

Study of the internal structure of the Kuranosuke snow patch in central Japan using ground penetrating radar survey

Hideo SAKAI¹, Yasuhiro URA¹, Takayuki NAKANO¹, Hajime IIDA² and Katsunori MUROI²

¹ Department of Earth Sciences, Toyama University, Gofuku 3190, Toyama 930-8555, Japan

² Tateyama Caldera Sabo Museum, Tateyama-machi, Toyama 930-1405, Japan

(Received October 5, 2005; Revised manuscript accepted November 14, 2005)

Abstract

We studied the internal structure of the Kuranosuke snow patch in the Northern Japanese Alps using ground penetrating radar (GPR) survey. The Kuranosuke snow patch consists of a perennial snow zone and an older ice zone. A GPR survey in Sep. 2004 elucidated the unconformity between the perennial snow zone and the older ice zone at a depth of 5 to 7 m. The thickness of the snow patch is over 20 m and five gravel layers were identified in the older ice zone. The gravel layers in the older ice zone seem to decline at different angles from the unconformity, which suggests they were formed under different conditions from the present. The Kuranosuke snow patch seems slightly shallower than 20 years ago, which may be mainly caused by melting of the perennial snow zone. GPR studies may be useful for ascertaining the formation and change of the Kuranosuke snow patch, and the related paleoenvironment.

1. Introduction

There are many perennial snow patches found in the mountain ranges of central Japan. The Kuranosuke snow patch (36°35'N, 137°37'E, 2,800 m a.s.l., Fig. 1) located in the Northern Japanese Alps is one of them, where snow accumulation is more than 10 m in winter, with nearly the same amount of snowmelt in summer. It is in a cirque formed during the last ice age and moulin-type vertical holes appear once every few years after the firn has melted. Its internal structure was studied by utilizing these vertical holes (Yoshida *et al.*, 1983; Iida *et al.*, 1990), indicating that the snow patch consists of a perennial snow zone and an older ice zone. The thickness of the snow patch was over 20 m. The ¹⁴C dating of plants collected from the lower ice zone in the vertical holes ranged between 1000 to 1700 BP (Nakamura, 1990). This indicates that the Kuranosuke snow patch is the oldest fossil ice body in Japan (dating back to the Kofun era).

Former studies using the vertical holes gave important findings, however the holes only permit limited examination of the general structure of the Kuranosuke snow patch. Ground penetrating radar (GPR) survey is a useful investigation method in glaciology and in the study of shallow snow/ice bodies through their dielectric property. At the Kuranosuke snow patch, GPR studies have been done on September 14,

1983 by Yamamoto *et al.* (1986) and Yamamoto and Yoshida (1987) and on September 30, 1997 by Sakai *et al.* (1999a, 1999b). Their surveys were conducted along several lines at the snow patch with 100 and 140 MHz antennas. Several important features of the snow patch such as its basal structure, and the existence of gravel layers, were ascertained.

In this study, we will show the results of a GPR survey conducted at the Kuranosuke snow patch on September 28 and 29, 2004. The survey was done in a season similar to the former GPR studies. Therefore, comparison of the studies at three times (1983, 1997 and 2004) can reveal the changes in depth and structure of the snow patch. The 2004 survey was especially concentrated around the deepest part of the snow patch. By using a closely-spaced GPR survey, and analyzing horizontal distribution maps of the reflection amplitude, we investigated the internal structure of the Kuranosuke snow patch in detail and increased our understandings of its variation over time.

2. Outline of the GPR study

The GPR survey was done in the rectangular area of 50 × 50 m shown in Fig. 1 by using the Noggin GPR system with a 250 MHz antenna. In this area, a total of 51 survey lines (spacing between neighboring lines being 1 m) from south to north were laid out. The

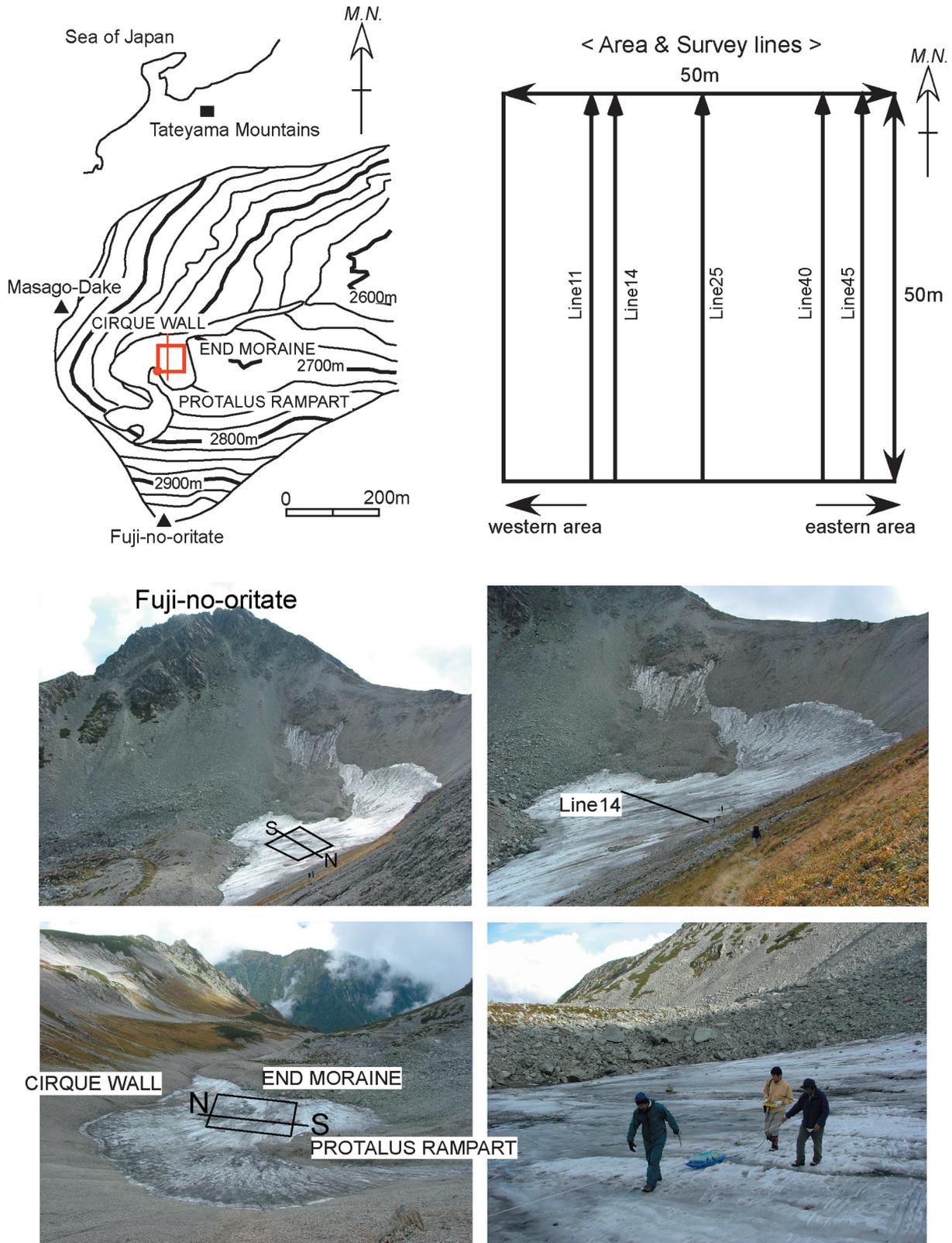


Fig. 1. Location and schematic map of the Kuranosuke snow patch. The red square in the map shows the survey area, where the survey lines whose GPR data explained in section 3 are also indicated. The photographs show the survey area and a snapshot of the survey.

length of each line was 50 m. Referring to the study of Iida *et al.* (1990), the area was located over the deepest part of the snow patch and the vertical holes.

GPR data along the 51 lines were examined in

radar profiles such as Fig. 2. In the profile, the relative amplitude of radar reflection from the vertical zone is shown, where the abscissa is the horizontal distance along the survey line and the ordinate shows the

travel time of the radar wave and the calculated depth on the left and right scales, respectively. In the calculation of depth, we used the velocity value of 0.163 m ns^{-1} , which is determined by fitting a hyperbola to diffracting objects (Moldoveanu-Constantinescu and Stewart, 2004).

In the next section, representative GPR profiles from the five lines shown in Fig. 1 are described. The profiles are those of lines 11 and 14 in the western area, that of line 25 in the middle area and those of lines 40 and 45 in the eastern area. Line 14 runs in the western area with 90 m length beyond both edges of the rectangular area.

Further, all the GPR profiles from 51 lines were combined into horizontal distribution maps of reflection amplitude (amplitude time-slice maps; Conyers and Goodman, 1997), which were examined at several depths.

3. Results and discussion

3.1. GPR profile along line 14

The upper image in Fig. 2 shows the profile along line 14, with lines and the inferred strata drawn around the distinct reflection areas.

We can identify a clear boundary C around 5 m in depth. It is consistent with the depth of the unconformity between the perennial snow zone and the older ice zone found in the vertical holes near the survey line (Iida *et al.*, 1990). A layer with gravel around the unconformity may cause the distinct radar reflection.

In the perennial snow zone, layers A and B of clear reflection are identified. Examination of the profile by changing the gain of reflection amplitude proved that the two layers are a continuous layer. It may be a dirt ice layer formed by concentrated (melted) annual layers over several years.

As for the bottom of the ice zone and internal layers, the basal plane under the snow patch resembled a bowl (U-type) shape as a whole. The inclined reflection over the distance of 0 to 40 m is the boundary between bottom of the ice zone and the lower zone. Regarding the geographical features, the lower zone corresponds to a protilus rampart. The sloping reflection at a distance of 70 to 85 m in the northern side is the boundary between the ice zone and the cirque wall. The reflection is strong around the basal plane at a distance from 35 to 45 m, which may be a concentration of gravel which probably collapsed from the cirque wall and protilus rampart. At the middle of the line, the snow patch has a maximum depth of about 25 m. Profiles show five clear reflection layers (D, E, F, G and H) between the unconformity and the basal plane. These may be gravel layers in the fossil ice zone.

3.2. Other GPR profiles

The profile of line 11 in Fig. 2 is another example of the results in the western area. We can identify the reflection inclined downward from south to north as the boundary between the ice zone and the protilus rampart. The cirque wall in the northern side is not reached in the survey line. At the right end of the profile, the snow patch reaches about 23 m in depth. Several clear reflections in the fossil ice zone may show layers of gravel.

The profile of line 25 shows the results in the middle area. Differing from the profiles in the western area, the profile shows a steeply inclined reflection at the boundary with the protilus rampart.

Similar steeply inclined reflection at the boundary between the ice zone and the protilus rampart is identified in the profile of line 40 in the eastern area, although the incline turns into to a gradual slope from the next line, and the reflection in line 45 has an angle similar to that in the western area (such as line 11).

In most of the survey lines apart from the eastern area, the unconformity is confirmed at the depth of 5 to 7 m. The depth of the unconformity at line 45 is shallow compared with those in profiles from the western and middle areas. The profiles near the eastern end of the area have a shallower unconformity, and in the profile of line 50, it is about 3 m in depth.

We can identify a strong reflection (dark) region at the unconformity in several lines, *e.g.* a region at a distance of 20 to 25 m in line 25. The region may be a concentration of gravel, possibly formed by falling stones from the cirque wall, or transported debris flow. In other words, debris flow or falling stones may have accumulated while the unconformity layer was an exposed surface.

In the profiles of lines 25 and 40, sloping reflections in the ice zone were identified. Sloping reflections are also visible in several other profiles. They may be inclined gravel layers, which have been formed under different conditions (*e.g.* by glacier flow) from the present and/or the period when the unconformity was an exposed surface. Therefore it is important to ascertain the distribution and structure of inclined reflections in the ice zone by GPR, as they may be useful for investigating the sedimentary condition and the related paleoclimate.

3.3. Comparison with former GPR studies at the Kuranosuke snow patch

In Fig. 3, the GPR profile along line 14 (the lower image) was compared with the previous profiles studied in 1983 (Yamamoto *et al.*, 1986) and in 1997 (Sakai *et al.*, 1999a). All the survey lines have a NS strike and cover similar areas. Yamamoto *et al.* (1986) used a 140 MHz antenna and in the study of Sakai *et al.* (1999a), a 100 MHz antenna was applied. In this study, a 250 MHz antenna was used. Compared with the profiles from former studies, the profile for 2004 has clearer refle-

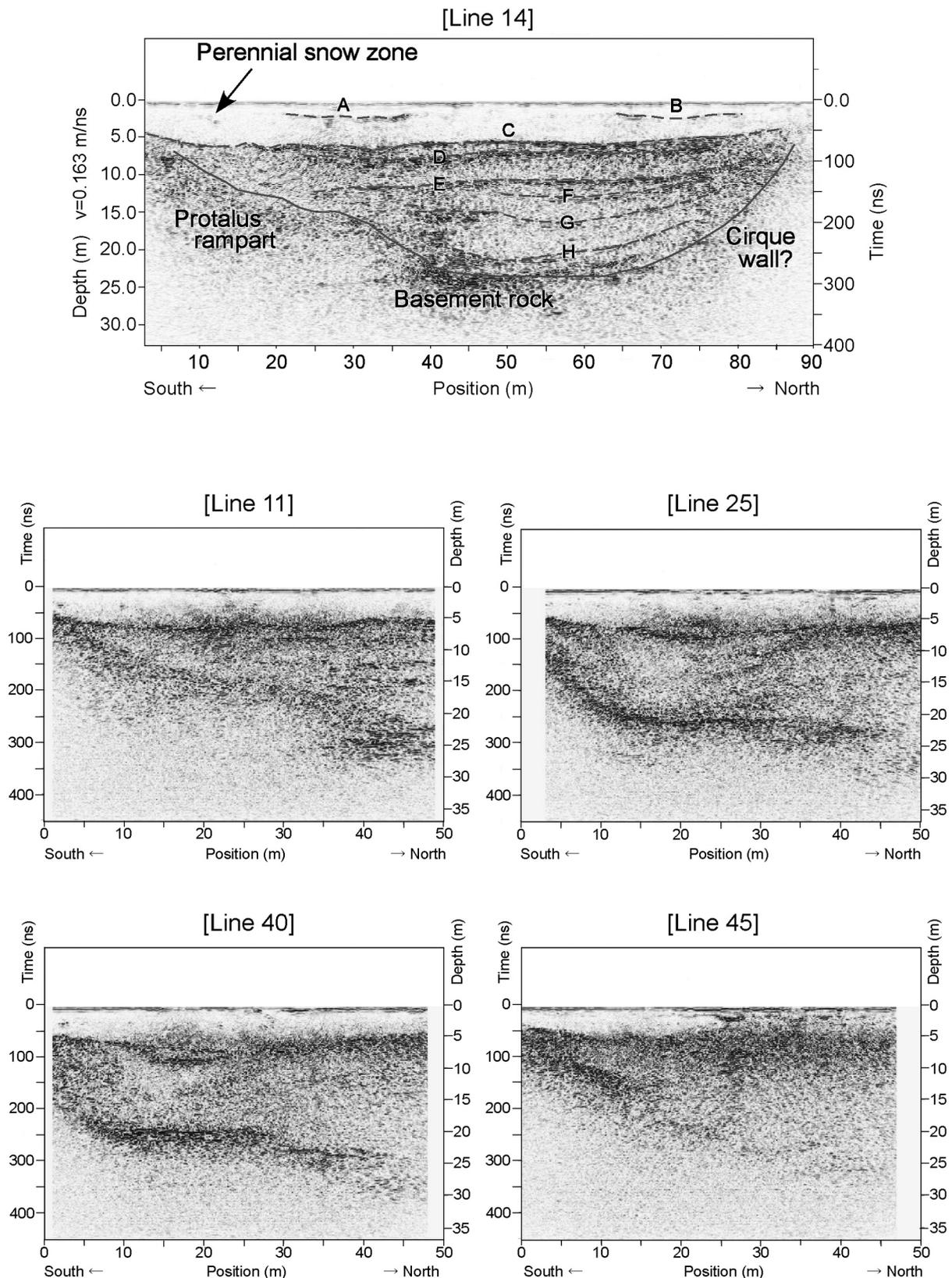


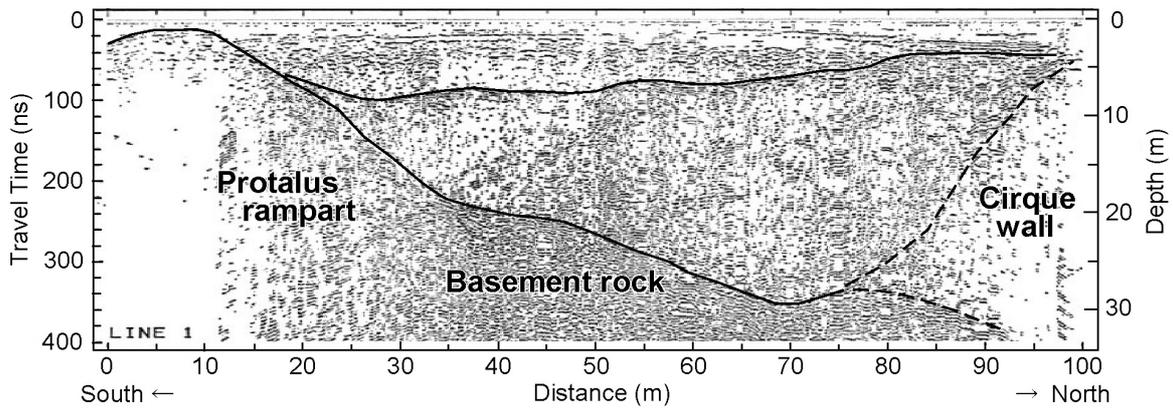
Fig. 2. GPR profiles along lines 14, 11, 25, 40 and 45. The darker parts represent stronger reflections.

ctions indicating the unconformity and the gravel layers. This suggests that the 250 MHz antenna is more effective for clarifying the internal structure of the snow patch up to several tens of meters in depth.

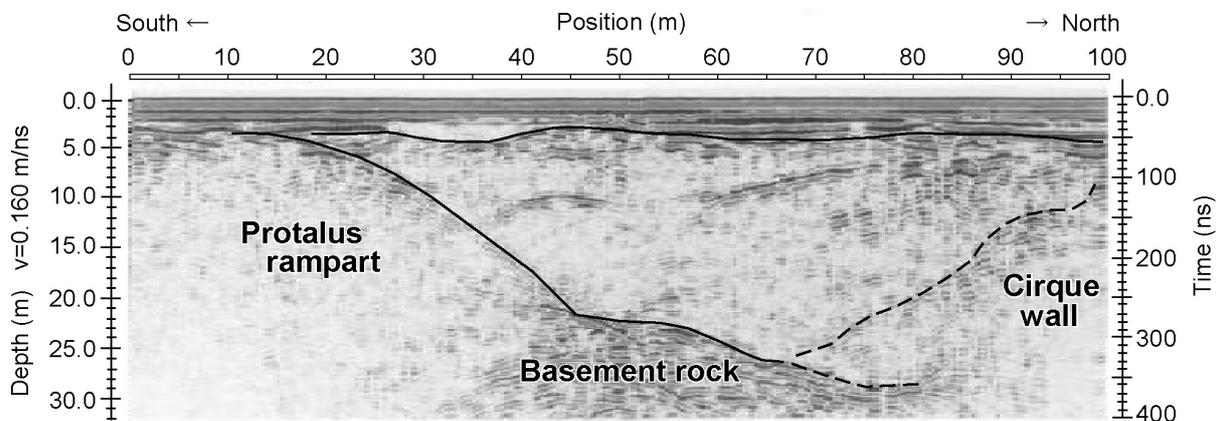
The three profiles show similar reflection pattern

in general, although differences such as the shape of boundary between the ice zone and the lower zone are visible. Locations of the survey lines were determined by topographical surveys. The locations of the three lines in Fig. 3 are close each other, but not exactly the

(a) 1983 (140MHz)



(b) 1997 (100MHz)



(c) 2004 (250MHz)

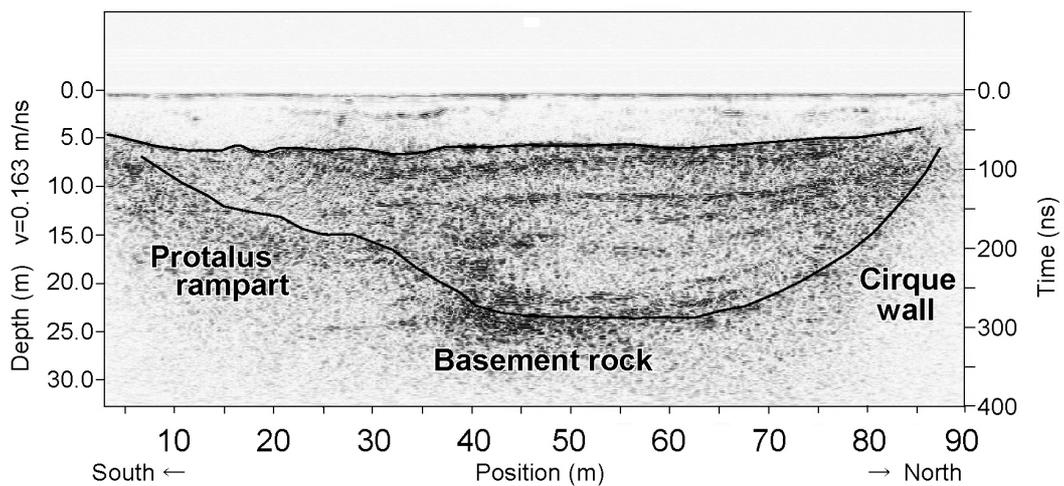


Fig. 3. Comparison of GPR profiles in the area of line 14 from three surveys: (a) 1983 (Yamamoto *et al.*, 1986), (b) 1997 (Sakai *et al.*, 1999a) and (c) 2004 (the current study).

same. One reason for the differences among the three profiles is considered to be the difference in location of the survey lines.

Comparison between the profiles for 1983 and 2004 suggests a reduction in the thickness of the perennial snow zone.

Regarding the profile for 2004 at line 14, the profiles at the neighboring lines show a similar depth for the perennial snow zone, suggesting that the unconformity is fairly flat around the area of line 14. Therefore, the depth of the perennial snow zone in the profile in 2004 may not differ greatly even across several survey lines.

The depth of the perennial snow zone may change depending on seasons. Concerning the season of the surveys, the survey in 1983 was conducted on September 14, the survey in 1997 was on September 30 and the survey in 2004 was on September 28. Therefore, the difference in season cannot explain large differences in the thickness of the perennial snow zone in these profiles.

In other words, the GPR studies suggest that the perennial snow patch may have diminished in thickness during the past 20 years. Iida and his colleagues are preparing to show that the surface area of the snow patch also seems to be smaller than 20 years ago (Iida, H., personal communication).

3.4. Analysis of horizontal distribution maps of the reflection amplitude

All data from the GPR profiles for 51 lines in the rectangular area were combined, and horizontal distribution maps of the reflection amplitude (amplitude time-slice maps) were made.

The process of analysis is described by Conyers and Goodman (1997) as follows: radar profiles which have been collected along parallel lines within an area are sliced at a particular time interval. The relative amplitudes of the reflected radar waves recorded between those times are then averaged and interpolated prior to printing them in map form. The resulting anomalies visible in a slice map therefore represent the spatial distribution of reflection amplitudes between specific depths across the area.

In Fig. 4, several maps at different depths down to about 16 m are shown. In these maps, the distribution of the relative intensity of reflection is shown by the color representation. The map at the depth 0–1.85 m shows a distinct reflection as a whole, which is caused by the reflection from the surface snow.

Small circles drawn in each map show a strong reflection region. The region corresponds to the vertical hole J which has been studied (Yoshida *et al.*, 1983; Iida *et al.*, 1990) to ascertain the internal structure of the snow patch.

The map at the depth 5.54 to 7.38 m corresponds to the unconformity layer. In this map, strong reflection regions are widely visible. The strong reflection region such as in the left lower (southwestern) side in the map suggests a concentration of gravel at the unconformity. This seems consistent with the profile for line 11 in Fig. 2, where a strong reflection (dark region) is found at a similar position on the unconfor-

mity.

The maps for depth deeper than 7.38 m show an arc shaped pattern of reflection in the eastern area of each map. This is the reflection from the boundary with the end moraine (Fig. 1). The radius of the arc is smaller in the deeper slice maps, which suggests that the snow patch is a bowl-shaped configuration in the studied area.

4. Conclusion

We conducted a GPR survey at the Kuranosuke snow patch, which has a fossil ice zone in the lower part, with its age going back to the Kofun era (*c.a.* 1700 BP). The survey was done in a rectangular area of 50 × 50 m located around the deep part of the snow patch and its vertical holes. The 51 survey lines having a NS strike with 50 m in length were laid out in the area. The GPR profiles show the unconformity between the perennial snow zone and the ice zone at the depth of 5 to 7 m. In the perennial snow zone, a clear reflection layer is identified suggesting a dirt layer formed from concentrated annual layers over several years.

At the bottom of ice zone, a clear reflection shows the boundary with the protalus rampart and the cirque wall. The ice zone has a maximum thickness of about 20 m and five reflection layers are identified within the ice zone, suggesting gravel layers.

The GPR profile for 2004 at the western side in the studied area with 90 m in length was compared with the profiles studied in 1983 by Yamamoto *et al.* (1986) and in 1997 Sakai *et al.* (1999a). The profile in 2004 was surveyed with a 250 MHz antenna (higher frequency than those in the previous studies). Comparison among three profiles shows that the profile for 2004 has a clearer reflection pattern, which suggests that the 250 MHz antenna is more effective for clarifying the internal structure of the Kuranosuke snow patch.

The maximum depth of the snow patch in this study is shallow compared with the depth studied by Yamamoto *et al.* (1986) and in particular, the depth of the perennial snow zone seems to be reduced. The GPR study indicates that the perennial snow patch may have diminished in size in recent years.

The profiles indicate that the unconformity is almost parallel to the surface. The strong reflection region such as in the southwestern side of the studied area suggests a concentration of gravels at the unconformity. This may be formed by falling stones from the cirque wall, and/or transported debris flow. During the accumulation of debris and falling stones, the unconformity may have been exposed as surface.

The maps at depth deeper than 7.38 m show an arc shaped pattern of reflection which may be the boundary with the end moraine. The radius of the arc is smaller in the deeper slice maps, suggesting that the snow patch is the bowl-shape configuration in the

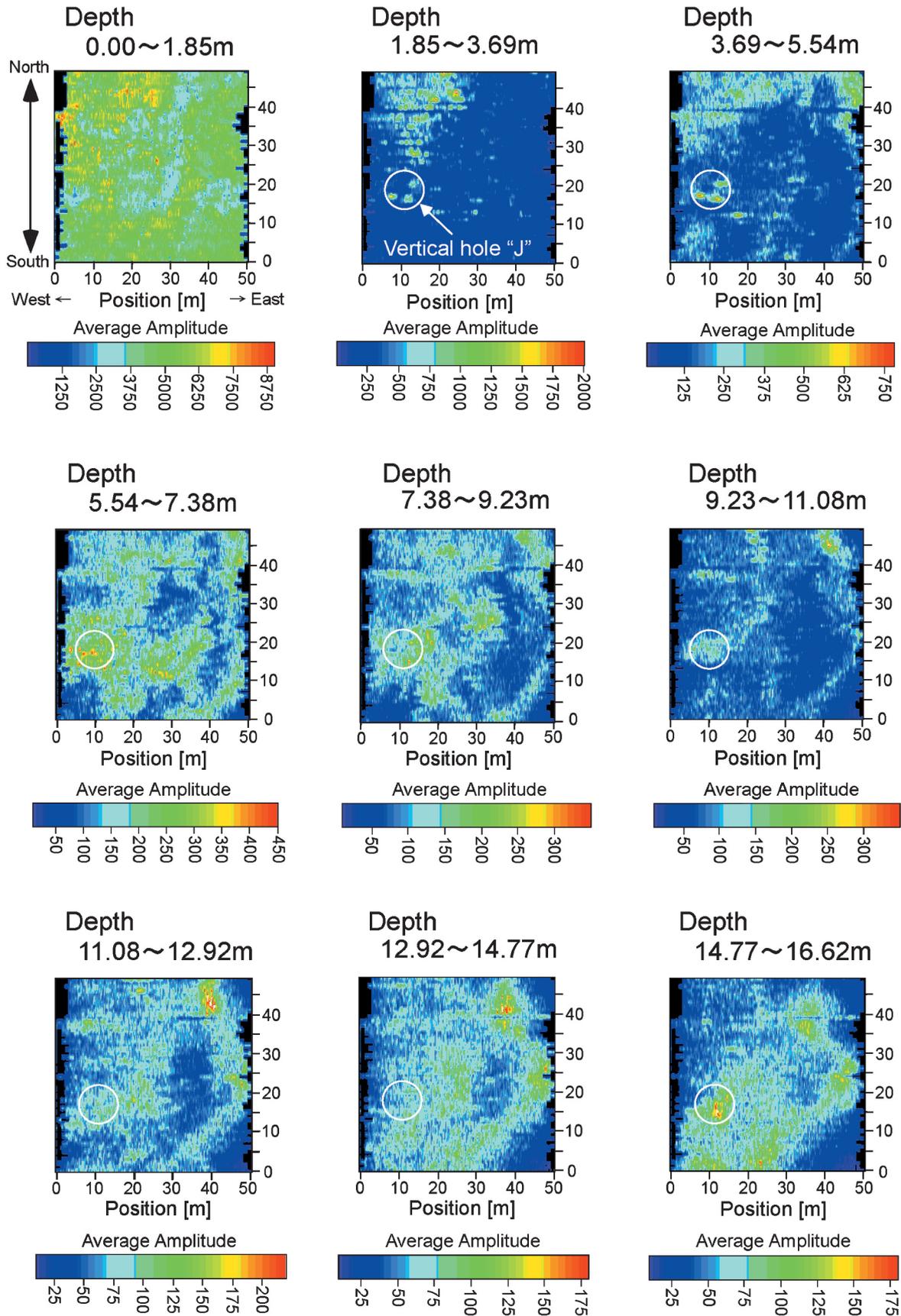


Fig. 4. Horizontal distribution maps of the reflection amplitude (amplitude time-slice maps) analyzed at several depths. The distribution of the relative intensity of reflection is shown by the color representation. Strong reflections are represented by red and weak reflections by dark blue. Small circles show a strong reflection region.

studied area.

Sloping reflections in the ice zone are identified in several profiles. They may be the inclined gravel layers, which were formed under different conditions (*e.g.* by glacier flow) from the present and/or the period when the unconformity was an exposed surface. The distribution and structure of inclined reflections revealed by GPR may be useful for investigating the sedimentary environment and the related paleoclimate.

The Kuranosuke snow patch, which has the oldest fossil ice in Japan, is important for study of the paleoclimate and paleoenvironment of the mountain ranges in Japan. Detailed continuous investigations are necessary and GPR may contribute to these studies.

Acknowledgments

We are grateful for constructive comments by Professor Yutaka Ageta and Dr. Nozomu Naito on this paper. This research was supported with funds from the "Discovering Toyama Prefecture's Snow Packs Project," Toyama Prefecture.

References

- Conyers, L.B. and Goodman, D. (1997): Ground-penetrating radar, Altamira press, California, 232 pp.
- Iida, H., Takenaka, S., Ageta, Y. and Fushimi, H. (1990): Internal structure of ice body of Kuranosuke snow patch in the Northern Japanese Alps (in Japanese), in Studies on the structure and formation of the oldest fossil ice body in Japan, Summary report of research project by Grant-in Aid for Scientific Research from Monbusho, edited by K. Higuchi, 19–30.
- Moldoveanu-Constantinescu, M. and Stewart, R. (2004): 3D ground penetrating radar surveys on a frozen river lagoon, SCEG Recorder, **32**, 34–36.
- Nakamura, T. (1990): The ^{14}C dating with tandemron acceleration system of the plant samples in ice body of Kuranosuke snow patch in the Northern Japanese Alps (in Japanese), in Studies on the structure and formation of the oldest fossil ice body in Japan, Summary report of research project by Grant-in Aid for Scientific Research from Monbusho, edited by K. Higuchi, 31–42.
- Sakai, H., Kawada, K., Tanaka, K. and Iida, H. (1999a): Study on the structure of snow/ice and its water content by the ground penetrating radar system (in Japanese). Cold Region Technology Conference '99, 26–30.
- Sakai, H., Tanaka, K. and Goodman, D. (1999b): Use of ground penetrating radar methods in archaeological and glaciological investigations (in Japanese). Chisitsu News, **537**, 16–23.
- Yamamoto, K., Iida, H., Takahara, H., Yoshida, M. and Hasegawa, H. (1986): Impulse radar sounding in Kuranosuke snow patch, Central Japan (in Japanese). Seppyo (J. Jpn. Soc. Snow and Ice), **48**, 1–9.
- Yamamoto, K. and Yoshida, M. (1987): Impulse radar sounding of fossil ice within the Kuranosuke perennial snow patch, central Japan. Annals of Glaciology, **9**, 218–220.
- Yoshida, M., Fushimi, H., Ikegami, K., Takenaka, S., Takahara, S. and Fujii, Y. (1983): Distribution and shape of the vertical holes formed in a perennial ice body of the Kuranosuke snow patch, central Japan (in Japanese). Seppyo (J. Jpn. Soc. Snow and Ice), **45**, 25–32.