ed. This is at the least 3-4 times the expected value which might be explained partly by inaccurate geometrical assumptions and, most likely, by a drag contribution from currents, although the meteorological postcasts do not indicate any strong currents. Even the rather low current velocity of 0.1 m/s, however, would have been sufficient to cause drag of the same order as the wind drag.

8. Analysis of the Björnklack case in the light of previous experiences and current design recommendations

In the design philosophy applied to the Swedish lighthouses a certain taking of risks has been accepted, at least for the smaller lighthouses, since it has been realized that the costs for obtaining absolute safety against ice overloading would have reduced the number of feasible projects considerably.

It has been realized that the ice forces depend on a large quantity of environmental conditions of a more or less random character, resulting in a multitude of possible combinations and, to use probabilistic terms, in an extraordinarily wide frequency distribution.

When the design rules for the first Swedish open sea lighthouses were formulated, the complex nature of the ice force prediction problem was probably imagined, but since experiences were so few, a parametric dissolution was not possible.

The design requirements were expressed by some different expressions, depending among other things on varying design philosophies used in applied codes (serviceability or ultimate limit state design), but in principle the ice force was expressed as a function of the contact area and the effective mean ice pressure:

$$F = b \cdot h \cdot p_{eff}$$

where the product $h \cdot p_{eff}$ was initially expressed without disintegration of the factors h and p_{eff}. Different design values for this product were given for the west coast, the Baltic proper and the Gulf of Bothnia.

In the Bothnian Sea and the Bothnian Bay there are today about 20 Swedish lighthouses located in areas with what can be roughly described as open sea conditions. Along the Finnish coast there are some more lighthouses of similar type as well as several smaller lightpiers with water line diameters around 1 m.

In general, the larger structures have withstood the ice forces without significant damage except for some abrasion and minor vibrational effects. Several smaller structures have been damaged, however, and some of them even destroyed. Thus some Finnish lighthouses of the 1 m diameter class have been damaged as well as some Swedish structures with diameters between 2.5 and 3.0 m.

An overview of the situation with respect to the ice resistance of the Swedish lighthouses in the Bothnian Sea and Bay was published first in 1974 and later, with some modifications, in 1983 (Figure 8.1).

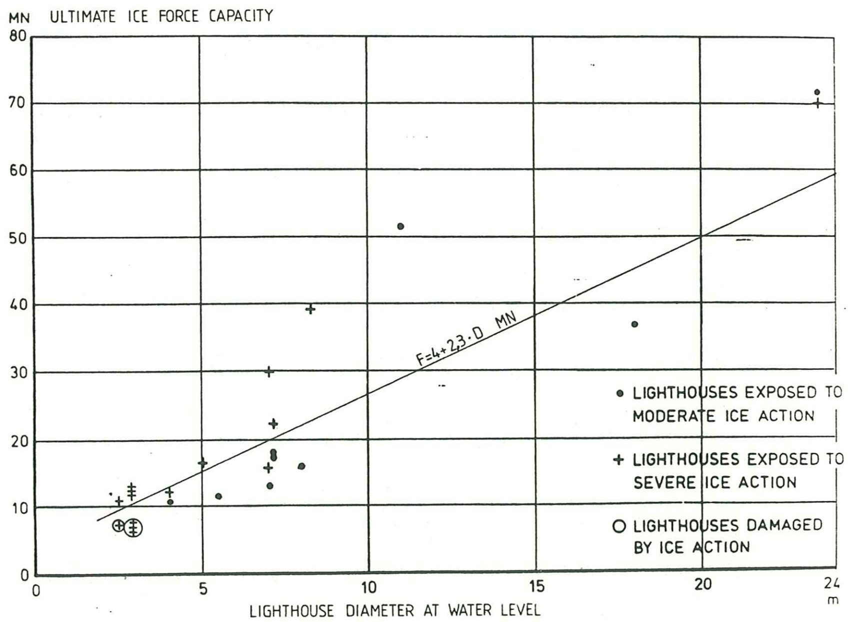

Figure 8.1 Overview of experiences with ice action on lighthouses in the Bothnian Sea and Bay

In the figure the design formula

$$F = 4 + 2.3 \cdot d \text{ MN} \qquad (6)$$

is illustrated grahpically together with symbols indicating sizes and ice force capabilities of existing lighthouses.

The formula is a simplification of

$$F = 1.6 \cdot \sqrt{1 + 5 \cdot \frac{h}{d}} \cdot h \cdot d \text{ MN} \qquad (7)$$

(the simplification valid for 2<d<23 m and h = 1.3 m, approx.)

This formula has been derived from the expression

$$F = k_S \cdot k_C \cdot k_I \cdot f_{um} \cdot h \cdot d$$

with the product $k_S \cdot k_C \cdot f_{um} = 1.6$ MPa, which can thus be defined as the mean effective design pressure on a very wide structure, to be multiplied by the indentation factor accounting for a limited width.

Reverting now to the overloading of the Björnklack lighthouse we see that the design formula would yield.

$$F = 1.6 \cdot k_I \cdot h \cdot d = 1.6 \cdot 1.8 \cdot 1.3 \cdot 2.9 = 10.8 \text{ MN}$$

This is exactly the same value as estimated for the overloading case as the most probable failure load.

Let us once more express the ice force in the simple form

$$F = p_{eff} \cdot h \cdot d$$

Then in accordance with the design formulae

$$F = 2.9 \cdot 1.3 \cdot d = 3.77 \cdot d \text{ MN}$$

and for the overloading case

$$F = 2.6 \cdot 1.45 \cdot d = 3.77 \cdot d \text{ MN}$$

The immediate conclusions are:

1) The design load, intended to have a mean recurrence frequency of one event in at least 1 000 year at each site, was obviously reached.

   (There are reasons to believe that the magnitude of the 1000-yr load has been underestimated)

2) Compared with design assumptions the ice thickness was the parameter, which was really extreme.

However, as will be dealt with in the next section, we feel that it is necessary to consider the interrelation between the parameters, when comparing predictions with observations from a probabilistic viewpoint.

Therefore, we prefer to conclude that primarily the overload was a result of an extreme combination of ice thickness, ice strength and ice movement.

9. Probabilistic aspects

In order to be able to deal with the problem in probabilistic terms, the most important causal relations between the "ice load parameters" chosen in the preceeding section and the most important environmental conditions have to be clarified.

Some of these relations are clearly indicated by collected field data and observations made in connection with the overloading event, but other relations are supported by indications rather than evidence. In a simple form with less important parameters passed over, the most probable course of event is sketched in Figure 9.1.

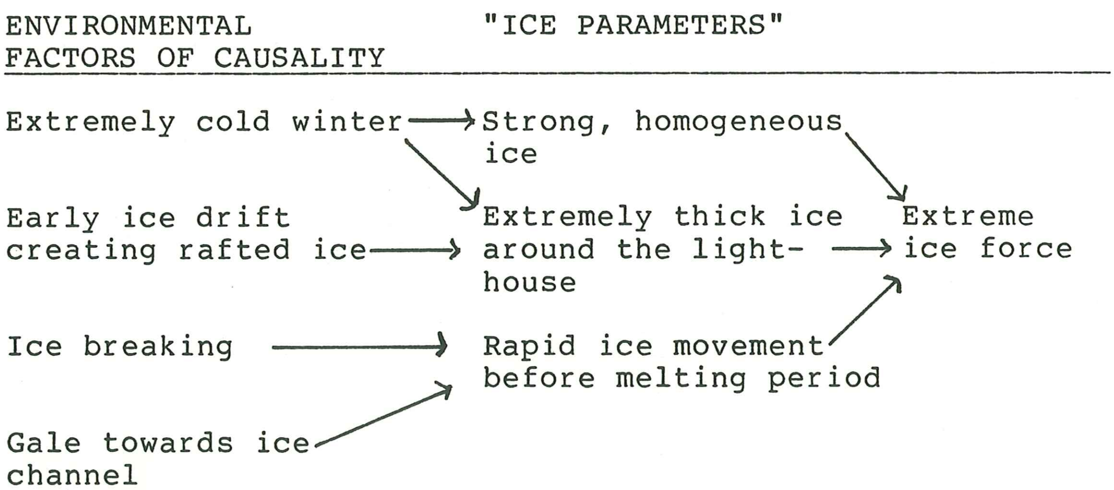

Figure 9.1 Course of main events resulting into the extreme ice load on the BJÖRNKLACK lighthouse

With respect to the "ice parameters" it has already been observed, that it is the combination rather than the individual values, which are remarkable. The strength of the ice was above the normal winter strength but not extremely so. Rafting of ice often occurs, although the ice sheets do not usually bond very well together. In the actual case the severe winter has probably been important in this respect.

Let us assume that the existence of rafted, about 1.5 m thick ice with a mean strength of 2.6 MPa within a certain area around the Björnklack lighthouse has an average recurrence period of about 100 years.

The problem is then to assess the probability that the thickened ice would move and reach the lighthouse before being softened due to increasing air temperature in the spring. It is obvious that this would depend on the size of the area considered, wind force, wind direction and currents, the crack pattern, the travel distance and velocity of the drifting ice etc. It is also obvious that the probability of such an ice movement taking place during a winter like the last is normally rather low, since the Bothnian Bay is then covered by a continuum of fast ice.

We can imagine that the joint probability of such an event would be several orders lower than 0.01, provided that the existence of a broken channel was disregarded.

Still disregarding the ice channel the most probable situations creating extreme loads would be indentation of softened ridges or rafted ice later in the spring, when ice drift is frequent, or ice thrust due to minor slow movements of a cover of cold and thick ice during mid-winter. In the latter case the ice pressure would most probably be mitigated by the low strain rate.

With regard to the statistic relation between ice strength and thickness and the movements of the ice cover, the Björnklack case also offers a valuable demonstration. The fact that the lighthouse remained undisplaced by the ice after the failure of the rock anchors, although its capability was reduced by about 50 per cent, shows that the large ice floe, after being stopped by the fast ice at the southern end of the broken channel, did not move very much before it was "softened" to the corresponding extent.

From the probability point of view the "environmental conditions" noted in Figure 9.1 may then be classified into at least two quite different groups: one with natural phenomena of more or less random character and the other with conditions established by human activites. Predominant in the latter group is of course the existence of the broken ice channel and its position in relation to the lighthouse, predominant wind directions, islands, shoals and coastlines. It is also obvious that there are modes of ice structure interaction, which contribute to increase the probability of thickened ice at the point of contact. Layering of relatively thin and large sheets of buckled ice is one mode. Development of thickened ice due to floading and refreezing has been observed around bridge piers etc. (ref. 8). Formation of rubble ridges is frequent, although such ridges are generally rather soft in the Gulf of Bothnia.

Our first conclusion is then, that our design rules as well as any ice load consideration with a probabilistic element should be selective in at least one more respect than the climatological and geographical and that is the consideration of consequences of breaking the ice in a way which can provoke movements of large and strong ice fields.

Considering indications from the Björnklack case a load factor of 1.5-2.0 does not seem exaggerated, to account for the presence of an ice channel. An increase of the current design loads for such conditions seems justified, as well as a reduction for conditions of clearly restricted ice movements.

10. A generalized interpretation of the field observations

The experiences from the Björnklack case together with previous observations from the Gulf of Bothnia emphasizes the urgency not only of supporting ice force predictions on field evidence but also of making clear distinctions with respect to different environmental conditions and related ice parameter values and combinations.

Particularly emphasized is the importance of considering the frequency of ice drift as related to different combinations of ice thickness and strength, also frequency distributed preferably both in time and space.

For wider application the following experiences from the Björnklack overloading event may provide useful quidance:

- The effective mean ice pressure was 2.6 MPa as was the mean uniaxial compressive ice strength.

Coincidentally or not, this is what would be predicted using current ice force prediction practice, when accounting for increased strength due to confined compression of the ice as well as an incomplete contact between the structure and the ice at brittle crushing.

The uniaxial strength 2.6 MPa is above average but not extreme for Baltic areas and is expected to be representative in order of magnitude for many Arctic and Subarctic areas.

- From the probabilistic point of view the conditions at Björnklack are probably more representative of Arctic areas with frequent ice drift than of the Bothnian Bay in general, where large movements of ice during severe winters are normally restricted.

11. Concluding remarks

Briefly the conclusions drawn from the BJÖRNKLACK case study can be summarized by the following points.

- The extreme ice force, which overloaded the lighthouse, developed basically as a sequel of an exceptionally severe winter and a partly random course of events, which caused an exceptionally early ice movement at the lighthouse site.

- Expressed in terms of ice parameters the ice force was a result of an extreme combination, where the ice thickness, the strength of the ice and primarily the large movement of ice with such properties are the most significant.

- The whole course of event and the results of the analysis of observations underline the necessity to use, at least partially, a probabilistic approach in the prediction of ice forces.

- Risk evaluation and corresponding risk classification of structures subjected to large ice forces then become logical elements in the design. Lighthouses, for example, should be classified with respect to operational, economical and environmental conditions.

- The mean effective ice pressure on the BJÖRNKLACK lighthouse was 2.6 MPa which is the same as the average value of the compressive strength of unconfined test samples. Multiaxial stress conditions in the ice cover due to the limited width of the contact area may have contributed with 10 to 50 per cent of the effectiv ice pressure.

- It is important to direct future field investigations within the actual project on finding out, among other factors, primarily the ratio $k = p_{eff}/f_{um}$ and its dependence on the aspect ratio b/h, the absolute area of contact etc. Secondly, it is of course of great interest to determine relations for the parameters k_I, k_S and k_C. It is expected, however, that a distinct separation of these factors might be obstructed by their reciprocal relations among other things.

REFERENCES

1. Ice forces against offshore structures.
   PROJECT DESCRIPTION.
   (Exhibit A to Agreement regarding the project).

2. Alf Engelbrektson: Ice force design of offshore structures in the light of experiences from the Baltic. VBB Techn. Rep. to the conference "Offshore Göteborg 83".

3. Alf Engelbrektson - Jan Erik Janson:
   Field observations of ice action on concrete structures in the Baltic Sea. Concrete International (ACI) Aug. 1985.

4. Lennart Fransson - George Danielsson:
   Ice conditions and ice properties close to the lightpier Björnklack shortly after the failure due to forces from a moving ice sheet. University of Luleå, Div. of Structural Eng. Paper 85:13. (Appendix 1)

5. Bernard Michel: Ice Mechanics, Québec 1978.

6. IALA Technical Committee to study the effect of ice on lighthouses.
   International Association for Lighthouse Authorities (IALA) Congress in Paris 1984.

7. B.C. Gerwick - M. Rojansky:
   Failure modes and forces of pressure ridges acting on cylindrical towers.
   POAC 81 Proceedings pp 663-673.

8. Lennart Fransson: Ice force measurements on a bridge pier in the Lule River.
   POAC Proceedings, 1983. V.4 pp 759-769.
   Also, full report in Licentiate Thesis 1984:12L, University of Luleå, 137 pp.

LIST OF SYMBOLS ETC.

Units

SI units are generally used in this study.

Symbols

h: ice thickness

b: instantaneous width of ice-structure contact area

d: diameter of a cylindrical indentor

f_u: uniaxial strength of the ice (compressive if not otherwise stated)

f_{um}: "mean uniaxial strength", averaged over the contact area (compressive if not otherwise stated)

p: contact pressure between the ice and the structure

p_{eff}: "mean effective ice pressure", the unidirectional ice pressure averaged over a defined gross contact area, normally hxb, i.e.

$$p_{eff} = \frac{F}{hxb}$$

F: "global ice force" i.e. the total unidirectional ice force on a structure, instantaneous or averaged over a certain period of time

F_{max}: the "peak global ice force" during a certain period of global ice force variations (in our studies the "peak force" is in fact also averaged, since it is related to the measured response of a structure, but it is normally averaged over a very small fraction of the period of the most significant mode of structural vibrations)

k_S: "shape factor", the ratio between global ice loads on e.g. cylindrical and plane indentors

k_I: "indentation factor", for factoring the ice load with respect to the aspect ration b/h

k_C: "contact factor", for factoring the ice load with respect to imperfect contact between the ice and the structure.

$k=\frac{p_{eff}}{f_{um}}$ a common factor, accounting for all the abovementioned and other factors for transformation of the uniaxial ice strength to effective ice pressure on a structure

STUDY PROJECT

ICE FORCES AGAINST OFFSHORE STRUCTURES

APPENDIX 1

This report, Document No. 85:13 from the Division of Structural Engineering, University of Luleå, contains results of ice investigations carried out by Lennart Fransson (planning and direction), Georg Danielsson (testing), Lars Åström och Håkan Johansson (core sampling, etc.) from the Div. of Struct. Eng. which is headed by Lennart Elfgren.

The report has been prepared by L. Fransson and G. Danielsson as a contribution to "existing data", providing a basis for Task No. 1 of the project ICE FORCES AGAINST OFFSHORE STRUCTURES.

CONTENTS

SUMMARY

The lightpier Björnklacken was overloaded by a moving ice sheet on April 4, 1985. The maximum wind speed at that time was 15 m/s from the north. The ice consisted of level ice and columnar ice with a total thickness of 1.4 m close to the lightpier. The mean yield strength, determined from 13 horizontal samples in a N-S direction, close to the lightpier, was 2.9 MPa. The salinity was less than 3 ppt.

1. INTRODUCTION

The ice in Luleå archipelago normally forms late in November and consists of a columnar rigid ice sheet at about 0.4-0.8 m. The winter of 1984/85 was extremely cold and the ice thickness exceeded 1 m.

A storm from the north occurred in early April. A large ice floe then moved south against an open track. The lightpier Björnklacken was embedded in the moving ice floe and became overloaded.

Shortly after the overloading event, the division of Structural Engineering conducted a field investigation of the ice situation close to the lightpier. Samples of the ice were taken, and the ice properties were examined at the ice laboratory in the University of Luleå.

The ice force acting on the structure can be estimated

1. as the force required to break the ice
2. as less than the driving force from the ice floe
3. as the force required to break the lightpier

This report serves as a foundation for calculations of the first two forces.

2. FIELD INVESTIGATION

2.1 Observations on the moving ice floe

Referring to observations made by Mr Tore Hjelte, Persön, Luleå the lightpier was intact on Thursday morning, 4th April. During the day the wind force from the north increased and a large crack (crack 1 in figure 2.2) developed. This crack isolated Mr Hjelte from the shore and he had to wait for rescue on the east side of crack no. 1. It was then he observed that the lightpier was tilted (Ref 1).

On the same day, 4th April, the Swedish Air Force flew over the area. Captain S-O Wiklund also observed that the lightpier Björnklacken had tilted at about noon, but he also said that the ice flow had not moved appreciably at that time. Further movement of the ice to the south occurred later (Ref 2).

Based on photos (figure 2.1) and on these two observations, the ice situation around the lightpier probably was as indicated by the sketch shown in figure 2.2.

Recordings of the weather situation on Thursday, 4th April was received from the Swedish Air Force at Kallax airport at the coast close to Björnklacken. The mean wind speed, direction and temperature are shown table 2.1.

Table 2.1 Mean wind speed, direction and temperature measured over a 10 minute interval

time	wind direction	wind speed (m/s)	temperature(C)
2 am	340	10	-2.4
8	340	9	-1.8
10	350	13	
11.20	north	15	
2 pm	350	11.5	+0.4
8	10	8	+1.2

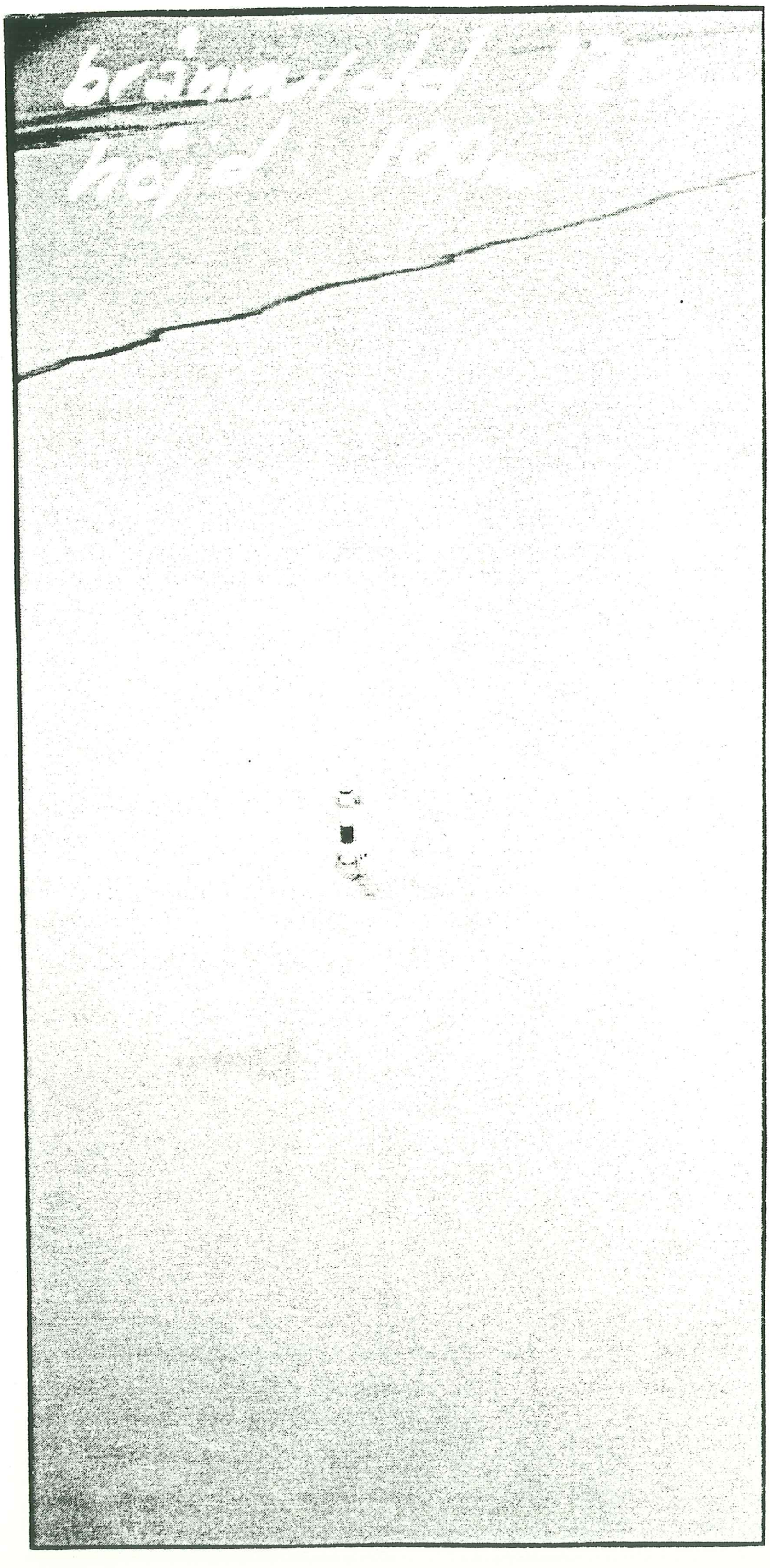

Fig 2.1 The icecrack north of the lightpier Björnklacken, April 15, 1985 (Photo: The Swedish Air Force)

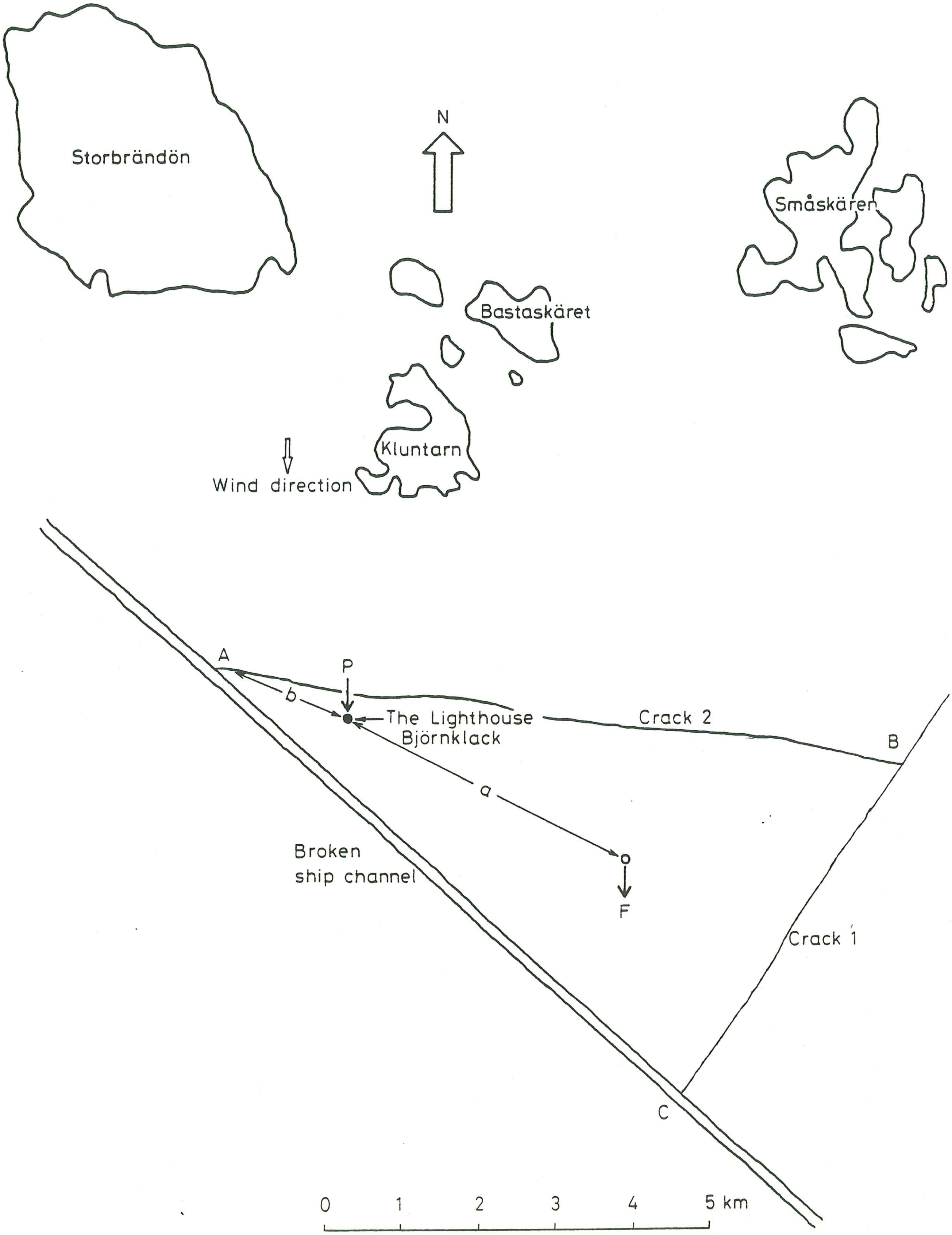

Fig 2.2 Probably ice situation around the lightpier based on observations (Ref 1 and 2)

Based on these facts we suppose that the lightpier Björnklacken was forced by the triangular ice floe ABC in figure 2.2. Initially the force (F) probably rotated the ice sheet. This resulted in an amplified force on the lightpier. If the location of the centroid of the driving load distribution was as shown in figure 2.2 and the effect of current is ignored, we can expect the magnitude of the ice load to be described by the equation

$$Pb < F(a+b)$$

$$P < (1 + a/b)\ F \qquad \ldots (1)$$

where P = ice load on the lightpier
F = total wind load on the ice floe ABC
a = distance from lightpier to load center
b = distance from lightpier to rotating center

2.2 Ice conditions close to the lightpier

South of the lightpier, a 6 m long ice track was observed. North of the lightpier a rubble field had formed. The ice was completely covered with packed snow. Small ice cracks were therefore not visible. Water had flooded some parts of the ice and during the drilling operation water was often discovered deep in the ice.

The ice formation close to the lightpier is shown in figure 2.3.

The ice thickness was measured in April in drilled holes along four profiles as shown in figures 2.4 to 2.6. The ice thickness was 1 m at a dis- tance from the pier where it was undisturbed. It was thicker close to the pier. East of the lightpier there was a ridge with a depth >2 m. The height of the rubble in front of the lightpier was about 1.4 m and the depth can be extrapolated from the profiles to 3 m below the water line.

Ice cores were taken from the three positions shown in figure 2.4. The north-south direction was marked on the top of each core before drilling so that the horizontal loading direction could be maintained in the laboratory tests. The core diameter was 200 mm and the maximum length of a continuous core was 0.7 m. Thicker ice was cored through by bending loose the first core.

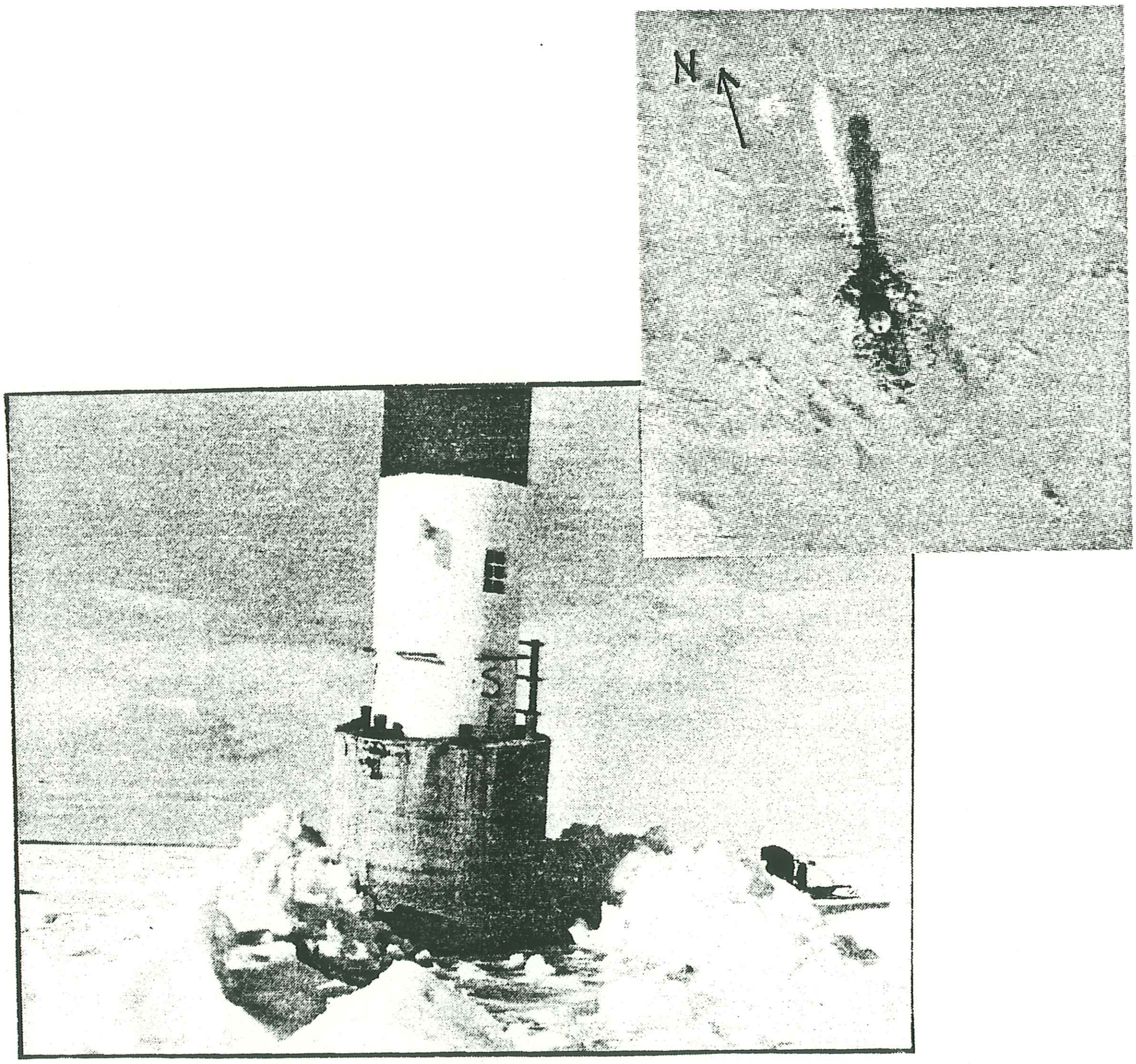

Fig 2.3 Ice situation close to the lightpier shortly after the overloading event
(Photo: Lars Åström and the Swedish Air Force)

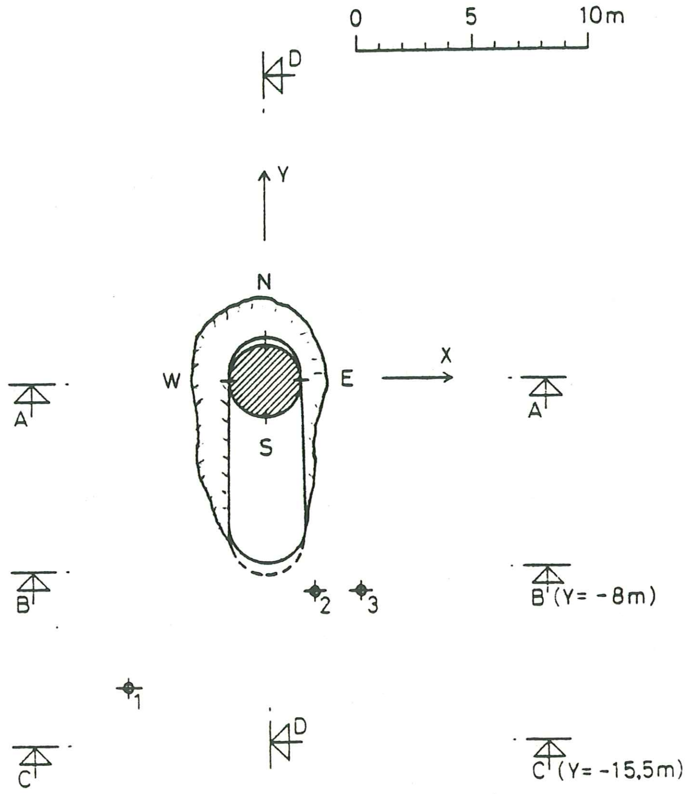

Fig 2.4 Site plan of the drilled profiles close to the lightpier Björnklacken, April 10, 1985

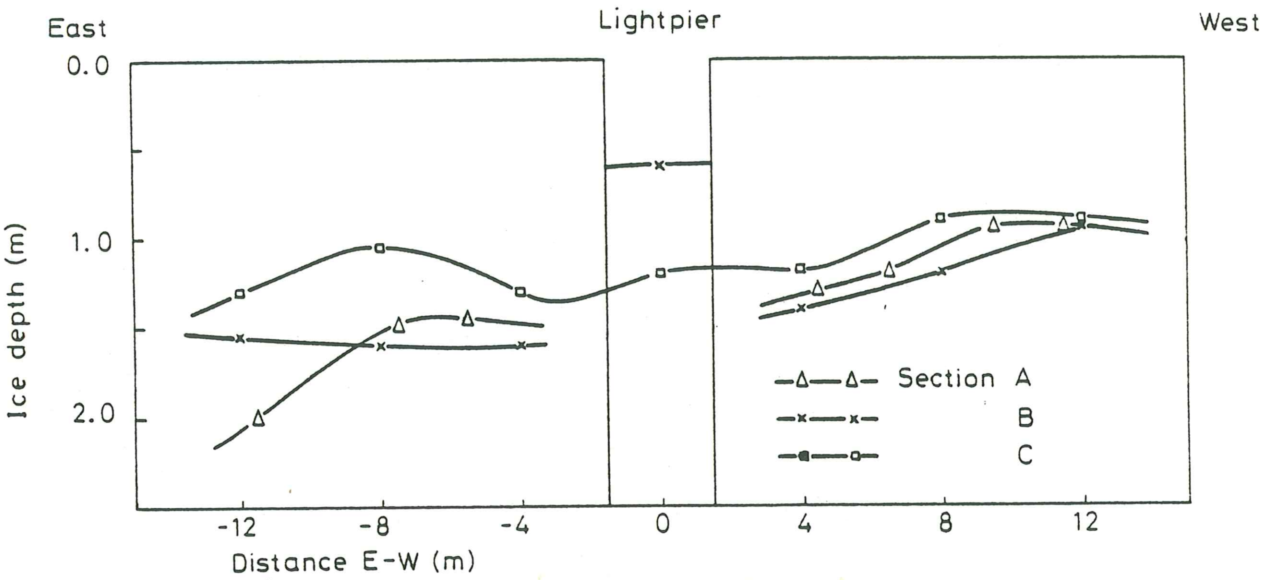

Fig 2.5 Ice thickness along profiles perpendicular to the ice moving direction. Björnklacken, April 10, 1985

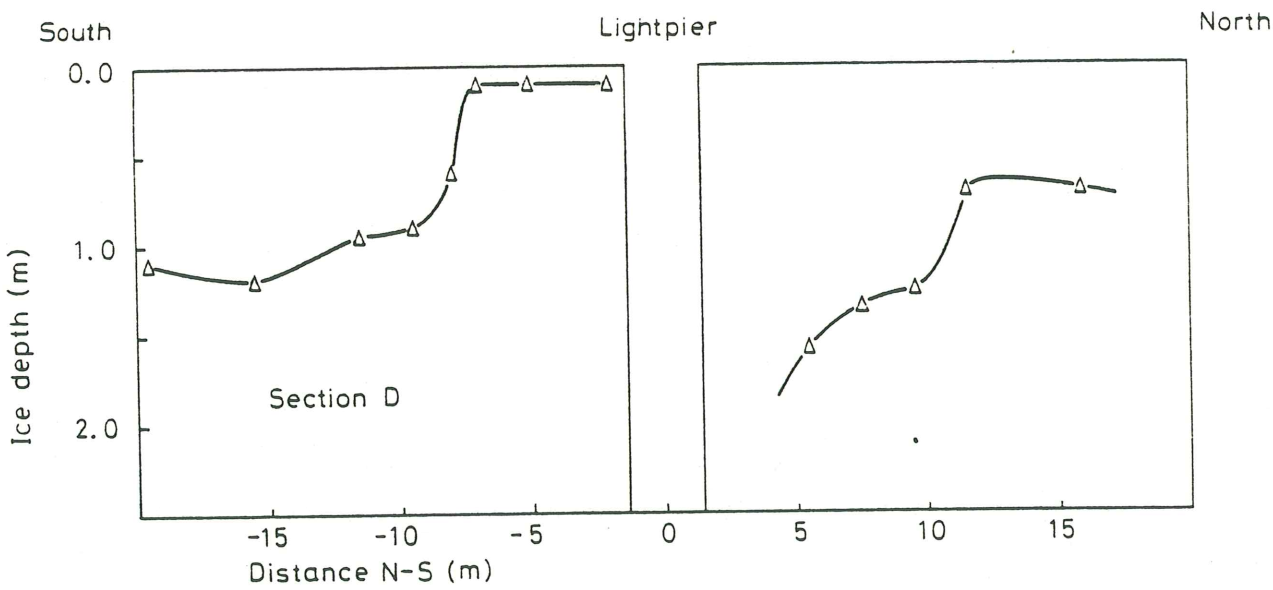

Fig 2.6 Ice thickness along the ice moving direction. Björnklacken, April 10, 1985

3. LABORATORY INVESTIGATION

3.1 Physical properties

The field samples were stored in a freezer in a cold room at the University at a temperature of -25°C. Each core sample was sealed in a plastic bag.

Horizontal cores in north-south direction with a diameter of 70 mm were taken at different levels from the larger vertical core. The distance between each horizontal core was about 0.25 m. After preparation, the small cores were also stored in tight plastic bags and at a temperature of -25°C.

To classify the different types of ice involved in the ice cover, vertical thin sections were examined between crossed polaroids. The thin sections were taken from the same core as the horizontal samples so that the ice type of each horizontal sample could be identified. In figure 3.1 the different ice types surrounding specimens 2a-e are shown.

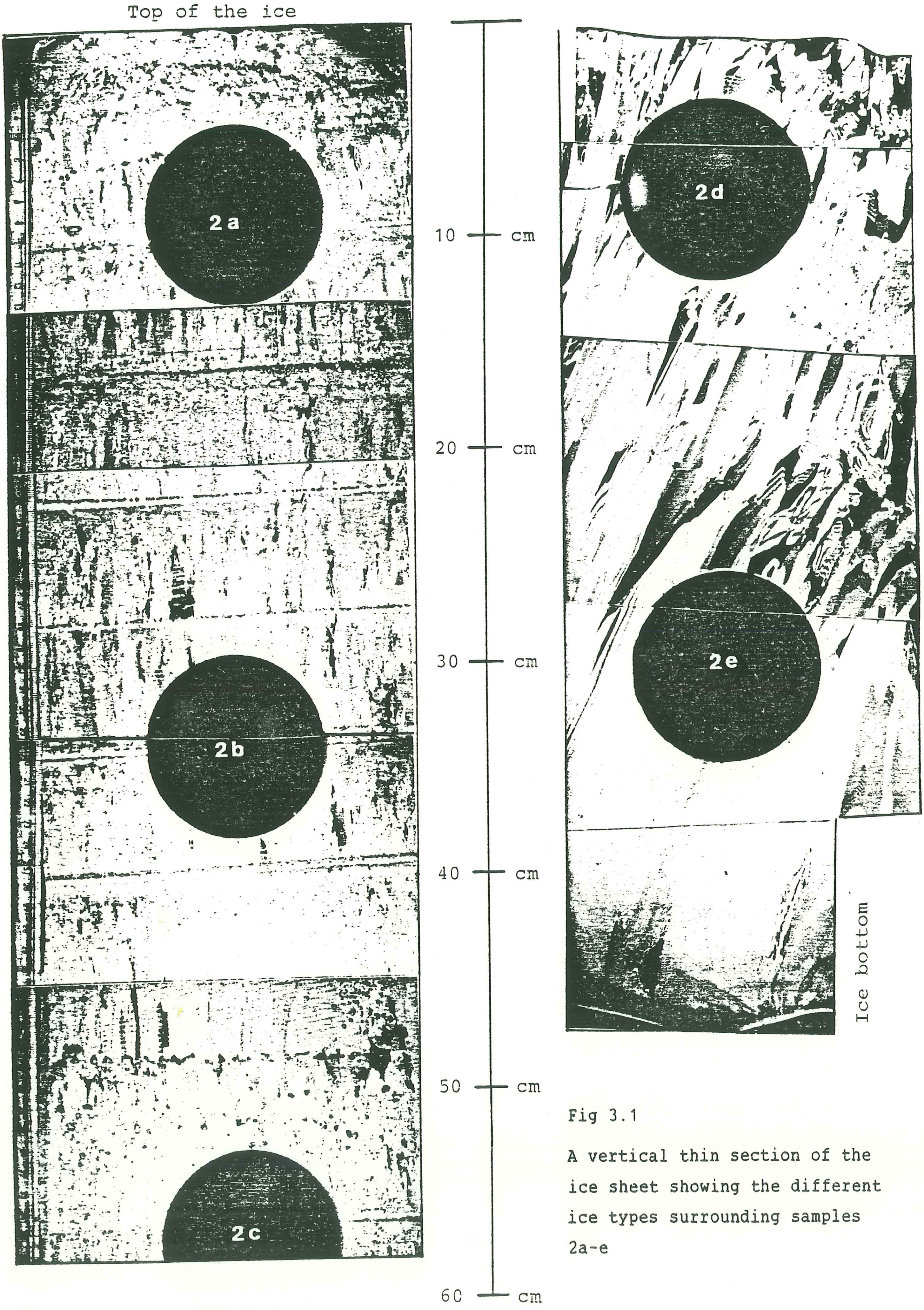

Fig 3.1

A vertical thin section of the ice sheet showing the different ice types surrounding samples 2a-e

In general, the upper half of the ice consisted of level ice (rafted or flooded) and the lower half consisted of columnar ice. In table 3.1, the ice types are divided into three groups, granular, columnar and level ice. The grain diameter of columnar ice and the level thickness of level ice are specified.

The density was calculated from the measured diameter, length and weight of the horizontal cores at a temperature of -5°C.

The salinity of a melted ice specimen was measured with a conductivity meter.

Table 3.1

Sample	Depth(mm)	Ice Type	Density(kg/m^3)	Salinity(0/00)
1a	80	granular	888	1.9
1b	330	level/gran.	832	0.2
1c	580	granular	903	0.2
2a	90	granular	802	2.6
2b	340	levels 60mm	888	2.4
2c	580	granular	823	1.8
2d	750	col. 8mm	909	1.2
2e	990	col. 14mm	910	0.1
3a	90	levels 90,60mm	887	0.4
3b	340	levels 60mm	892	0.2
3c	585	levels 80,65mm	897	0.5
3d	745	granular	902	0.0
3e	990	col. 10mm	912	0.1

3.2 Mechanical properties

Uniaxial compression tests according to the IAHR standard (Ref 3) were performed on the horizontal cores in N-S direction. The diameter of the cores was 70 mm and the length was about twice the diameter. The load was applied with a servo-hydraulic loading machine (INSTRON T1) on a specimen placed inside a cold cabinet. The steel load surfaces were cooled before each test, and a fibreplaten was placed between the steel and ice. The test set up is shown in figure 3.2.

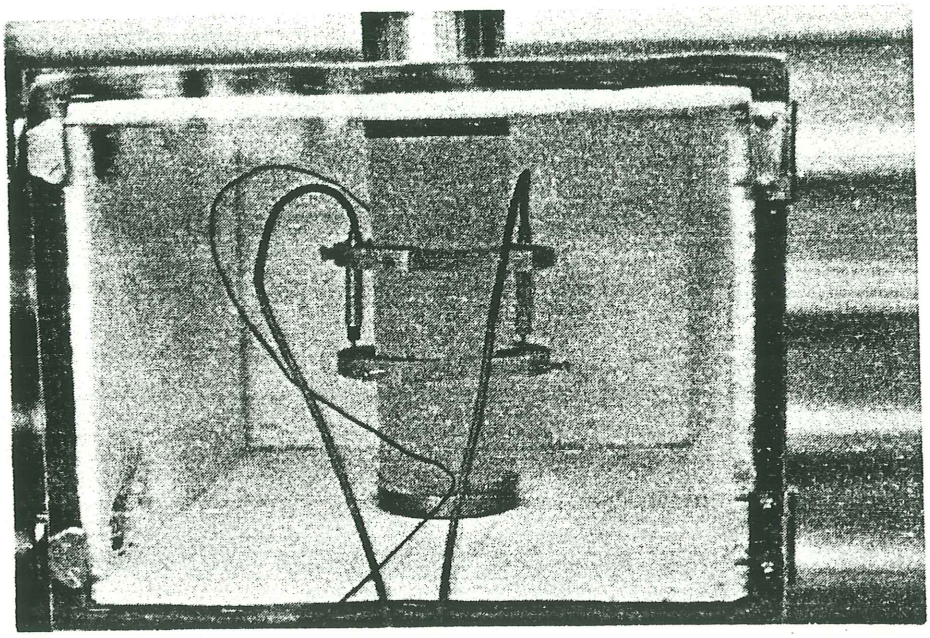

Fig 3.2 Uniaxial compression tests of cylindrical specimen (d=70 mm). The deformation of the ice is measured with two LVDT:s fixed at the middle part of the specimen

The ice temperature was held constant at about -3.5^{o}C for the vertical section 2. For section 3 the test temperature was held at -4.2^{o}C for sample 3a and for each sample the temperature was increased by 1^{o}C. See table 3.2, below.

The load was measured with a high precision load cell (INTERFACE SSM-3000), and the deformation of the ice was measured with two LVDT:s on a length of 50 mm. All tests were performed at a constant rate of deformation, 0.01 mm/sec. (Strain rate = $2 \cdot 10^{-4}$ s^{-1}) in the middle part of the specimen.

The yield stress recorded in table 3.2 is defined as the maximum stress during a constant strain rate. The yield strain is defined as the strain measured at the yield stress. The stress-strain curves from all tests are shown in appendix 1.

Table 3.2

Sample	length(mm)	Temperature(^oC)	Yield strain(%)	Yield stress(MPa)
1a	160.0	-4.3	.11	3.48
1b	159.5	-4.5	.13	3.68
1c	158.0	-3.0	.12	3.89
2a	169.5	-3.5	.14	4.14
2b	160.0	-3.5	.10	3.37
2c	138.5	-3.5	.05	1.83
2d	144.0	-3.5	.05	2.69
2e	131.0	-3.5	.04	1.72
3a	160.5	-4.2	.14	3.18
3b	160.0	-3.2	.16	2.91
3c	159.5	-2.2	.12	3.06
3d	159.5	-1.2	.06	2.37
3e	148.5	-0.2	.09	1.36

The low stress maximum for sample 2c can be explained to be due to the presence of air pockets observed in the sample. This sample also had a low density (823 kg/m3) and it is possible that the core was crossed by a refrozen crack. The stress-strain curve (2c) in appendix 1 supports this claim. The curve illustrates a post failure behaviour typical for a cracked body.

4. REFERENCES

1. Hjelte T, Fisherman from Persön, Luleå. Personal communication.

2. Wiklund S-O, Helicopter pilot at the Swedish Air Force, Luleå. Personal communication.

3. Schwarz et al, Standardized testing methods for measuring mechanical properties of ice. IAHR:s section on ice problems. Cold Reg Sci and Tech 4 (1981), 245-253.

SAMPLE 1 a