

Sea Ice Investigation in the Weddell Sea

By Joachim Schwarz*

Summary: During the German Antarctic Expedition 1979/80, the sea ice conditions in the Weddell Sea were studied along the ice shelf between Cape Fiske (root of the Antarctic Peninsula) and Atka Bay. Most intensively was the sea ice investigated in an area about 100 km northwest of Berkner Island, where a suitable site for the German station was found. In addition to the drift conditions, ice thickness as well as temperature and salinity of the ice were measured and the mechanical properties established. Several ice cores were taken back to Germany, where the compressive strength was measured in respect to strain rate, salinity; depth and temperature.

Zusammenfassung: Während der Deutschen Antarktis-Expedition 1979/80 wurde das Meereis in der Weddell-See entlang der Schelfeiskante von Kap Fiske (Wurzel der Antarktischen Halbinsel) bis zur Atka-Bucht mit einem Schwerpunkt in einem Gebiet rd. 100 km nordwestlich der Berkner-Insel untersucht. Zusätzlich zu den Driftverhältnissen des Eises wurden die Eisdicke, die Eistemperatur sowie der Salzgehalt im Eis gemessen und die mechanischen Eigenschaften des Eises ermittelt.

Einige Einbohrkerne wurden mit nach Deutschland genommen, wo die Druckfestigkeit in Abhängigkeit von der Belastungsrate, vom Salzgehalt, von der Temperatur und der Tiefe im Eis gemessen wurde.

1. INTRODUCTION

From December 1979 till March 1980 the Federal Republic of Germany carried out an Antarctic Expedition in order to search out a suitable site on the Filchner/Ronne Shelf for the German Antarctic station to be constructed in 1980/81.

This part of the report covers investigations on sea ice which were carried out for three reasons:

1. Accessibility of the station site by icebreaking ships transporting the construction materials for the station to the site, and later on by the German Polar Research and Supply Vessel (now under construction) on annual supply missions to the station,
2. Collection of field data in the Weddell Sea to aid in the design of the Polar Research and Supply Vessel,
3. Establishment of a research programme on sea ice dynamics in the Weddell Sea and on ice engineering problems.

The sea ice investigations included the following topics: 1. sea ice conditions during the voyage, 2. sea ice conditions during the site survey, 3. physical properties, 4. mechanical properties, 5. strain measurements.

The investigations were carried out from board the ship POLARSIRKEL with the assistance of the helicopters. The principal investigator, J. Schwarz, was assisted by K. Menssen and partly also by K. Henning, M. Keller, and L. Suhrmeyer.

2. SEA ICE CONDITIONS

2.1. *Introductory Remarks*

The sea ice conditions are described by the percentage of ice covering the water (ice concentration), the ice thickness, the stage of development of the ice, the form of ice and the topography etc. These condi-

* Dr.-Ing. Joachim Schwarz, Hamburgische Schiffbau-Versuchsanstalt, Bramfelder Str. 164, D-2000 Hamburg 60.

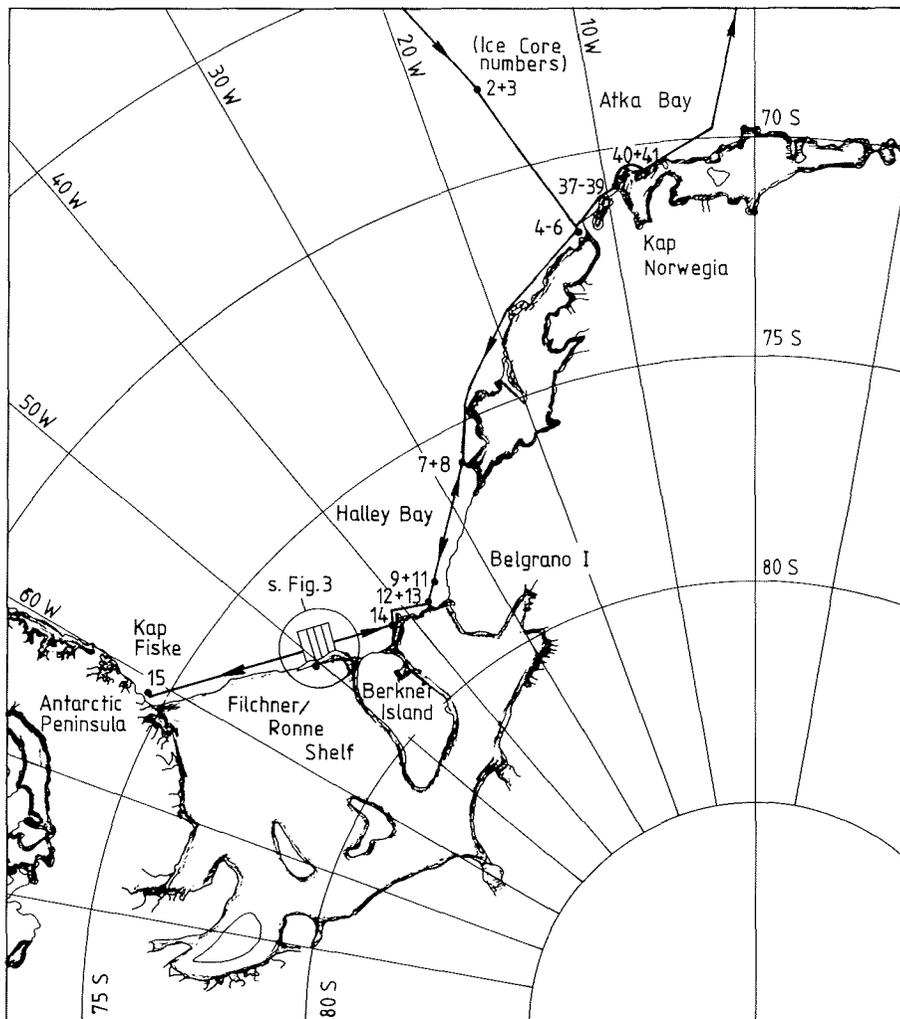


Fig. 1: Route of POLARSIRKEL and location of ice core collection.

Abb. 1: Route der POLARSIRKEL und Orte der Eisprobenentnahme.

tions were monitored during the voyage as well as during the site survey from the ship, on the ice itself, and partly with the assistance of the helicopters (Fig. 1). The visual observations of the ice conditions were carried out and documented according to the Ice Analysis Code (ICEAN).

As an aid in forming an overall view of the sea ice conditions, i. e. the extent of the ice cover and especially of the polynya along the ice front, a satellite picture receiving instrument, Skyceiver IV, was installed on board the POLARSIRKEL. This instrument was adjusted to receive pictures from NOAA 6 and TIROS-N, at frequencies of 137.5 MHz and 137.6 MHz respectively. The area on earth covered by one picture from TIROS-N is 7000 km from north to south and 5000 km from east to west. The pictures were received in the visible and in the infrared ranges of the spectrum. With the knowledge of the time/when and the geographical degree/where the satellite passed the equator and a ground grid map it was possible to locate our own position in the pictures.

2.2. Sea Ice Conditions During the Voyage

The visual observations of the sea ice conditions began on December 26, 1979 during the voyage from South Georgia to Kap Norwegia at Position S 55° 00' and W 34° 00'. They were carried out several times per day until January 27, 1980. In addition to these visual observations, photographs had been taken from the crow's-nest of the ship as part of the coverage documentation.

During the voyage from South Georgia to Kap Norwegia the satellite pictures taken several times per day mostly showed a cloudy sky. Only when the ship approached the ice at Kap Norwegia and sailed along its front was the sky mostly clear. A satellite picture taken some miles north of Kap Norwegia (Pos. S 63° 58', W 20° 33') in December 1979 from the TIROS-N satellite showed a wide polynya in front of the eastern part of the Filchner Ice Shelf. The water in front of the westerly half of the Ronne Ice Shelf seemed to be covered by ice up to the Arctic Peninsula. The polynya from Halley Bay on eastward was smaller. The satellite picture from January 3, 1980, showed the ice-free zone in front of the Filchner/Ronne Ice Shelf extending almost up to the root of the Antarctic Peninsula. This picture was received when the POLARSIRKEL was sailing close to Belgrano I. On the basis of these pictures it was decided to sail as fast as possible along the front of the Filchner and Ronne Ice Shelves toward the Antarctic Peninsula in order to inspect the whole length of the ice front for a potentially suitable site for the German station. The most westerly position in the southern Weddell Sea was reached on January 5, without any difficulty. No other ship has sailed this far west before. The observations during the voyage proved the information on the extent of the polynya provided by the satellite pictures to be accurate. The overall extent of the polynya did not change very much until the ship left the Filchner/Ronne Ice Shelf on February 10, 1980 (Fig. 2). The quality of the satellite pictures was adequate enough to form an overall picture of the sea ice conditions and to help the ship's captain in deciding, for example, how far into the polynya he could navigate. The resolution of the pictures was, however, not sufficient to detect small leads or difficult ice areas, which

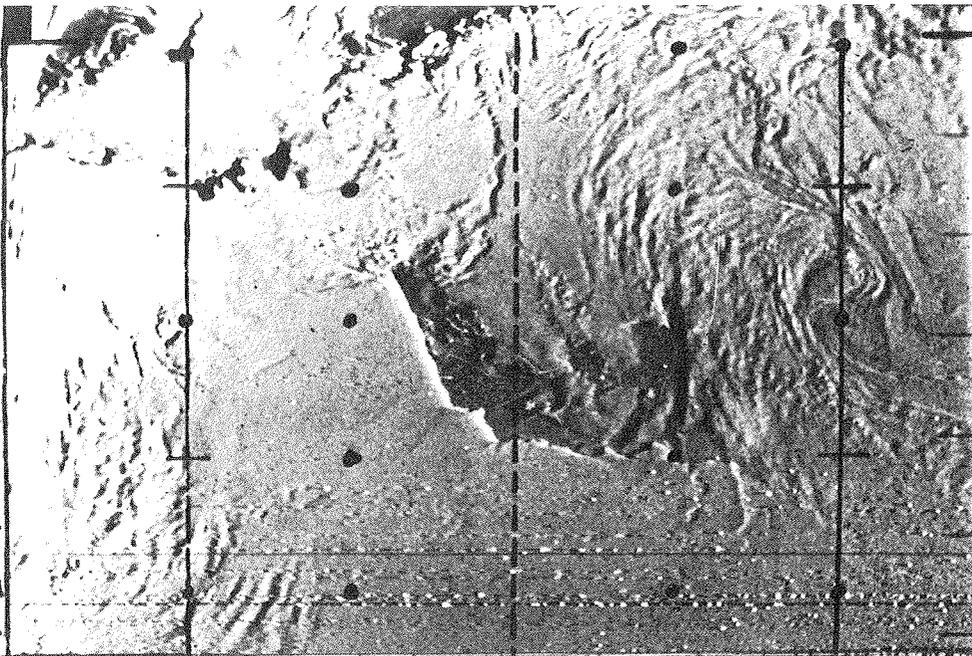


Fig. 2: Satellite picture of ice conditions in the southern Weddell Sea on February 10, 1980.

Abb. 2: Satellitenbild der Eisverhältnisse in der südlichen Weddell-See am 10. Februar 1980.

would be an important information for the selection of optimal shipping routes if the ship had to navigate through ice of high concentration.

2.3. Sea Condition During the Site Investigation

A potential site for the German Antarctic station was investigated between January 6, and February 10, 1981, on the Filchner Ice Shelf. During this time the sea ice conditions (degree of ice concentration, ice thickness, ice strength, and ice movement) were investigated in front of the ice shelf (Position S 77°00', W 50°07').

When the POLARSIRKEL arrived at the ice shelf in front of the so-called Filchner Station on January 7, 1980, a ca. 200 m wide belt of partially ridged sea ice was floating adjacent to the ice shelf. Some 100 m east of the berth the sea ice was still unbroken fast ice of 1.5 m thickness. During the following days while the ship was moored to the ice shelf for unloading (January 7—15, 1980) a 100—200 m wide strip of broken ice moved intermittently at a varying distance from the ice front in a WNW direction at a mean velocity of 0.5 kn. At high tide the ice was pushed against the ice shelf; at this tidal phase the friction prevented the ice from moving parallel to the ice front. Only after the tidal current changed from flood to ebb tide did the broken ice move out in a northwesterly direction and leave the ice front.

Similar ice movements were observed during the sea ice measurement at location E₀ (Position S 77°0.7', W 49°03') from January 16, until January 22, 1980. E₀ was located 30 nm east of the berth for Filchner

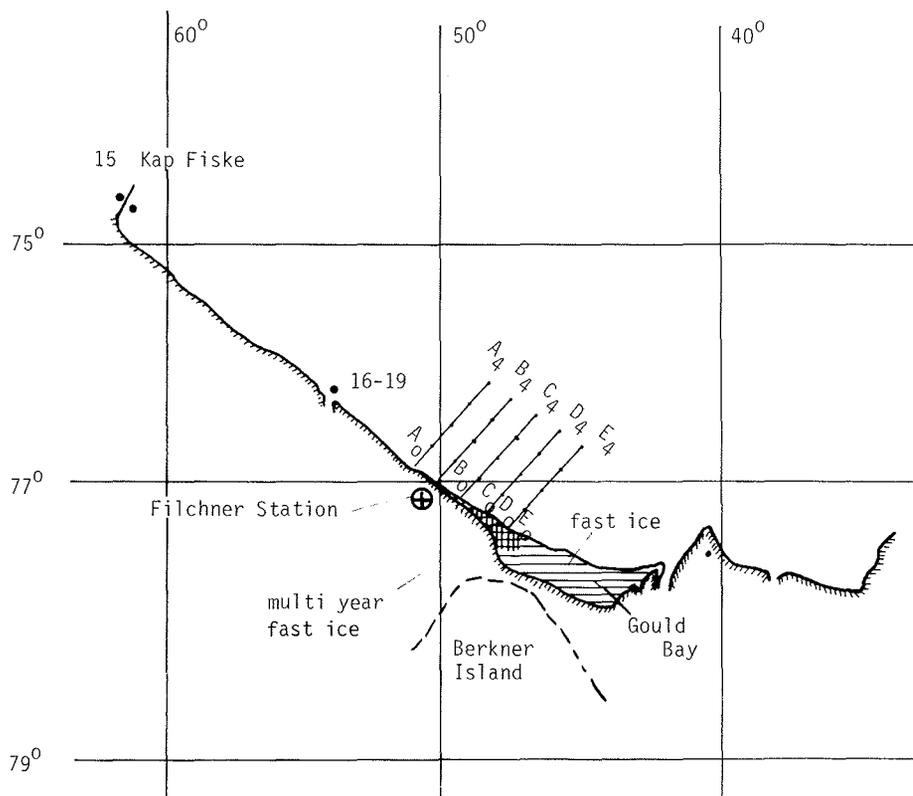


Fig. 3: Area of site survey.

Abb. 3: Das Untersuchungsgebiet.

Station at the sea side edge of a ca. 6 mile wide sea ice cover frozen in front of the ice shelf (Fig. 3). At this location the tidal range was measured by GAMMELSRØD & SLOTSVIK (1981) to be as high as 2.60 m during our stay. The current measurements at 100 m depth showed that the maximum tidal current almost normal to the ice front was about twice as high as at location B₀. The reason for this phenomenon is probably the difference in distance (30 nm) from Berkner Island. The much stronger tidal current at location E₀ caused the pack ice to move faster and over a longer distance almost normal to the sea ice edge. The actual ice movement was irregular according to the superposition of the tidal current and the ice shelf parallel to the sea current. Radar measurements of the drift velocity of large ice floes in front of location E₀ on January 20, 1980 show that at flood the sea ice moved about 1.2 knots almost normal towards the fast ice edge. The velocity at ebb away from the fast ice edge was smaller.

During the sea ice investigations at location E₀ the POLARSIRKEL had to leave the anchoring place twice for several hours due to ice patches (4 km x 4 km) drifting towards the location E₀; the ice impact forces were expected to be too dangerous for the ship.

On January 23, 1980 sea waves caused 30—50% of the fast ice east of Filchner Station including a large area of the Gould Bay to break up and to move in a northwesterly direction. On January 25, 1980 the most westerly edge of the drifting ice belt had reached the location B₀. The ice concentration was 6/10, which allowed the ship to navigate through this and to find a safe anchoring place at the ice front between C₀ and D₀. On the afternoon of January 27 the ice concentration became so high and the size of the 25 m thick ice floes so large that the ship had to leave the anchoring place (Fig. 4). During the following days until February 9, the ship operated on the northerly edge of the drifting ice belt.

Helicopter reconnaissance flights were carried out every other day in order to inspect the drift ice conditions, i. e. speed, ice concentration, areal extent, with special emphasis on the movement of the easterly



Fig. 4: POLARSIRKEL escapes due to danger from large ice floes.

Abb. 4: POLARSIRKEL flieht vor großen Eisschollen.

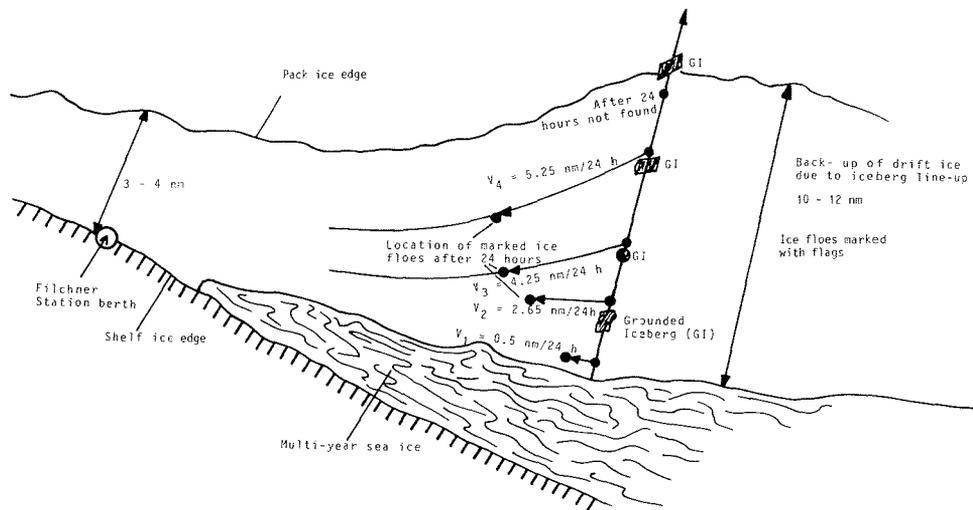


Fig. 5: Drift record of marked ice floes (Jan. 31/Febr. 1, 1980).

Abb. 5: Treibbahnen von markierten Eisschollen (31. Jan./1. Febr. 1980).

edge. This latter information was important in order to find out whether the ice belt would have passed the berth of Filchner Station by February 9, when the ship was scheduled to load for departure. On January 29, 1980 the easterly edge of the ice belt was located about 65 nm east of the Filchner Station berth. By additional reconnaissance flights on January 31, and February 5, it was found that the easterly edge of the ice belt moved about 7.5 nm per day. The drifting ice belt was 8—12 nm wide at the E and D profile, whereas at the profiles A and B (Filchner Station berth) the width of the drift ice belt was only 3 to 6 nm wide. The reason for this narrowing process of the drift ice was probably the line-up of four grounded icebergs almost normal to the ice edge at the D-profile (see Fig. 5). Four of these marked ice floes were found 24 hours later, their positions were established by compass, helicopter flying time and speed.

Fig. 5 shows rather low speed of the ice floes close to the fast ice edge (0.5 nm/24h). The speed increased with distance from the fast ice edge up to 5.2 nm/24h. The graph also shows that after passing the line-up of the icebergs the ice floes originally furthest away tended to move in closer to the fast ice edge. The low speed of the ice floes close to the fast ice edge was caused by the flood stream which pushed the ice together and against the fast ice, whereby due to the friction between the ice floes, the ice was kept in place. Only at low tide when they became loose, did they move parallel to the ice edge.

At location B_0 and A_0 the drift situation was different. Because of the weaker tidal current and thereby the smaller friction at the ice shelf the drift velocity even close to the ice shelf front was much higher: Measurements of this drift velocity were carried out on January 30, 1980 immediately in front of the berth for the Filchner Station (location B_0): At low tide when the ice coverage was 5/10—6/10 the velocity of an ice floe of 150 m x 75 m x 15 m (estimated) moving parallel to the ice front was measured to be 0.78 knots. At high tide the ice coverage increased to 9/10 and the ice floe velocity decreased to 0.45 knots.

2.4. Special Features of Sea Ice

During the POLARSIRKEL's reconnaissance voyage along the edge of the sea ice at the Filchner Ronne Ice Shelf, a special feature of multi-year sea ice was found west of Berkner Island up to the Position S 77° 00', W 49° 06'. The freeboard of this ice was 3 to 7 m high. This multi-year fast ice was frozen to the ice shelf up to a width of 6 nm. According to FEDOTOV (1970) this ice formed in the following manner: Sea ice grew in front of the ice shelf and did not break during the summer seasons. Snow then accumulated on

the surface of this multiyear sea ice which caused the ice to sink due to the weight of the snow. The water-soaked snow froze whereby the ice cover grew thicker from above.

In some places the height of the current snow cover (freeboard) was 7 m. Assuming a snow density of 0.4 g/cm^3 the underwater thickness of this multiyear fast ice would be about 25 m. Presuming a yearly snow accumulation of 30 to 50 cm (this was the thickness range of the yearly stratification measured at the border of the multi-year sea ice) the age of this ice would be 50 to 80 years.

The transition from the multi-year fast ice to the ice shelf was rather steep and therefore visible from far away. At the westerly end of this transition a hinge had developed in the form of cracks parallel to the ice front. The long period sea waves caused a wide strip of this 15—25 m thick ice to break up into large ice floes which then drifted off in a westerly direction. From the surface of one of these ice floes two ice cores were collected by core drilling after a 2.50 m thick snow cover had been removed. Below this 2.50 m thick dry snow cover a layer of 2 m water soaked snow (slush) was found above the surface of the solid ice. The examination of these ice cores showed that this multi-year fast sea ice had a fine grained crystal structure. Its salinity content was about 4‰. The compressive strength of this ice was stronger than that of the columnar grained sea ice.

2.5. Sea Ice Conditions in the Atka Bay

The ice shelf on the west side of the Atka Bay was inspected as an alternative to the site of the Filchner Ronne Ice Shelf. For this purpose the ship was moored to the shelf on the west side half way into the bay. During our 2 day stay in the bay (February 17/18, 1980), pack ice moved in and out corresponding to a strong tidal current (1.0—1.5 m/s). The direction of the ebb tide was NW, which caused the ice to move against the west side of the ice shelf. On the afternoon of February 18, 1980 a small iceberg crashed into the fast ice cover a few meters from the ship's anchoring place. On February 17, two ice cores were drilled from the fast ice cover in the inner part of Atka Bay. The ice here was 2.0 to 2.5 m thick, which is 50 to 100 cm thicker than that which was measured in front of the ice shelf at the Filchner Station. This greater thickness is caused by the bay situation, where the ice starts forming a fast ice cover relatively early in the season. One day later (Febr. 18), the fast ice cover had broken up completely and was in the process of moving out.

2.6. Conclusion

1. The selection of the berth for the Filchner Station at Pos. S $70^{\circ}00'$, W $50^{\circ}07'$ (B_0) seems to be advantageous not only with respect to the low height of the ice front (7—10 m) but also with respect to the sea ice movement.
2. At this location the tidal effects on the floe movement is much less than further east which reduces the danger of the ships in the berth of being pressured by ice.
3. If accessible, the location where the POLARSIRKEL was loaded of February 9/10, 1980 is recommended as berth for future operations. This location is situated just 3 nm east of B_0 in an embayment of the ice front. In this ice port it is possible to prevent the ship at berth from being pushed by drifting ice floes parallel to the ice front.
4. With heavy ice drift, the ice conditions east of the D-profile are difficult for ship navigation due to the hinderance of the drifting ice by the grounded iceberg alley. It is recommended to pass the area north of this iceberg line-up.
5. Due to the tidal current, the ice concentration varies. At high tide a ship passage is often impossible while a few hours later at low tide the ice floes drift apart and enable the ship to pass.

3. PHYSICAL AND MECHANICAL PROPERTIES OF SEA ICE IN THE WEDDELL SEA

3.1. Introduction

The investigations of the physical and mechanical properties of Antarctic sea ice were concerned with salinity, temperature, crystal structure, flexural strength, uniaxial compressive strength and Young's mo-

dulus. So that these properties could be determined, cores were drilled from level ice sheets using the 3'' SIPRE — core drill. The sea ice investigations started during the voyage near the South Sandwich Islands down to the southwest corner of the Weddell Sea (Kap Fiske). The locations at which the cores have been collected both from the ship and by helicopter are shown in Fig. 1.

3.2. Temperature and Salinity Measurements

Immediately after the core or part of the core had been pulled out from the bore hole in the ice, the temperature of the ice was measured by an electric Pt 100 temperature indicator and also recorded. Half of the cores were melted on board the ship in small samples of about 10 cm length in order to measure the salinity of the melt. The other half of the cores were packed in plastic bags and stored in a freezer at -30°C. These deep-frozen cores were taken back to Germany for further investigations. The salinity was determined by measuring the electrical conductivity, K_i . An example of a temperature and salinity profile is given in Tab. 1 and plotted in Fig. 6.

3.3. Flexural Strength and Young's Modulus

The flexural strength and the Young's modulus (strain modulus) are usually established through cantilever or simple supported beam tests. In the case of ice covers thicker than 1.0 m it is, however, much too difficult and time consuming to perform such tests. Fortunately, WEEKS & ASSUR (1958), have established a relationship between the flexural strength, σ_f , elasticity, E , and brine volume, ν_o , which has been verified by experiments as those of SCHWARZ (1975). This relationship

$$\sigma_f = \sigma_o (1 - \sqrt{\nu_o})^2 \text{ and} \quad (2)$$

$$E = E_o (1 - \nu_o)^4 \quad (3)$$

can be used to calculate both σ_f and E , if the brine volume is known; ν_o and E_o are the flexural strength and elasticity of ice structured like sea ice, but without salinity. According to FRANKENSTEIN & GARNER (1969) the brine volume is a function of the salinity and the temperature of the ice:

$$\nu_o = \frac{S_i}{1000} \left(\frac{49.185}{T_i} + 0.532 \right) \quad (4)$$

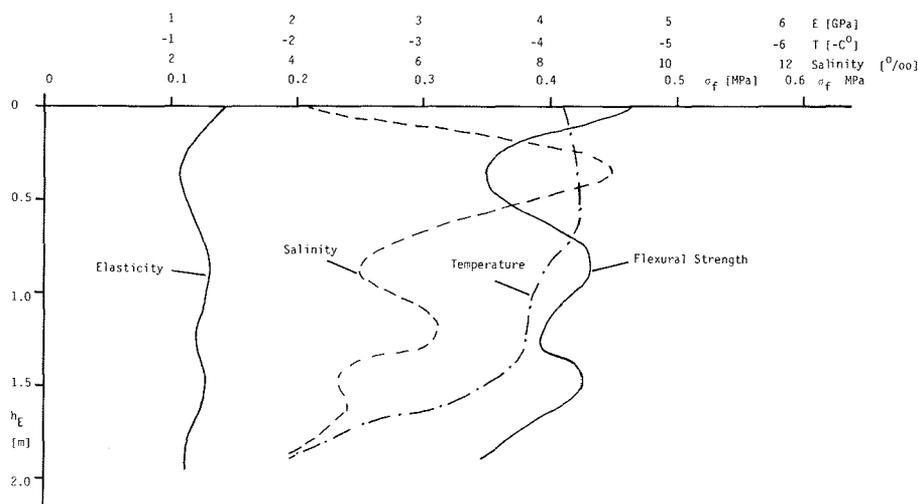


Fig. 6: Temperature, salinity, flexural strength and Young's modulus vs. depth of core No. 24 (Jan. 17, 1980).

Abb. 6: Temperatur, Salzgehalt, Biegefestigkeit und E-Modul als Funktion der Tiefe der Bohrung Nr. 24 (17. Januar 1980).

strength and elasticity mean values over the depth of the ice sheets are presented for all investigated ice cores in Tab. 2, in which the geographic position of the core collection site is also given.

According to the results in Tab. 2, the flexural strength of the Antarctic sea ice varies between 0.24 MPa, and 0.5 MPa, with most of the results within the range of 0.35 MPa and 0.45 MPa. The low values belong to the most northern locations, where the air temperature was about 0 °C.

3.4. Uniaxial Compressive Strength

3.4.1. Test Set-up and Performance

Ice samples were transported in a freezer on board the POLARSIRKEL from the Weddell Sea to Germany where the uniaxial compressive strength of the Antarctic sea ice was established in the ice laboratory of

Core No.	Date of Collection	Location	S_{im} ‰	T_{im}	σ_{fm} MPa	E_m GPa
4	79.12.31	S 71° 14' W 12° 33'	4.26	-1.1	0.24	0.71
5	79.12.31	S 71° 14' W 12° 33'	3.21	-0.9	0.27	0.80
8	80.1.2	S 75° 29' W 26° 50'	5.15	-2.3	0.34	1.04
9	80.1.3	S 77° 35' W 35° 13'	3.53	-2.4	0.40	1.23
13	80.1.3	S 77° 44' W 37° 10'	3.72	-4.8	0.50	1.44
14	80.1.4	S 77° 38' W 41° 34'	5.51	-4.7	0.45	1.33
15	80.1.5	S 74° 41.5' W 61° 16.18'	5.21	-2.0	0.29	0.96
16	80.1.7	S 76° 14' W 54° 20.4'	4.41	-2.4	0.37	1.10
17	80.1.7	S 76° 14' W 54° 20.4'	4.81	-2.2	0.35	1.06
20	80.1.7	S 77° 00' W 50° 06'	5.85	-2.2	0.31	0.95
21	80.1.15	S 77° 00' W 50° 06'	5.30	-2.6	0.36	1.09
22	80.1.15	S 77° 00' W 50° 06'	4.25	-2.1	0.36	1.11
24	80.1.17	S 77° 17' W 48° 18'	5.80	-5.5	0.40	1.21
25	80.1.17	S 77° 17' W 48° 18'	5.45	-3.5	0.41	1.23
26	80.1.18	S 77° 17' W 48° 18'	6.20	-3.4	0.38	1.16
27	80.1.18	S 77° 17' W 48° 18'	6.19	-3.5	0.38	1.16
31	80.1.18	S 77° 17' W 48° 18'	5.73	-3.6	0.40	1.21
33	80.1.30	S 76° 55' W 50° 07'	3.57	-4.0	0.49	1.41
36	80.2.6	S 76° 55' W 50° 07'	4.48	-2.9	0.40	1.21
40	80.2.17	Atka Bay	3.64	-2.0	0.38	1.15

Tab. 2: Ice salinity, flexural strength, and Young's Modulus (mean various locations in the Weddell Sea).

Tab. 2: Salzgehalt im Eis, Biegefestigkeit, E-Modul (Mittelwerte) an verschiedenen Orten in der Weddell-See.

the Hamburgische Schiffbau-Versuchsanstalt. These tests were carried out according to standardized testing methods (SCHWARZ 1981). The principal means of testing was the 100 kN capacity closed-loop testing machine which operates in the constant strain rate mode. The ice cores were cut by a band saw into specimens of 10 cm length with a diameter of 7.2 cm. An uniaxial state of stress throughout the specimen was produced by loading the specimen through compliant platens. These platens consist of a plug of low modulus elastic material confined radially within a metal ring in order to prevent gross radial deformation. It offers the possibility of uniform normal pressure to the end of a conventional cylindrical test specimen without imposing significant radial or tangential stresses, either positive or negative.

All cores collected in the Antarctic were taken vertically from the ice floes. This restricted the investigation to the force applied parallel to the direction of growth. From other basic investigations on sea ice we know, however, that the strength parallel to the direction of growth is about twice as high as the strength in the horizontal direction.

It should be noted that the uniaxial compressive strength is not the ultimate strength possible, it is just one point on the failure envelope of ice which in practical cases fails under multiaxial stress states. The uniaxial compressive strength can, however, be regarded as an index strength which is the most common value by which the material ice is described.

3.4.2. Results

The results of all uniaxial compression tests are given in Tab. 3 in which the uniaxial compressive strength, salinity, strain rate, test temperature in the ice, and the date of sampling are given.

3.5. Strain Rate Effect

In most of the previous investigations into the strain rate effect on the uniaxial compressive strength of ice (sea ice and freshwater ice) it was found that the strength increases with the strain rate in the ductile range of deformation (SCHWARZ & WEEKS 1976). At higher strain rates the strength drops off again. The maximum is found to be in the range of transition between the ductile and the brittle mode of failure.

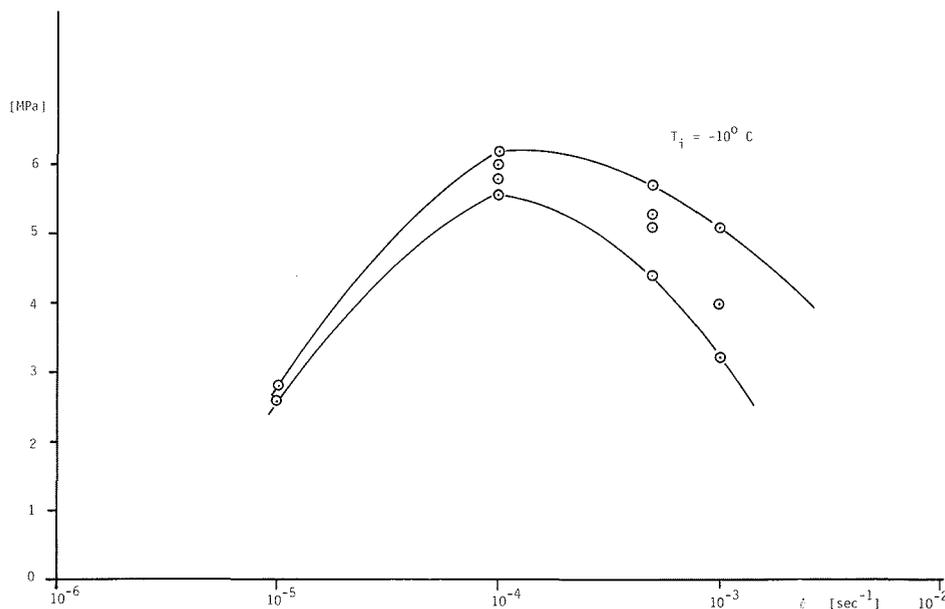


Fig. 7: Uniaxial compressive strength of Antarctic sea ice vs. strain rate.

Abb. 7: Einachsige Druckfestigkeit des antarktischen Meereises als Funktion der Verformungsrate.

σ_c [MPa]	T_i [°C]	$\dot{\epsilon}$ [sec ⁻¹]	S_i [‰]	Date of Sample Collection	Core No.
2.9	-4.9	10 ⁻⁴	4.0	3.1.80	12
2.4	-4.9	10 ⁻⁴	4.0	3.1.80	12
2.7	-4.9	10 ⁻⁴	5.6	21.1.80	29
4.8	-9.9	10 ⁻⁴	5.6	21.1.80	29
4.5	-9.9	10 ⁻⁴	5.5	21.1.80	29
4.4	-9.9	10 ⁻⁴	5.1	21.1.80	29
4.7	-9.9	10 ⁻⁴	4.8	21.1.80	29
5.6	-9.9	10 ⁻⁴	4.7	21.1.80	29
5.8	-9.9	10 ⁻⁴	4.7	21.1.80	29
4.0	-9.9	10 ⁻⁴	4.1	21.1.80	29
6.4	-9.9	10 ⁻⁴	3.3	21.1.80	29
8.1	-9.9	10 ⁻⁴	3.0	21.1.80	29
6.2	-9.6	10 ⁻⁴	4.0	23.1.80	30
2.1	-9.9	10 ⁻⁴	4.5	23.1.80	30
2.8	-9.7	10 ⁻⁵	3.6	23.1.80	30
2.6	-9.8	10 ⁻⁵	3.8	23.1.80	30
5.7	-9.8	10 ⁻⁴	3.6	23.1.80	30
5.3	-10.0	10 ⁻⁴	4.8	23.1.80	30
5.1	-10.1	10 ⁻⁴	4.7	23.1.80	30
4.4	-10.1	10 ⁻⁴	4.3	23.1.80	30
4.0	-10.0	10 ⁻³	5.5	23.1.80	30
5.1	-10.0	10 ⁻³	4.2	23.1.80	30
3.2	-10.0	10 ⁻³	4.4	23.1.80	30
3.3	-10.0	10 ⁻⁴	5.3	23.1.80	30
5.6	-10.0	10 ⁻⁴	5.0	23.1.80	30
3.3	-10.0	10 ⁻⁴	5.0	23.1.80	30
5.8	-10.0	10 ⁻⁴	5.2	23.1.80	30
6.0	-10.0	10 ⁻⁴	4.8	23.1.80	30
3.6	-10.0	10 ⁻⁴	5.4	30.1.80	32
5.8	-10.0	10 ⁻⁴	2.9	30.1.80	32
5.7	-10.0	10 ⁻⁴	3.2	30.1.80	32
1.6	-5.4	10 ⁻⁴	4.2	15.1.80	23
1.8	-5.4	10 ⁻⁴	4.7	15.1.80	23
2.3	-5.4	10 ⁻⁴	5.3	15.1.80	23
1.6	-5.4	10 ⁻⁴	3.8	15.1.80	23
2.3	-5.4	10 ⁻⁴	3.4	15.1.80	23
6.2	-5.3	10 ⁻⁴	2.7	15.1.80	23
3.1	-5.3	10 ⁻⁴	3.4	30.1.80	32
2.6	-5.3	10 ⁻⁴	3.5	30.1.80	32
2.6	-5.3	10 ⁻⁴	3.2	30.1.80	32
4.0	-5.3	10 ⁻⁴	3.0	30.1.80	32
5.4	-5.3	10 ⁻⁴	2.9	30.1.80	32
2.5	-5.3	10 ⁻⁴	4.8	30.1.80	32
4.2	-9.6	10 ⁻⁴	3.8	30.1.80	32
5.6	-10.4	10 ⁻⁴	2.9	30.1.80	32
8.1	-10.4	10 ⁻⁴	3.3	30.1.80	32
6.5	-10.4	10 ⁻⁴	2.6	30.1.80	32
4.4	-9.4	10 ⁻⁴	2.6	30.1.80	32
8.8	-10.4	10 ⁻⁴	3.1	30.1.80	32
3.0	-10.3	10 ⁻⁴	5.0	3.1.80	12
2.7	-10.5	10 ⁻⁴	6.9	3.1.80	12
3.5	-10.5	10 ⁻⁴	5.3	3.1.80	12
4.5	-10.4	10 ⁻⁴	5.5	3.1.80	12
3.1	-10.4	10 ⁻⁴	5.1	3.1.80	12
6.0	-10.4	10 ⁻⁴	4.9	3.1.80	12
5.7	-10.4	10 ⁻⁴	4.0	3.1.80	12
8.0	-10.4	10 ⁻⁴	3.9	3.1.80	12
4.5	-10.4	10 ⁻⁴	4.9	3.1.80	12
5.2	-4.9	10 ⁻⁴	4.0	30.1.80	32
4.3	-4.9	10 ⁻⁴	2.8	30.1.80	32
5.9	-4.9	10 ⁻⁴	2.4	30.1.80	32
5.9	-4.8	10 ⁻⁴	3.9	30.1.80	32
2.8	-5.0	10 ⁻⁴	7.1	3.1.80	12
1.9	-5.0	10 ⁻⁴	5.9	3.1.80	12
2.5	-4.9	10 ⁻⁴	5.1	3.1.80	12
2.6	-4.9	10 ⁻⁴	5.5	3.1.80	12
3.4	-4.9	10 ⁻⁴	4.3	3.1.80	12

Tab. 3: Uniaxial compressive strength, strain rate and ice salinity of Antarctic sea ice.

Tab. 3: Einachsige Druckfestigkeit, Verformungsrate und Salzgehalt im Eis des antarktischen Meereises.

In order to investigate the compressive strength of the Antarctic sea ice at a strain rate at which the strength is the highest, a primary series of uniaxial strength tests was carried out at different strain rates ranging from 10^{-5} to 10^{-3} sec⁻¹. The results of these investigations are shown in Fig. 7, which indicates that the Antarctic sea ice of -10 °C has its highest strength at a strain rate range of $1 \cdot 10^{-4}$ sec⁻¹. Due

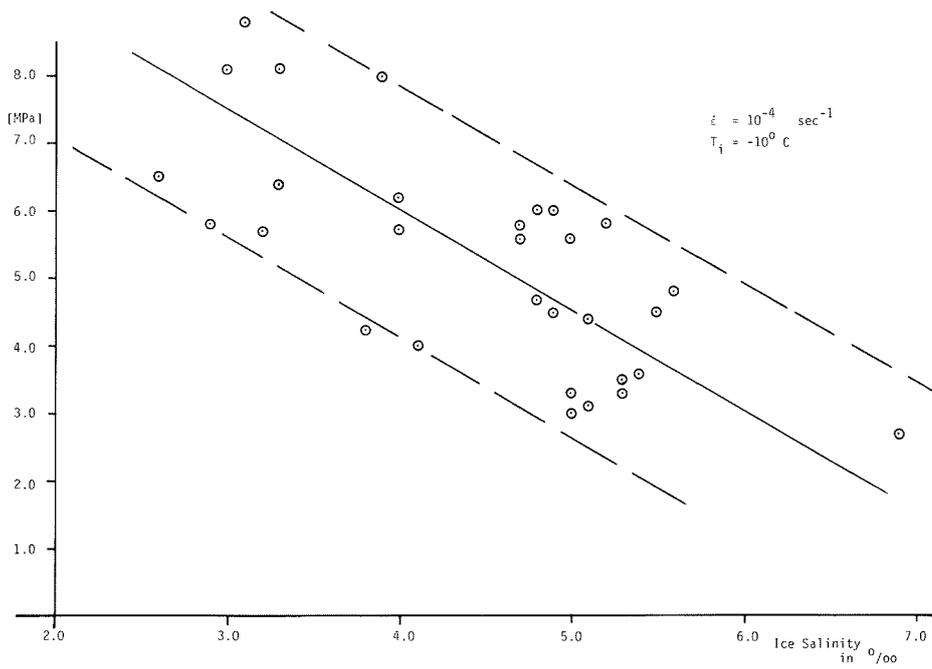


Fig. 8: Uniaxial compressive strength of Antarctic sea ice vs. ice salinity.

Abb. 8: Einachsige Druckfestigkeit des antarktischen Meereises als Funktion des Salzgehaltes im Eis.

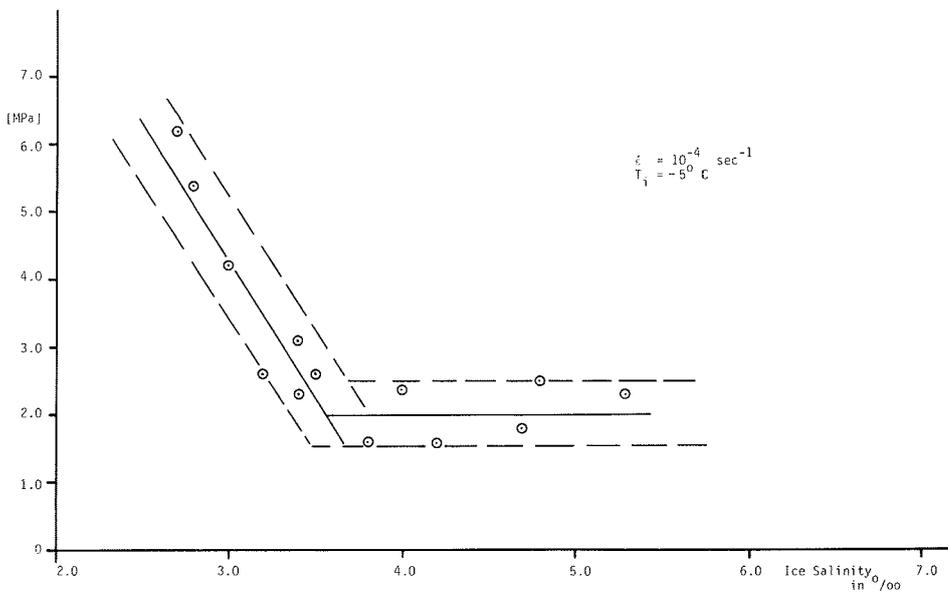


Fig. 9: Uniaxial compressive strength of Antarctic sea ice vs. ice salinity.

Abb. 9: Einachsige Druckfestigkeit des antarktischen Meereises als Funktion des Salzgehaltes im Eis.

to this result all the succeeding strength tests were carried out at a strain rate of $\dot{\epsilon} = 10^{-4} \text{sec}^{-1}$ in order to obtain the maximum strength in regard to strain rate.

3.6. Salinity Effect

Test results of the uniaxial compressive strength tests of the Antarctic sea ice were plotted versus the salinity for -10°C in Fig. 8 and for -5°C in Fig. 9. Both figures could be combined by plotting the strength versus brine volume, which combines salinity and temperature, instead of plotting strength versus salinity.

3.7. Temperature Effect

The uniaxial compressive strength tests were carried out at a temperature of about -5°C and -10°C . Because no ice sample was exactly like the others due to their different origins and different positions within the depth of the ice sheets, the investigations into temperature effect on sea ice strength were carried out in such a way that every other sample of each core was tested at -5°C and -10°C . Hereby it was anticipated to minimize the error factor caused by the differences in the ice origins. The result of the investigations on the temperature effect is plotted in Fig. 10, it shows the evidently strong increase in strength caused by lowering the temperature from -5°C to -10°C .

3.8. Strength Variation over the Depth of the Ice Sheet

By dividing the whole core length into samples of 10 cm length, it was possible to acquire information on strength variation as a function of ice thickness. The results are given in Fig. 11, which shows the uniaxial compressive strength at -10°C (two examples) and -5°C . All three curves of strength variation with depth show the increase with depth before just above the bottom the strength decreases again.

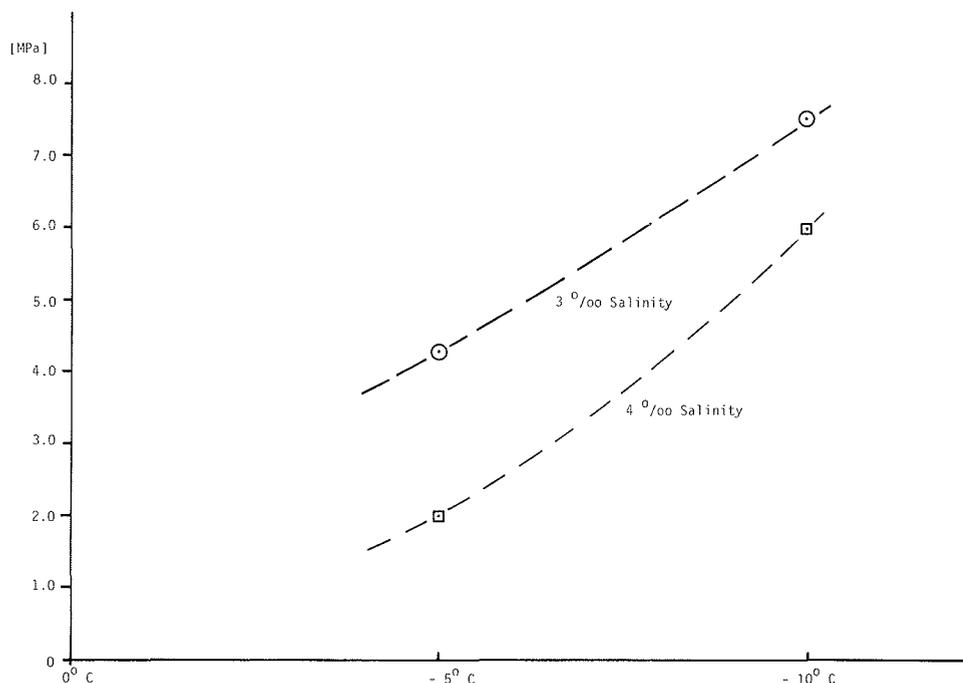


Fig. 10: Uniaxial compressive strength of Antarctic sea ice vs. temperature.

Abb.10: Einachsige Druckfestigkeit des antarktischen Meereises als Funktion der Temperatur.

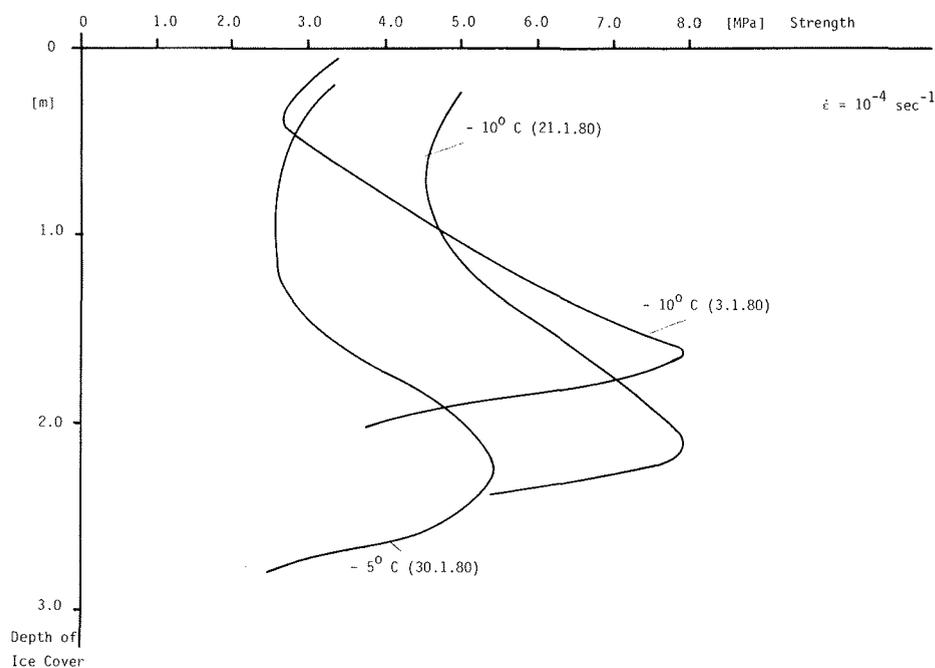


Fig. 11: Uniaxial compressive strength of Antarctic sea ice cores over the depth of ice cover.

Abb.11: Einachsige Druckfestigkeit von antarktischen Meereisproben als Funktion der Tiefe in der Eisdecke.

3.9. Crystal structure

For some of the ice core samples the crystal structure was investigated with respect to crystal size and crystal orientation. For this purpose thin sections were cut and photographed. The pictures show the common crystal structure for first year sea ice, i. e. a columnar grained ice without any preferred orientation of the horizontal c — axis. The size of the ice crystal was in the order of 1 cm in the upper ice layer increasing with depth to about 5 cm in 1.5 m depth.

4. ICE THICKNESS MEASUREMENTS

4.1. Introduction

In ice engineering research, for example, in investigations into the icebreaking capability of ships or of ice forces on structures, the ice thickness is one of the most important parameters. Therefore a continuous record of the ice thickness is mandatory.

Ice thickness measurements were carried out during the Antarctic expedition in order to develop the impulse radar technique such that this method could be applied on board of the German Polar Research Vessel when it goes into operation in 1982.

4.2. Impulse Radar Unit

In order to obtain a continuous record of the ice thickness a Subsurface Interface Radar-System (SIR) was applied, which was purchased from the Geophysical Survey System Inc., N. H. (USA). This system consists of a control unit, a magnetic tape recorder, a graphical recorder and the following antennas of different impulse frequencies suitable for different modes of operation:

- | | |
|---------------------------------------|-----------|
| a) sea ice surface glider antenna | (120 MHz) |
| b) sea ice airborne antenna | (300 MHz) |
| c) deep probing antenna for shelf ice | (80 MHz) |

The electromagnetic impulse is propagated into the ice from a transducer unit which is either moved directly across the ice surface or which is mounted to a helicopter; both methods have been applied during the Antarctic expedition. When the impulse strikes the bottom of the ice cover some of the impulse energy is reflected which is then received by the transducer. Both the transmitted pulse and the reflected signal are monitored on the oscillograph of the control unit, printed on a graphic recorder, and recorded on magnetic tape. The time lap between the transmitted impulse and the received one is a function of the dielectric conductivity of the ice and the ice thickness.

In case (1), the SIR-System including a power supply (Diesel generator) was put on a Nansen sledge, which with the antenna running behind the sledge was pulled across the surface of the level ice cover. At the beginning and at the end of the measurement the graphic printout of the reflection of the electromagnetic impulses was calibrated by measuring the ice thickness manually. In case (2), it was intended to measure the thickness of drifting ice floes from board of the POLARSIRKEL. This operation was not successful. A reflection of the impulse was received, but this was independent of the ice thickness, which led to the conclusion that the subject of the reflection was not the underside of the ice cover, but a layer of saline water between the snow layer and the surface of the solid ice. It is well known that the electromagnetic energy of our impulse radar unit is absorbed by water of more than 10‰ salinity whereby no reflections are possible from the underside of the ice cover. The third method of operating the SIR-System was the airborne thickness measurement, in which the antenna was mounted sideways on the helicopter by a wooden cantilever bar and the rest of the SIR-System inside the helicopter, except for the graphic recorder. In this case, the impulses were recorded on magnetic tape and after the flight printed out on the graphic recorder. These measurements turned out to be unsuccessful. What was originally thought to be the reflection from the underside of the ice cover was later on identified as the reflection of the ice surface reflected impulse from the helicopter.

Assuming the electrical properties of the ice are constant within a certain area at a certain time, the time interval between a transmitted pulse and its reflection is a measure for the ice thickness. For pure fresh-water ice the electric properties are constant which means that the pulse's traveling velocity can be calculated and the distance on the printed record between the first pulse and its reflection is a measure for the

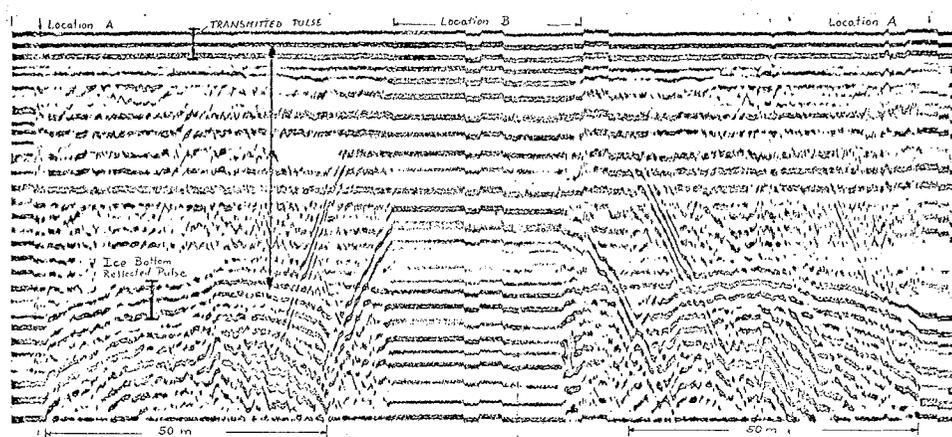


Fig. 12: Graphic record of impulse radar ice thickness measurement (forward and reverse ice thickness profile).

Abb.12: Graphische Darstellung von Eisdickenmessungen mit dem Impuls-Radargerät (Eisdickenprofil von Hin- und Rückfahrt).

ice thickness.

In the case of sea ice, the electrical properties are strongly affected by the salinity and temperature within the ice. Because the salinity and temperature vary with the ice thickness and with the time (due to temperature changes) the travelling velocity of the pulse can not be calculated. Therefore before and after each ice thickness measurement the printed record must be calibrated by measuring the ice thickness manually. For further technical details of the SIR-System see publications such as KOVACS & MORY (1980).

4.3. Results

An example on the feasibility of measuring sea ice thickness by impuls radar is presented in Fig. 12, in which the thickness over a distance of 100 m is recorded: On the left side the antenna was moved from point A to B and on the right side backwards from B to A. The record shows indeed a symmetrical image of the reflected pulses from the bottom of the ice cover. Unfortunately time was not available to make real use of this instrument and measure the ice thickness over longer distance of ice covers.

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