PERMAFROST OCCURRENCE OF SEYMOUR ISLAND AND JAMES ROSS ISLAND, ANTARCTIC PENINSULA REGION

M. FUKUDA, J. STRELIN, K. SHIMOKAWA, N. TAKAHASHI, T. SONE and D. TROMBOTT

Abstract: A field survey on Seymour Island and James Ross Island, Antarctic Peninsula region was conducted in 1989/90 specifically related to the genesis and occurrence of permafrost. On Seymour Island, marine terraces occur at the three different levels. The thickness of permafrost on each terrace was investigated by means of measurements of geo-electrical resistivity in the ground. The depths of permafrost base on Seymour Island were estimated to be 200 m, 105 m and 35 m, respectively. Annual mean ground temperatures at various depths in the ground on lower terraces were calculated from the obtained data of temperature fluctuations for two years. Temperature gradient indicates the depth of permafrost on the lowest terraces as to be 34 m, which coincides with the value derived from geo-electrical resistivity profile in the ground. Tundra polygons with ice-wedge development on both upper and lower terraces indicate that active cracking occurs under present climatic condition. On James Ross Island, coastal terraces have been formed near Santa Marta Cove in Croft Bay. Results of geo-electrical resistivity measurements indicate that depths of permafrost on the upper and lower terraces are to be 45–40 m and 6 m, respectively. 14C dating measurements using fossil shells from the sediments revealed the upheaval of the lower terrace above the sea level at 2500 y BP. Thus the rate of permafrost formation is estimated at about 0.002 m/y.

Keywords: permafrost, Antarctic Peninsula, Seymour Island, James Ross Island, geo-electrical resistivity

Introduction
The present authors conducted field work related to the genesis and occurrence of permafrost on Seymour Island and James Ross Island, east Antarctic Peninsula, during the 1989–90 austral summer season. The area of study is shown in Fig. 1. The climatic conditions of the area, with an annual mean air temperature of −10°C, are favorable for the existence and formation of permafrost, if the ground surface is not covered by glaciers or ice caps. Aiming to elucidate relationship between the climatic changes and permafrost occurrence, permafrost thickness was examined by means of long-term measurements of ground temperatures and geo-electrical resistivity. Estimation of ages of the permafrost formation were made based on the 14C dating measurements. The geo-electrical resistivity profiles were obtained by the conventional method and equipment with four electrodes located as Wenner arrays. Osterkamp et al. (1980) and Sellmann et al. (1988) reported the applications of the geo-electrical resistivity survey to estimate the permafrost depths in Alaska. However, there are no attempts of the estimation of permafrost depths in Antarctica by this method except by McGinnis et al. (1973) in Dry Valleys in the McMurdo Sound region. In addition to the estimation of permafrost depths, 14C dating was attempted by means of Acceleration Mass Spectrometry (AMS) using samples from deltaic and marine sediments. Based on these results, the rate of formation of permafrost after the upheaval of the ground above the sea level was calculated.

Permafrost on Seymour Island
Seymour Island is located in the westernmost Weddell Sea. As there is no indication of ice sheet coverage in the Last Glaciation such as moraines or till, the ground has remained frozen and permafrost of considerable depth has developed. From geological and geomorphological aspects, Seymour Island is divided into two parts. The northeastern part consists of Tertiary sediments (Elliot et al., 1975). Marine terraces at three different elevations are found in this part; upper terrace at Meseta (about 200 m a.s.l.), middle terrace at Sub-Meseta (about 50 m a.s.l.) and lower terrace at Larsen (about 5 m a.s.l.). Tundra polygons with ice-wedges are developed on the upper and lower terraces, which indicate the existence of the thick permafrost underneath tundra polygons.

Characteristic features of permafrost
Typical patterns of tundra polygons are shown in Fig. 2. By the boring core sampling, the ice-wedge ice was obtained in the middle of the depression under where ice-wedge exists. Vertical fissures in the ice samples are clearly observed in Fig. 3. These fissures are typically formed at the middle point of ice-wedge. The fact implies that the active cracking of ice-wedge occurs under present climatic condition. According to Harris (1982), active ice-wedge cracking develops with an annual mean temperature of lower than −6°C and freezing index of more than 3000°C days. Temperature readout on the same spot was made for two years.
The results indicate the mean annual ground temperature is 
-6.6°C. In order to monitor the cracking processes, at 13
localities two poles were installed across a depression under
where ice-wedge exists. The distance between two poles
was measured at all locations after installation was made in
December 1987. To avoid the differential movements of
poles due to frost heaving, a 3 m-long wood peg was
anchored beneath a pole. The results of measurements were
summarized in Table 1. Points from No. 1 to No. 8 are the
results on the upper terrace and points from No. 9 to No. 13
are the results on the lower terrace. Measurements in mid
winter, 1988 were made on the upper terrace. There are no
significant changes of distances except No. 2 and No. 7. The
increase of distance at points No. 2 and No. 7 was detected
with the formation of cracking. The increments of distance
in mid winter of 1988 were about 2 cm or more. Similar
observations were made in Mackenzie delta area, Arctic
Canada by Mackey (1974) and Fukuda (1982). As the nature
of expansion of the frozen ground in summer and shrinkage
in winter, the results of measurements in Table 1 imply that
some of ice-wedges are active under present climatic con-
ditions. Increments of ice-wedge width were not determined
from these results. In Arctic Canada, an annual increment of
ice-wedge is about 2 mm or less (Mackay, 1974; Fukuda,
1982). However on the terraces of Seymour Island, no
definite values of ice-wedge growth were obtained. One of
the reasons of this tendency is due to arid environments in
summer. After opening of cracks in the frozen ground,
snow-melt water tends to flow into cracks under humid
summer environments in the Arctic region. On Seymour
Island, few moisture in active layers was observed in summer
season. Once snow melts, water is easily absorbed into an
unfrozen layer and no water is available to flow into cracks
during summer in an upper layer. Kato et al. (1990) reported
peculiar characters of salt concentrations in ice-wedge ice
on Seymour Island. High concentrations of CaCO₃ and
Na₂SO₄ indicate that melt water percolation into cracks
occurs under extremely arid environment.

Information on ground temperature fluctuations at differ-
ent depths on the lower terrace at Larsen was obtained using
the data logging system which was installed in December
1987. Temperature was hourly measured at the four different

Fig. 1. Study area (contours in feet).
Fig. 2. Tundra polygon patterns on the lower terrace at Larsen. A: wide trough, B: narrow trough.

Fig. 3A. Ice-wedge ice sample with vertical fissures collected at 80 cm deep from the ground surface on the lower terrace at Larsen. 10 cm long and 5 cm in diameter.

Fig. 3B. Ice-wedge ice sample with fissures. Horizontal cross-section of Fig. 3A.

depths for two years. The results of measurements were shown in Fig. 4. The maximum thickness of an active layer was about 60 cm, and it is shallower than that at locations in the Arctic region with similar mean annual temperature. This is because of lower summer temperature on Seymour Island than in the Arctic region. The mean annual ground temperatures at 2, 60, 130 and 230 cm deep were \(-6.60, -6.10, -6.25\) and \(-6.25^\circ\text{C}\) respectively (Fig. 4B). As shallower layers are easily affected by surface boundary anomaly such as local snow accumulations, steady state temperature gradient is accomplished in deeper than 100 cm layer. Therefore, temperature gradient between 130 cm and 230 cm was calculated, in stead of the one between 60 cm and 130 cm. Mean annual temperature gradient is determined as \(0.19^\circ\text{C}/\text{m}\) assuming steady state condition. Extrapolation of this gradient to lower layers in the permafrost would give \(0^\circ\text{C}\) at the depth of 34 m. This may give the reasonable value for the depth of the permafrost base at Larsen.
**Fig. 4.** Ground temperature profiles (A) and distribution of mean, maximum and minimum ground temperatures (B) at Larsen, Seymour Island, from 20 December 1987 until 10 January 1990.

<table>
<thead>
<tr>
<th>Point No.</th>
<th>Dec. 22. 87</th>
<th>Aug. 22. 88</th>
<th>Dec. 10. 89</th>
<th>Jan. 8. 92</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>23.7 cm</td>
<td>23.7 cm</td>
<td>23.65 cm</td>
<td>23.7 cm</td>
</tr>
<tr>
<td>No. 2</td>
<td>34.2 cm</td>
<td>36.4 cm</td>
<td>34.87 cm</td>
<td>35.7 cm</td>
</tr>
<tr>
<td>No. 3</td>
<td>32.3 cm</td>
<td>33.4 cm</td>
<td>33.2 cm</td>
<td>33.2 cm</td>
</tr>
<tr>
<td>No. 4</td>
<td>39.4 cm</td>
<td>39.9 cm</td>
<td>39.65 cm</td>
<td>39.4 cm</td>
</tr>
<tr>
<td>No. 5</td>
<td>25.1 cm</td>
<td>----</td>
<td>24.0 cm</td>
<td>----</td>
</tr>
<tr>
<td>No. 6</td>
<td>33.3 cm</td>
<td>33.4 cm</td>
<td>33.8 cm</td>
<td>33.8 cm</td>
</tr>
<tr>
<td>No. 7</td>
<td>34.2 cm</td>
<td>39.8 cm</td>
<td>33.87 cm</td>
<td>34.87 cm</td>
</tr>
<tr>
<td>No. 8</td>
<td>35.3 cm</td>
<td>36.8 cm</td>
<td>36.5 cm</td>
<td>36.8 cm</td>
</tr>
<tr>
<td>No. 9</td>
<td>58.7 cm</td>
<td>----</td>
<td>58.37 cm</td>
<td>58.4 cm</td>
</tr>
<tr>
<td>No. 10</td>
<td>44.4 cm</td>
<td>----</td>
<td>44.38 cm</td>
<td>44.6 cm</td>
</tr>
<tr>
<td>No. 11</td>
<td>28.5 cm</td>
<td>----</td>
<td>26.98 cm</td>
<td>26.5 cm</td>
</tr>
<tr>
<td>No. 12</td>
<td>36.1 cm</td>
<td>----</td>
<td>37.14 cm</td>
<td>37.2 cm</td>
</tr>
<tr>
<td>No. 13</td>
<td>36.3 cm</td>
<td>----</td>
<td>35.81 cm</td>
<td>36.3 cm</td>
</tr>
</tbody>
</table>

**Geo-electrical resistivity measurements**

In order to estimate the thickness of permafrost on three different terrace levels, geo-electrical resistivities were observed. Readouts of differences in electric potential in different arrangements of four electrodes with Wenner arrays were adapted to multi-layered resistor network model so as to assume the existence of three different layers in the ground. Results of analysis are summarized in Table 2. The second layer in each terrace is regarded as the permafrost layer, as permafrost was confirmed at least up to 2.4 m deep by bore hole test. Based upon the ground temperature profile, the third layer of the lower terrace at Larsen is also interpreted as permafrost. The lower limit of the third layer at Larsen coincides with the depth of permafrost base estimated from the ground temperature analysis.

The permafrost in the upper and middle terraces should have developed deeper than in the lower terrace, as upper two terraces are older than lower one. Thus, the third layer in the upper and middle terraces are considered to be included within the permafrost zone. The depths of the permafrost base in the middle and upper terraces are estimated at 105 m and 200 m, respectively with some uncertainty.

Fournier et al. (1990) also investigated the geo-electrical resistivity measurements using Schlumberger configuration, which is slightly different with present authors' arrangements of four electrodes, almost at the same sites as where present authors did. According to their results of analysis, layers with high salt concentrations were estimated. However, present authors could not detect such anomaly in resistivity profiles in permafrost. Their estimated values of permafrost thickness are 28.55 m, 44 m and 127.5 m in the lower, middle and upper terraces, respectively. If one compares

<table>
<thead>
<tr>
<th>Layer</th>
<th>Lower terrace c.5m a.s.l.</th>
<th>Middle terrace c.50m a.s.l.</th>
<th>Upper terrace c.200m a.s.l.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>depth resistivity (Ω.m)</td>
<td>depth resistivity (Ω.m)</td>
<td>depth resistivity (Ω.m)</td>
</tr>
<tr>
<td>1st</td>
<td>0.1 - 1.1</td>
<td>150</td>
<td>0.6 - 0.6</td>
</tr>
<tr>
<td>2nd</td>
<td>1.1 - 3.1</td>
<td>5</td>
<td>0.6 - 1.1</td>
</tr>
<tr>
<td>3rd</td>
<td>3.1 - 5.5</td>
<td>30</td>
<td>0.6 - 30</td>
</tr>
<tr>
<td>4th</td>
<td>35 - 100</td>
<td>105</td>
<td>30 - 200</td>
</tr>
</tbody>
</table>

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these values with data in the present paper, he may find that the latter is larger than the former. It is well known that DC resistivity of frozen ground is very sensitive to the amount of unfrozen water in frozen layers (Harlan et al., 1971). If soil temperature is nearly 0°C, there may exist a large amount of unfrozen water in it. Abundance of unfrozen water in frozen soil acts as low conductor so that low resistivity is expected near 0°C. At the basement of permafrost, temperature is assumed as 0°C, where electrical resistivity of a frozen layer is as low as an unfrozen layer. Thus the boundary of frozen and unfrozen layers is very difficult to determine on the basis of resistivity data. Due to these uncertainty of the resistivity profile in the ground near 0°C isothermal line, estimation of thickness of permafrost by present authors does not coincide with that by the previous investigators.

**Ages of terraces and permafrost**

As no direct indication of the ages of upper and lower terraces such as fossil or organic materials is found, sediments and erratics on the surface of both terraces are only available indicators. Zinsmeister (1980) suggested that the surface of the upper terrace may have been formed by glacial erosion. There are no indicating remnants of marine sediments on the surface of the upper terrace. Corte (1983) suggested the surface of the upper terrace was originated as cryoplanation surface in the last glaciation.

According to Omoto (1990), 14C dates of buried algae obtained from the sediment of the lower terrace at Larsen, 3 m a.s.l., were given ages of 3900 ± 90 y BP and 3910 ± 120 y BP. In Antarctic coastal regions low concentration of 14C in sea water is expected because of melt water from an iceberg, which is originated from the ice sheet contains CO2 with almost decayed 14C. Under this condition, concentration of 14C in algae may be diluted in some degree. Thus obtained ages by 14C dating are biased to be older than actual age. Omoto (1990) also reported the age of actual algae collected on the present shore is about 1000 y BP. The age correction, using this value, gives 2900 ± 90 y BP and 2910 ± 120 y BP for the algae. Assuming the thickness of permafrost is about 30 m or less at that site, the rate of permafrost growth on the lower terrace is estimated as 0.011–0.015 m/y.

**Permafrost on James Ross Island**

**Terraces and their ages**

About 80% of the ground of James Ross Island is covered by glaciers (Rabassa et al., 1982). Ice-free ground is mainly distributed on the northwestern part of the island (Fig. 1). Coastal and fluvioglacial terraces of four different elevations have been developed around Santa Marta Cove in Croft Bay; two upper terraces (35–32 m and 24–21 m a.s.l.), a middle terrace (17–10 m a.s.l.), and a lower terrace (5–3 m a.s.l.). The group of upper terraces is composed of glacial till or fluvioglacial deposit. At an outcrop of the middle terrace, a cross-laminated structure developed in the sediment. This structure indicates that the sedimentation occurred in front of delta. Shell samples were collected from this deposit and from marine sandy sediments covering the surface of the lower terrace. 14C dating on these samples, which was made by Acceleration Mass Spectrometry at the University of Tokyo, gave 25254 ± 64 y BP and 3147 ± 98 y BP, respectively. Sea shell samples were collected at the present shore for correction of the 14C dating measurement. 14C dating on these samples gave 228 ± 189 y BP. Using these data, values of 14C dating were corrected to be about 25000 y BP for the sediment forming the middle terrace and 2900 y BP for the sediment forming the lower terrace.

**Geo-electrical resistivity measurements**

Geo-electrical resistivity measurements were also conducted on the surfaces of these terraces. The method and procedure of measurements are the same as those made on Seymour Island. The results of analysis are summarized in Table 3. The second layer in every terrace exhibit higher resistivity values than the first and the third layers do. An active layer on each terrace is about 1 m. As the second layer is considered to mark the permafrost, the depths of permafrost base in the upper, middle and lower terraces are estimated at 45–40 m, 3.4 m and 5.8 m, respectively. The value for the middle terrace is extraordinarily shallow. The resistivity value is also somewhat low, compared with those of other terraces. As the resistivity of frozen soil is very sensitive to the salt concentration in it, this low value of resistivity may reflect the salt concentration in the second layer.

Based upon these results of 14C dating and depths of permafrost, the age of permafrost on each terrace is discussed. As surface boundary temperature of shallow sea floor cannot be below −1.8°C in Arctic and Antarctic continental shelf regions, no permafrost develops in these regions. Once ground emerges from the sea, surface of ground is subjected to severe climatic conditions as to form permafrost in the ground. The initiation of permafrost development may be assumed to be at the time same as the emergence of the land or slightly later. Thus it is considered that the formation of permafrost on the upper terrace has initiated on 25000 y BP. The rate of permafrost development from 25000 y BP is estimated as 0.0018–0.0016 m/y. In case of the lower terrace, permafrost formation initiated 2900 y BP and the rate of permafrost development is calculated as 0.002 m/y. These values of development rate are smaller by 1/10 than those obtained on Seymour Island. On the basis of 14C dating on northern James Ross Island, Hjort et al. (1991) suggested the deglaciation occurred between 10000 and 8000 y BP. They also pointed out that the post glacial sedimentation of glacial lacustrine did not occur until between 6000 and 5000 y BP. However, present authors

<table>
<thead>
<tr>
<th>Layer</th>
<th>Lower terrace 3–5 m a.s.l.</th>
<th>Middle terrace 10–17 m a.s.l.</th>
<th>Upper terrace 21–24 m a.s.l.</th>
<th>Upper terrace 32–35 m a.s.l.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>0.8–5.8</td>
<td>1200</td>
<td>0.9–3.4</td>
<td>1000</td>
</tr>
<tr>
<td>2nd</td>
<td>5.8–26</td>
<td>12</td>
<td>34.3–23.5</td>
<td>70</td>
</tr>
<tr>
<td>3rd</td>
<td>26–60</td>
<td>60</td>
<td>68.5–50</td>
<td>800</td>
</tr>
</tbody>
</table>

Table 3. Results of an electrical resistivity survey on James Ross Island. Depths in meter, resistivity in Ohm-meter.
showed that the fluvioglacial sedimentation occurred at least 25,000 y BP near Santa Marta Cove area, followed by marine sedimentation which covered this fluvioglacial deposit and formed the middle terrace. Retreat of local glaciers is considered not to occur simultaneously in James Ross Island. The transgression of sea water was recorded at Santa Marta Cove area during Holocene, forming the lower terrace. As Hjort et al. (1991) suggested the sequential relationship between glacier retreat and upheaval of ground synchronized in both Arctic and Antarctic region. However, present authors consider that deglaciation sequence and upheaval of ground are strongly affected by the local conditions. As there was no direct evidence of coverage by the ice sheet over northern James Ross Island except fluvioglacial deposit dated as 25,000 y BP, present authors assume the initiation of permafrost formation is 25,000 y BP. Calculated rates of permafrost penetration into the ground in the last Glacial and during Holocene were almost same in both periods. It suggests that during Holocene no glacier had covered again over these areas. Generally, permafrost has developed more than 100 m deep in the Arctic region of North America since the deglaciation in the Last Glacial (Washburn, 1979). On James Ross Island, depth of permafrost developed since the Last Glacial is less than half of that in the Arctic region. The effects of marine transgression and local glacial activities during Holocene must be taken into account in future research.

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