Some seismic, electrical, and thermal properties of sub-seabottom permafrost from the Beaufort Sea

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Ultrasonic compressional and shear-wave velocities, complex resistivity and phase-angle relationships, and thermal conductivity have been measured in the laboratory at subzero temperatures on sub-seabottom samples of sand, silt, and clay permafrost recovered from the Beaufort Sea. The physical properties of the off-shore permafrost samples are similar to those measured on similar samples of on-shore permafrost recovered from the Mackenzie River; the slight differences observed are attributed to the slightly saline pore fluid solutions contained in the off-shore permafrost. The compressional-wave velocities measured in the laboratory agree well with those inferred from seismic and temperature surveys conducted in the same areas as those from which the test samples were obtained.

In view of the generally higher temperatures observed in permafrost off-shore than on-shore, it is concluded that more measurements are required of the physical properties of off-shore permafrost in the critical temperature range −2 to 1°C.

En laboratoire, à des températures inférieures à zéro, on a mesuré sur des échantillons de pergélisol composés de sable, de limon et d'argile, et prélevés dans les fonds marins de la mer de Beaufort, les vitesses de propagation d'ondes ultrasoniques (ondes de cisaillement et ondes de compression), ainsi que des relations complexes de résistivité et de déphasage et la conductibilité thermique caractérisant les sédiments du fond. Les propriétés physiques des échantillons de ce pergélisol sous-marin sont comparables à celles que l'on a mesurées sur des échantillons similaires d'un pergélisol échantillonné le long des rives du Mackenzie; on a attribué les légères différences observées aux solutions faiblement salines contenues dans les espaces interstitiels du pergélisol sous-marin. Les résultats des mesures de la vitesse de propagation des ondes de compression, faites en laboratoire, concordent bien avec les résultats déduits des levés sismiques et thermiques réalisés là où l'on a prélevé les échantillons.

Étant donné que l'on a observé des températures plus élevées en général dans le pergélisol sous-marin que dans le pergélisol littoral, on en a conclu qu'il fallait faire plus de mesures des propriétés physiques du pergélisol sous-marin dans la gamme de températures critiques allant de −2 à 1°C.

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Introduction

Conditions suitable for the existence of permafrost have been shown by Hunter *et al.* (1976) to exist beneath most of the Beaufort Sea shelf area. These workers have demonstrated that the permafrost is generally at higher temperatures off-shore than the equivalent permafrost conditions on-shore. As a result, they have indicated that off-shore permafrost is more susceptible to thawing by thermal disturbance. Hunter *et al.* have also shown that the low off-shore sediment temperatures are conducive to the formation of gas (clathrate) hydrates, which are probably seismically indistinguishable from ice-bonded permafrost.

Hunter *et al.* outline some of the problems posed by the occurrence of subsea permafrost for off-shore drilling and for the design and construction of large structures and pipelines founded on the sea-bottom. They note that the potential adverse consequences of an engineering failure in permafrost off-shore are far more severe than on-shore. It is essential, therefore, to recognize the presence of permafrost and to know its physical properties prior to the design of major off-shore drilling or construction programmes.

In this paper are reported the results of laboratory measurements of ultrasonic velocities, complex resistivity and phase-angle relationships, and thermal conductivity of a number of samples of naturally-occurring, subsea permafrost from boreholes drilled in the Beaufort Sea, which were recovered and stored at subzero temperatures. Laboratory measurements of the physical properties of naturally-occurring permafrost in its original frozen state have been reported by Kurfurst (1976) and King (1977) for ultrasonic compressional and shear-wave velocities; by King (1977) and Olhoeft (1978) for electrical properties; and by Judge (1973) for thermal properties. Laboratory measurements of the physical properties of frozen rocks and soils have been reported by Timur (1968), Kurfurst and King (1972), Nakano *et al.* (1972), and Pandit and King (1979) for the ultrasonic velocities; by Pandit and King (1979) for the electrical properties; and by King (1979) for the thermal conductivity. These workers have all reported that the ultrasonic velocities, electrical resistivity, and thermal conductivity were larger in magnitude in the frozen state than when unfrozen. The difference in magnitude of the physical property and the temperature rate of change were found to depend on the water content of the porous material, the chemical composition of the pore saturant, and the grain-size distribution of the mineral component of the porous medium.

Specimen Preparation

The permafrost samples were received in their naturally-frozen state in the form of short lengths of core sealed tightly in plastic film. Test sample storage and specimen preparation at subzero temperatures followed the procedures described by King (1977), except that six cylindrical specimens 50 mm in diameter and approximately 75 mm in length were first prepared for the ultrasonic velocity tests. Upon completion of these tests, during which the specimens were not permitted to rise in temperature above $-1°C$, the specimens were cooled to $-9°C$ and removed from the triaxial cell. They were then machined down to a diameter of 38 mm and two new specimens approximately 38 and 10 mm in length were prepared from each of the six original ones. The specimens of 38-mm length were used for the electrical properties measurements and those of 10-mm length for the thermal conductivity tests. The remaining discs and cuttings were used to measure the bulk density, porosity, water content, and grain-size distribution for the samples. The three original Beaufort sub-sea-bottom permafrost samples (S21, S49, and S107), and three on-shore permafrost samples (GSC3, GSC5, and GSC8) of approximately the same composition from the Mackenzie River for comparison, are described briefly (Table 1).

Upon completion of the electrical properties and thermal conductivity measurements, the specimens were removed from the apparatus, sealed tightly in plastic film, and stored in a freezer cabinet at $-9°C$. Some months later the specimens were removed and their pore-water salinities measured.

Experimental Procedure

Block diagrams of the apparatus for performing the tests are illustrated. Ultrasonic velocity measurements were made on specimens in the triaxial cell (Figure 1) and the electrical properties in the pressure cell (Figure 2). The velocity and electrical properties cells have been described by Pandit and King (1979). Thermal conductivity measurements were made in the divided bar apparatus (Figure 3), described in detail by King (1979).

The ultrasonic velocities and electrical properties were measured following essentially the procedures described by Pandit and King (1979), except that the ultrasonic velocities were measured only under a hydrostatic stress of 0.34 MPa at constant temperatures in the range -10 to $-1°C$. In no case was the temperature permitted to rise above $-0.9°C$, because it was necessary to preserve the specimens in their original frozen state for subsequent tests. The electrical properties measurements were made on specimens subjected to a hydrostatic stress of 0.34 MPa at constant temperatures in the range -13 to $-1°C$. Thermal conductivity measurements were made following essentially the procedure described by King (1979),

TABLE 1. Descriptions of permafrost samples

Sample number	Depth* (m)	Description	Clay fraction**	Porosity	Water content***
Beaufort Sea S21	7.2	clay	0.51	0.43	0.29
Beaufort Sea S49	34.2	sand	0.05	0.40	0.25
Beaufort Sea S107	81.1	silt	0.18	0.37	0.22
Mackenzie River GSC3	23.1	silt	0.20	0.36	0.23
Mackenzie River GSC5	9.6	clay	0.62	0.39	0.25
Mackenzie River GSC8	2.8	sand	0.05	0.37	0.22

* Sub-seabottom or subsurface
** Size $< 2 \times 10^{-3}$ mm
*** Based on dry mass.

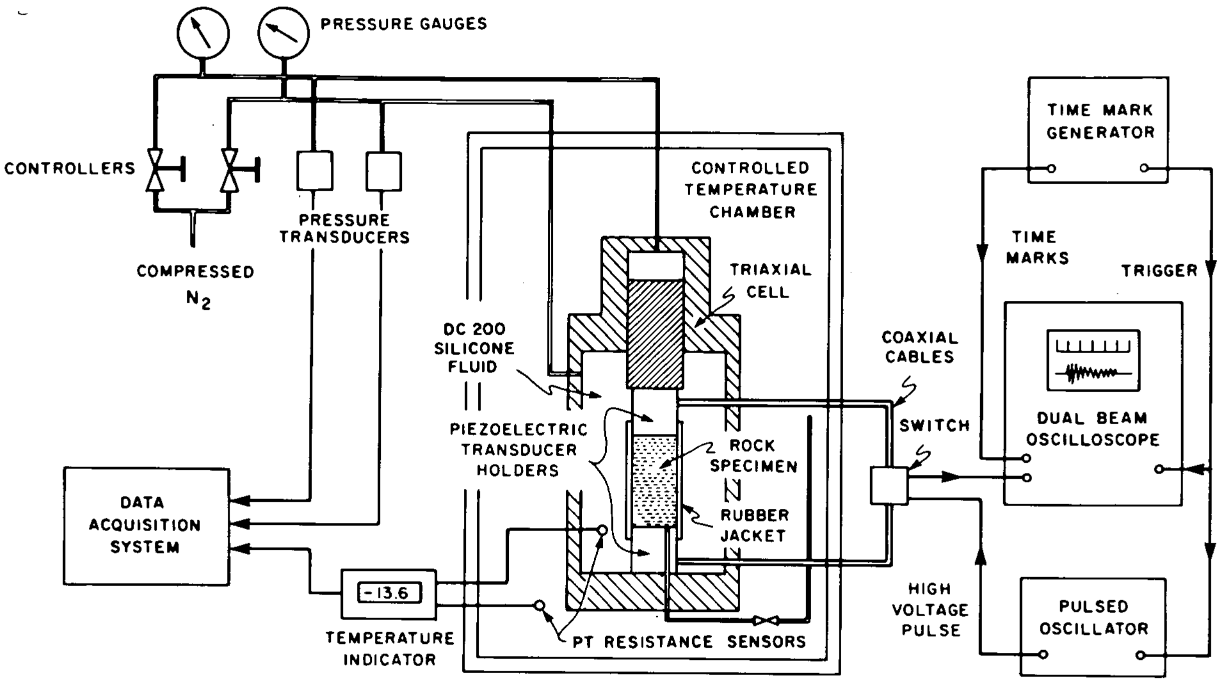

FIGURE 1. Block diagram of apparatus for ultrasonic velocity measurements.

with the specimens subjected to a uniaxial stress of 0.70 MPa at mean temperatures in the range − 10 to − 1.3°C.

Pore-water salinities were measured by placing a frozen specimen of known bulk and pore volume in a known volume of distilled water. Upon thawing, each of the specimens disintegrated and the pore water mixed with the distilled water. The resulting solution was decanted and the salinity determined by measuring its electrical resistivity.

A study of experimental errors indicates that the measured compressional-wave velocities are expected to be within ± 1 per cent and shear-wave velocities

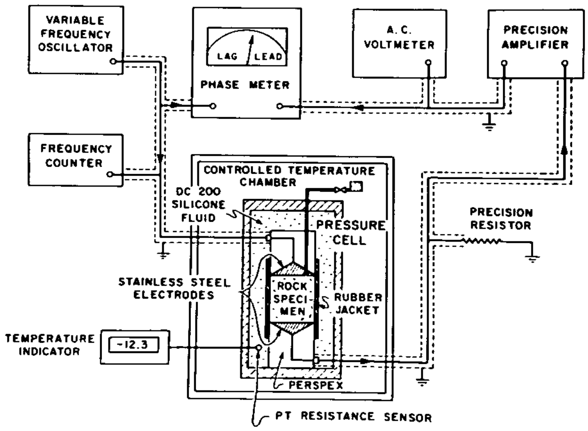

FIGURE 2. Block diagram of apparatus for electrical property measurements.

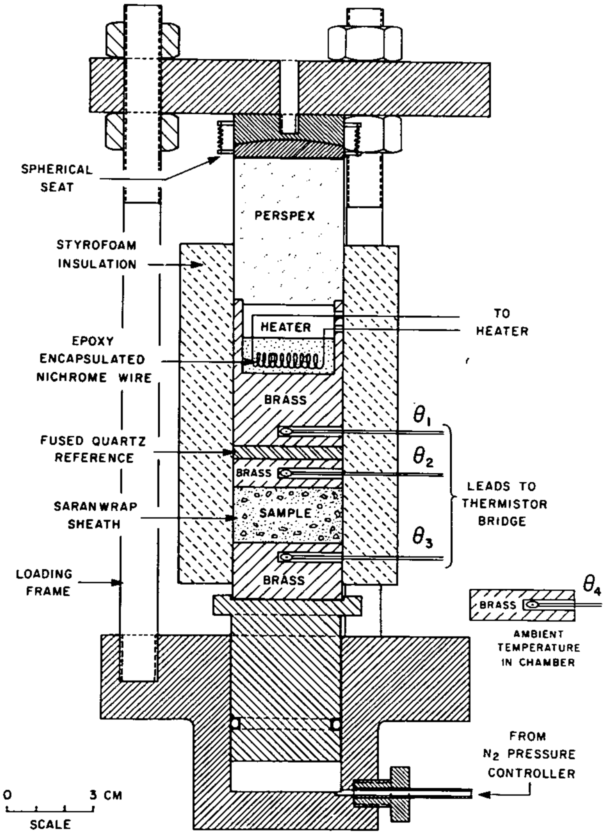

FIGURE 3. Cross-section of divided-bar thermal conductivity apparatus.

within ± 2 per cent; the measured electrical resistivities and phase angles to be within ± 10 per cent; and the measured thermal conductivities to be within ± 5 per cent of the true values.

Results and Discussion

Compressional and shear-wave velocities for the six specimens from the three samples of Beaufort subsea permafrost are shown (Figures 4 and 5) as a function of temperature in the range − 10 to − 1°C. For comparison, the results for three similar samples of on-shore permafrost from the Mackenzie River are also shown, with velocities above 0°C included. The results for the silts and clays are in close agreement. The difference between the results for off-shore and on-shore permafrost sand samples is explained by the slightly saline solutions contained in the pore spaces of the off-shore permafrost, in contrast to the fresh water pore fluid of the on-shore permafrost. The differences between the results plotted for specimens from each of the samples of off-shore permafrost are probably due, especially in the case of the sand S49, to a difference in pore-water salinity. The influence of pore-fluid salinity on ultrasonic velocities and electrical properties has been studied by Pandit and King (1979) for some frozen sedimentary rocks; this point is referred to later under results of the electrical properties tests.

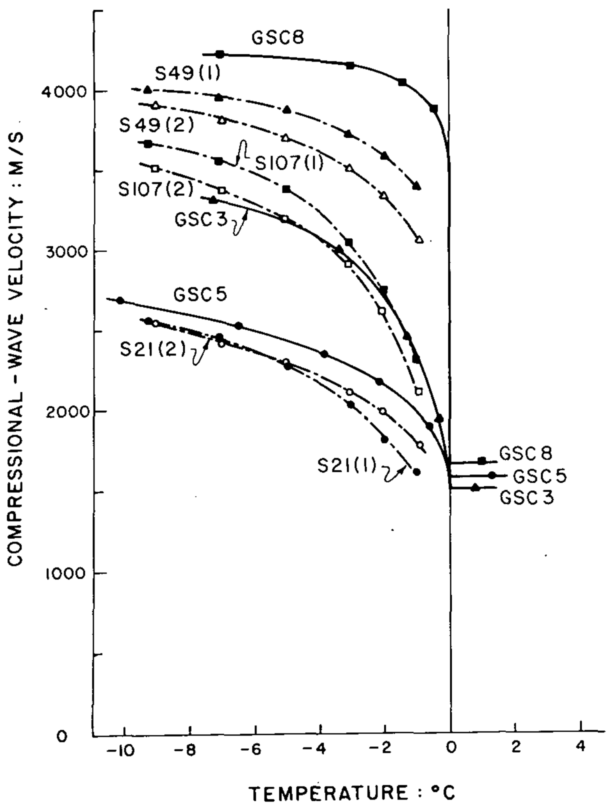

FIGURE 4. Compressional-wave velocities of permafrost samples as a function of temperature.

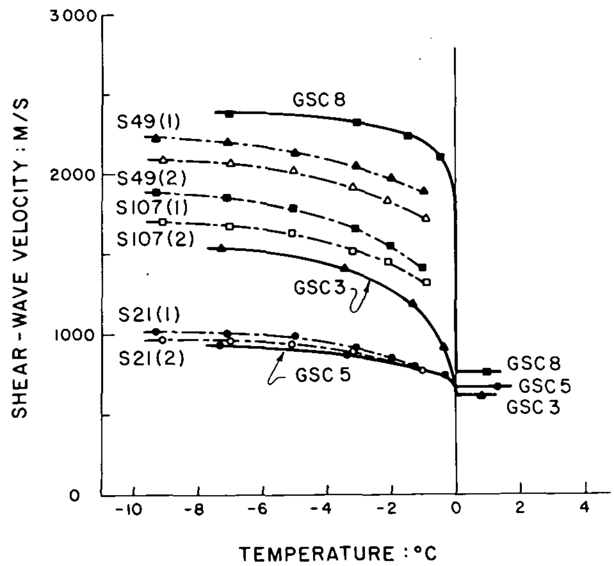

FIGURE 5. Shear-wave velocities of permafrost samples as a function of temperature.

Before the off-shore permafrost specimens were removed from the pressure cell, the temperature was reduced to − 9°C and the velocities were re-measured at this temperature. In each case, a small reduction in velocity was observed: approximately 1.0 per cent for S21, 0.7 per cent for S49, and 1.5 per cent for S107 for the compressional-wave velocity. These small differences indicate that, at temperatures rising from − 9 to − 1°C, very little unfrozen pore water was expelled at the confining stress of 0.34 MPa.

The compressional-wave velocities for the Beaufort subsea permafrost samples agree very well with those inferred from seismic and temperature surveys conducted in the same area, reported by Hunter *et al.* (1976).

Complex resistivities and phase-angle relationships for the off-shore permafrost are shown (Figures 6 and 7) as a function of temperature in the range − 13 to − 1°C, at a frequency of 1 kHz. The complex resistivities for samples of on-shore permafrost silt and clay, for which the ultrasonic velocities were reported above, are shown for comparison (*see* Figure 6); they also indicate the behaviour above 0°C. In Figure 8, the complex resistivities for two adjacent specimens of the on-shore permafrost silt (GSC3) of different lengths are shown as a function of frequency in the range 5 to 10^5 Hz, for different temperatures in the range − 10.1 to 1.1°C. It will be seen that specimen

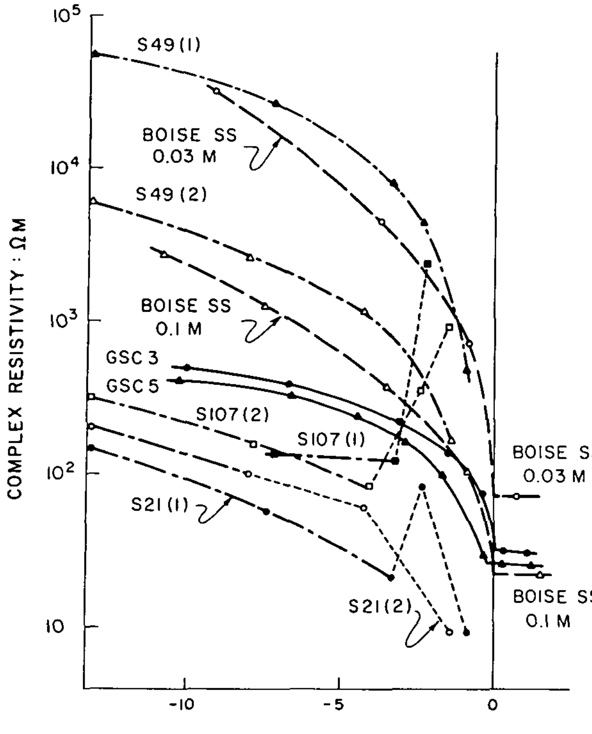

FIGURE 6. Complex resistivity of permafrost samples as a function of temperature.

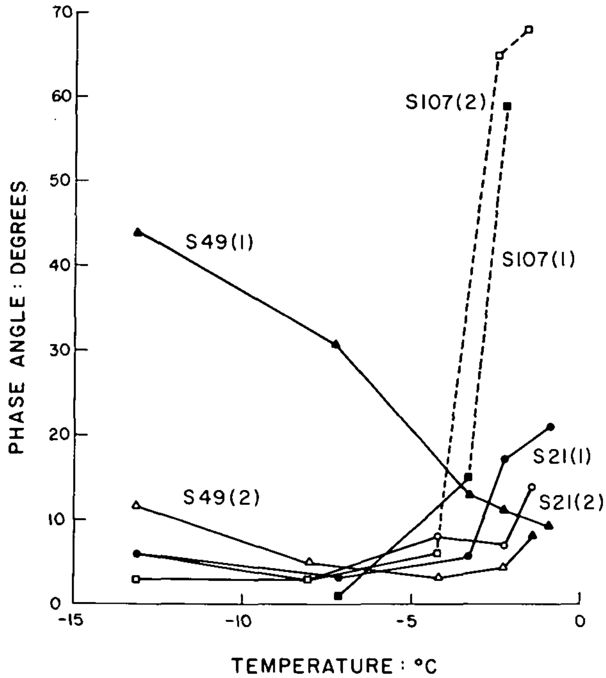

FIGURE 7. Phase angle as a function of temperature for off-shore permafrost samples.

contact resistance becomes a problem only for frequencies less than 200 Hz at temperatures lower than −5°C. The measured phase angles for the on-shore permafrost silt and clay were less than 15° for the range of temperatures and frequencies reported.

At temperatures below −4°C (*see* Figure 6) the off-shore permafrost silt and clay have lower complex resistivities than the equivalent on-shore permafrost samples. This is explained by the slightly saline solutions contained in the off-shore samples in contrast to fresh water in the on-shore permafrost. Pandit and King (1979) have reported dramatic reductions in complex resistivity as the salinity of the pore fluid in frozen sedimentary rocks is increased. The complex resistivities measured on the off-shore sand specimens illustrate this behaviour very well. The complex resistivities for Boise sandstone of 0.26 porosity (*from* Pandit and King 1979) saturated with 0.03 and 0.10 molar (M) concentrations of NaCl solution are also plotted (*see* Figure 7). The results for the two off-shore sand specimens fall in the neighbourhood of those for the two pore-fluid salinities of Boise sandstone. Upon conclusion of the test programme, permission was obtained from Dome Petroleum to unfreeze and measure the pore-water salinity on small specimens of each of the off-shore sample of permafrost. The results, in terms of NaCl, were as follows:

Sand: S49(1)	0.02M	Clay: S21	0.3M
Sand: S49(2)	0.08M	Silt: S107	0.13M.

The difference in pore-water salinity between the two sand specimens is also clearly indicated (*see* Figure 7) where S49(1) with fresher pore water shows higher values of phase angle than S49(2). These results agree very well with findings reported by Hunter *et al.* (1976) for salinities of pore water in subsea samples from the Beaufort Sea.

The anomalous behaviour for complex resistivity and phase angle exhibited in the temperature range −4 to −1°C by the silt and clay specimens of off-shore permafrost cannot, at this point, be explained in a satisfactory manner. Similar behaviour has, however, been observed on a number of other frozen samples occurring in approximately the same temperature range. This point has been discussed by Pandit and King (1979), who have reported that the problem can be eliminated, or at least reduced in magnitude, by raising the confining stress from 0.34 MPa to approximately 1.3 MPa. In the case of the off-shore permafrost the authors were reluctant to raise the confining stress to this level, because they suspected an irreversible expulsion of unfrozen pore water might then have occurred. On cycling the temperature

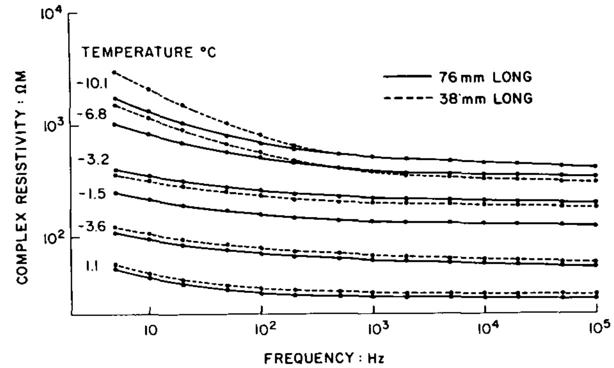

FIGURE 8. Complex resistivity of on-shore permafrost silt sample (GSC3) as a function of frequency.

between −6 to −1°C several times, the anomalous increases in complex resistivity and phase angle measured were reproduced with little change. Neither of the two on-shore permafrost specimens exhibited this anomalous behaviour.

The thermal conductivity of the three off-shore permafrost samples is shown (Figure 9) as a function of temperature in the range −10 to −1°C. For comparison are shown the thermal conductivity of three sandstones of different quartz contents and different porosities (ϕ). The results for the permafrost silt and clay agree well with the values reported by Judge (1973). The relatively high thermal conductivity for

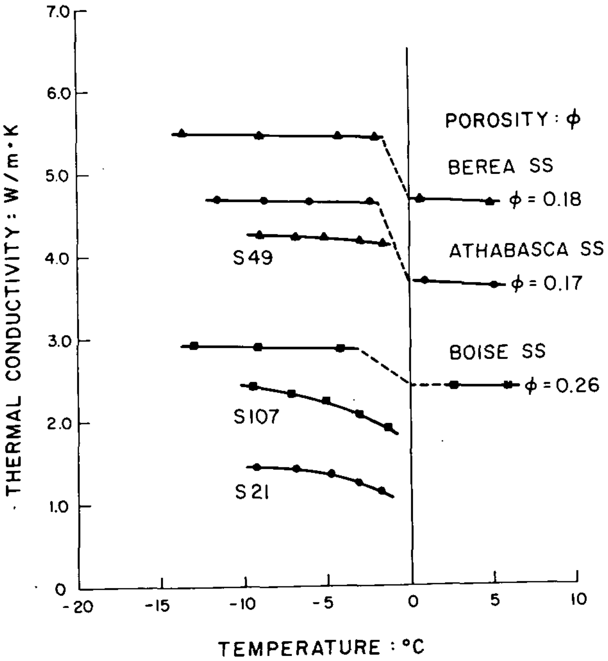

FIGURE 9. Thermal conductivity of permafrost and frozen sandstones as a function of temperature.

the permafrost sand sample reflects its high quartz content. This point has been discussed by King (1979).

Conclusions

It is concluded that the Beaufort subsea permafrost has physical properties similar to those of on-shore permafrost. Any small differences are explained by the slightly more-saline pore water found in the off-shore permafrost.

More measurements of physical properties of off-shore permafrost are required in the critical temperature range of −2 to +1°C.

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