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MORPHOLOGY OF A BALTIC SEA ICE PRESSURE RIDGE

by

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Abstract

Six transverse profiles across a pressure ridge of typical height in the Gulf of Bothnia are presented. The sail was levelled. The keel and the porosity of the whole ridge were measured with a motor drill. Measurements of the sizes and orientations of 60 ice blocks of the sail were made. A diver photographed the keel and measured ten ice blocks of it.

The height of the sail was 1.06 m and the depth of the keel was 2.65 m. The average slope angle of the sail was 25° and of the keel 18°. The porosity was 27 % and it ranged between 21 % and 32 %. On the whole the ridge was in isostatic balance but local imbalance occurred. The thickness of the ice blocks correlated strongly with the profile height.

1. *Introduction*

Sea ice ridges occur every winter in the Baltic Sea and they constitute a severe problem to winter navigation and offshore structures. Knowledge of ice ridges, their size, geometry and internal structure, distribution and formation mechanisms, is therefore important. In various research areas in sea ice geophysics ridges play an important role. There is also an increasing interest in the morphology of ice ridges for better interpretation of remote sensing images.

Rubble fields of ice and ice ridges are formed in drifting ice fields and they consist of piles of ice blocks. The ice field is caused to move and deform by winds and currents. Ridges result from compressional and shearing motion between ice floes. Ridges pile up also in shallow water and on shore.

Many parameters in the current models of the ice ridge formation process have to be assumed because of the lack of measured data. The height of the ridge is an exception because it is relatively easy to study for example by laser profilometry and manual surveying techniques.

There is much less information about the size and shape of the ridge keel. The keel geometry can be measured by a scanning narrow beam sonar lowered under the water surface by a long rod or carried by a submarine. Also drills and divers have been used to make direct measurements.

There is only little information about the effect of ice thickness, ice block sizes and orientations on the ridge size and shape in the Baltic Sea, which are, however, very important to know for modellings and for remote sensing studies.

It is also important to know the porosity (percent of rubble feature volume consisting inter-block voids) of the whole ridge. There is no optic, acoustic, electromagnetic or any other technique that can probe the porosity of a rubble feature from the outside of a ridge. So determining porosity is one of the most difficult tasks of ice ridge studies, and it can be made only by drilling. When the porosity is known, the mass of an ice pile may be estimated. If we get to know the friction and cohesion in a ridge, it is possible for example to determine how much energy is needed for an icebreaking vessel to penetrate a ridge or how much explosive material will be needed to destroy an ice pile which jams a river.

Measurements of the porosity of a whole ridge have not been made in the Baltic Sea before. Also very few measurements of ice ridge porosity exist from the whole Arctic Sea area. The variations between rubble features are virtually unknown, thus it is not known whether porosity varies between different morphological characteristics (TUCKER *et al.* 1984).

This work is concerned with a careful study of geometry and internal structure of one pressure ridge based on field measurements in the Gulf of Bothnia (Fig. 1). 6 profiles were determined across the ridge whose upper surfaces were surveyed with standard levelling methods. The shape of the keel and the porosity of the whole ridge were measured with a motor drill. After the drillings a diver photographed the keel. According to his measurements the porosity measurements by the drill proved to be reliable.

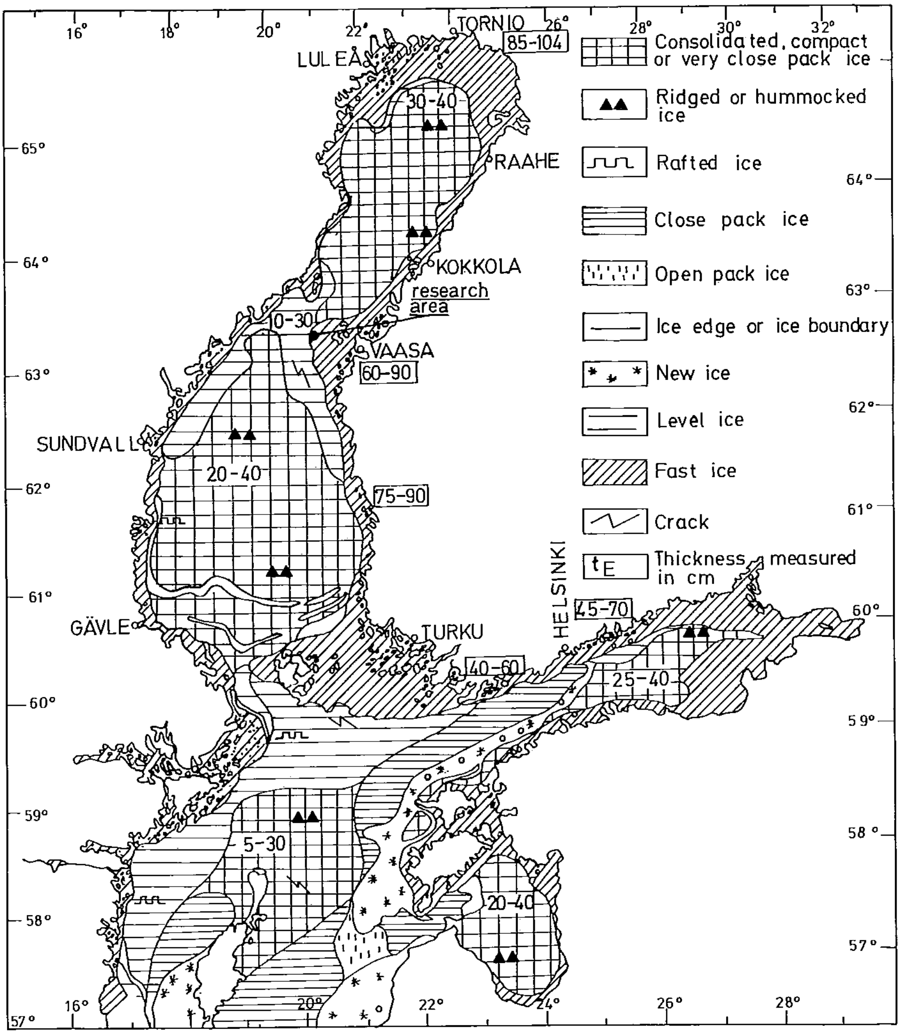

Figure 1. A routine chart for ice conditions on the 16th of March 1987 when the conditions were unusually severe. The study area is marked on the map.

The collected data also includes measurements of the dimensions, thickness and orientations of ice blocks in the ridge. Isostasy calculations based on the ridge size and porosity measurements were made.

Furthermore a cross-section in the ridge sail was made and both sides were mapped.

2. *Earlier studies*

The morphology, size, shape and structure of ice ridges, have been studied relatively extensively in the Arctic Sea. The measurements have been made mostly by surveying methods, drill and narrow beam scanning sonar. Some salinity, temperature and density profiles have also been made. However, much more data of Arctic ice ridges and specially of their internal structure is needed.

Measurements of several ridge profiles in the Baltic Sea are given in PALOSUO (1975). He studied the size and geometry of ridges by means of diving. He also examined the applicability of a narrow beam scanning sonar for measuring the ridge keel, finding it to be an useful method to study the shape of a keel. After this experimental study there has not been any sonar available for ridge studies in Finland.

The height of the most of the ridges measured by Palosuo varied between 0.5 to 2 m. The keel depth varied typically from 6 to 14 m. Sail inclination was between 10° and 50° and the average was 30°. Keel inclination was between 30° and 60°. The profile geometry can be approximated quite well by a triangular shape for both the sail and the keel (Fig. 2). The dimensions varied to a great extent and they were mainly dependent on the thickness of ice.

It was characteristic of the keel that floes in a depth greater than 1 m below the sea level were not frozen together but remained loose. It was also noticed that the ice blocks in the sail were loose or only lightly frozen together.

On the whole very few measurements of porosity of ice block accumulations exist. In mechanistic models of sea ice pressure ridges and rubble features, estimates

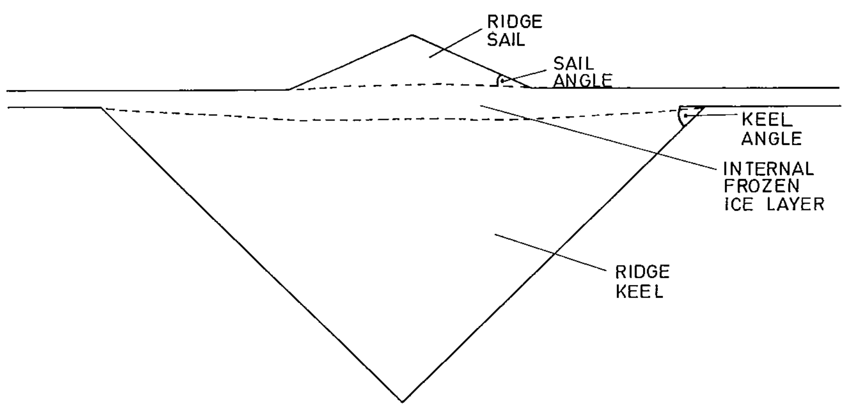

Figure 2. Idealized cross-sectional profile of a ridge.

of 10 to 30 % void ratios have been assumed, based upon measurements and theoretical considerations of soil and other aggregate porosities. There are four porosity estimates obtained from actual measurements. (TUCKER *et al.*, 1984).

The cavities of one large pressure ridge (10–12 m) in the Beaufort Sea were detected during drilling by RIDGBY and HANSON 1976, (*cit.* TUCKER *et al.*, 1984) and a rough estimate of the porosity was from 5 to 10 %. In a laboratory study, where rubble was loaded into a box designed for a model shear test, measurements of the volume of ice in the box were also made. According to the measurements the porosity was calculated to be from 19 to 50 % (WEISS *et al.* 1980, *cit.* TUCKER *et al.*, 1984).

TUCKER *et al.* (1984) have developed an ice ridge porosimeter which can be lowered into a drill hole through a ridge. They found the instrument useful, but in need of many improvements; for example the prototype was not capable of detecting voids filled with sea water. Also the ice remnants from the drilling occasionally caused problems. However, they measured successfully the porosities of three grounded ridges in the Prudhoe Bay by detecting voids with the porosimeter of two drill holes of each ridge. The average porosity calculated of the six measured holes was 21 %.

According to KOVACS and MELLOR (1974) the porosity of Arctic ridges varies between 10 and 40 % depending on the deforming origin. In the Baltic Sea a study of porosity of two ridge sails were made by KEINONEN (1977). He sawed a cross-section through both ridge sails and mapped the sides of the cross-sections. He found the porosity to be between 36 and 43 %.

An intensive study of ridge sail height distribution in the Gulf of Bothnia was made by LEPPÄRANTA (1980). He made the observations with a laser profilometer from an ice-breaker deck. According to him the mean sail height varied between 38 and 67 cm and ridge density was between 2.1 and 22.1 ridges/km. The cutoff height for sails was 30 cm.

3. *The method of measurements*

This report presents the results of a study of one first-year pressure ridge in the Gulf of Bothnia. The observations were made about 50 km northwest of the city of Vaasa and about 15 km southwest of the island Valassaaret. The research vessel Aranda was attached firmly into fast ice near to its outer edge (63°17.8'N, 20°48.1'E) (Fig. 1). The field program took place during the last two weeks of March, 1987.

A pressure ridge of typical height (Fig. 3 and 4) was identified at the edge of

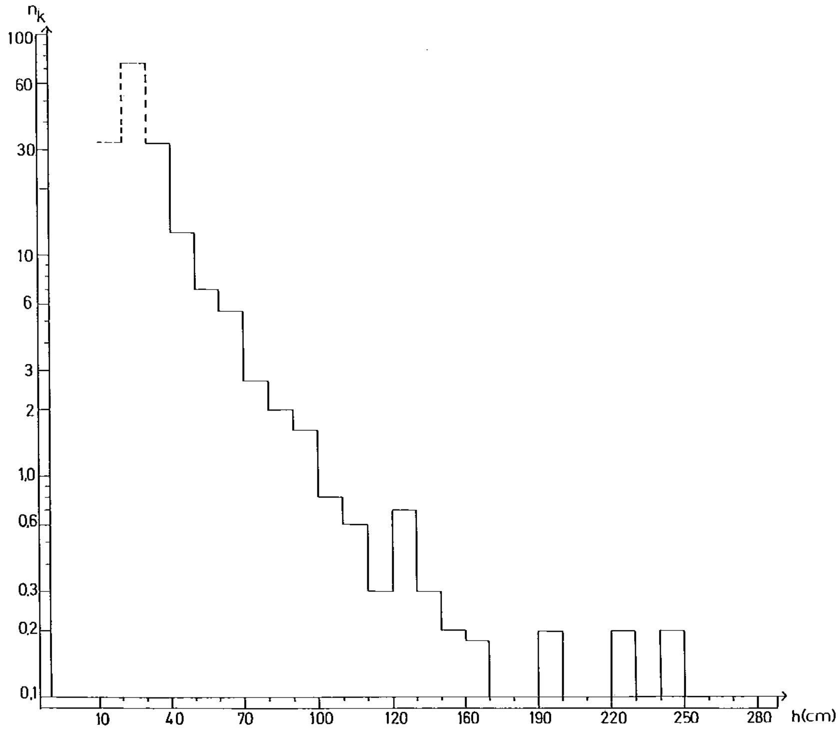

Figure 3. Distribution of sail heights (*h*) in the Gulf of Bothnia during the winter 1979. Observations were made with a laser profilometer. Class interval is 10 cm and n_k gives average number of each class along 10 km profile; cut off height is 30 cm (LEPPÄRANTA 1980).

the fast ice (Fig. 5). The locally highest point along the ridge was selected for one profile (B). The whole area of study was fixed around this point. The studied profiles are marked in Fig. 6.

Further, about 300 m north of the studied area the ridge was grounded on a small islet rock, Råbergskallan. This grounded ridge was about 5 m high. The depth of the water around the studied area was about 17 m so here the ridge was floating freely.

Observations include the determination of the surface relief of the ridge sail and the snow thickness by levelling. After that the size and geometry of the keel and the porosity of the whole ridge were determined by a motor drill. This drill has been designed by Dr. Austin Kovacs for ridge profiling (diameter = 5 cm). The drilling holes were made at about 1–3 m intervals along the profiles.

Figure 4. The studied ridge.

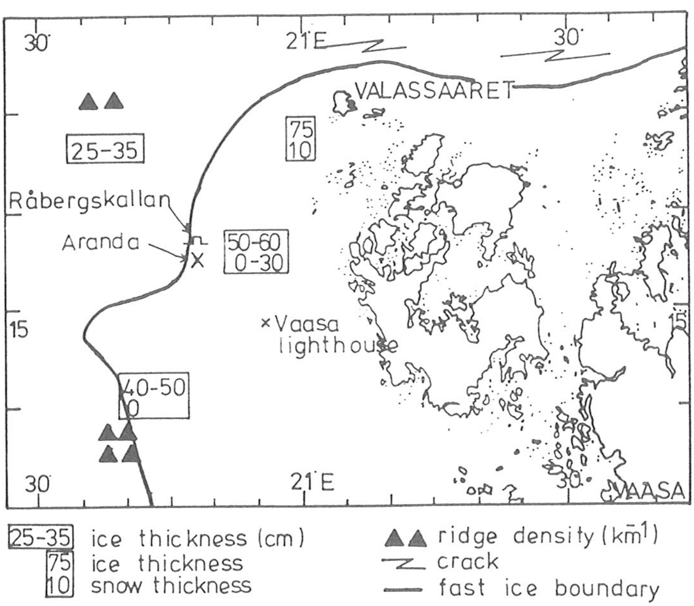

Figure 5. The location of the studied area was between Aranda and Råbergskallan.

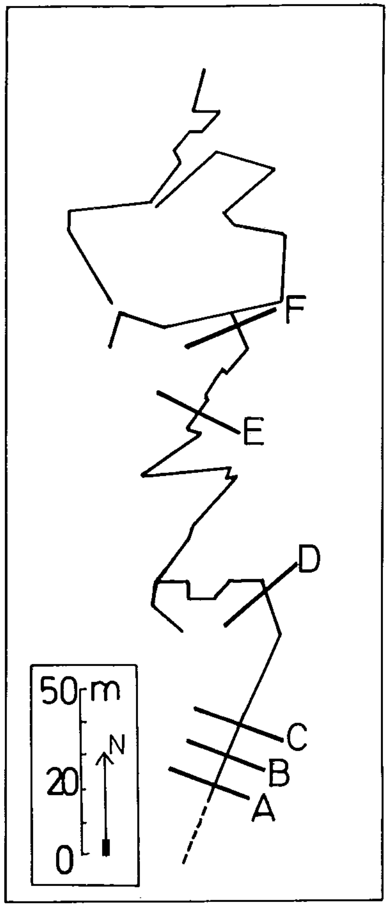

Figure 6. The studied ridge and the locations of the profiles.

The dimensions of ten ice blocks in every section were measured. The blocks were selected randomly from both sides of the sail. The measurements were made of the longest axis of the top surface of the block and the short axis which was fixed at the half way of the longest axis perpendicular to it. The thickness was also measured. The orientation of the blocks were defined by measuring the steepest angle of the surface of the block (dip).

At the end a diver photographed and filmed the keel and measured the dimensions of 10 ice blocks under the profiles A, B and C.

4. *Results*

4.1 Profile geometry

The studied ridge was a pressure ridge of typical height in the Gulf of Bothnia. The sail was quite symmetrical and the keel was very low and wide. It is likely that the ice was pressed against the fast ice edge and the keel had spread when the drifting ice has slid on top of fast ice.

The shape of the ridge was the clearest along profile B, as can be seen from the cross-section in Figure 7. The drill holes and voids are marked in the figure. The porosity of B was 32 %. All measured values of the studied profiles can be seen in Table 1. The average height of the studied ridge was 1.06 m and the depth was 2.65 m.

According to this study and PALOSUO's (1975) measurements the higher the ridge is the deeper it is (Fig. 8). The average free board to depth ratio for this ridge was calculated to be 1 to 2.8. KOVACS (1971) has determined the same mean ratio to be on an average 1 to 4.5 for first year pressure ridges in the Arctic and PALOSUO (1975) got a mean ratio 1 to 5.3 in the Baltic Sea. The ratio of the studied ridge here was bigger because the keel was relatively wide and low.

The average width of the ridge sail was 4.6 m. The higher the ridge was at a profile the wider it was.

The average angle of the slope of the sail was 25° with a standard deviation of 5.3°. The slope angles were in close agreement with 24° reported by KOVACS (1974) and 25° with standard deviation of 5° reported by TUCKER *et al.* (1982). PALOSUO (1975) measured 13 ridges in the Baltic Sea and the average sail slope angle was 30°.

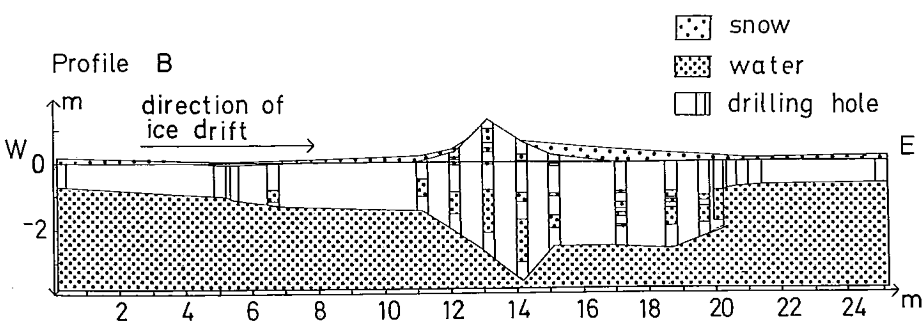

Figure 7. Profile B.

Table 1. Measured values of the studied profiles.

Profile	A	B	C	D	E	F
height (m)	0.5	1.27	1.07	0.66	1.22	1.72
depth (m)	2.09	3.53	2.94	–	2.41	2.3
width (m)	2.4	5.3	5.0	4.55	5.2	5.0
height/depth	1/5.2	1/2.8	1/2.7	–	1/2	1/1.3
sail mass/keel mass	1/6.9	1/7.6	1/4.8	–	1/4	1/8.4
porosity (%)	21.2	32.3	31.6	–	29.6	22.1
average thickness of ice blocks (cm)	13.3	19.7	20	19	21.8	24.4
sail angle at the drifting ice side (°)	33	34	25	10	15	27
sail angle at the fast ice side (°)	22	27	27	28	29	24
keel angle at the drifting ice side (°)	12	37	22	–	10	10
keel angle at the fast ice side (°)	20	24	20	–	12	10

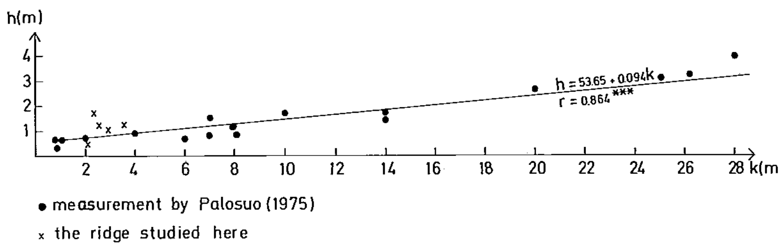

Figure 8. Sail height (*h*) versus keel depth (*k*).

The average angle of the slope of the keel was 17.7°. According to earlier studies the slope of the keel is normally about 10° steeper than the slope of the sail. The formation process of the ridge is likely to be the cause of the small angle.

4.2 Isostasy

The isostasy of the ridge was defined by calculating separately the amount of ice under and above the water. The weight of snow on the ridge sail was taken

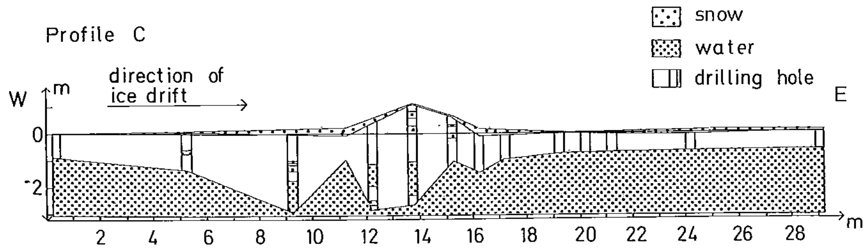

Figure 9. Profile C.

into account. The density of ice was supposed to be homogenous in the whole ridge and the used value was 871 kg/m^3 measured from the ridge sail by KEINONEN (1977).

The average keel-sail mass ratio of the six measured profiles was 1/6.5. The ratio varied from 1/4 to 1/8 between different profiles. The isostatic value was calculated by using Archimedes' law and it resulted in a ratio of 1/6.7. Consequently it can be said that the whole ridge was in isostatic balance, but the separate profiles were in imbalance. Local isostatic anomaly in ridges has been found in many studies before (for example ZUBOV 1945, KOVACS 1971, WEEKS *et al.* 1971, PALOSUO 1975).

For example the keel-sail mass ratio of profile C (Fig. 9) was 1/4.8. So here the sail was too massive for the keel (note in Fig. 9 that the porosity of the keel is high) and the upper surface at the edges of the sail shows downward deflection under the water surface. This phenomenon has been observed in many first-year ridge studies (KOVACS *et al.* 1973). Imbalance in one place is always compensated somewhere in the icefield around it.

4.3 Internal structure

4.3.1 Porosity and internal frozen icelayer

The porosity of the ridge was 27.4 %. It varied from 21 to 32 % between separate sections. The voids between ice blocks in the sail were partly filled with snow and in the keel they naturally were full of water. The porosity between the keel and the sail did not differ from each other significantly.

The internal frozen ice layer (Fig. 2) was in some places thicker than the ice field around the ridge (profiles B, C and E, Figs. 7, 9 and 10) and in some places no clear icelayer was identified at all (profiles F and A, Figs. 11 and 12). In

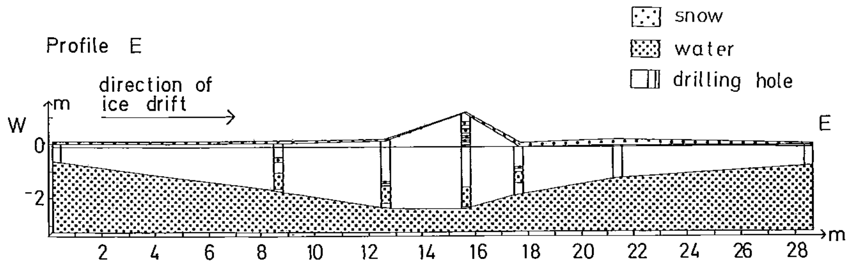

Figure 10. Profile E.

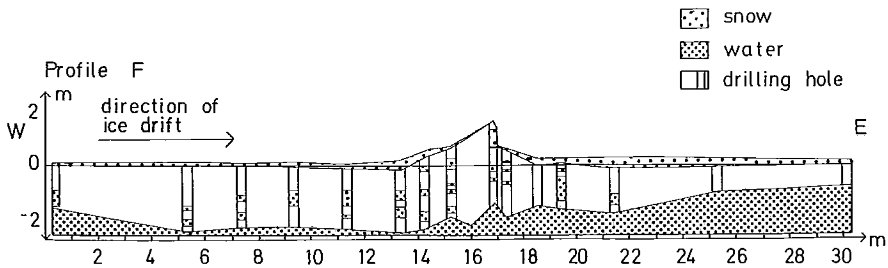

Figure 11. Profile F.

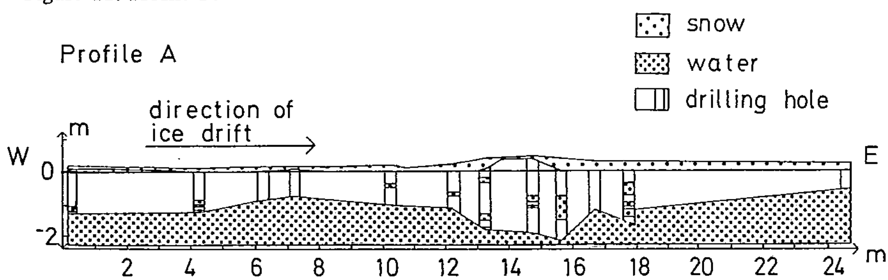

Figure 12. Profile A.

profile E (Fig. 10) the internal frozen ice layer was about 1.5 m thick. The ice-field around the ridge was 65–80 cm thick and 75 cm on an average, so here the internal frozen ice layer was about two times thicker than it. The frozen ice layer is formed when the water between the ice blocks freezes. Perhaps because there is a smaller amount of water to freeze and the ice blocks are cold already the ice-layer grows thicker. This probably partly explains the additional thickness of the icelayer below the sail. However, it is interesting that the thicker icelayer was not found in every place. More information, especially crystallographic studies, is needed for understanding fully the formation process of the ice layer.

4.3.2 The ice blocks in the ridge

The average thickness of the ice blocks in the ridge sail was 20 cm. Their average longest axis was 92 cm and short axis was 66 cm. There was positive correlation between the longest and the short axises: the longest axis was about 1.5 times longer than the length of the short axis (Fig. 13).

The thicker the block was, the longer the longest axis. The average ratio between the longest axis and the thickness was 4.6. KEINONEN (1977) had got a corresponding ratio 2.95–3.6 in the Baltic Sea.

In the keel the average thickness of the blocks was 22 cm. The average longest axis was 118 cm and the shortest axis was 66 cm. Therefore the blocks under the water were a little larger than the blocks in the sail.

Under profile B (Fig. 7) some exceptionally large ice blocks were found: in the bottom of the keel there was a 5 m long and 70–100 cm thick unusually large ice block and at the west side of the keel there was a 2 m long and about 80 cm thick ice block in an oblique position. Because these blocks were much

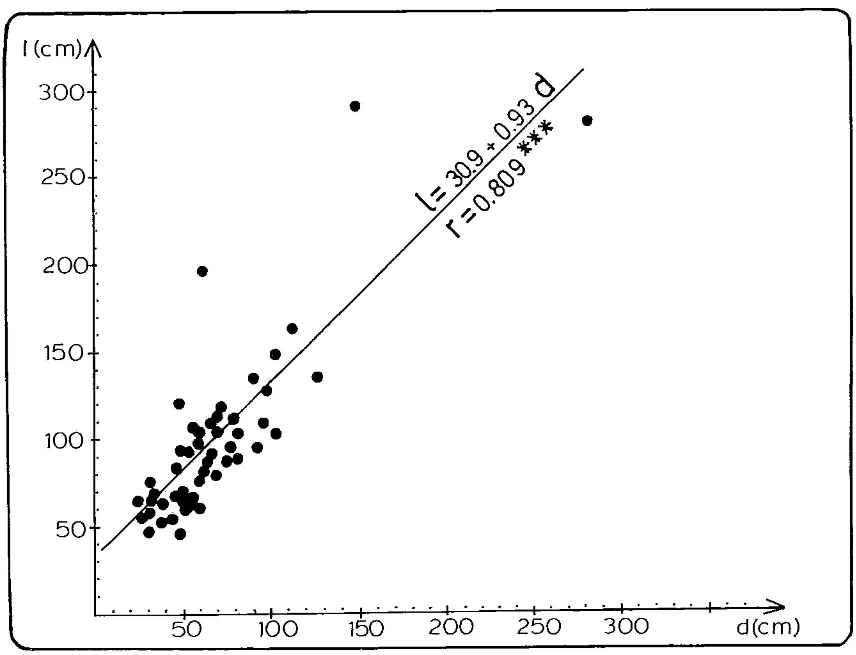

Figure 13. The longest axis (l) versus the shortest axis (d) of ice blocks.

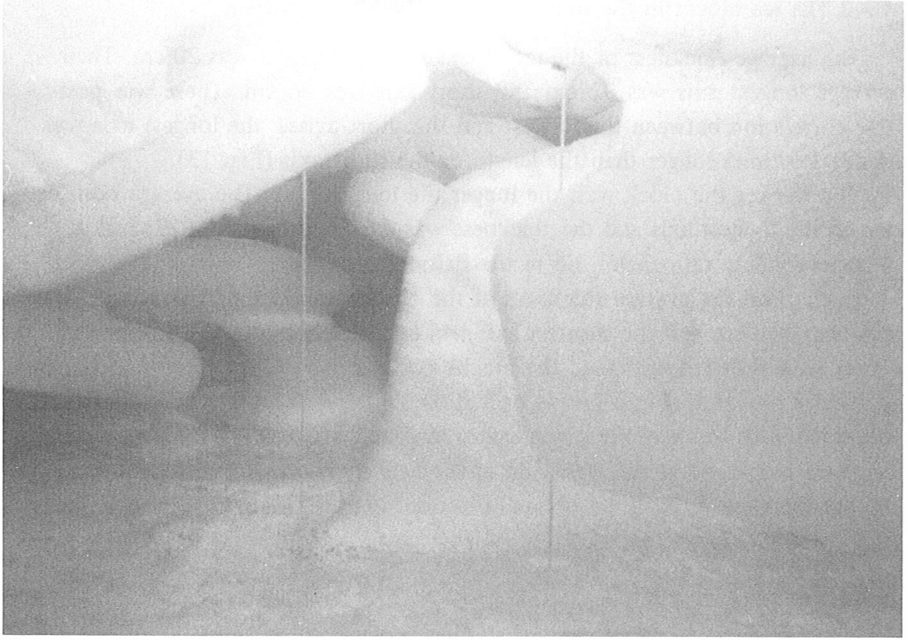

Figure 14. Photo of the keel under profile B. Below there is the large 5 m long and 80 cm thick ice block which lied at the bottom of the keel. The hanging lines are marks for the diver.

thicker than the other ones, they must have been parts of a drifting icefield which was about 80 cm thick near the ridge (the fast ice was about 65 cm thick).

According to the diver the large horizontal ice block was also several meters wide. He noticed that the smaller ice blocks in the keel were in disorder and that there were no regularities between the sizes of the blocks and their situations. PALOSUO (1975) has also found some unusually big ice blocks in the bottom of the keel.

The shapes of the blocks in the keel varied (Fig. 14). The water had melted and rounded the corners of the blocks and they were mostly not frozen together. But also in many places there had formed ice between the blocks which connected them with each other.

The average steepest slope of the blocks in the sail was 36. There was no correlation between the sail height and the orientation of the blocks. A weak correlation existed between the block size and its orientation: the larger the block was, the more horizontally it laid.

A cross-section in the ridge sail between profiles B and C was made by an ice

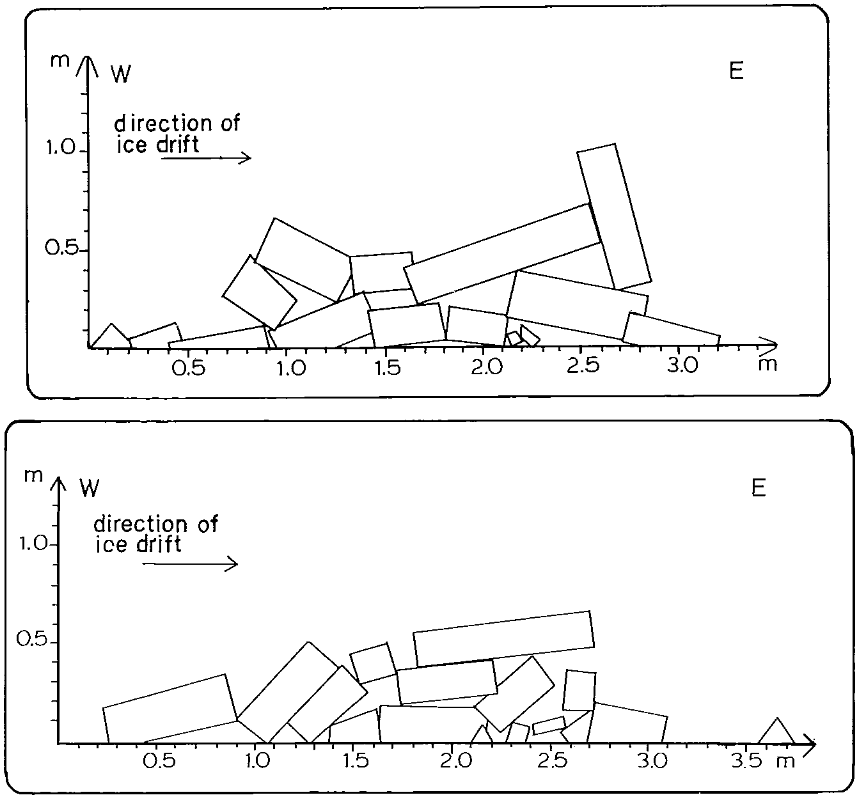

Figure 15. A schematic mapping of both sides of the cross-section made in the sail.

pick and a saw. Both sides of the cross-section were mapped. Figure 15 is a sketch of how the ice blocks are situated in relation to the course of the ridge. It is easy to see how the ice blocks are pushed on each other along the movement direction of the pressed ice.

The positive correlation between the height of the profile and the average thickness of the ice blocks along it was clear (Fig. 16). The area of the cross-section of the sail and the block thickness correlated also positively with each other. Thus at places where the ice was thicker the ridge had grown higher.

The icefield around the ridge was about 65–80 cm thick and the iceblocks in the ridge were about 20 cm thick. Consequently the ridge was formed earlier in winter perhaps in a refrozen lead. As mentioned above, it is likely that the ridge had pressed against the fast ice. In some places the drifting ice had slid on top of

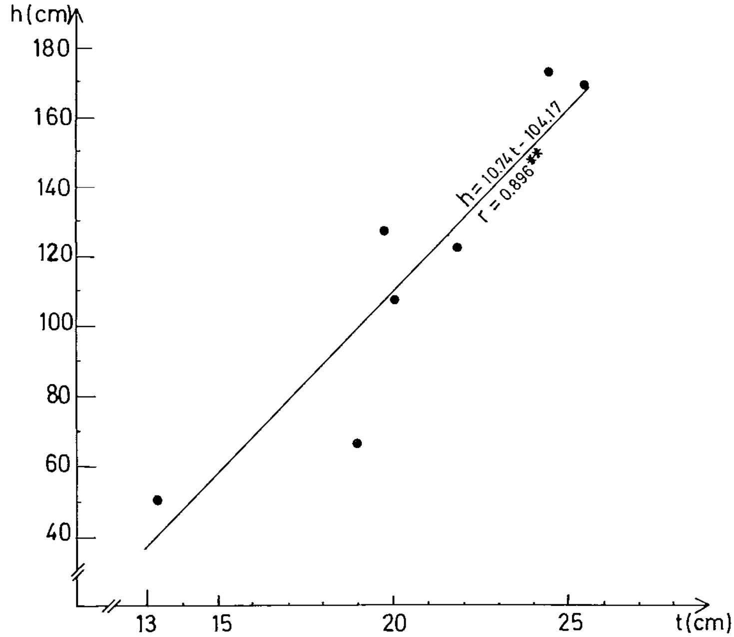

Figure 16. Sail height (h) versus ice block thickness (t) along the profile.

Figure 17. Profile D.

the fast ice. For example profile D (Fig. 17) was placed at the end of an ice slab (see Fig. 6), which was slid on to the fast ice. Note that in this profile the keel was missing under the top of the ridge. The keel was left behind when the ice slab had slid on top of the fast ice pushing the ridge sail in front of the slab. According to the drillings there is no sign of the keel 7 m from the sail towards the seaside. Not until 26 m away from the sail was there 3 m ice under the level ice. Because there were no measurements between the two points, the size of the keel was estimated in the figure (dashed line).

5. *Discussion*

If we compare the studied ridge to ridges studied by PALOSUO (1975) it was a quite typical pressure ridge. The difference between the porosity of the studied ridge and the two ridge sails studied by KEINONEN (1977) is interesting. It seems that the porosities of whole ridges (the sail and keel together) are about 10 % smaller than earlier assumed in the Baltic Sea. Of course much more data are needed to make sure of this result.

Compared with first-year ridges in the Arctic this ridge was small. TUCKER *et al.* (1982) have studied several ridges in the Arctic Sea and they also got a positive correlation between sail height and thickness of ice blocks. They noticed that ridges formed of thin ice (less than 1 m) more often reach their limiting height – the height after which the ridge doesn't grow upwards anymore but may go on widening – than the ridges fromed of thick ice, because the pressure force is seldom so high that ridges formed of thick ice can reach their limiting height. Consequently the height of ridges of thick ice depends mostly on the pressure force and the height of thin ice depends more often on the thickness of the ice. The ridge studied here was formed of thin ice but it had not reached its limiting height: its height was determined by the pressure force, which had been too small for it to reach the limiting height.

It has been found that in the Arctic the sail height and keel depth ratio varies between 1/3 and 1/9. The average ratio is calculated to be 1/4.5 (KOVACS.1971). PALOSUO (1975) got a ratio of 1/5.3. The ratio of 1/2.8 measured here was bigger than earlier definitions because of the lowness and wideness of the keel.

6. *Conclusions*

In this study the geometry and internal structure of one freely floating pressure ridge at the edge of the fast ice in the Gulf of Bothnia was studied carefully. According to this study it can be said that the morphology varies along one ice ridge. For example at places were an ice slab had slid up upon fast ice, there were differences between the morphology of the ridge at the end of the ice slab and at the side of it. The sail-keel mass ratio also varied along the ridge; different places of the ridge were in isostatic imbalance. On the whole the ridge and the surrounding ice field near the ridge were in isostatic balance.

Good measurements of the density of the ice are needed both from the keel and the sail in order to determine the isostacy of the ridges better. The most important measurements of this study were the porosity definitions which had not been made in the Baltic before. The porosity was 27 % and it seems that the porosity of the whole ridge is approximately 10 % smaller than earlier assumed in the Baltic.

As far as this work is concerned, it was an experimental study for further studies of the morphology of sea ice ridges in the Baltic. Valuable experience was gained of new methods which will be used in future.

In future studies about ice density, brine and temperature profiles are needed of Baltic ridges. Also more data are needed of ice block dimensions of different sized ridges to interprete remote sensing images better.

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