Seismic and ultrasonic measurements on the sea ice of Eclipse Sound near Pond Inlet, N.W.T., on northern Baffin Island

By H. Kohnen*

Abstract: During May and June 1972 extensive seismic and ultrasonic measurements were carried out on the sea ice of Eclipse Sound outside Pond Inlet, N.W.T. between Baffin Island and Bylot Island. These investigations were part of the Canadian Arctic Channel Project.
In the paper, the elastic moduli of the sea ice cover are determined from the seismic measurements and an empirical relation between the plate wave velocity and the flexural strength is proved. The distribution of the velocity and the elasticity within the ice cover and its relation to the brine volume is deduced from ultrasonic measurements.

Zusammenfassung: Während der Monate Mai und Juni 1972 wurden umfangreiche seismische Messungen und Ultraschalluntersuchungen auf dem Meereis des Eclipse Sound bei Pond Inlet, N.W.T. zwischen Baffin Island und Bylot Island durchgeführt.
Aus den seismischen Messungen werden die elastischen Konstanten der Meereisdecke bestimmt, und die empirische Beziehung zwischen Plattenwellengeschwindigkeit und Biegefestigkeit wird überprüft. Die Verteilung der Geschwindigkeiten und elatischen Parameter innerhalb der Eisplatte ist aus den Ultraschalluntersuchungen abgeleitet.

Introduction

As current ship types are not suitable for marine transport of oil and ores in ice bound areas, new technics must be developed to provide us with an economical transport system, which is done by EOS and other efforts (Canadian Arctic Channel Project, Memorandum, March 7, 1972). To gather more information on relevant parameters necessary for ship construction and navigation in Arctic waters a joint Canadian-German expedition was sent to Pond Inlet, N. W. T., on northern Baffin Island.

This expedition concentrated on glaciological investigations on the sea ice of Eclipse Sound between Pond Inlet and Bylot Island during May and June 1972. The emphazis was on studying the physical and mechanical properties of sea ice, like elasticity, strength, resistivity, dielectric constants as well as on friction against metals and the pressure within the ice cover.

Since the physical parameters are more or less affected by the petrological structure of the ice, the ice movement and by meteorological and oceanographic factors, detailed studies in these fields supplemented the scientific program.

Extensive seismic and ultrasonic measurements were carried out during the field season as part of the physics program. The results of these measurements are presented in this paper.

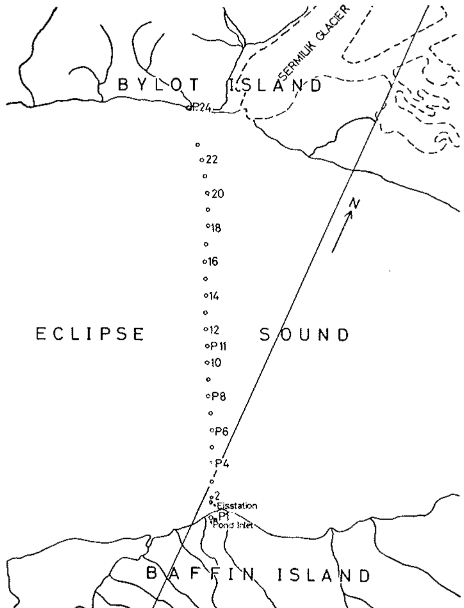

Fig. 1: The investigation area near Pond Inlet.
Abb. 1: Karte des Meßgebietes.

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The seismic measurements

The seismic measurements comprised five profiles, 1150 m each, at Eisstation, P 4, P 6, P 8 and P 11 (Fig. 1). Shots were recorded from both ends. A T 111 (Geospace) Seismograph System, together with 4,5 Hz vertical and horizontal geophones (Geospace), was used for all measurements. The geophone spacing was 50 m, the distances being measured with a steel tape. The errors, both of the distances and the timing of the seismic recorder, are less than 0,1%. Charges of two to three pounds of seismic explosives were used to generate the seismic waves. On all profiles good breaks of the plate waves, transversal waves and bottom reflected P-waves were recorded.

Figures 2 and 3 show the travel time curves of the stations P 8 and P 11. The velocity in the sea water: $\bar{v}_p$ = 1,45 km/sec is calculated from the reflected P-waves. The depth of the sound at the end of the seismic profiles, as indicated in Figure 2 and 3, was determined by using this velocity.

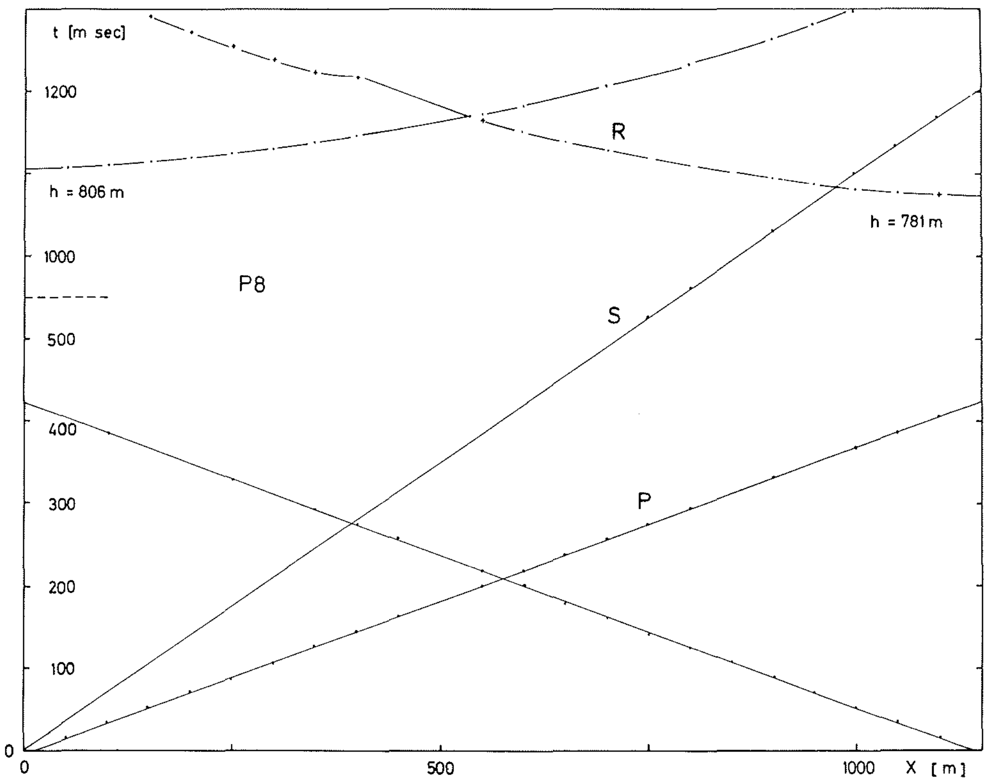

Fig. 2: Travel time plot of the profile at P8. P = P-wave, S = S-wave, R = bottom reflected P-wave, h = depth of the sound.
Abb. 2: Laufzeitkurven des Profils P8.

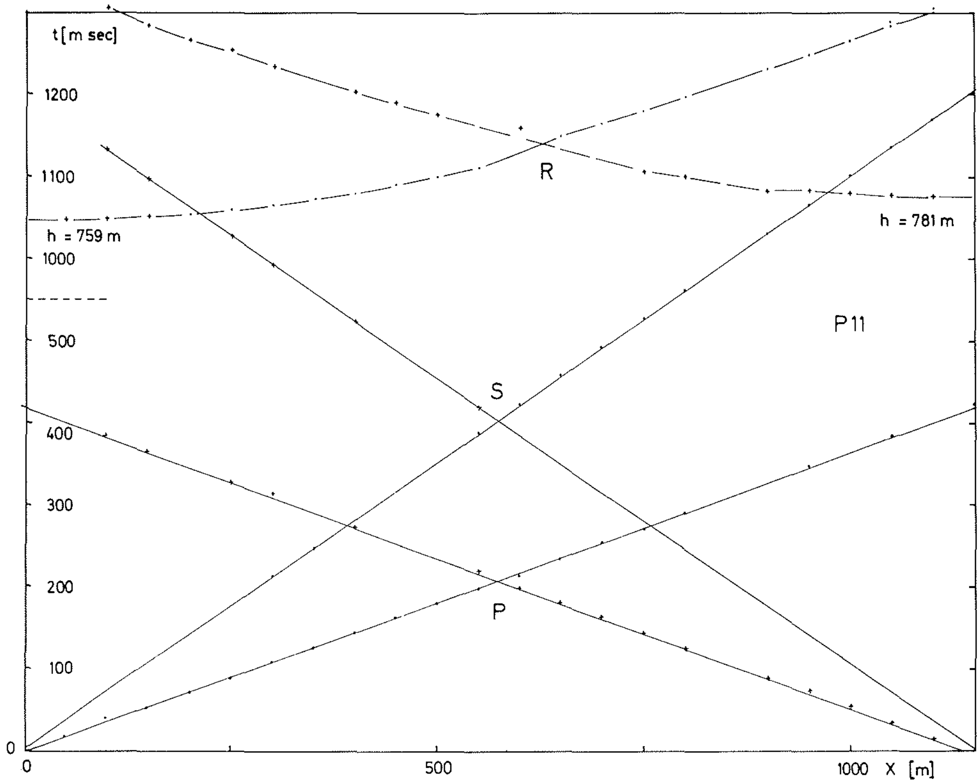

Fig. 3: Travel time plot of the profile at P11.
Abb. 3: Laufzeitkurven des Profils P11.

The velocities of the plate waves and the transversal waves are listed in Table 1. The standard deviation is remarkably small. Poisson's ratio, Young's and shear modulus (Table 1) are calculated from these velocities using the following formulas:

$E = \varrho V_{pl}^2 (1 - \sigma)$ Young's modulus

$\mu = \varrho V_T^2$ shear modulus

$\sigma = 1 - 2 (V_T/V_{pl})^2$ Poisson's ratio

Location	V_{pl} (km/sec)	V_T (km/sec)	σ	$E \cdot 10^{-10}$ (dyn/cm²)	$\mu \cdot 10^{-10}$ (dyn/cm²)	h (m)
Eisstation	2,512 ± 0,007	1,419 ± 0,015	0,361	4,98	1,83	1,80
P 4	2,607 ± 0,009	1,433 ± 0,006	0,396	5,20	1,86	1,80
P 6	2,631 ± 0,004	1,457 ± 0,003	0,387	5,34	1,93	2,34
P 8	2,695 ± 0,004	1,440 ± 0,004	0,428	5,38	1,88	2,31
P 11	2,719 ± 0,006	1,438 ± 0,010	0,440	5,41	1,88	2,28

Table 1: The velocities and elastic moduli determined from the seismic measurements. V_{pl}: plate wave velocity; V_T: transversal velocity; E: Young's modulus; μ: shear modulus; σ: Poisson's ratio; h: thickness of the ice cover (K. Blewett, pers. communication).

Tabelle 1: Die Geschwindigkeiten und elastischen Konstanten, bestimmt aus den seismischen Messungen. V_{pl}: Plattenwellengeschwindigkeit; V_T: Geschwindigkeit der Transversalwellen; E: E-Modul; Scherungsmodul; Poisson'sche Konstante; h: Dicke der Eisdecke nach Blewett (pers. Mitteilung).

A density of 0,907 g/cm³ was used for the calculations. This value is the average of the density curve (Fig. 4) which proves that the density does not change to any great extent with varying depth through the ice cover. The densities were determined by drilling cylindrical samples, weighing the samples and calculating the volume from the dimensions. The plate wave velocities as well as the elastic moduli show a slight increase from the shore to the center of the sound (Table 1). This increase cannot be due to the differences in ice thickness because the wave length of the plate waves is about 50 m to 100 m and still great compared with the ice thickness. Different types of ice, annual ice or multi year ice, could also affect the velocities and the elastic moduli but the resistivity measurements (Thyssen, Kohnen, Cowan and Timco, in preparation) show that there was no multi year ice on the traverse profile in this season. The salinity

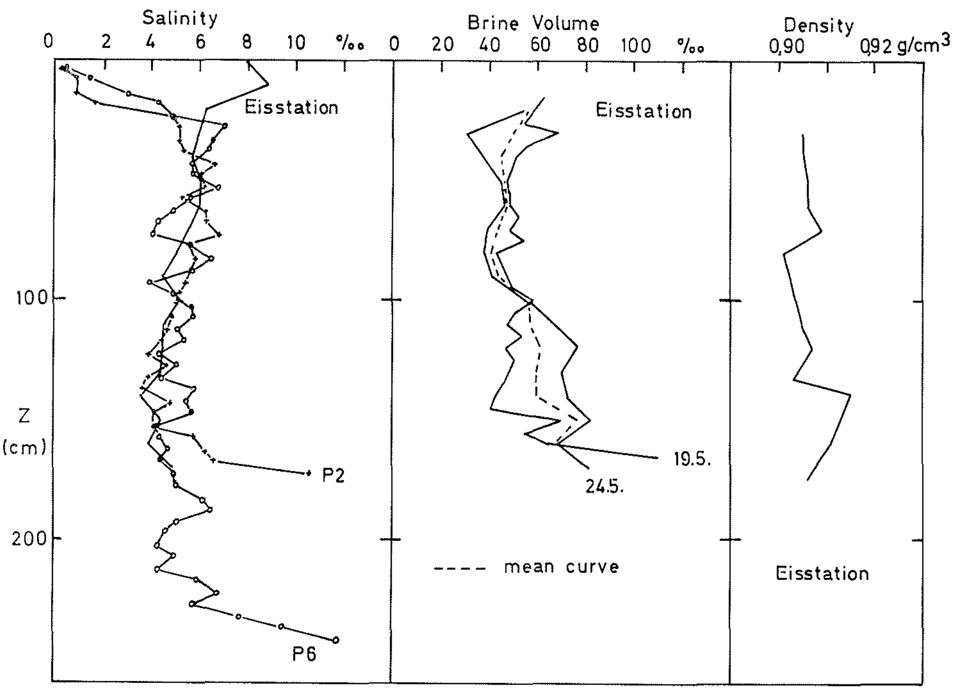

Fig. 4: Salinity (after Walter and Jesseau), brine volume, and density of the sea ice at Eisstation.
Abb. 4: Salzgehalt (nach Walter und Jesseau), Laugengehalt und Dichte des Meereises bei der Eisstation.

profiles (Fig. 4), taken at three different locations (Eisstation, P 2 and P 6) (Jesseau, Walter, pers. communication) also do not show any significant differences indicating different types of the ice. However, the temperatures in the ice, measured by the author at Eisstation and by J. Werner (pers. communication, 1972) at the site P 9 are remarkably different. The sensors were frozen into the ice-sheet at 4 and 5 resp. different levels. Figure 5 indicates that at the same time the temperatures in the ice at P 9 were approximately 2° C to 2,5° C lower than at Eisstation. According to Frankenstein and Garner (1967) the brine volume is a simple function of salinity and temperature provided that the entrapped air is negligible:

$$\nu = S\,(45{,}917/T + 0{,}930)$$

(ν: Brine content; S: Salinity; T: Temperature)

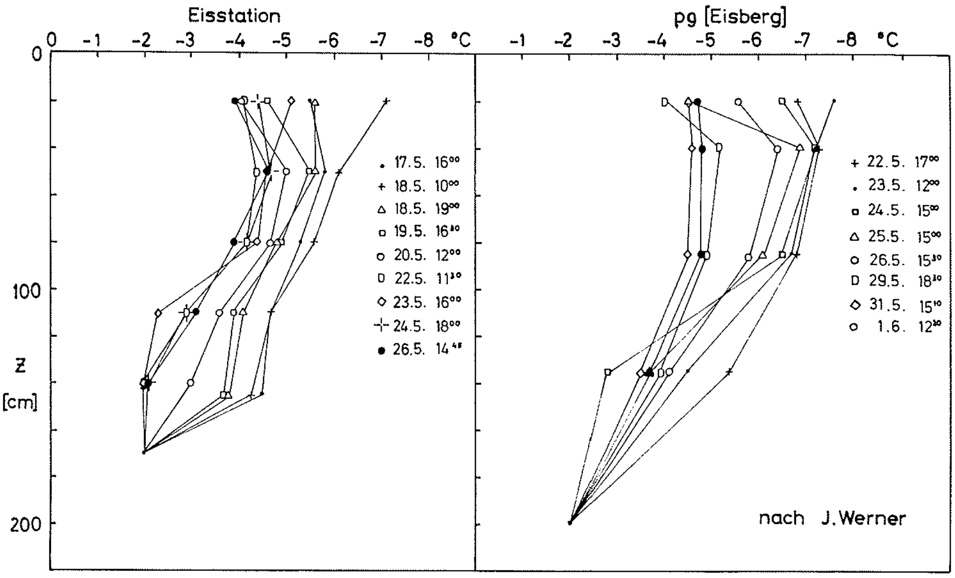

Fig. 5: The temperature distribution in the ice at P9 (after Werner) and at Eisstation.
Abb. 5: Temperaturverteilung im Eis bei P9 (nach Werner) und an der Eisstation.

The distribution of the brine in the ice, as shown in Figure 4, is calculated from this equation. Unfortunately there are no salinity measurements available from P 9. Deducing from the data in Fig. 4 and from the resistivity measurements that there are no significant lateral salinity variations we may expect from the temperature difference a brine value lower by approximately 20% at the central stations. Brown (1963) has shown how much the plate wave velocity and Young's modulus are affected by the brine content. From his results we may expect an increase in the plate wave velocity and Young's modulus from the marginal sites to the center. However, it is surprising that the transversal velocity, and therefore also the shear modulus does not increase significantly the same way.

Despite the velocity and the elasticity variation mean values are calculated for the sea ice at Pond Inlet for this season: $\overline{V}_{pl} = 2{,}633$ km/sec; $\overline{V}_T = 1{,}438$ km/sec; $\overline{E} = 5{,}26 \cdot 10^{10}$ dyn/cm^2; $\overline{\mu} = 1{,}88 \cdot 10^{10}$ dyn/cm^2; $\overline{\sigma} = 0{,}4$; $h = 2{,}10$ m. In addition to these resistivity measurements, careful structural investigations (Walter, 1972, pers. communication), which yielded also that there was no other ice than annual ice in the investigation area, justify this procedure.

Brown (1963) demonstrated the close relationship between plate wave velocity and brine content, flexural strength and brine content and finally between plate wave velocity and flexural strength. From his empirical relation and the mean value $\overline{V}_{pl} = 2{,}633$ km/sec we obtain a flexural strength of 4,44 kp/cm^2 which is in fairly good agreement with the value of 4,7 kp/cm^2 (Finke, 1972, in press) and 5,2 kp/cm^2 (Airaksinen, 1972), measured at Eisstation during the 1972 field season. Despite its empirical nature, Brown's relation seems to provide a good tool to determine the flexural strength of sea ice from seismic measurements.

The ultrasonic measurements

The ultrasonic investigations were carried out at Eisstation and P 2. An USIP 11 (Krautkrämer) ultrasonic equipment, together with barium titanate transducers and receivers,

was used. Five cores (4 at Eisstation and one at P 2) about 1,70 m in length, being the total thickness of the sea ice cover at these sites, were drilled with an SIPRE drill. From the cylindrical cores, samples of approximately 5 x 5 x 5 cm were cut with a saw. These dimensions are great when compared with the wave length of the 2 MHz frequency range applied for all measurements, but still small enough to obtain a readable signal at the receiving end. The maximum gain of the equipment is 80db.
The impulses were transmitted through the samples in the horizontal and vertical direction (relative to the surface). Core 1 and 2 were measured only in one horizontal direction whereas core 3 was measured in two perpendicular horizontal directions (Fig. 6). Only the first breaks of the longitudinal waves could clearly be identified and the velocities were calculated from their travel times. No readable signals in the horizontal directions could be obtained from core 4 and 5*). When working on these cores the outside temperature had risen remarkably, and a rapidly increasing portion of brine could be observed as soon as the samples were prepared. The increasing portion of the liquid phase is most likely responsable for the increased attenuation. This effect finally made the measurements come to an end after May 25.

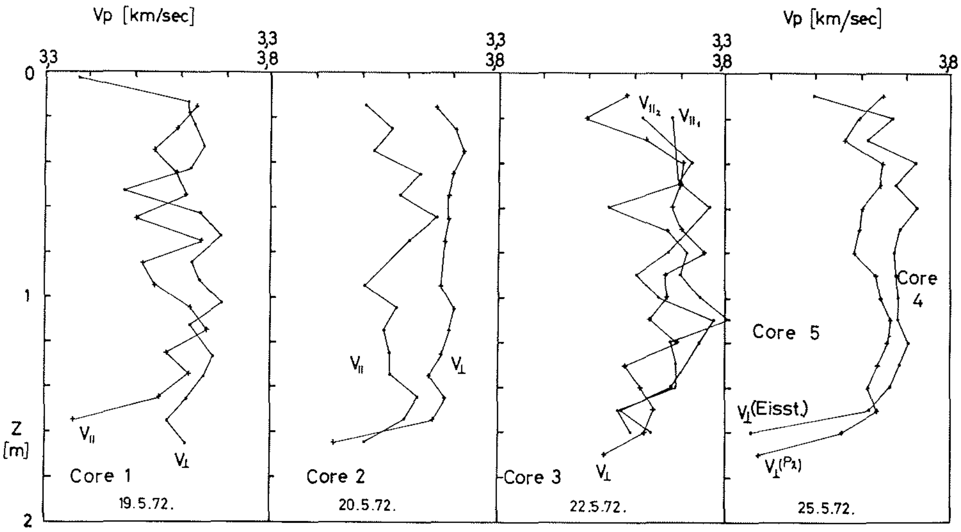

Fig. 6: Results of the ultrasonic measurements at Eisstation and P2.
Abb. 6: Ergebnisse der Ultraschalluntersuchugen an der Eisstation und bei P2.

The random error of the velocities is estimated to be about $\pm$/,1 km/sec, mainly caused by errors in measuring the dimensions of the samples. Additionally, there is a systematic error of approximately $\pm$0,05 km/sec, induced by the transducing technic. These considerable errors unfortunately prevent any differentiation between the velocities in the vertical and horizontal or in the two perpendicular horizontal directions, as may be seen from Figure 6. Furthermore, it is not possible to correct the measurements by evaluating the systematic errors, nor to attribute any residual differences to structural features. Therefore, a mean velocity distribution (Fig. 7) is calculated from the 9 velocity curves. These are the basic data for the calculation of Young's modulus. The standard deviation of these velocities is approximately 0,02 km/sec.
Since no shear waves could be identified Young's modulus is determined from the

*) These cores were measured by Dr. M. Cowan and Mr. G. Timco

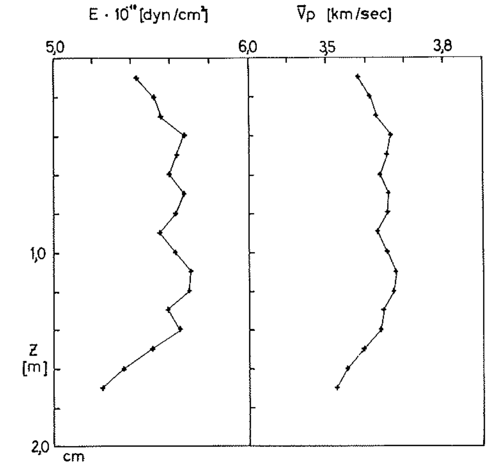

Fig. 7: The distribution of the P-wave velocity and Young's modulus with depth in the ice.
Abb. 7: Die Verteilung der P-Wellengeschwindigkeiten und des E-Moduls im Meereis.

longitudinal wave velocities and from Poisson's ratio $\sigma = 0{,}4$, being the mean value of the seismic measurements. Only the mean velocities are taken for the calculation of E, and no differentiation is made between the vertical and horizontal directions. The error of Young's modulus is estimated to 5% to 10%, mainly caused by the uncertainty in Poisson's ratio. However, the principal feature of the elasticity distribution is hardly affected by this error because the variation of Poisson's ratio with depth is most likely negligible. The feature of the E-curve therefore is essentially determined by the velocity distribution. A marked increase of E is observed in the upper 40 cm and then an almost constant value of about $5{,}6 \cdot 10^{10}$ dyn/cm² down to a depth of 140 cm. In the bottom part E decreases again rapidly. This increase and decrease of E is not due to a density

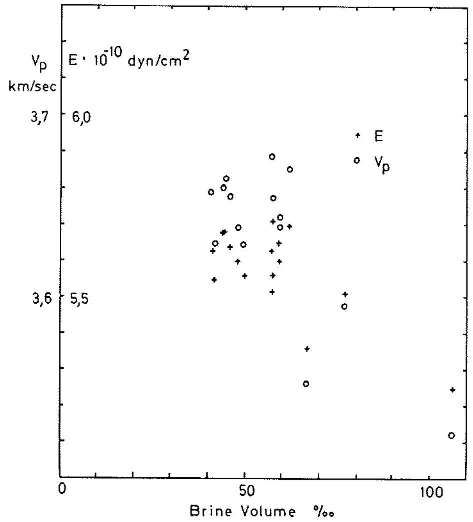

Fig. 8: P-wave velocity and Young's modulus versus brine volume.
Abb. 8: P-Wellengeschwindigkeiten und E-Modul in Abhängigkeit vom Laugengehalt.

variation because the observed density variations would change the velocities by only 0,01 to 0,02 km/sec.

Young's modulus, averaged over the whole depth, is $5{,}57 \cdot 10^{10}$ dyn/cm^2 in accordance to an average velocity of 3,629 km/sec. This value is in good agreement with the mean value of the seismic measurements indicating that the value choosen for Poisson's ratio is appropriate.

From Brown's results (1963) as well as from the investigations of Langleben and Pounder (1963) we know that velocity and elasticity are primarily affected by changes in the brine volume. In Figure 8, the velocities and Young's moduli are plotted against the brine content (mean curve of Fig. 4). The range of the velocity and the elasticity as well as the range of the brine volume are too small to allow any deduction of an analytical relation. Figure 8, however, shows how much the velocity and Young's modulus depend on the brine volume. Both decrease rapidly with increasing brine.

Summary

Five seismic profiles were measured at representative sites on the sea ice between Pond Inlet and Bylot Island. From the plate wave velocities, the shear wave velocities and the density the elastic moduli, Young's modulus, shear modulus and Poisson's ratio are calculated. The plate wave velocities as well as Young's moduli show a remarkable increase from the marginal zone to the central part of the sound. This increase is attributed to a decrease in the brine volume due to a temperature difference of approximately 2° C in the ice between the marginal and central part. The salinity, the resistivity and the structural investigations suggest that there were no other types of ice than annual ice in the area of the profile. Therefore mean values of the elastic moduli are calculated. An average flexural strength is deduced from Brown's empirical relation and compared with the values of Airaksinen (1972) and Finke (1972); a fairly good agreement could be obtained.

5 cores, taken at Eisstation and P 2, were investigated by the ultrasonics method and the distribution of the P-wave velocity and Young's modulus in the ice is determined from these data. For the computation of E, a value of Poisson's ratio is deduced from the seismic results, the mean value of E is found to be in line with the seismic value. Both velocity and Young's modulus increase in the upper 40 cm, than are more or less constant and decrease again in the bottom part of the ice. This distinct feature is related to the distribution of the brine volume.

Acknowledgements

The author is indebted to Dr. M. Cowan and Mr. G. Timco who a. o. did the seismic blasting as well as to Drs. S. Finke, F. Thyssen, E. Treude, R. Walter and J. Werner for their assistance during the field work. It is very much acknowledged that Mr. K. Blewett, Mr. W. Jesseau, Dr. R. Walter and Dr. J. Werner made their data available to the author prior to publication. Dr. Thyssen's valuable suggestions and review of the paper are appreciated.

The investigations were done under grant of the German Ministry of Education and Science and sponsored by the German shipyard A. G. "Weser", Bremen.

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