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THE TEMPERATURE DEPENDENCE OF SEISMIC WAVES IN ICE

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ABSTRACT. In this paper all available seismic velocity data from Greenland and Antarctica are used to determine the relation between seismic velocities and temperatures in the ice.

RÉSUMÉ. *Une note a propos de l'influence de la temperature sur les ondes sismiques dans la glace.* Dans cette étude on utilise toutes les données disponibles sur les vitesses de propagation des ondes sismiques dans les indlandsis de Groenland et l'Antarctique pour déterminer la relation entre ces vitesses et les températures.

ZUSAMMENFASSUNG. *Eine Bemerkung zur Temperaturabhängigkeit seismischer Wellen im Eis.* In den nachfolgenden Betrachtungen sind alle verfügbaren seismischen Feldmessungen aus Grönland und Antarktika verwendet, um die Beziehung zwischen seismischen Geschwindigkeiten und der Temperatur im Eis zu bestimmen.

INTRODUCTION

Since the early seismic measurements of the Wegener Expedition on the Greenland ice sheet 1929–31 (Brockamp, 1935) many investigations on the temperature dependence of seismic waves in ice have been carried out by various authors. Besides being of general interest, it is essential for the computation of ice thicknesses from reflection shooting to know how seismic velocities vary with temperature. Table I shows the results of various laboratory and *in situ* investigations and how they differ much from each other. In particular there seems to be an inconsistency between the laboratory and *in situ* measurements. However, Bentley ([^{c}1964]) and Röthlisberger (1972) have already pointed out that the results of the field measurements in the Antarctic are in good agreement with the ultrasonic results of Robin (1958).

TABLE I. VELOCITY GRADIENTS FROM *in situ* AND LABORATORY MEASUREMENTS

Velocity gradient m/s deg		*Author*
in situ:		
dv_p/dT	−18	Joset and Holtzscherer (1953)
	−7.4	Thiel and Ostenso (1961)
	−5.5	Brockamp and Kohnen ([1967)]
	−4.5	Thyssen (1967)
dv_s/dT	−3.4	Thiel and Ostenso (1961)
	−3.6	Brockamp and Kohnen ([1967])
laboratory:		
dv_p/dT	−2.3	Robin (1958)
	−3.4	Bass and others (1957)
	−2.2	Brockamp and Querfurth ([1965])
dv_s/dT	−1.4	Bass and others (1957)
	−1.1	Brockamp and Querfurth ([1965])

RESULTS

The main reason for the inconsistency and also for the differences between the various field results has been that there were not enough field data available and that some field data applied for the determination of dv/dT, did not represent properly the velocities in polycrystalline ice at the given temperature. The reason for the latter may in some cases have been the inclusion of velocities obtained from refraction profiles which were too short to yield the maximum velocities, and the inclusion of velocities affected by anisotropy in the ice, but in some cases also inaccuracy. If such velocities are used for the determination of the temperature dependence the result is not reliable, especially if there are, statistically, not enough values. To determine the temperature relation the author has used all the velocity values available obtained either on the Greenland or the Antarctic ice sheet (Table II). Glaciers have been excluded because of their complexity. To make sure that the velocities correspond to maximum velocities in the ice, only velocities from refraction profiles longer than 3 000 m were taken. The velocities are plotted against temperature in Figure 1. The relation for the P-waves is

$$v_p = -(2.30 \pm 0.17)T + 3\,795 \text{ m/s.} \tag{1}$$

The correlation coefficient is 0.94 showing that the result is highly significant. The gradient $dv_p/dT = -2.30$ m/s deg is in perfect agreement with the ultrasonic laboratory result of Robin (1958).

TABLE II. THE SEISMIC VELOCITIES AND THE TEMPERATURES USED FOR THE COMPUTATIONS

V_p m/s	V_s m/s	T °C	σ	x m	*Author*	*Location*
3 836	1 940	−16.5	0.328	5 800	Kohnen (unpublished)	Greenland
3 840	1 940	−22	0.329	9 200	Kohnen (unpublished)	Greenland
3 855	—	−22	—	4 500	Kohnen (unpublished)	Greenland
3 865	1 960	−27	0.327	20 000	Kohnen (unpublished)	Greenland
3 873	—	−27	—	9 000	Kohnen (unpublished)	Greenland
3 860	—	−30	—	9 900	Kohnen (unpublished)	Greenland
3 860	1 955	−29	0.327	15 000	Kohnen (unpublished)	Greenland
3 859	1 955	−27.5	0.327	6 150	Kohnen (unpublished)	Greenland
3 861	1 949	−28	0.329	10 000	Kohnen and Bentley (1973)	Antarctic
3 865	1 940	−24.4	0.332	16 000	Bentley and others (1957)	Greenland
3 925	—	−51	—	16 000	Weihaupt (1963)	Antarctic
3 839	—	−22.3	—	8 400	Thiel and Ostenso (1961)	Antarctic
3 905	—	−50.8	—	5 480	Robinson (1962)	Antarctic
3 900	—	−48	—	20 000	Robinson (1962)	Antarctic
3 870	—	−24.8	—	6 000	Behrendt (1963)	Antarctic
3 902	—	−45.7	—	4 382	Crary (1963)	Antarctic
3 880	—	−41.7	—	5 000	Crary (1963)	Antarctic
3 920	—	−47.9	—	10 000	Crary (1963)	Antarctic
3 920	—	−58.5	—	16 000	Beitzel (1971)	Antarctic
3 950	—	−55	—	22 000	Beitzel (1971)	Antarctic
3 900	—	−57	—	17 000	Beitzel (1971)	Antarctic
3 910	—	−43	—	23 000	Bentley and Clough (1971)	Antarctic
3 840	—	−23	—	6 000	Bentley (1971)	Antarctic
3 847	1 937	−24.2	0.33	5 000	Bentley (1971)	Antarctic
3 842	—	−25.9	—	15 000	Bentley (1971)	Antarctic
3 848	—	−25.5	—	5 000	Bentley (1971)	Antarctic
3 851	1 943	−26.6	0.329	16 000	Bentley (1971)	Antarctic
3 853	1 946	−27.7	0.329	20 000	Bentley (1971)	Antarctic
3 855	1 943	−27.7	0.330	5 900	Bentley (1971)	Antarctic
3 855	—	−28	—	8 500	Bentley (1971)	Antarctic
3 853	1 934	−28	0.331	17 000	Bentley (1971)	Antarctic

x is the maximum distance and also the distance range except for the second and third values from Crary (1963), which correspond to only one geophone spread at the given distance, and the values from Beitzel (1971) for which the range was 12 000–16 000 m, 17 000–22 000 m and 12 000–17 000 m for the three values entered respectively.

It is well known that the breaks of the shear waves are often hard to identify in the seismic records. The gaps in shear-wave velocities in Table II is obviously due to this fact. The shear-wave velocities are also plotted versus the temperatures in Figure 1 yielding the linear relation ($r = 0.99$)

$$v_s = -(1.2 \pm 0.58)T + 1\,915 \text{ m/s.} \tag{2}$$

The gradient $dv_s/dT = -1.2$ m/s deg is close to the value Brockamp and Querfurth ([1965]) computed from their ultrasonic measurements on single crystals. Unfortunately, there are no shear-wave values for temperatures below −29° C.

Poisson's ratio σ was calculated from the P- and S-wave velocities (Fig. 2). There is no significant temperature dependence of Poisson's ratio seen from the graph. Assuming a constant Poisson's ratio of 0.329, shear-wave velocities have been calculated from P-wave velocities at temperatures below −30° C (open circles). These values fit well to the extrapolated straight line from Equation (2). This could be an indication that we may extrapolate Equation (2) to approximately −60° C.

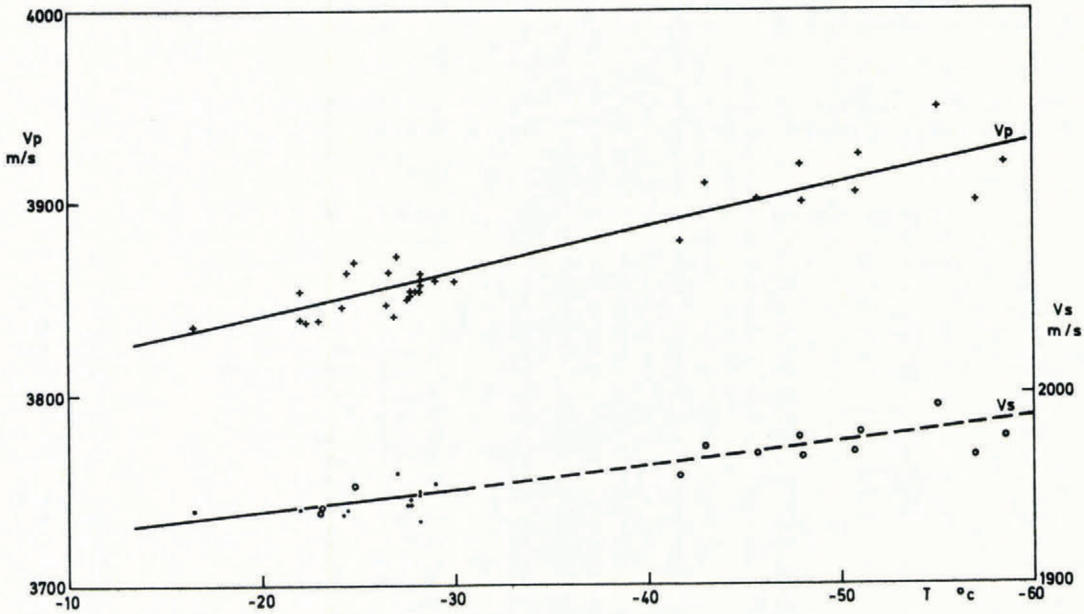

Fig. 1. The P- and S-wave velocities versus temperature. Dots are measured S-wave velocities, circles are values calculated with Poisson's ratio of 0.329.

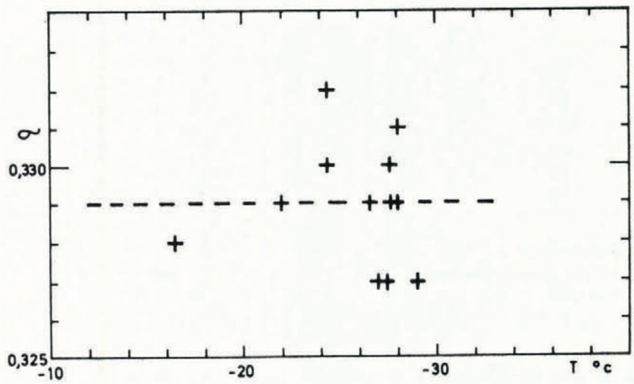

Fig. 2. Poisson's ratio versus temperature.

Conclusions

From carefully selected seismic velocity values, the temperature dependence of P- and S-wave velocities has been determined. The gradients $dv_p/dT = -2.30$ m/s deg and $dv_s/dT = -1.2$ m/s deg are in close agreement with the ultrasonic measurements of Robin (1958) and Brockamp and Querfurth ([1965]) showing that there is no discrepancy between seismic field and ultrasonic laboratory results.

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