightly askew immediately below the frozen ice layer. This is a special case when compared with the great majority of observations. The block orientation and distribution in the keel is assumed to be random at this stage of knowledge.

This amount of slush may be significant inside a keel. Ref. 18 reports

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the appearance of a considerable amount of granular slush below the water surface inside a cored ridge.

Ref. 5 shows that there is good reason to believe in the existence of an approximate mass balance in a single profile in a ridge. Thus the amount of ice below the water level can be calculated from the better known ice mass above the water surface, provided that the densities of the ice and snow below and above the water surface are known. In Fig. 14 the curves show the effect of changes of ice density (no snow assumed) on the balanced flotation coefficient.

The porosity (i.e. the not ice-filled volume compared with the ice-filled volume) of the keel is assumed to be the same as that of the sail, no other indication being available.

5 Summary

The structure of a Baltic type pressure ridge can be summarized as follows:

The sail

- loose ice blocks with a thickness of normally 0.2...0.4 m and maximum length 3...5 times the thickness
- ice density 870 kg/m^3
- porosity 36 to 43 per cent
- blocks near the frozen ice layer horizontal or skew, in the upper parts random
- snow cover may or may not exist. If snow-covered, the voids of a sail are also mainly filled with snow. Snow accumulates to both sides of the sail.

The frozen ice layer

- the level ice thickness is generally the same on both sides of a ridge, 0.25...0.7 m. It is bound to

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the ice block thickness of the sail, the average difference of the level ice and the sail block thickness is about 0.2 m at the end of March
- below the sail the thickness of the frozen ice layer is greater than the level ice around. The difference was 50...72 per cent of the sail block thickness at the end of March
- ice density 915 kg/m^3
- the most saline ice of the ridge is in the topmost part of the frozen ice layer
- the bending strength of the frozen ice layer is considerably lower than that of the surrounding level ice.

The keel

- loose ice blocks of the same thickness, size, shape, density and porosity as in the sail
- ice blocks rounded, deteriorated, strength decreasing downwards, a representative strength value for the ice in the keel is below 2×10^5 M/m^2
- random ice block orientation
- some granular snow may be expected to be found inside the keel.

This kind of description of the structure of a ridge is most approximate. The data behind it are limited, even in some basic variables there is some uncertainty.

The characteristics of the keel determine the behaviour of the ice mass in it and thus it is important to discuss the characteristics some more than the hard facts show today. When the formation of a pressure ridge is going on, there will naturally happen breaking of ice by bending, but it seems reasonable to assume that secondary breaking takes place, too even though the ice blocks in the sail are all large, evidently broken by bending mechanism. Then the small ice ice blocks caused by secondary breaking by shear mechanism, must be all lying inside the keel, The amount of these secondary ice blocks is unknown and thus, at this stage, they can only be constituted to be there.

In the near future the characteristics of modelled ice ridges will be investigated in an ice model basin. The purpose is then to determine the porosity, ice density and other characteristics of importance which the present field data do not give satisfactorily.

The author believes that the essentials of the ridge structure are understodd and after model tests an approach to the behaviour of ridges when penetrated by ships can be made.

Acknowledgements

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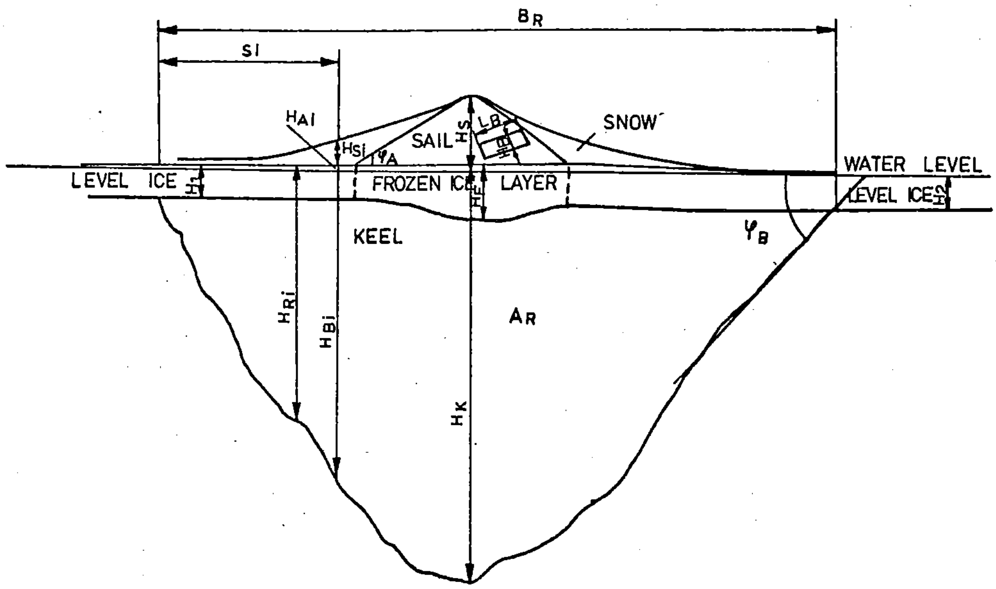
FIGURE 1

A CROSS SECTION OF A RIDGE



NOMENCLATURE

A_R = $\overline{H}_R \times B_R$ = Cross sectional area of ridge
B_R = Ridge breadth
C_B = L_B/H_B = Ice block aspect ratio
C_F = $\rho_i/(\rho_W - \rho_i)$ = Ice floatation coefficient
C_K = H_K/H_S = Keel to sail ratio
C_L = $B_R/(H_K + H_S)$ = Breadth to depth ratio
H = Thickness in general
$H_{A(i)}$ = Ridge height above water surface
$H_{B(i)}$ = Ridge depth below water surface
H_B = Ice block thickness (in sail or keel)
$H_{F(i)}$ = Thickness of frozen ice layer (below sail)
H_K = Maximum depth of keel below water level
$H_{R(i)}$ = Total ridge thickness
$\overline{H}_R$ = Average thickness of a ridge or ridge field $\sum_{i=1}^{N} H_{R(i)}/N$
H_S = Maximum height of sail above water level
$H_{S(i)}$ = Snow thickness
$H_{1,2}$ = Level ice thickness left/right from a ridge or ridge field
L_B = Maximum dimension of ice blocks in sail or keel
N = Number of measuring points of a ridge or ridge field
$S_{(i)}$ = The distance from origin to a ridge measuring point
μ_B = Porosity of ice block structure of sail or keel
ρ_i = Ice density (ρ_A = above water level, ρ_B = below water level)
ρ_W = Water density
φ_A = Sail angle
φ_B = Keel angle

Fig. 2
A typical ridge
in the Baltic

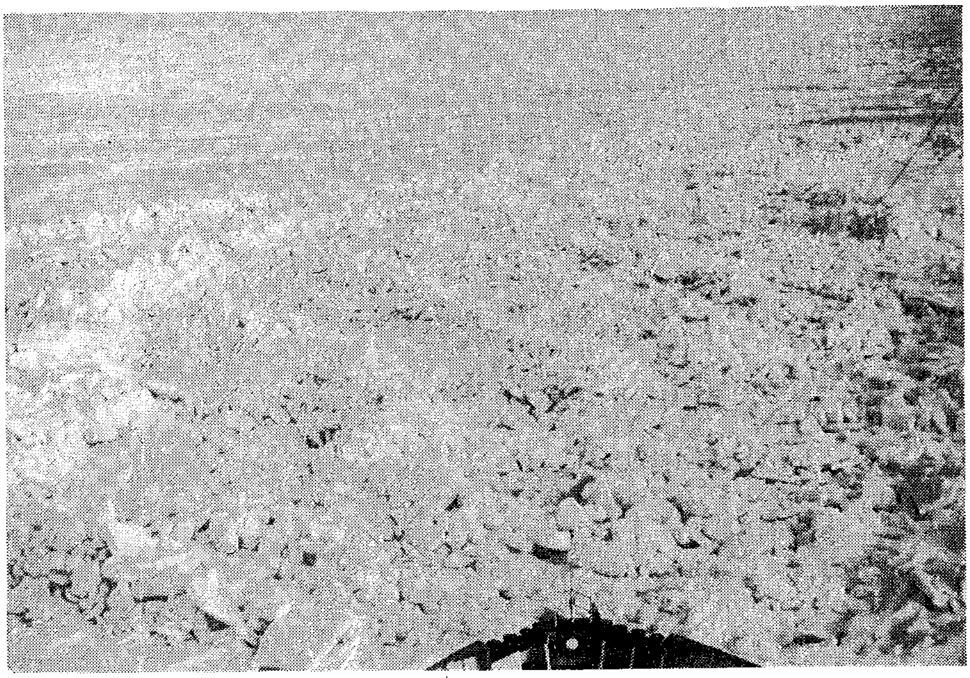
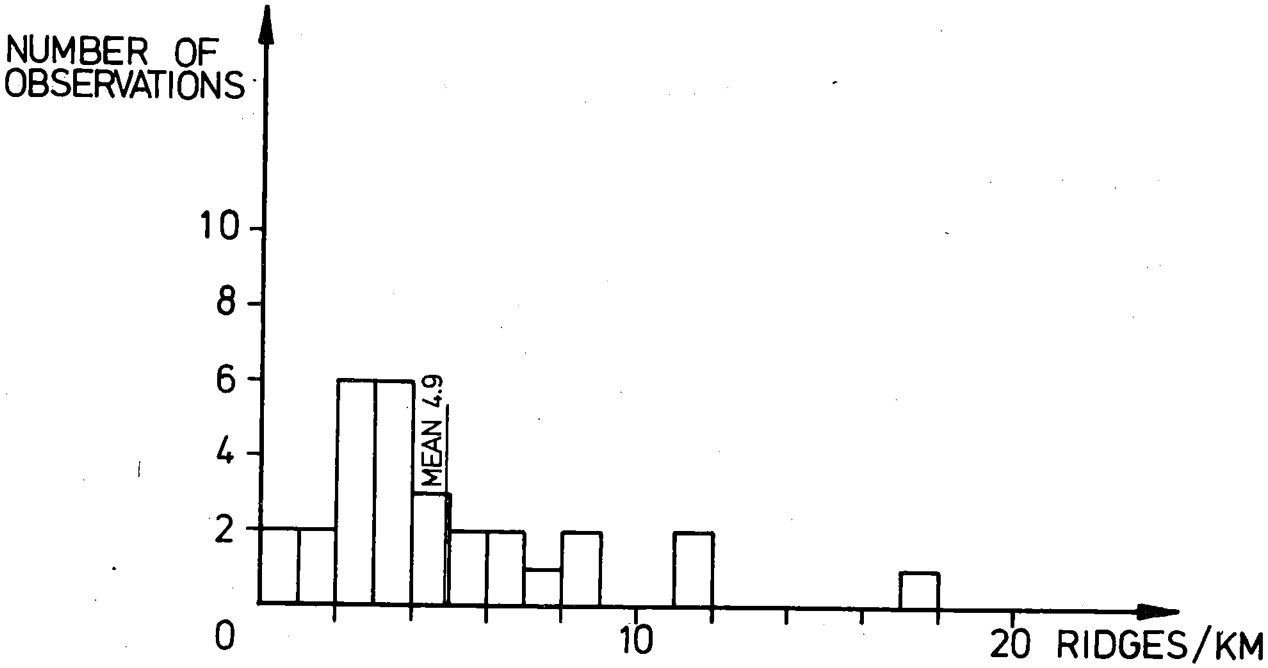
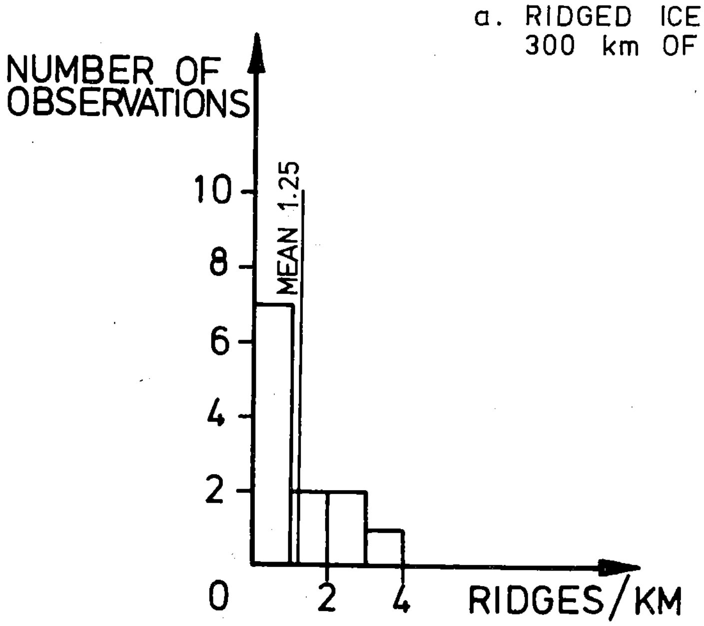


Fig. 3
A weathered ridge
field in the
Northern Baltic

Fig. 4
A ridge field
(hummocked ice field)
in the Northern
Baltic. Maximum
thickness about 20
metres



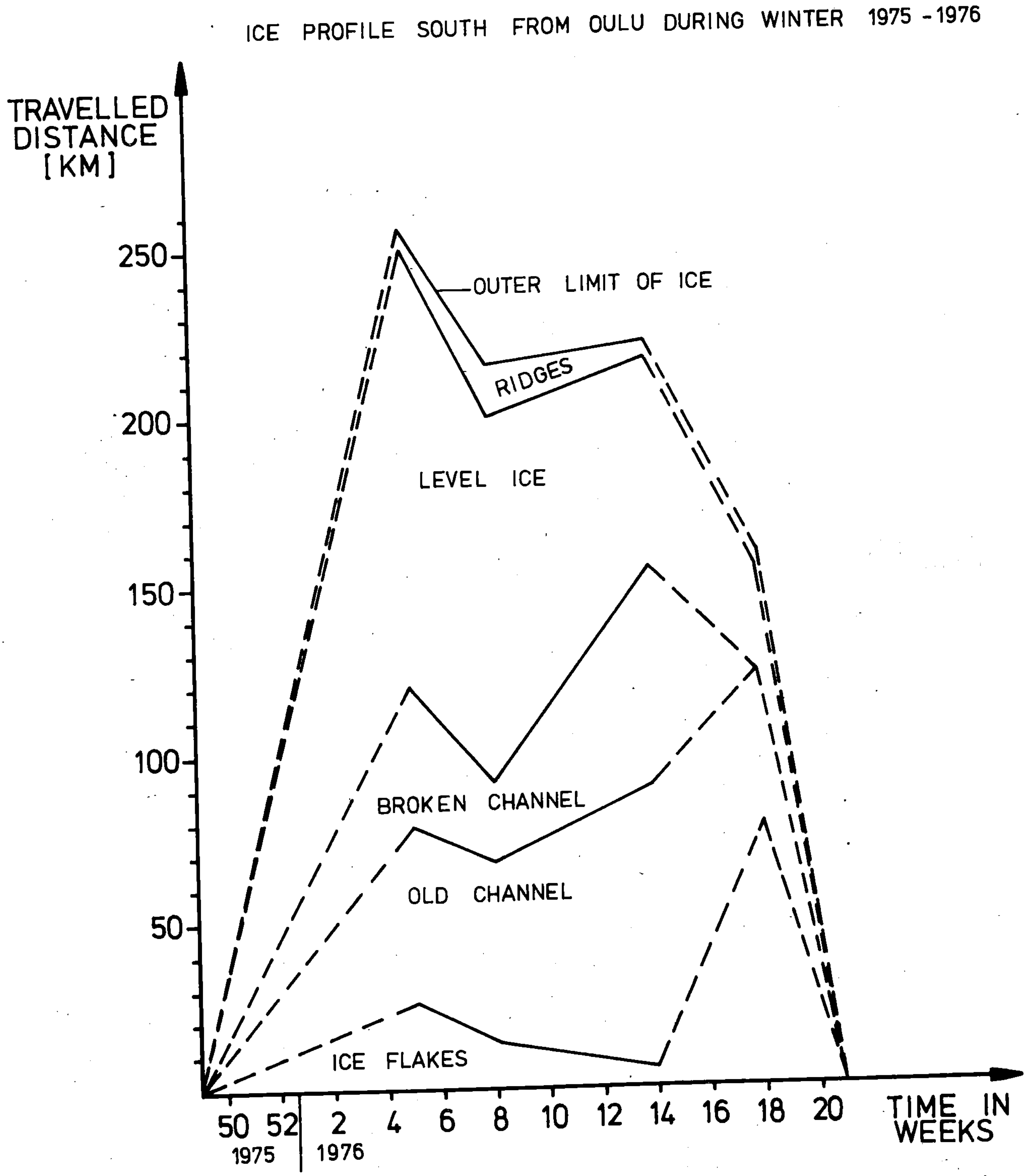
a. RIDGED ICE FIELDS ONLY CONSIDERED
300 km OF RIDGED FIELDS IS PENETRATED



b. TOTAL TRACK CONSIDERED
3600 km TRACK IS OBSERVED

FIG. 5 DISTRIBUTION OF BALTIC RIDGES ALONG ICEBREAKERS ROUTE. AVERAGE ESTIMATED RIDGE THICKNESS 4 m. WINTER 1976
PRODUCED FROM THE ORIGINAL DATA FOR /17/

FIG. 6 VINTBOTT - ANALYSIS /17/



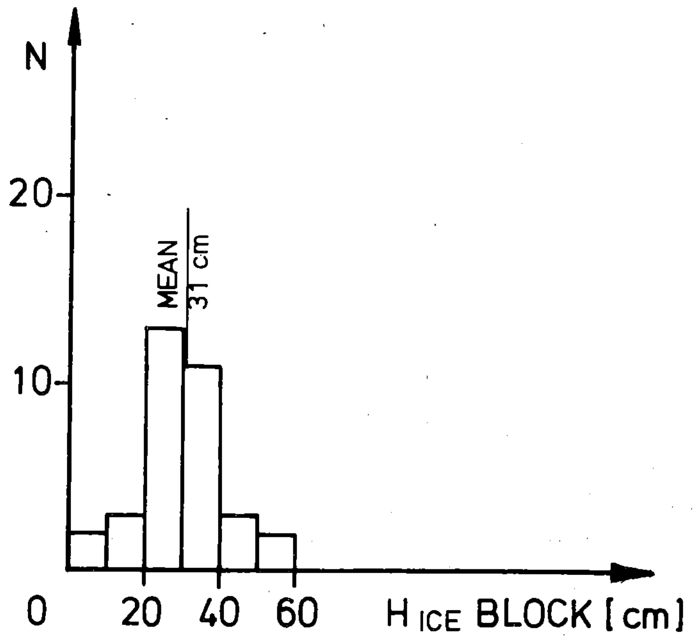


FIG. 7 ICE BLOCK THICKNESS IN RIDGES, 1974 – 1977 NORTHERN GULF OF BOTHNIA, DURING SHIP TESTS OF WÄRTSILÄ /9/-/12/

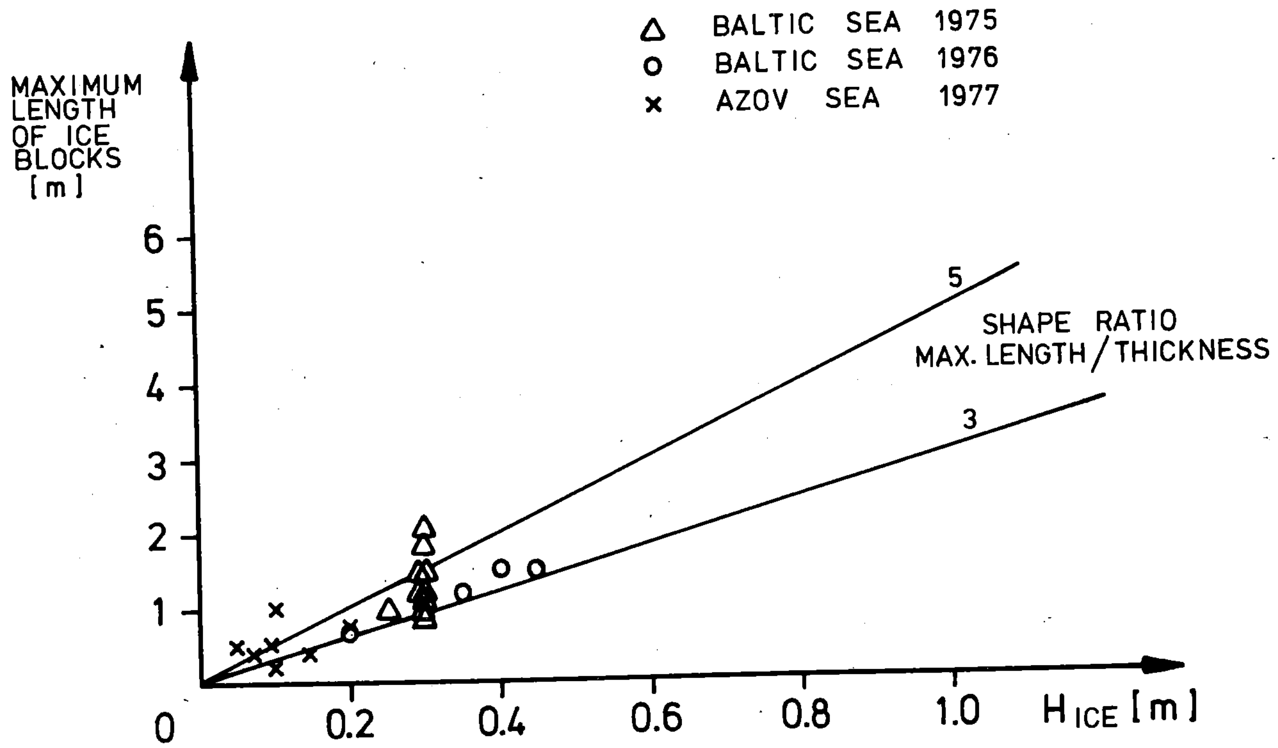


FIGURE 8 DIMENSIONS OF ICE BLOCKS IN RIDGES.
BASED ON ANALYSIS FROM SLIDES /3/,/10/,/11/

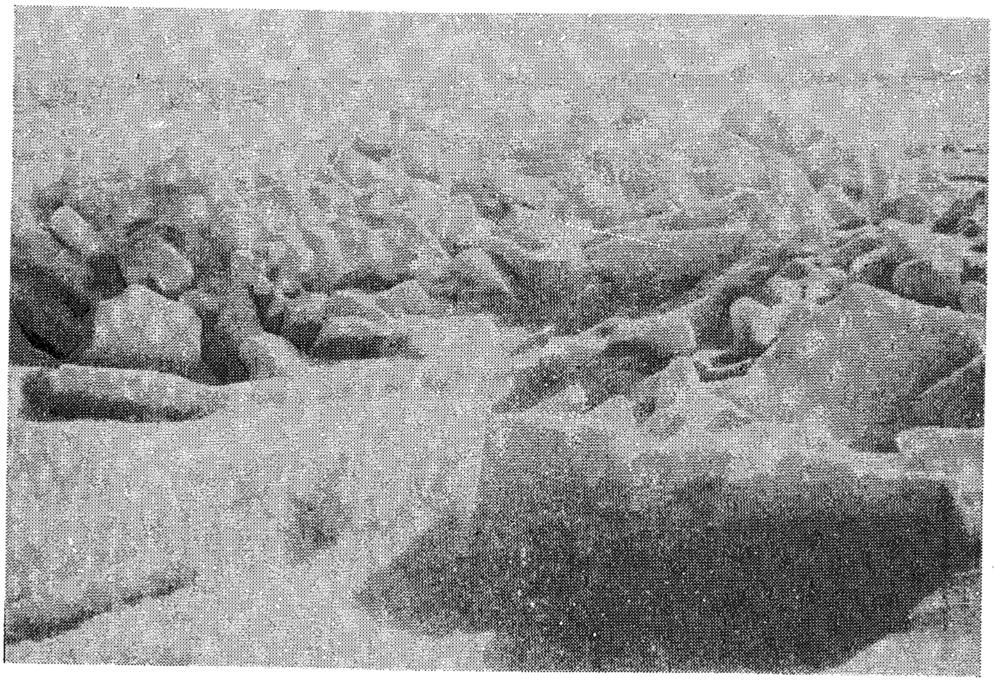


Fig. 9
A normal ridge sail in respect of the ice block size distribution

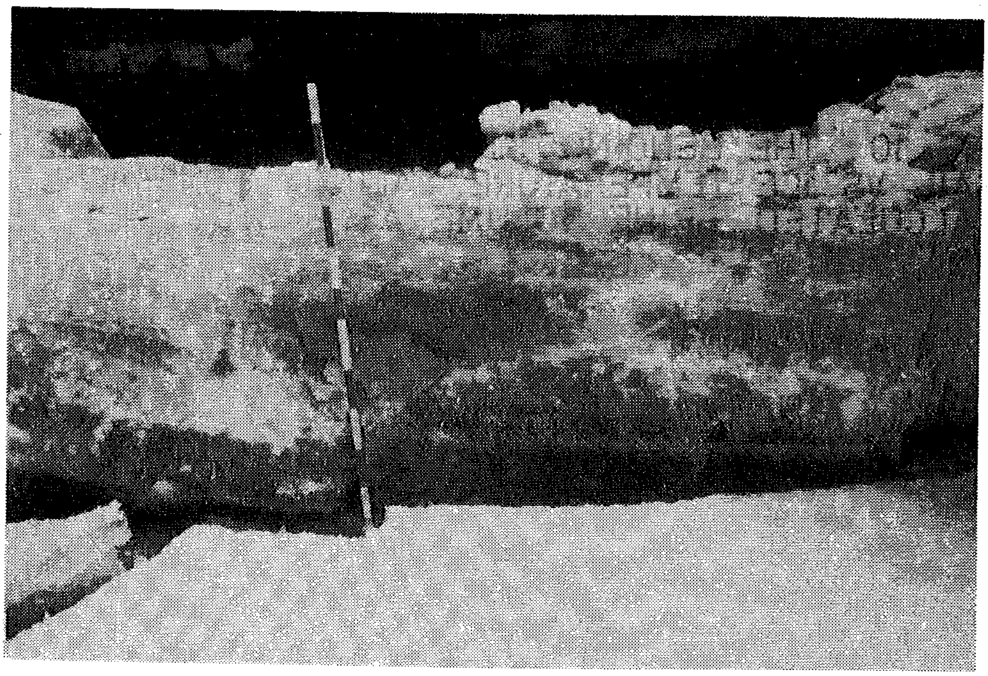


Fig. 12
A multiple rafted-frozen ice layer inside a ridge in the Azov Sea

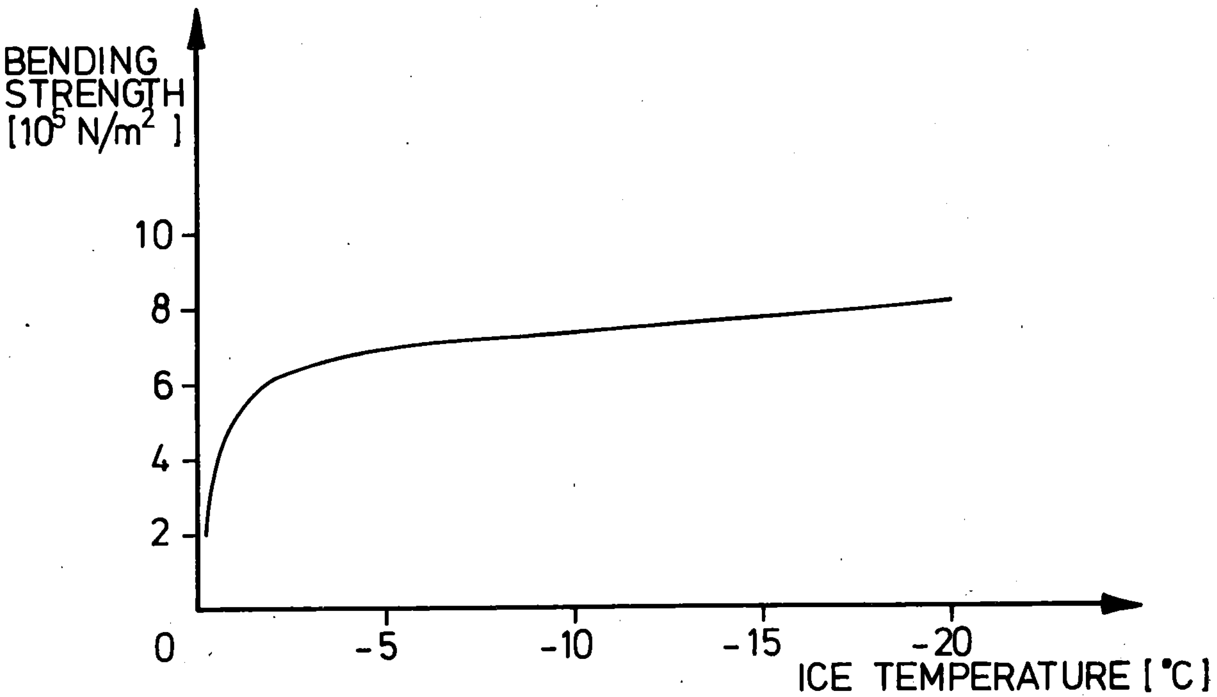


FIG. 10 THE BENDING STRENGTH OF ICE IN RIDGE SAIL VS ICE TEMPERATURE. SALINITY CONSTANT .5 ‰ CALCULATED, BRINE VOLUME AS BASIS

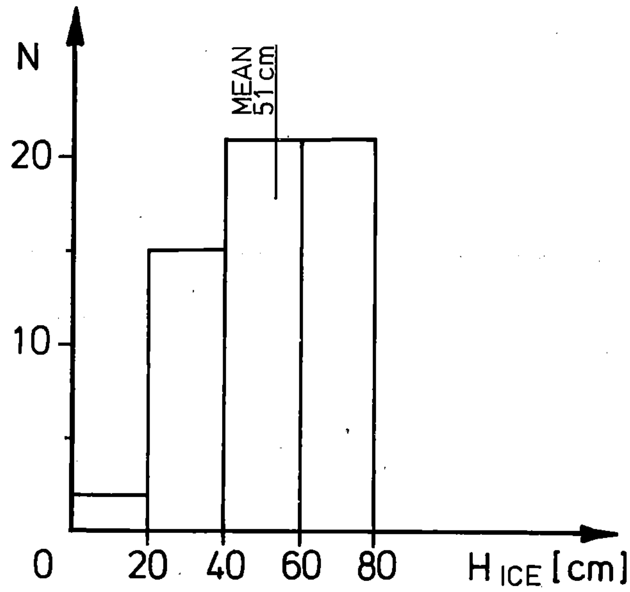


FIG. 11 LEVEL ICE THICKNESS AROUND RIDGES, 1974 - 1977 NORTHERN GULF OF BOTHNIA, DURING SHIP TESTS OF WÄRTSILÄ /9/-/12/

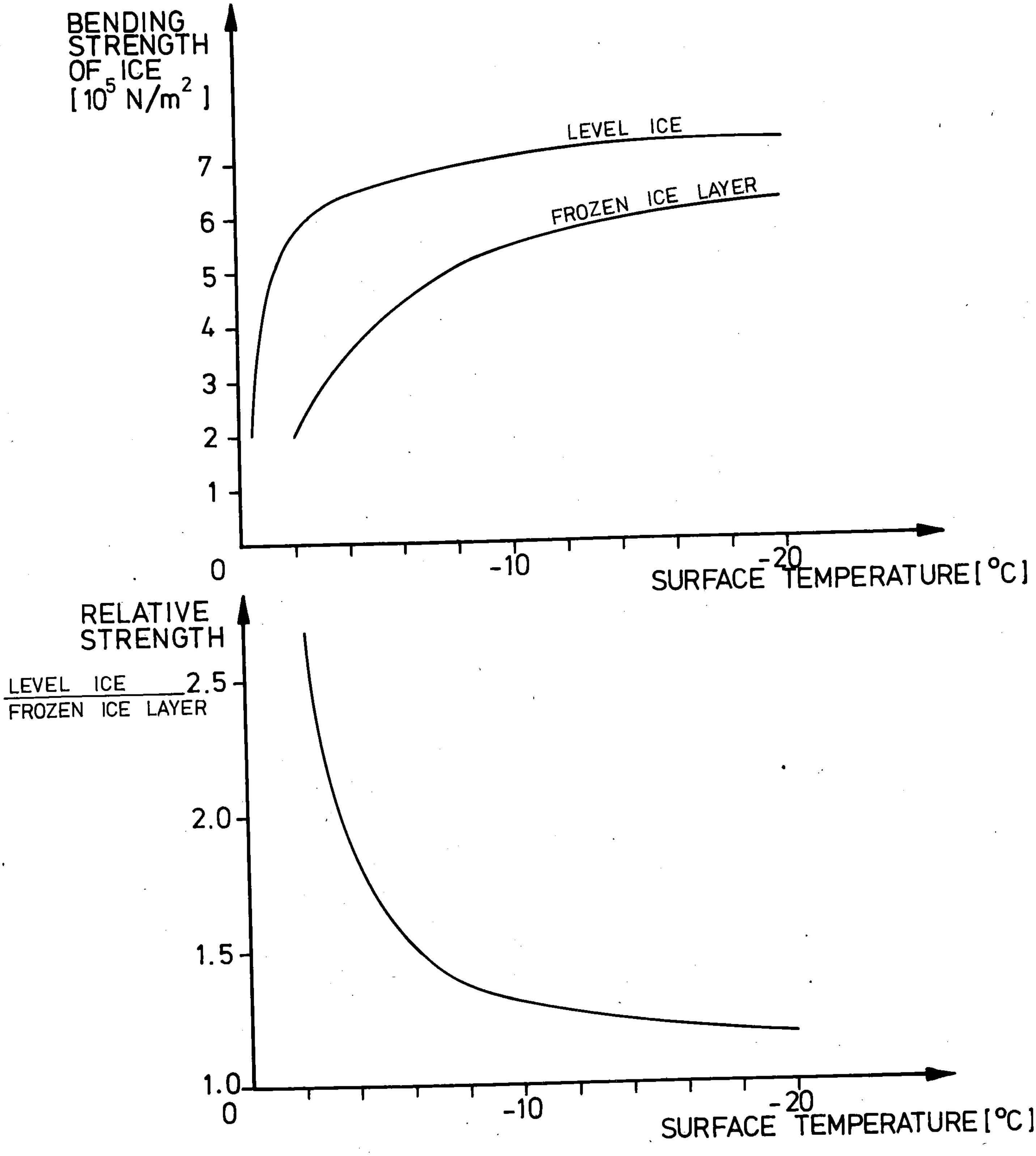


FIG. 13 STRENGTH OF LEVEL ICE COMPARED TO FROZEN ICE LAYER OF A RIDGE, CALCULATED BRINE VOLUME AS BASIS

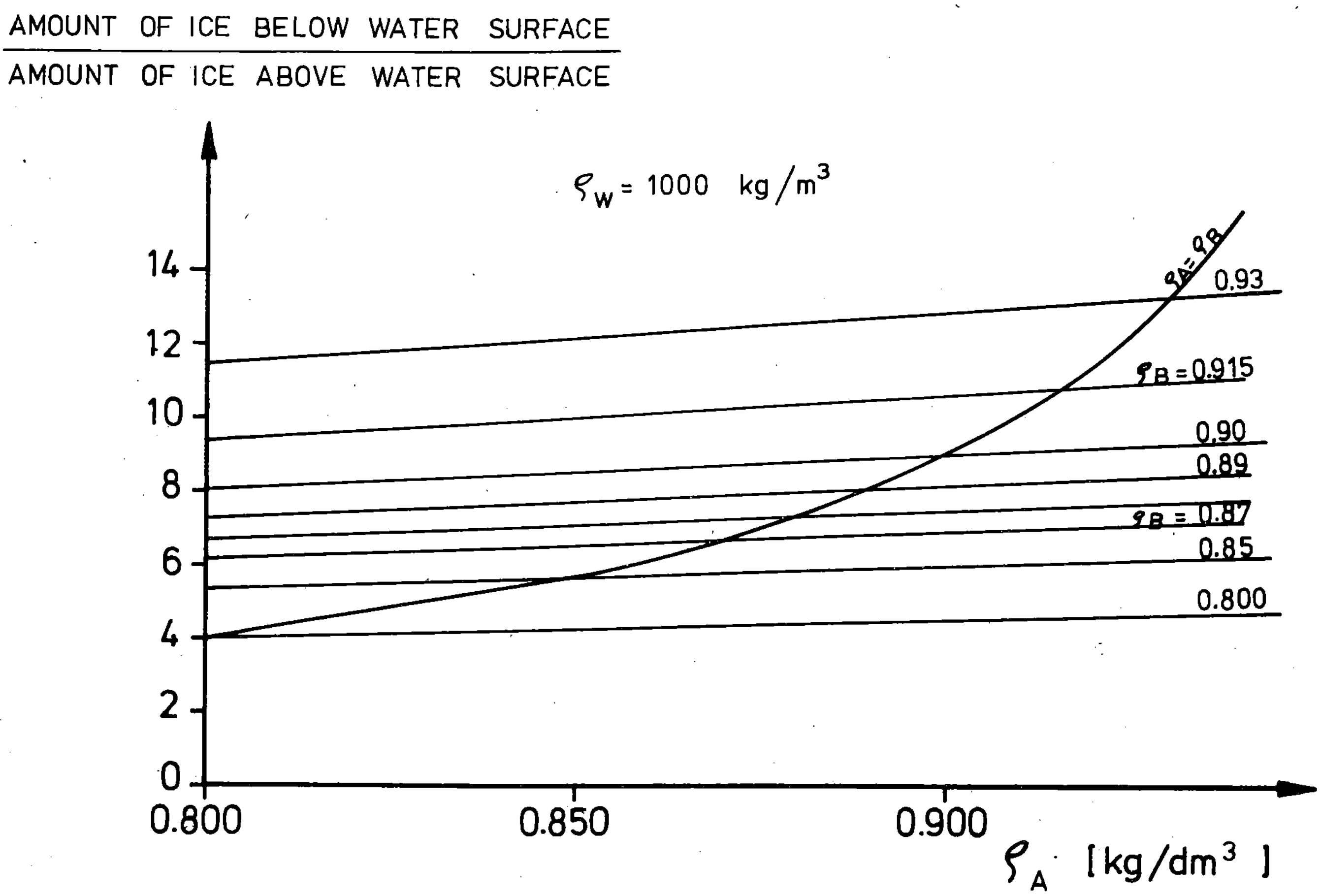


FIG. 14 ICE FLOATATION COEFFICIENTS FOR DIFFERENT ICE DENSITIES, NOTATION SEE FIG. 1

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