Snow pit studies and radio-echo soundings on Mt. McKinley 2004

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Abstract

In June 2004, we made snow pit studies and radio-echo soundings to seek ice core drilling sites on Mt. McKinley (63˚N, 151˚W, 6194 m a. s. l.), Alaska. Pit studies at Denali Pass (5560 m a. s. l.) and Medical Camp (4350 m a. s. l.) show high-density layers near surface. These layers seem to relate with strong wind. From the comparison of the observed temperatures at the pits and temperatures at other ice coring sites in Alaska and Yukon, we suppose that no significant melting occurs at observed sites. Radio-echo soundings show that the ice thicknesses at High Camp (5220 m a. s. l.) and Denali Pass are 46 – 48 m and 63 – 67 m, respectively. Although we have a little information about accumulation rates, the thicknesses are too thin to drill the ice cores which can provide the climate record for more than hundreds years. We suggest that the eastward of Denali Pass and the Summit Plateau of the North Peak (5690 m a. s. l.)

may have thicker ice.

1. Introduction

For reconstructing past climate history, several ice cores are obtained from glaciers in the Wrangell-St. Elias Mountains in southern Alaska and south western Yukon Territory (e.g. Benson, 1984; Holdsworth et al., 1992; Yalcin et al., 2001; Goto-Azuma et al., 2003, Interagency Arctic Research Policy Committee, 2004; Shiraiwa et al., 2004) (Fig.1). Remarkable melting that disturbs past climate signal largely does not occur at the ice coring sites and various signals are preserved in the ice cores. These ice cores are thought to reflect climate and environmental change in North Pacific region on interannual to millennial time scale because locations of the ice-core drilling sites are close from the North Pacific Ocean. However, the previous ice coring sites locate only in Wrangell-St. Elias Mountains. To develop our understanding climate or environmental change in North Pacific region, ice-core records from other area are needed. To compare and develop the study on various time scales, the new ice cores that can provide more than a few hundred years history of climate are desirable.

Mt. McKinley (63˚N, 151˚W, 6194 m a. s. l.) in the Alaska Range is one of the candidates for ice coring. The purpose of this study is to seek ideal ice-core drilling sites which provide the climate record for more than hundreds years Mt. McKinley. In June 2004, we made reconnaissance and carried out snow pit studies and radio-echo soundings. This paper presents the preliminary results.

2. Observation sites

Figure 2 shows the vicinity of Mt. McKinley. In general, there are cliffs on the south and west faces of the South Peak (6194 m a. s. l.). The east face of the South Peak is also steep and covered by glacier. North side of the South Peak is less steep. There is Summit Plateau (5690 m a. s. l.) on the western south side of the North Peak (5934 m a. s. l.). The area of Summit Plateau of the North Peak is about 800 x 500 m. The main peak of Mt McKinley is the South Peak and few people climb the North Peak. Denali Pass (5560 m a. s. l.) is a saddle between North and South Peaks. Eastern side of Denali Pass is a gentle slope and it is beginning of the Harper Glacier. Western side of Denali Pass is a steep slope and West Buttress route, which is the most popular climbing route traverses the slope. There is a place called High Camp (5220 m a. s. l.) at the base of this slope. West Buttress hit the body of the South Peak near High Camp. Medical Camp (4350 m a. s. l.) locates bottom of the cliff at east face of the South Peak. Rangers of the Denali National Park and medical doctors stay here every summer for climbers. Most of climbers camp at High Camp and Medical Camp because they are logistically the best places to camp for climbing the South Peak.

One of the authors (Y. O.) built and maintained the weather station at 5715 m a. s. l. for 15 years. This weather station is on a ridge near Denali Pass (Fig. 2). Prevailing wind on Mt. McKinley is from south or southwest in winter and no prevailing direction in summer. We think wind speed on Mt. McKinley is extremely high because the wind gauges were destroyed or deformed every year. We assume wind at Denali Pass is strong because the saddle shape seems to concentrate wind.

Ice-core drilling sites require flat snowfield and no contamination by climbers. More than 1,000 climbers come to Mt. McKinley every year, so the contamination by them is not negligible. In the vicinity of Mt. McKinley, Summit Plateau of the North Peak, Denali Pass and High Camp answer to the requirements. We thought these sites the candidates of ice-core drilling sites. Remarkable melting that can disturb climate signals largely is also a problem for ice cores. These sites seem to be free from concern for melting because the elevation of these sites are higher than most of previous ice coring sites in the North Pacific region which are shown in Fig. 1. As a first step, we made radio-echo soundings at Denali Pass and High Camp and snow-pit studies at Denali Pass and Medical Camp due to logistic limitation. We could not make any measurement at Summit Plateau of the North Peak and we have little information about this site. However, we suppose that the site has possibility to be an ideal site for ice-core drilling because we could recognize that wide basin was covered by snow there (Fig. 3).

At High Camp, radio-echo soundings were conducted. High Camp is 340 m lower than Denali Pass in elevation and the horizontal distance from Denali Pass is 1.2 km. Most of climbers camp at the same point near the edge of West Buttress. The target of the radio-echo soundings is a flat snowfield which locates on the east side of the campsite (Fig. 4a). Area of this snowfield is about 150 x 150 m. The surface was rough. Height and length of each relief were about 0.5 m and several meters, respectively (Fig. 4b). Bedrocks were exposed to the surface at south and west edge of the snowfield (not shown in the figure). The observation point was about 150 m southeast from the campsite and it was close to the center of the snowfield.

At Denali Pass, radio-echo soundings and a pit study were done. The observation site was about 300 m far from the climbing route. Bedrocks were exposed to the surface at the west edge. Gentle slope less than 5° continues eastward for 700 m from the edge (Fig. 5). The observation site was about 150 m east from the edge (Fig. 6). The surface shape was partly rough. Height and length of each relief were several centimeters and several tens centimeters, respectively. The snow pit was dug at a point with smooth surface.

Snow pit studies were carried out at Medical Camp. This place is 1200 m lower than Denali Pass in elevation. There is information about accumulation rate at this site. Rangers of Denali National Park left a metal pole, which was a part of antennas at Medical Camp in summer 2003. The pole had been buried in snow. We met the rangers digging the pole for using it again. The pole still stood in snow and its bottom was about 4 m below the surface. It implies that the accumulation from summer 2003 to summer 2004 was about 4 m in snow thickness. This value is not so accurate because it is unclear that how deep the pole was stuck into snow in 2003 and exactly date when the rangers stood the pole. However, this value is useful as an approximation.

The high accumulation rate at Medical Camp seems to be caused by concentration of snowdrift. Because there are walls of more than several hundred meters high at the north and the east of Medical Camp. At the candidate sites, High Camp, Denali Pass and the Summit Plateau on the North Peak have no huge walls that may catch snowdrift like Medical Camp. Therefore we assume that accumulation rates at the candidate sites are smaller than in Medical Camp.

3. Snow pit studies

Densities and snow temperatures as well as stratigraphic features were examined at the snow pits. Density measurements were carried out every 30 mm by the conventional weighing method. Snow temperatures were measured by using a thermistor digital thermometer.

3.1. Denali Pass

Figure 7 shows visible snow stratigraphy, density and temperature at Denali Pass. Depth and width of the pit were 1.15 m and 1 m, respectively. Top 1.15 m of the snow consisted of compacted snow and no ice layers were found. Hard layers and soft layers were alternated and each snow layers had no inclination. It implies that rough surface structure like sastrugi did not develop largely here. Variations of the snow hardness are coincident with visible stratigrapy. So in density measurement, density was assumed to be the same value in a similar layer. Snow at 1.15 m was too hard to dig the pit deeper with shovels. Density was measured continuously from the surface to 0.42 m deep. At depths deeper than 0.42 m, density was measured at each layer. At 0.6 m deep, there was very hard layer and its density was 450 kg m^{-3}. Density of the hard layer at the bottom also seemed to be high. We speculate that such high-density layers relate strong wind. Snow temperature was lower at deeper depth. At 1.1 m deep, the temperature was –24.8 ˚C.

3.2. Medical Camp

Figure 8 shows visible snow stratigraphy, density and temperature at Medical Camp. The pit was 2.50 m deep. Snow in the pit seemed to be accumulated within one year because the accumulation from previous year was approximately 4 m in snow here. Top 2.5 m of the snow consisted of compacted snow and no ice layers were found. The surface was smooth and each snow layer had no inclination. There were a softer layer at 0.40 –0.41 m and a harder layer at 0.56 – 0.57 m. It heavily snowed for the last five days following to several sunny days so that it is likely that the hard layer is a sun-crust layer and the top 0.56-m snow had been deposited for the last five days.

Density was measured continuously from the surface to 1.02 m. At depths deeper than 1.02 m, measurement was done every 0.1 m. Density was 350 kg m^{-3} at 0.75 m deep and 430 kg m^{-3} at 0.90 m deep. At 1.5 m deep, density was relatively low. In the temperature profile, there is a daily fluctuation at the surface. Temperature at Medical Camp was 7 ˚C higher than at Denali Pass in the same depth.

3.3. Discussion on the snow pit studies

Density at the pits shows fluctuations in the profiles. Although the low-density snow at the surface of Medical Camp may blow off, other relative low-density layers seem to be preserved. Kanamori et al. (unpublished) obtained detailed density profiles from ice cores at Mt. Wrangell and King Col, Mt. Logan that locate in Wrangell-St. Elias Mountains (Fig. 1). These sites are cold mountain glacier like the observation sites in Mt. McKinley. They found that density fluctuation exist over depths of 50 m there and discuss the meaning as past climate signals. We speculate that the density fluctuations on Mt. McKinley are also preserved in firn layers and the fluctuations have some meaning as past climate signals which relate with wind and other factors.

There were no ice layers at the snow pits. However, it does not mean no melting occur through a year. Because we may not dig the layers of previous summer at the pits. Therefore, to examine whether melting occur at the candidate sites on Mt. McKinley or not, we compared snow temperature at previous ice coring sites at Mt. Logan and Mt. Wrangell. The temperature data on Mt. McKinley is limited to the surface data in early summer season, so we compared the temperature data at depth of 1.1 m in early summer with other ice coring sites (Table 1). The comparison shows that the surface snow temperature at Denali Pass was lower than the temperatures at the previous ice coring sites and a little higher at Medical Camp in early summer season. We suppose that seasonal variation of temperature on Mt. McKinley is similar with that on Mt. Logan and Mt. Wrangell because the mountains all locate in North Pacific region in the North America and latitude of them are close. From the comparison, we guess that the snow temperature of the candidate sites, which locate above 5220 m a. s. l. are lower than snow temperatures of ice coring sites at King Col, Mt. Logan and Mt. Wrangell. From the ice cores, melting is insignificant at King Col, Mt. Logan (Shiraiwa et al., 2003) and Mt. Wrangell (Shiraiwa et al., 2004). Therefore, we guess that melting are also insignificant at the candidate sites in Mt. McKinley. No ice layers at the visible stratigraphies support this idea.

4. Radio-echo soundings

4.1. Method

The ice-penetrating radar system was composed of an impulse transmitter and a set of transmission and receiving antennas. The antennas were half-wavelength dipole. The central frequency was 5 MHz. The time series of received voltage were digitized with a portable oscilloscope.

At each site, antennas were set on the surface. Distance between the antennas was set at 30 m and 50 m. The long axis of the dipole antenna was set to orient bare walls and ridges to decrease clutters from them. In addition, we made another measurement for the orthogonal antenna orientation at Denali Pass.

The thickness of ice d is calculated using

$$d = \sqrt{\left(\frac{vT}{2}\right)^2 - L^2} \quad , (1)$$

where v (m μs^{-1}) is the propagation speed of the radio wave, T (μs) is the two-way travel time and $2L$ (m) is the distance between the antennas (Matsuoka et al., 1999). The propagation speed v is required to convert two-way travel time into ice depth and the speed can be written as $300/\sqrt{\varepsilon}$ (m μs^{-1}), where ε is permittivity of firn. The permittivity of firn ε depends on density of the firn. It can be calculated by Looyenga's eauation (Glen and Paren, 1975):

$$\varepsilon^{\frac{1}{3}} - 1 = \frac{\rho}{\rho_i}\left(\varepsilon_i^{\frac{1}{3}} - 1\right). \quad (2)$$

Here, ε_i is the permittivity of pure ice, that is eventually independent of firn temperature (Fujita et al., 2000), ρ is density of the glacier and ρ_i is density of pure ice. Our density measurement was done only for top several meters, so that we assumed ρ from density profiles of other glaciers. In mountain glaciers, the thickness of firn layers take large part of the all thickness and it controls the density of all thickness. So we assumed that density at any depth on Mt. McKinley ranges between the densities of the same depths at two glaciers that have extremely thin and thick firn layers. We used the density profiles at King Col, Mt. Logan (firn thickness: 50 m; Shiraiwa et al., 2003) and Mt. Wrangell (firn thickness: 100 m) as the two extreme values. In this assumption, the density ρ depends on the thickness, d. So we gave the propagation speed v to be 169 – 205 m μs^{-1} as first estimate from density of 550 – 900 kg m^{-3} and calculated tentative thickness d' from Eq. 1. The range of the density is enough wide to include density of all mountain glaciers in the world. Next, we estimated density from the tentative thickness, d' and recalculated d' using newly estimated density and v. The calculation was repeated until range of density converged. In the case of High Camp, we assume the propagation speed v to be 196 – 202 m μs^{-1} from the estimated mean density of 580 – 630 kg m^{-3} and in the case of Denali Pass, we assume v to be 190 – 198 m μs^{-1} from the estimated mean density of 580 – 630 kg m^{-3}.

Origin of two-way travel time is uncertain in this radar-system. So we considered first highest peak at the time series of radio echo as a standard point of direct wave. The zero point of two-way travel time was considered to be $2L/300$ (μs) before the standard point.

4.2 Results

4.2.1 High Camp

Figure 9 shows time series of the radio echo at High Camp. Clear echoes are shown at 0.5 and 1.1 μs. The measurement site is 150 - 200 m far from the walls that is likely to reflect the radio wave. If the radio wave is reflected off the wall, the propagation speed through the air of 300 m μs^{-1} gives two-way travel time of the echoes 1.0 – 1.3 μs. Therefore, we interpret that the echoes at the two-way travel time of 0.5 μs was reflected off the bedrock beneath the ice. Thickness of ice was calculated as 46 – 48 m with T and $2L$ shown in Fig. 9. The echoes at 1.1μs seem to be reflected off the bared bedrock or surrounding ridges of the measurement site, or off nadir reflection from beneath the ice.

The measurement site is close to the center of the 150 m by 150 m area that is covered by snow. Since bare bedrock was found at the edge of this area, the thickness of the snow and ice increases from 0 m to 46 – 48 m within the lateral distance of 75 m.

Target of the ice core is at least more than a few hundred years. The thickness seems too thin to obtain such aged ice cores.

4.2.2 Denali Pass

Figure 10 shows the time series of the radio waves at Denali Pass. Figures 10a and 10c are the case that the long axis of the dipole antenna was set to orient bare walls and ridges to decrease clutters from them. Fig. 10b and 10d are the case of the orthogonal antenna orientation. Clear echoes are shown at 0.7 μs. The two-way travel time of the clear echoes were a little shorter at shorter antenna separations. This may be from uncertain of the zero point of two-way travel time. The measurement site is about 150 m far from the walls that is likely to reflect the radio wave. If the radio wave is reflected off the wall, the propagation speed through the air of 300 m μs^{-1} gives two-way travel time of the echoes 1.3 μs. Therefore, we interpret that the echoes at the two-way travel time of 0.7 μs was reflected off the bedrock beneath the ice, not the bare bedrock or surrounding ridges of the measurement site. The thickness of ice was calculated as 63 – 67 m with the *T* and *2L* shown in fig. 10. The measured thickness does not seem to be enough to obtain aged ice cores. However, we suppose that thickness of glacier increases eastward. At the west edge of this snow field, bedrock was exposed to the surface and at the measurement site, bedrock was about 60 m below the surface. Gentle slope of less than 5° continues eastward. Thus we can expect much thicker ice at the east of the observation site.

5. Concluding remarks

We carried out snow pit studies and radio-echo soundings on Mt. McKinley to seek the ideal ice-core drilling site which can provide ice core with at least a few hundred years of climate record. Annual accumulation at Medical Camp was about 4 m in snow. We consider that drift snow was concentrated at Medical Camp because of its topographical condition and annual accumulation rates at the candidate sites are lower than accumulation rate at Medical Camp. The high-density layers at the pits imply that strong wind blows and relates to forming of the layers. From the comparison of temperature with previous ice coring sites, we suppose that no significant melting occur at the candidate sites. The thicknesses of glaciers are estimated to be 46 – 48 m at High Camp and 63 – 67 m at Denali Pass. The thickness of High Camp is too thin to drill ice cores which are suitable for our purpose. The thickness at Denali Pass was also thin, however, thicker ice can be expected to exist at the eastward area of the site. In addition, the Summit Plateau of the North Peak seems to be a good site in the view from the vicinity. These two sites, Denali Pass and the Summit Plateau of the North Peak have possibility to be ideal sites to drill ice cores with hundreds years of climate history.

Acknowledgments

We thank Roger Robinson and all rangers of Denali National Park. They supported our climbing and transport of equipment. We thank all the members of our climbing team and the team “Wind of Denali” for their help in climbing and scientific operations. Syun-Ichi Akasofu and Itsuro Kato supported our climbing team in Fairbanks and Anchorage. Carl S. Benson, Kevin Abnett and Gary Newman supported the preparations for the fieldwork. We also thank Kenichi Matsuoka for the lecture on radar operations and advise on the interpretation of the results. Finally, we thank the reviewer for his/her many variable comments.

References

Benson, C. S. (1984): Ice core drilling on Mt. Wrangell, Alaska, 1982.2nd International Workshop/Symposium on Ice Drilling Technology. CRREL Special Report, 84-34, 61-68.

Fujita, S., Matsuoka, T., Ishida, T., Matsuoka, K. and Mae, S. (2000): A summary of the complex dielectric permittivity office in the megahertz range and its applications for radar soundings of polar ice sheets. Physics of Ice Core Records, Hondoh, T. (ed), Hokkaido University Press, 185-212.

Glen. J.W. and Paren, J.G. (1975): The electrical properties of snow and ice. J. Glaciol., **15**(73), 15-38.

Holdsworth, G., Krouse, H. R. and Nosal, M. (1992): Ice core climate signals from Mount Logan, Yukon, AD 1700-1987. In Climate Since A.D. 1500, R. S. Bradley and P. D. Jones(Eds.), Routledge, London, pp. 483-504.

Interagency Arctic Research Policy Committee. (2004): Arctic research of the United States Vol. 18 Spring/Summer 2004., the Interagency Arctic Research Policy Committee, National Science Foundation., pp. 5.

Matsuoka, K., Horikawa, S., Shiraiwa, T., Muravyev, Y.D., Salamatin, A.N., Ovsyannikov, A.A., Maeno, H. and Ohi, M. (1999): Radio-echo sounding at the summit ice cap of the Ushkovsky volcano, Kamchatka. In Naruse, R. (ed) Cryospheric Studies in Kamchatka II, Institute of Low Temperature Science, Hokkaido University, Sapporo, 20-24.

Shiraiwa, T., Goto-Azuma, K., Matoba, S., Yamasaki, T., Segawa, T., Kanamori, S., Matsuoka, K. and Fujii, Y. (2003): Ice core drilling at King Col, Mount Logan 2002. Bull. Glaciol. Res. **20**, 57-63.

Shiraiwa, T., Kanamori, S., Benson, C. S., Solie, D. and Muravyev, Y. D. (2004): Shallow ice-core drilling at Mount Wrangell, Alaska. Bull. Glaciol. Res. **21**, 71-77.

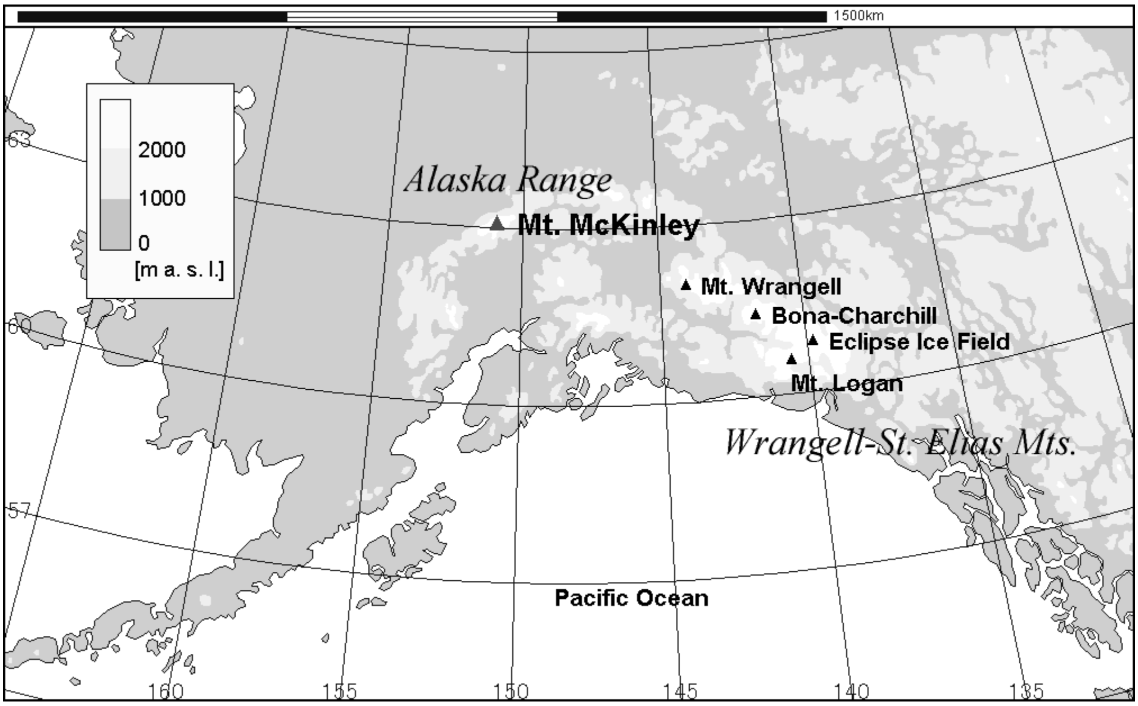
Goto-Azuma, K., Shiraiwa, T., Matoba, S., Segawa, T., Kanamori, S., Fujii, Y. and Yamasaki, T. (2003): An overview of the Japanese glaciological studies on Mt. Logan, Yukon Territory, Canada in 2002. Bull. Glaciol. Res. **20**, 65-72.

Yalcin, K. and Wake, C. P. (2001): Anthropogenic signals recorded in an ice core from Eclipse Icefield, Yukon Territory, Canada. Geophys. Res. Lett., **28**, 4487-4490.

Table 1. Snow temperatures on Mt. McKinley and at two drilling sites.

	Denali Pass, Mt. McKinley	Medical Camp, Mt. McKinley	King Col, Mt. Logan	Mt. Wrangell
Temperature at 1.1-m depth (˚C)	-24.8	-14.6	-17.8*	-16.5**
Date	June 28, 2004	June 22, 2004	May 26, 2002	June 25, 2003
Latitude	63˚04’57”N	63˚04’11”N	60˚35’20”N	61˚59’54”N
Longitude	151˚01’43”W	151˚04’25”W	140˚36’15”W	144˚02’30”W
Elevation(m a.s.l.)	5560	4350	4135	4100

*Goto-Azuma et al. (2003); **Shiraiwa et al. (2004)



1500km
2000
1000
0
[m a. s. l.]
Alaska Range
Mt. McKinley
Mt. Wrangell
Bona-Charchill
Eclipse Ice Field
Mt. Logan
Wrangell-St. Elias Mts.
Pacific Ocean
63
60
57
160
155
150
145
140
135

Fig.1

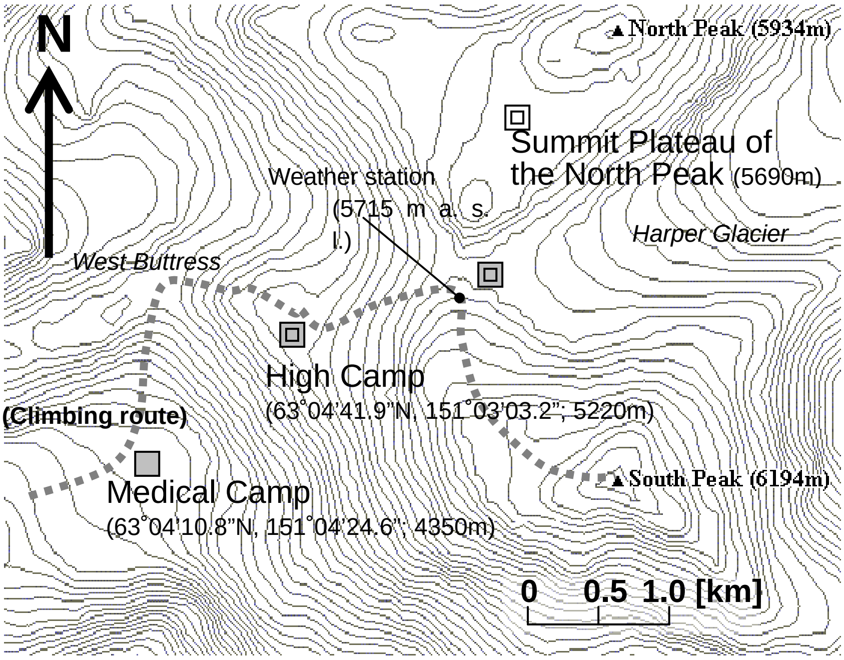

N
North Peak (5934m)
Summit Plateau of
the North Peak (5690m)
Weather station
(5715 m a. s. l.)
Harper Glacier
West Buttress
High Camp
(63˚04'41.9"N, 151˚03'03.2"; 5220m)
(Climbing route)
South Peak (6194m)
Medical Camp
(63˚04'10.8"N, 151˚04'24.6"; 4350m)
0 0.5 1.0 [km]

Fig.2

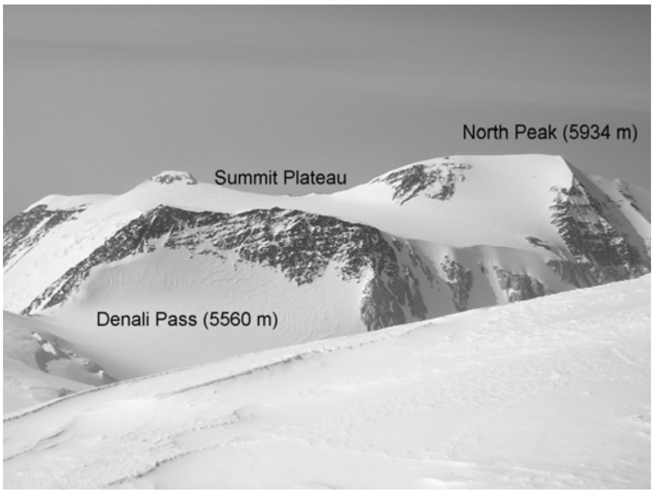


Fig.3

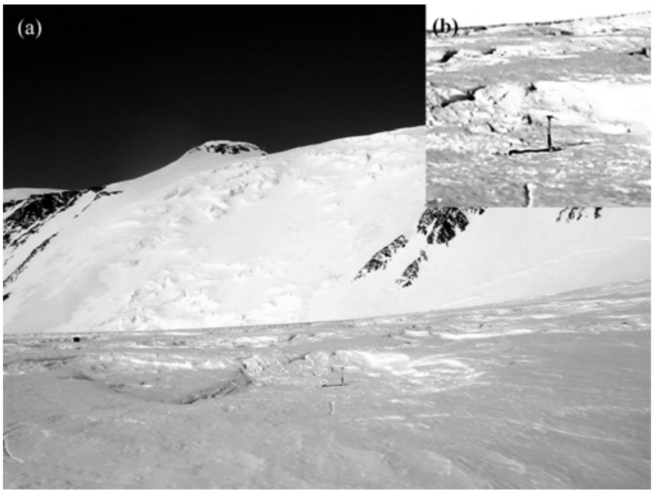


Fig.4

Fig.5

Fig.6

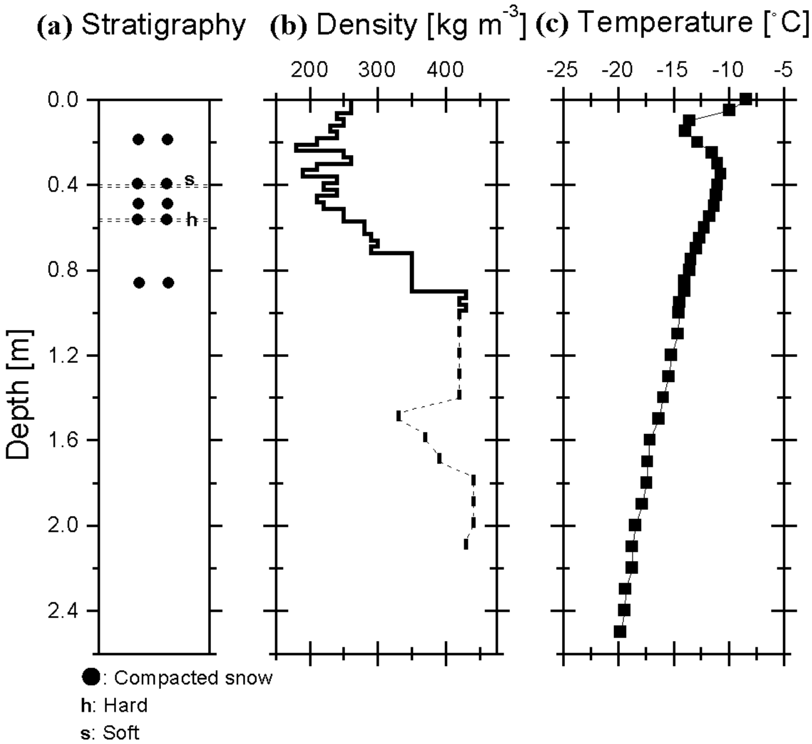
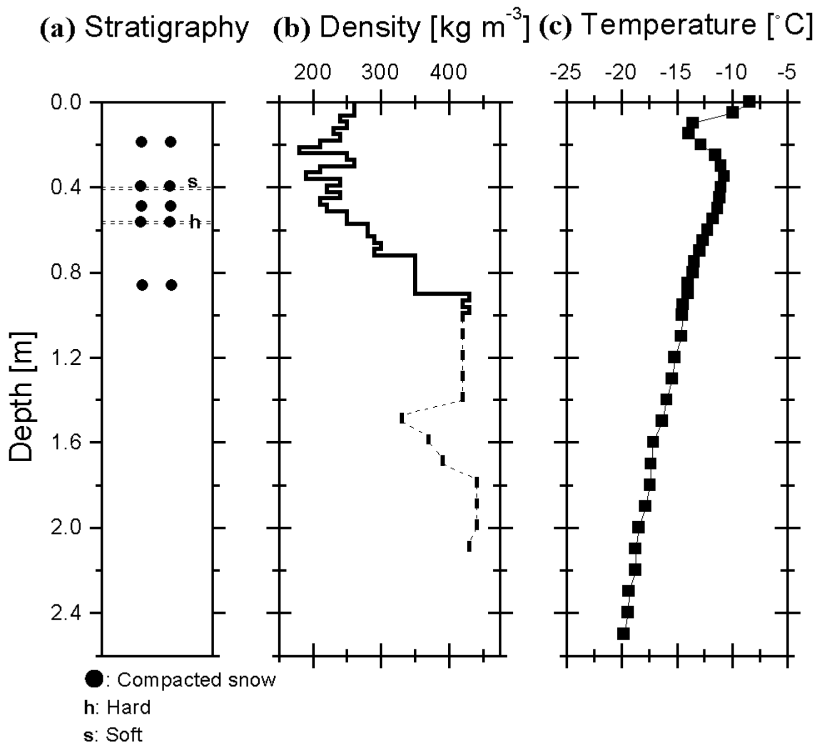
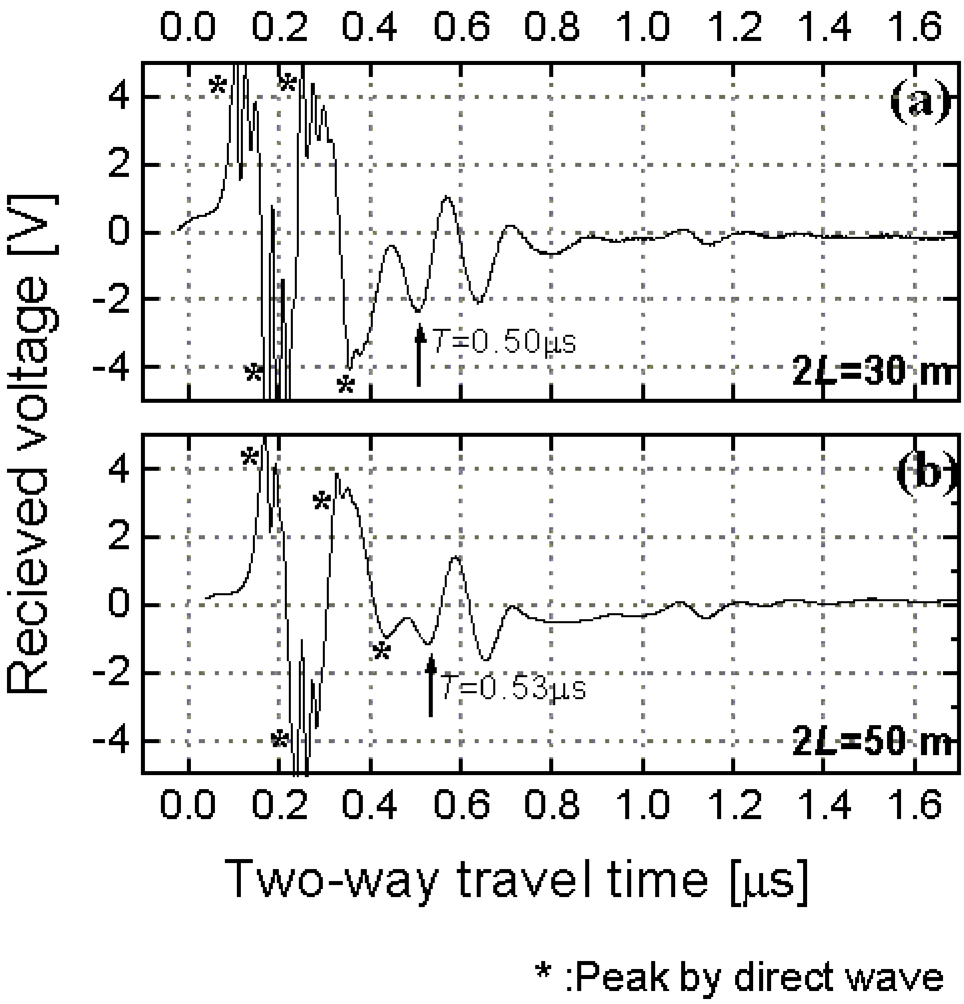

(a) Stratigraphy
(b) Density [kg m-3]
(c) Temperature [°C]
200 300 400
-25 -20 -15 -10 -5
0.0
0.4
0.8
1.2
1.6
2.0
2.4
Depth [m]
s
h
●: Compacted snow
h: Hard
s: Soft

Fig.7



(a) Stratigraphy
(b) Density [kg m-3]
(c) Temperature [°C]
200
300
400
-25
-20
-15
-10
-5
0.0
0.4
0.8
1.2
1.6
2.0
2.4
Depth [m]
s
h
●: Compacted snow
h: Hard
s: Soft

Fig.8



0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6
(a)
T=0.50μs
2L=30 m
(b)
T=0.53μs
2L=50 m
4
2
0
-2
-4
Recieved voltage [V]
Two-way travel time [μs]
* :Peak by direct wave

Fig.9

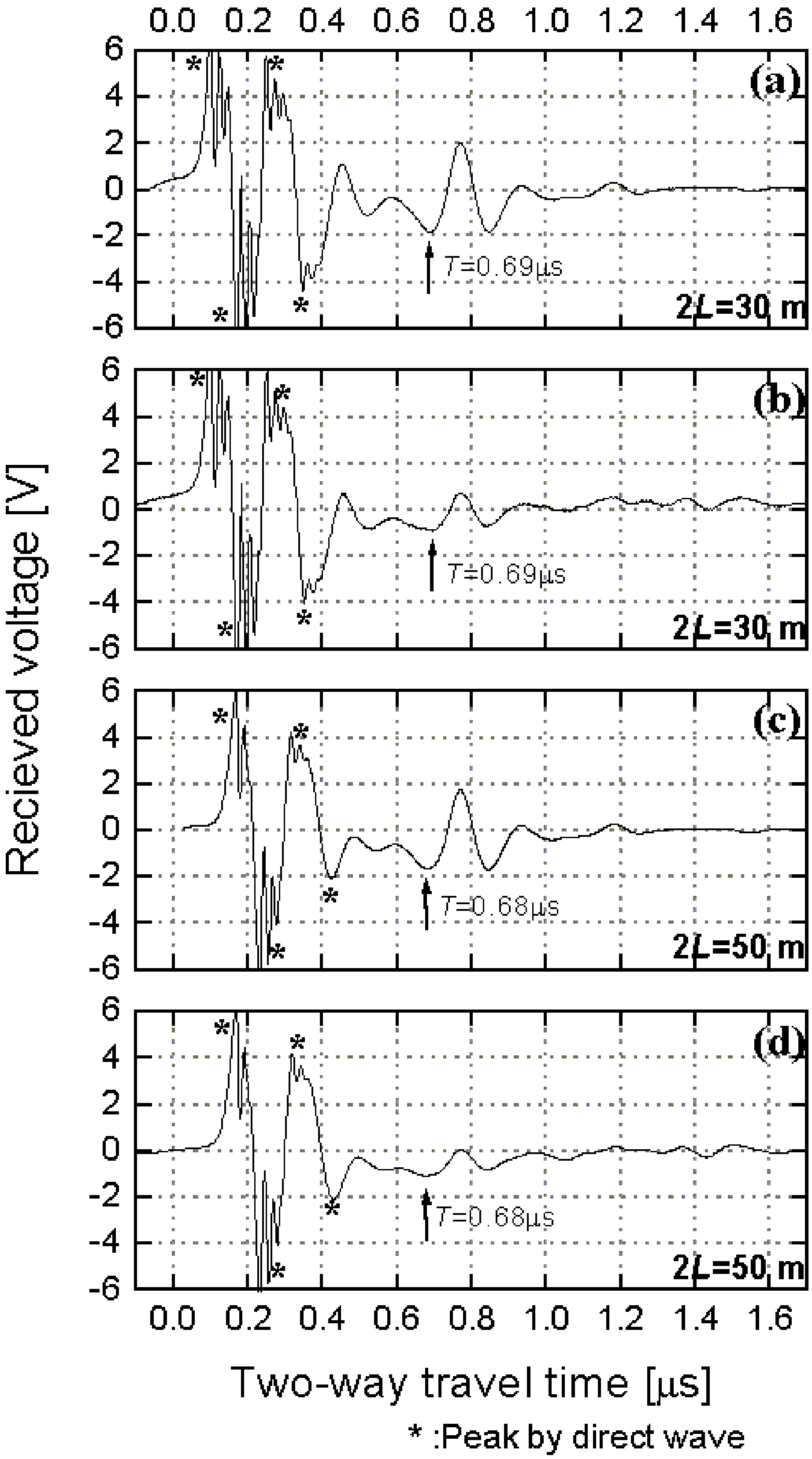

(a)
T=0.69μs
2L=30 m
(b)
T=0.69μs
2L=30 m
(c)
T=0.68μs
2L=50 m
(d)
T=0.68μs
2L=50 m
Recieved voltage [V]
Two-way travel time [μs]
* :Peak by direct wave

Fig.10

Figure Captions

Fig. 1: Locations of Mt. McKinley (6194 m a. s. l.). Ice cores longer than 40 m were obtained from 6 sites close to Mt. McKinley: Mt. Logan (Northwest Col: 5340 m a. s. l.; Holdsworth et al., 1992, Prospect-Russell Col: 5340 m a. s. l. and King Col: 4135 m a. s. l.; Goto-Azuma et al., 2003), Eclipse Ice Field (3071 m a. s, l; Yalcin and Wake, 2001), Bona-Charchill (4420 m a. s. l.; Interagency Arctic Research Policy Committee, 2004) and Mt. Wrangell (Summit Plateau:4100 m a. s. l.; Benson, 1984; Shiraiwa et al., 2004).

Fig. 2: Topographical map of Mt. McKinley. A broken line shows the most popular climbing route, West Buttress Route. Double squares show candidate sites for ice core drilling and gray squares show observation sites. Thin solid lines show 100-m interval contours of the surface elevation. Original digital elevation data was Global 30 Arc Second Elevation Data (GTOPO30) by U. S. Geological Survey, http://edcdaac.usgs.gov/main.asp

Fig. 3: A view of the summit plateau of the North Peak from the South Peak. (June 27,

2004).

Fig. 4: High Camp (June 26, 2004). a: A view of the observation site. b: An enlarged picture of Fig. 4a. The object at rough surface is an ice ax.

Fig. 5: A view of Denali Pass from the weather station (June 27, 2004).

Fig. 6: The observation site at Denali Pass (June 28,2004). All photos in Figs. 3 – 6 are taken by S. Kanamori.

Fig. 7: Results of pit studies at Denali Pass. a:visible stratigraphy; b:density profile. A broken line is estimated value by stratigraphy; c:temperature profiles.

Fig. 8: Results of pit studies at Medical Camp. a:visible stratigraphy; b:density profile; c: temperature profiles.

Fig. 9: The time series of radio echo at High Camp. a: Antenna separation was 30 m; b:Antenna separation was 50 m. Arrows indicate clear reflections that we interpreted

the echo from the nadir bedrock beneath the ice.

Fig. 10: The time series of radio echo at Denali Pass. Arrows indicate clear reflections. a and b: Antenna separation was 30 m; c and d: Antenna separation was 50 m. a and c, b and d were obtained with the orthogonal antenna orientations each other. See text for detail.