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PERMAFROST AGE AND THICKNESS AT MOSKUSLAGOON, SPITSBERGEN

Koichiro Harada[1], Kenji Yoshikawa[2]

1. Institute of Low Temperature Science, Hokkaido University, Sapporo 060, Japan
e-mail : harada@frost.lowtem.hokudai.ac.jp

2. Water and Environmental Research Center, University of Alaska Fairbanks, Alaska 99775-5860, USA
e-mail : kenji@polarnet.com

Abstract

Permafrost thickness in the Adventfjorden area of Spitsbergen was estimated, and the age of permafrost occurrence was estimated based on the permafrost thickness. At the Adventdalen area, there was no pre-existing permafrost under the sea bottom and permafrost thickness is interpreted to reflect the duration of exposure to the subaerial temperature regime. Permafrost thickness was estimated to be 31.7 m for Moskuslagoon. A numerical calculation indicated that the time required to form permafrost with a thickness of 31.7 m is 533 years. This age appears to be reasonable compared to the age of 240±50 yr B.P derived from the radiocarbon dating of sediments.

Introduction

The major factors controlling permafrost thickness are mean annual ground-surface temperature, soil type (thermal conductivity), and terrestrial heat flow. In areas of old permafrost that have existed for more than 10,000 years, permafrost (and hence its thickness) has attained thermal equilibrium with modern climate. However, in areas of new permafrost that began to form after the last glacial period, permafrost has not yet reached thermal equilibrium. After the end of the last glacial period, permafrost began to form immediately upon uplift of coastal areas from the sea floor as a result of isostatic rebound. The Adventdalen delta area, Spitsbergen, consists of a series of such coastal terraces, each with a different thickness of permafrost. These differences appear to reflect differential durations of exposure (uplift) to the subaerial temperature regime.

Many reports have described the history of the emergence of Spitsbergen on the basis of radiocarbon dating (e.g., Salvigsen and Osterholm, 1982; Salvigsen, 1984; Landvik et al., 1987). This paper correlates the duration of permafrost formation with the timing of uplift, estimating permafrost age on the basis of permafrost thickness. The latter was estimated by electrical resistivity sounding, which is based on measuring the electrical resistivity of a soil (e.g., McGinnis et al., 1973). The objective of this paper, therefore, is to clarify the emergence history of Spitsbergen on the basis of ages derived from permafrost thickness. In addition, laboratory electrical measurements are made on a soil sample obtained from the study site, and unfrozen water content is measured, in order to better define and predict subsurface physical conditions.

Study area

The principal study location encompasses Adventfjorden and adjacent land areas (Latitude 78°20' N Longitude 15°33' E) on the island of Spitsbergen (Figure 1), where permafrost is continuous. The mean annual air temperature of Longyearbyen in this area is -4.8°C (normals 1961-1990), and precipitation is 210 mm/year (1916-1977) (Aune, 1993). The mean annual ground surface temperature, measured between 1993-1994, is -5.7°C. The maximum thickness of first-year sea ice in the fjord is about 50 cm, although sea ice is not present there every winter.

Spitsbergen was completely covered by glaciers (without a nunatak zone) until 18,000 years B.P. (Ohta, 1982). In Longyearbyen, glacial retreat began 14,250±300 years B.P. (NU-464) or earlier, as indicated by the age of peat near the settlement. The extent of marine deposition can be distinctly traced along the fjords and valleys, and is 64 m a.s.l. at Ytterdalen (Landvik et al., 1987). The shoreline has retreated gradually since the end of the glacial period.

Measurements of permafrost thickness were made at a site located 2 m above sea level at Moskuslagoon and at the present shoreline near the Longyearbyen airport. Surface material at the Moskuslagoon site is clayey silt

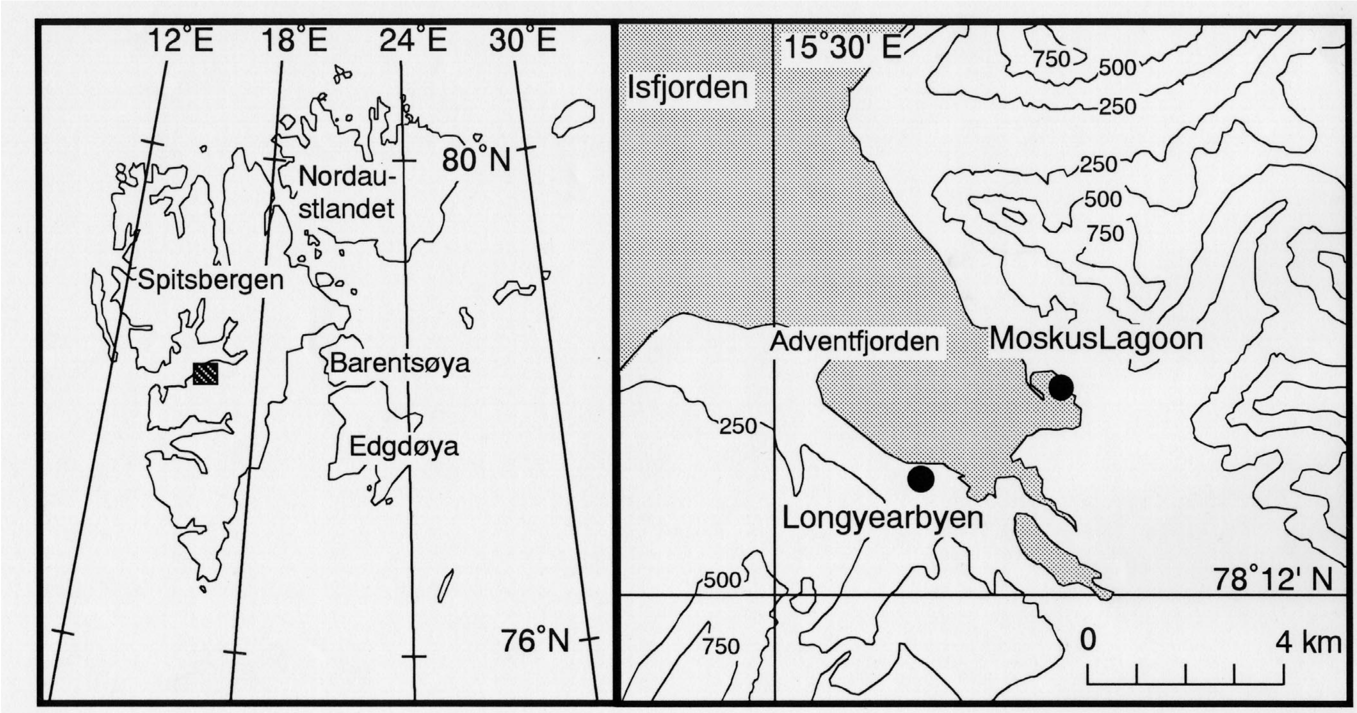

Figure 1. Map of study area location on island of Spitsbergen, Svalbard.

with high water content, and the active layer is 0.8 m thick. Surface vegetation is absent as a result of sea water intrusion, and some pingos have developed.

Methods

Field observations were made in September 1992 and in April and July 1993. In 1992, electrical soundings were carried out to measure the permafrost thickness. In April 1993, sea-ice thickness, snow depth, and ground surface temperature were measured. Sea-water temperatures also were measured in Adventfjorden during the field observation period. On the sea bottom (2 m below sea level) offshore from Adventdalen, and at the surface in Moskuslagoon, temperatures were continuously measured at 30-minute intervals with thermistor cables and recorded with an automatic data logger.

Electrical Sounding

The electrical resistivity of soil depends on soil type, temperature, water content, porosity, and salinity. Generally, the electrical resistivity values of frozen soil are 10 to 100 times greater than those of unfrozen soil (Lévesque et al., 1988). The degree of resistivity change also depends on soil type and water content, especially at temperatures near 0°C (Harada et al., 1994).

In clay or other fine-grained soils, electrical resistivity increases in inverse proportion to water content. At constant depth, resistivity in these soils generally depends on differences in soil temperature or water content. The influence of water content on electrical resistivity in sand or coarse-grained soil is much smaller according to experimental results. Here resistivity differences are assumed to depend only on temperature.

For the measurements, a conventional resistivity sounding meter (OYO Co., Ltd., McOHM model-2115) was used to set up a Wenner electrode configuration. A current I is delivered and received between the outer electrodes, and the resulting potential difference V is measured between the inner electrodes. For this array on the ground surface, an apparent resistivity ra is computed from:

$$\rho_a = 2\pi a \frac{V}{I} \qquad [1]$$

where a is the distance separating the electrodes.

Laboratory Experiments

Measurements of electrical resistivity values of soil also were made in the laboratory. These values were obtained by measuring the electrical potential difference generated by a direct current, which was altered into a square wave with a frequency of a few Hz; this prevented the accumulation of an electrical charge on the surface of the electrodes as a result of polarization.

The soil sample tested in the laboratory was obtained from Moskuslagoon. Dry densities were constant at

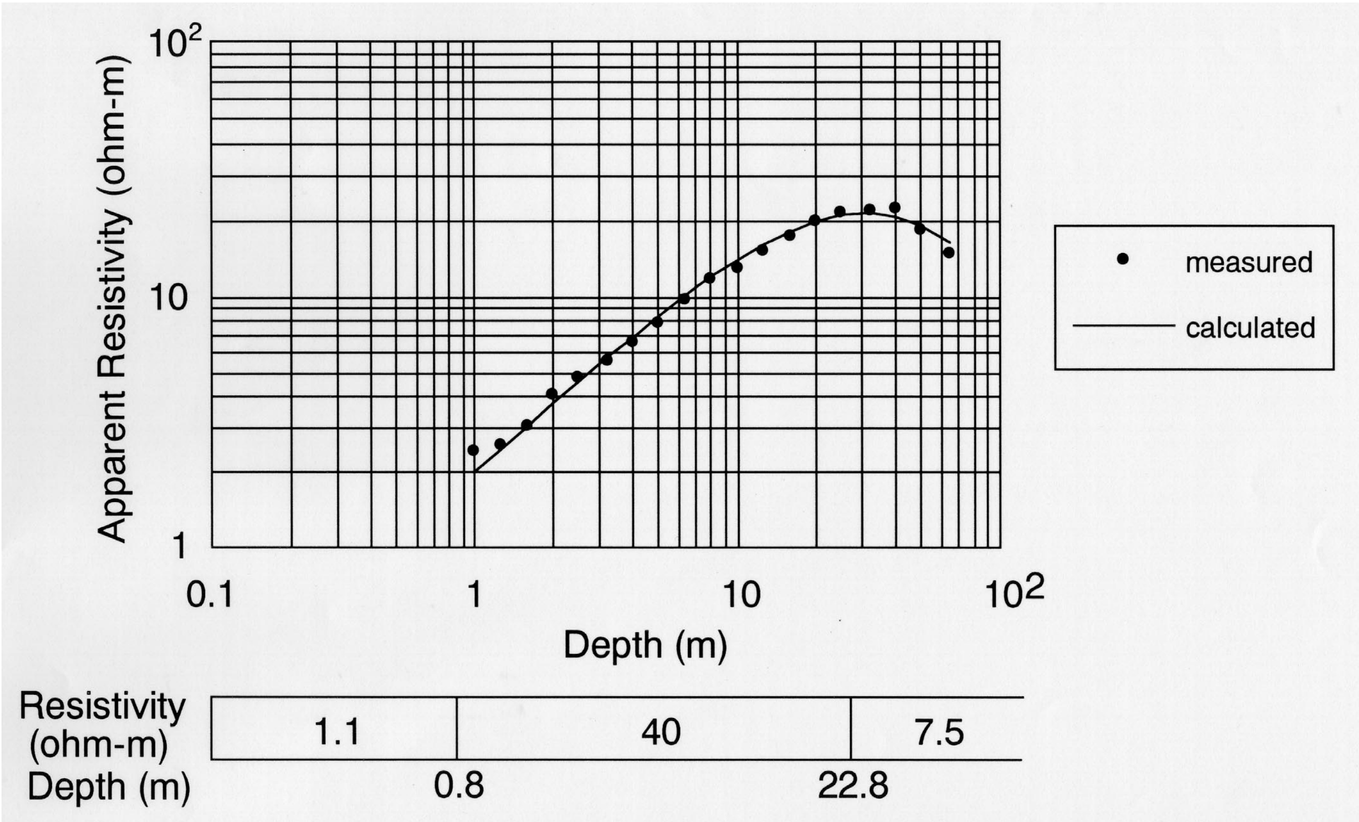

Figure 2. Apparent resistivity profile and its interpretation, Moskuslagoon.

1.0 g/cm^3, and the volumetric water contents were set at 12 % and 67%. The specific gravity of the sample was 2.53. After preparation of the samples at the different water contents, they were frozen at a temperature of -30˚C. Later, during warming from -8˚C to 10˚C, electrical resistivities were measured at various temperatures. A conventional resistivity sounding meter was also used to supply the specific current.

For the measurements of unfrozen water content of the soil sample from Moskuslagoon, NMR method was used. The volumetric water was set at 29.2%. During the measurements, temperature was changed from -43˚C to 10˚C.

Results

Sea Water Temperature and Sub-sea Permafrost

Water temperature on the sea bottom at a depth of 55 m was 3.3˚C in September 1992 and 0.5˚C in July 1993. In April 1993, sea-water temperatures were between -1.2 and -1.5˚C. The mean annual sea-bottom temperature is +0.5˚C and the freezing index is 375˚C•days. These temperatures are too high to form sub-sea permafrost, and thus no sub-sea permafrost exists in the study area under present climatic conditions. Landvik et al. (1988) also reported that the climate during long periods of the Holocene had been much warmer than at present. Therefore, the site from which samples were obtained for laboratory experiments did not contain permafrost prior to its emergence from the sea.

Permafrost Thickness at Moskuslagoon

Figure 2 shows the apparent resistivity profile at Moskuslagoon obtained by electrical sounding and the result of numerical calculation. As noted earlier, soil type affects resistivity values, especially when bedrock is present near the surface and interpretation becomes complex. This is because bedrock has a low water content and its resistivity value is quite high, even though the bedrock is unfrozen. In Longyearbyen, it was reported that the thickness of the sediment was 10 m inland and more than 70 m near shore (Gregersen and Eidsmoen, 1988), and as a result it was not necessary to consider the influence of the bedrock on the resistivity value.

For Moskuslagoon, three layers of differing resistivity were obtained (Figure. 2). The first layer, with a value of 1.1 ohm-m, had a thickness of 0.8 m, which corresponded to the depth of the active layer that was measured while digging. The second layer had a resistivity value more than ten times higher. Digging confirmed that this layer consisted of permafrost. For a third layer, the resistivity layer was again low. The resistivity values obtained by electrical sounding correlated well with experimental values derived from a soil sample taken from the study site (Figure 4).

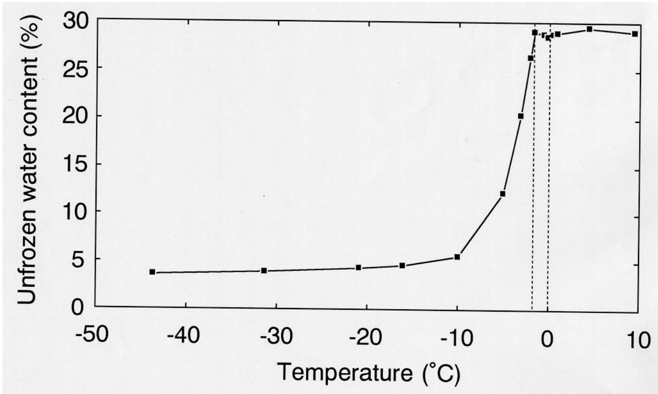

Figure 3. The relationship between temperature and unfrozen water content, soil sample from Moskuslagoon.

Because the soil type did not change between the second and third layers, the resistivity difference was caused by a transition from frozen to unfrozen soil, which occurred at a depth of 22.8 m. However, the result of measurements of unfrozen water content shows that freezing point depression is observed, about -1.6˚C (Figure 3). The soil at 22.8 m was frozen, but not at 0˚C. Assuming that temperature gradient is 1˚C/ 5.56 m, the depth of the 0˚C isotherm becomes 31.7 m.

Permafrost was not found along the present shoreline of Adventfjorden at the Longyearbyen airport. In 1993, A. Brekken (pers. comm., 1994) conducted seismic sounding measurements for the construction of the new Longyearbyen pier, and also did not encounter any permafrost.

Figure 4 depicts the relationship between temperature and the electrical resistivity of the soil in Moskuslagoon at various water contents. The dependence of electrical resistivity on temperature below 0˚C is high given a high water content (67%) and low under a low water content (12%). These results are similar to those obtained for clay samples (Harada et al., 1994) and for rocks (Seguin, 1978).

These resistivity values are low compared to those in other soils (Harada et al., 1994), which is a function of their high salinity. The salinity of supernatant fluid of the lagoon sample is 5‰, and its resistivity is 2.11 ohm-m at 10 ˚C. This value is very low compared to the value of Fujinomori clay, 33.84 ohm-m (Harada et al., 1994). Figure 4 also shows the freezing point depression.

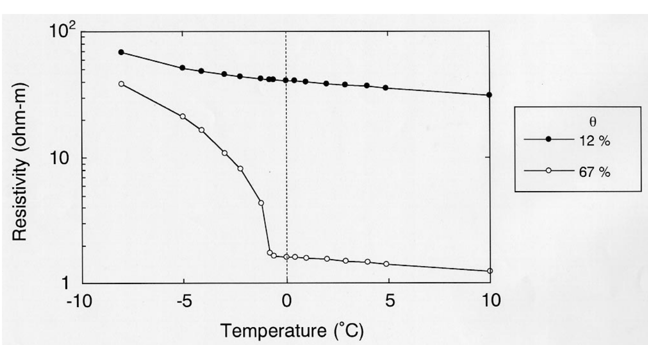

Figure 4. The relationship between temperature and the electrical resistivity of a soil sample obtained from Moskuslagoon (q= volumetric water content).

Discussion

PERMAFROST THICKNESS SIMULATION AND PERMAFROST AGE

As noted at the outset, a primary goal of the present research was to estimate permafrost age in Moskuslagoon from permafrost thickness and thermal properties in the soil. It was assumed that the constant initial surface temperature is 0˚C, that the temperature gradient is 1˚C/50 m, and that surface temperature changes instantaneously upon exposure to a new constant temperature of -5.7˚C, which is the present mean annual ground surface temperature. In this model, the migration of water and materials is not considered. The ground temperature variation of the permafrost to the new boundary condition is described by the heat conduction equation:

$$\frac{\partial T}{\partial t} = \alpha \cdot \frac{\partial^2 T}{\partial x^2} \qquad [2]$$

$$\alpha = \frac{k}{C} \qquad [3]$$

where T is temperature, t is time, x is location, α is thermal diffusivity, k is thermal conductivity, and C is heat capacity. In order to solve this heat conduction equation, the explicit finite difference method was used.

Figure 5 depicts the relationship between elapsed time and permafrost thickness at Moskuslagoon. The time needed to form a 31.7 m thick permafrost layer at Moskuslagoon is 533 years.

PERMAFROST CONDITION

Moskuslagoon consists of deltaic sediments and a thin layer of peat (0.5 to 1 mm). Åhman's(1973) radiocarbon dating of the sediments indicates an age of 240±50 yr

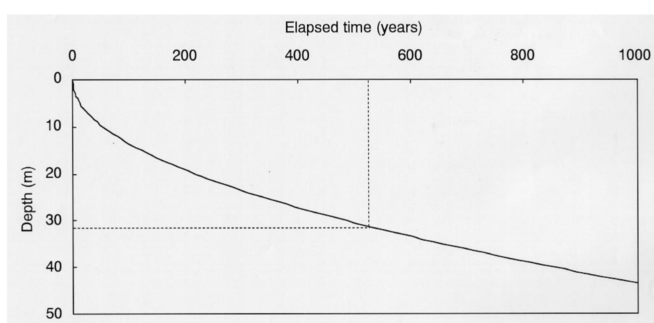

Figure 5. Calculated permafrost thickness versus elapsed time in years in Moskuslagoon and the Moskushamn terrace.

B.P. (LU-743), which indicates that this lagoon began to be exposed earlier. Although the difference between our calculated age and the radiocarbon dating age is not small, the calculated age of 533 years appears to be reasonable.

At this lagoon, results of electrical sounding indicate that permafrost depth is 31.7 m. Mean annual ground surface temperature is -5.7 ˚C, and the temperature gradient is 1˚C/5.56 m in the frozen ground. This is quite steep compared to data at Sarkofagen, 1˚C/50 m (Liestøl, 1977), indicating that the temperature gradient in Moskuslagoon is not in equilibrium. Assuming that 1˚C/50 m is the equilibrium gradient, permafrost can attain a thickness of 285 m over a period of over 30,000 years, assuming no further changes in surface temperature during this period.

Conclusion

Permafrost thickness in the Adventfjorden area of Spitsbergen was estimated at Moskuslagoon and the age of permafrost occurrence was estimated based on the permafrost thickness.

At the Adventdalen area, continuous permafrost is found distributed onshore. However, mean annual sea-bottom temperature offshore is above 0˚C, thus, there was no pre-existing permafrost under the sea bottom and permafrost thickness is interpreted to reflect the duration of exposure to the subaerial temperature regime.

Permafrost thickness was estimated to be 31.7 m for Moskuslagoon by electrical sounding and including a correction using NMR method, and the temperature gradient is 1˚C/5.56 m. This steep gradient indicates that the current permafrost layer is not in equilibrium.

A numerical calculation yields information on the change in permafrost thickness in relation to a change in mean annual ground surface temperature. This calculation indicated that the time required to form permafrost with a thickness of 31.7 m is 533 years. This age appears to be reasonable compared to the age derived from the radiocarbon dating of sediments 240±50 yr B.P.

Acknowledgments

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