Chinese Journal of Polar Science, Vol. 14, No. 2, 90 - 98, December 2003

Determination of ice thickness, subice topography and ice volume at Glacier No. 1 in Tien Shan, China by ground penetrating radar

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Received March 18, 2003

Abstract We describe a radio-echo sounding (RES) survey for the determination of ice thickness, subglacial topography and ice volume of Glacier No. 1, in Tien Shan, China, using ground-penetrating radar (GPR). Radar data were collected with 100-MHz antennas that were spaced at 4 m with a step size of 8 m. The images produced from radar survey clearly show the continuity of bedrock echoes and the undulation features of the bedrock surface. Radar results show that the maximum ice thickness of Glacier No. 1 is 133 m, the thickness of the east branch of Glacier No. 1 averages at 58.77 m while that of the west branch of Glacier No. 1 averages at 44.84 m. Calculation on ice volume indicates that the ice volume of the east branch of Glacier No. 1 is 51.87×10^6 m^3 and that of the west branch of Glacier No. 1 is 20.21×10^6 m^3. The amplitude of the undulation of the bedrock surface topography revealed by radar profiles is larger than that of the glacier surface topography, indicating that the surface relief does not directly depend on that of the bedrock undulation in Glacier No. 1, in Tien Shan.

Key words radio - echo sounding, ice thickness, ice volumn, subice topography.

1 Introduction

Glacier No. 1 in Tien Shan (43°05′- 43°06′N, 86°48′- 86°49′E) lies on the north slope of Tiangeer Peak in the middle of the Tien Shan mountain of far western China. It is the riverhead of Urumchi River and composed of two separated cirque-valley typed glaciers, namely the east and the west branches of Glacier No. 1. It is one of the glaciers monitored by the World Glacier Monitoring Service (WGMS). Furthermore, understanding this glacier is of great importance for diagnosing future water resources regime in Urumchi River drainage basin.

Ice thickness, subice topography and ice volume are crucial elements for the advance in glaciology (e. g. Paterson 1994; Shi 2000). Ice thickness is an essential input parameter in numerical models of glacier dynamics and it is also an indicator for climate change (e. g. Van Der Ven 1999; Liu *et al.* 1999). The model of glacier recession and thinning (Shi 2001) in response to climate warming in Tibet plateau in recent years clearly suggests the sensitivity of ice thickness to climate change. Subice topography is important both in glaciology and geomorphology. Because subice topography is the result of the interaction between glacier ice and bedrock, understanding the ice-bedrock interface reveals glacial erosion processes and formation mechanisms. In turn, glacier flow is influenced by bedrock topography. Finally, ice volume is a direct indication of glacier water reserves.

The observation and study of Glacier No. 1 has lasted over 40 years since 1959. Determination and analysis of Glacier No. 1's ice thickness, subice topography and ice volumes has been receiving attention all the time, and many advances have been achieved (Zhang *et al.* 1985; Chen *et al.* 1996; Liu *et al.* 1997; Cui *et al.* 1998), Yet, due to limits of measurement techniques and lack of data, research on Glacier No. 1 up to now has been constrained (Liu *et al.* 1986).

During the past decades, with the extensive developments of high-resolution ground penetrating radar (GPR) survey technology (Annan 1999) and advancement of radio-echo sounding in glaciology (Plewes and Hubbard 2001), we have reached a point where we could use radar glaciology methodology to survey Glacier No. 1's thickness, subice topography and ice volumes. In Oct. 2001, we employed GPR to survey Glacier No. 1 in Tien Shan. The results of radar survey for ice thickness, subice topography and ice volumes of Glacier No. 1, in Tien Shan are presented in this paper.

2 Method

The physical basis of radar sounding is as follows: a short electromagnetic pulse is emitted by an transmitting antenna, the pulse penetrates the glacier and is reflected by the interface between ice and bedrock because of a sharp contrast in dielectric properties between ice and rock, and an echo signal returns to the receiving antenna (Bogorodskiy *et al.* 1985). The glacier thickness can be determined by the analysis of the pulse's two-way travel time in the ice (the time of the pulse traveling from the transmitter to reflector and from there to the receiver is called two-way travel time). When radar-sounding equipment is moved over the glacier surface, it enables information about the glacier to be obtained continuously. Due to the low attenuation of radar wave traveling in glacier ice, radar sounding is a powerful tool to measure glacier thickness.

In a radar image, the horizontal axis displays the antenna position in relation to the starting point of the profile; the vertical axis represents a time scale for the radar signal two-way travel time. Radar data can be displayed in a wiggle trace format or a line intensity format. Radar image can visually display ice-bedrock interface and its fluctuations as being represented as a strong reflection amplitude. Given the velocity of propagation in ice, ice thickness can be directly calculated from radar data.

Penetration depth and resolution are basic parameters for radar survey design decisions established by selection of radar antenna frequency and system geometry. In this study, we gave priority to the penetration. Theoretically speaking, electromagnetic wave penetration is determined by the transmitter power, the frequency, the receiver performance and the medium losses (attenuation). These factors dictate specific radar system and survey parameters which encompass the distance between receiver and transmitter, the recording time window, the number of stacks and so on.

We use a new generation pulseEKKO 100A GPR enhanced radar system manufactured by Canada SSI (Sensors & software Inc.). The system has a system performance of 176 dB. The separated transmit and receive antennas make it easy to adjust the distance between transmitter and receiver. Radar data were collected with 100-MHz antennae that were spaced at 4 m with a step size of 4 m. A velocity of 0.169 m ns^{-1} has been calculated from reflection survey data.

In order to obtain data on ice thickness, subice topography and ice volume of Glacier No. 1, we have separately conducted one longitudinal radar survey line and four transverse radar survey lines on both the east and west branches of this glacier. We used survey stakes used in prior mass balance and ice flow observation surveys for positioning control (Fig. 1). We set the longitudinal radar survey line along the main flow line of the glacier. We set the transverse radar survey lines based on knowledge of the glacier surface status, glacier movement and mass balance situation. The DE'-DE' radar survey line lies in the middle of stakes D-row and stakes E-row in the east branch; the rest survey lines are superposed with the corresponding stakes. Some radar survey lines did not reach the edge of the glacier because some conditions such as steep ice surfaces, crevasses and thick snow made the area inaccessible.

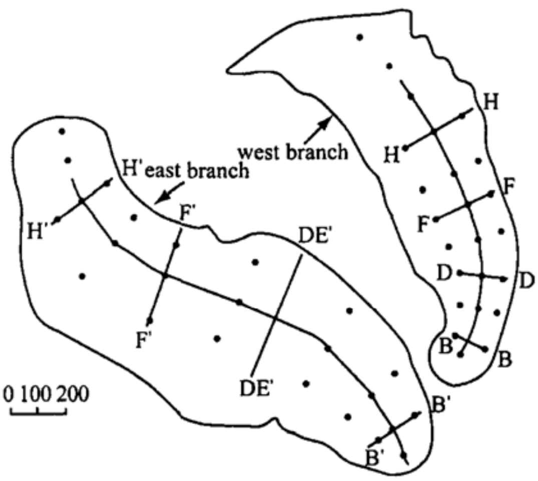

Fig. 1. Location Map of Radar survey lines of Glacier No. 1, in Tien Shan.
Remarks: the dots show the location of mass-balance and ice flow observation stakes.

3 Results

3.1 Ice Thickness along the main flow line

The images obtained from GPR clearly show continuous bedrock echoes and undulations in the bedrock surface. Fig. 2(1) shows the ice thickness variations along the main flow line from the glacier terminus to the firn basin. This figure shows that the ice thickness of east branch along main ice-flow line is thicker than that of west branch along main ice-flow line. The ice thickness data deduced from the radar results show that the ice thickness of east branch along main ice-flow line averages at 85.3 m with a maximum of 133 m at the middle of stakes D-row and E-row. The ice thickness of west branch along main ice-flow line averages at 66.5 m with a maximum of 108 m at the middle of stakes F-row and G.-row.

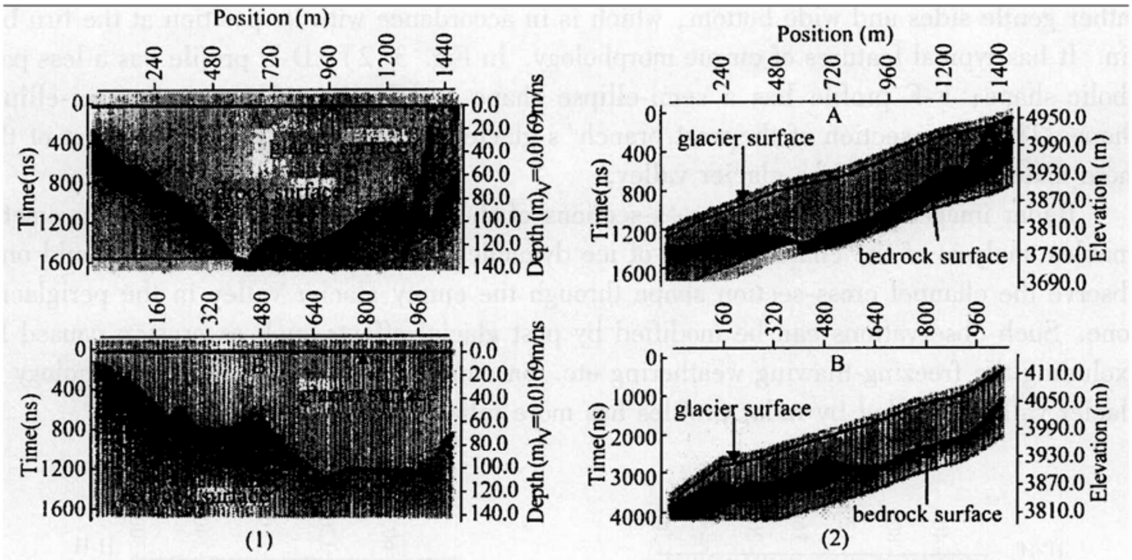

Fig. 2. Radar Results of Glacier No. 1 along the main flow line.
Fig. 2(1) Ice Thickness Distribution of Glacier No. 1 along the main flow line.
Fig. 2(2) Glacier Surface and Bedrock Topography of Glacier No. 1 along the main flow line.

3.2 Longitudinal Morphology of the subice valley along main ice-flow line

Fig. 2(2) is transformed from Fig. 2(1) after radar survey line topography data modification with glacier surface topography data, based on the precise mapping of the glacier surface contour and stake positions. It visually shows the topographic profile features of the glacier and bedrock surfaces along main ice-flow line. The bedrock topography fluctuates more than that of glacier surface and reflects strong glacial erosion processes on bedrock. We find that the bedrock has three cirque basins, which result from differential headward erosion processes with the climate change. This is in agreement with the evolution model of longitudinal glacier valley's upward extension (Cui 1981). This figure also reveals that there is little correlation between glacier surface topography and bedrock topography indicating ice rheology.

3.3 Transverse Morphology of the subice valley

In the four transverse radar profiles respectively made at east and west branches of Glacier No. 1, the two profiles at B-B and B′-B′ are located at glacier snout, the radar profiles don't completely demonstrate the topography the subice valley at this position. Because the Side melting processes resulting in ice margins separating from the valley walls made access impossible, we omit these data in this paper. Fig. 3 shows the remaining radar profiles on the east and west branches.

In Fig. 3(1), DE′-DE′ and F′-F′ profiles show out the parabola-shaped subice valley in the middle area of east branch. The valley has steep sides and a narrow bottom at the area of maximum thickness indicating strong over-deepening glacier erosion. H′-H′ profile shows a semi-ellipse-shaped valley in the upper area of the east branch. The valley has rather gentle sides and wide bottom, which is in accordance with its position at the firn basin. It has typical features of cirque morphology. In Fig. 3(2), D-D profile has a less parabolic shape; F-F profile has a semi-ellipse shape and H-H profile a near semi-ellipse shape. The cross-section of the west branch's glacier valley is not the same as that of the more mature east branch's glacier valley.

Radar images provide clear cross-sections of the glacial valleys. The valley geometry enables analysis of the characteristics of ice dynamics. In the past, researchers could only observe the channel cross-section shape through the empty glacier valley in the periglacial zone. Such observations can be modified by post glacial effects such as erosion caused by excluding the freezing-thawing weathering etc. on empty glacier valley. The morphology of glacier valley revealed by radar profiles has more reliability.

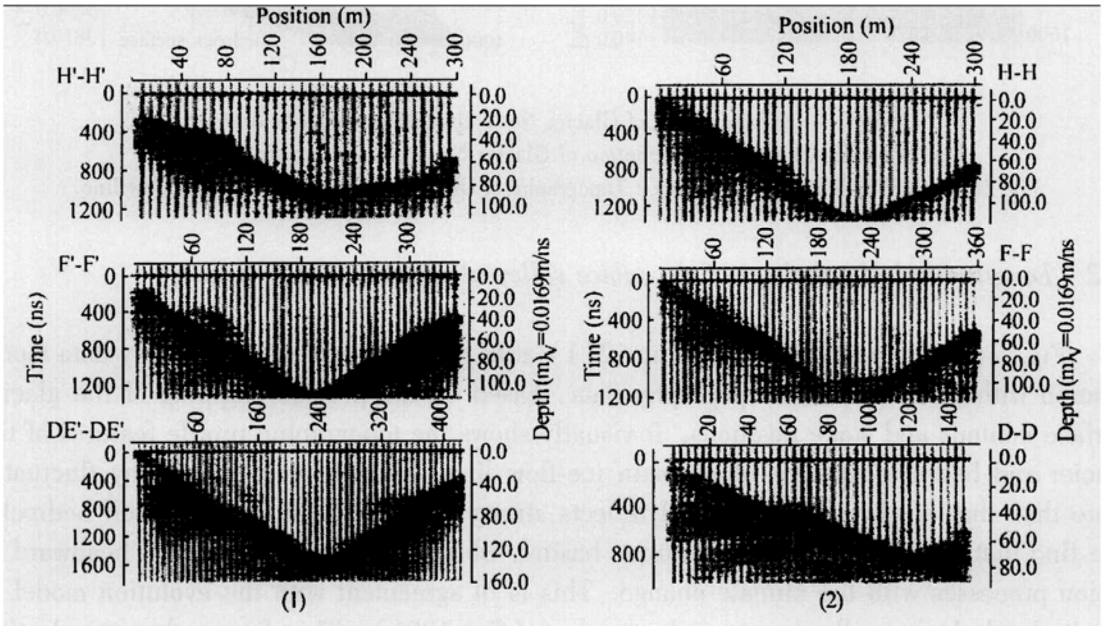

Fig. 3. Radar Results of Transverse Profiles of Glacier No. 1, Tien Shan.
(1) East branch (2) West branch.

3.4 *Ice Thickness Distribution and Ice volume Calculation*

The ice thickness data derived by radar profiles were combined withal other information to map the Glacier No. 1 thickness distribution.

We used Surfer software to create a contour map of the glacier thickness and estimate the glacier volume, Kriging was used to grid the data. Fig. 4 is the contour map of glacier thickness with an interval of 10 meters. We can see from the map that the ice thickness distribution pattern of the two branches of Glacier No. 1 are similar. The thickness is least at both end areas and greatest in the middle area; the thickness increases from both sides to the main flow line, which is in accordance with glacier dynamics. The ice thickness contour map indicates zones or isobaths in the ice thickness. Isobaths indicate three closed areas on the east branch and two areas on the west branch.

In this paper, we exploit the advantage that radar sounding and topography can obtain simultaneously the position data of glacier surface and bottom. By gridding data of the whole glacier area, we can integrate to calculate ice volume. We can also compute the average glacier thickness by averaging the radar data. The glacier average thickness data can be used in quantitative analysis of climatic change. Table 1 is the average ice thickness data derived from radar profiles and ice volume calculation results.

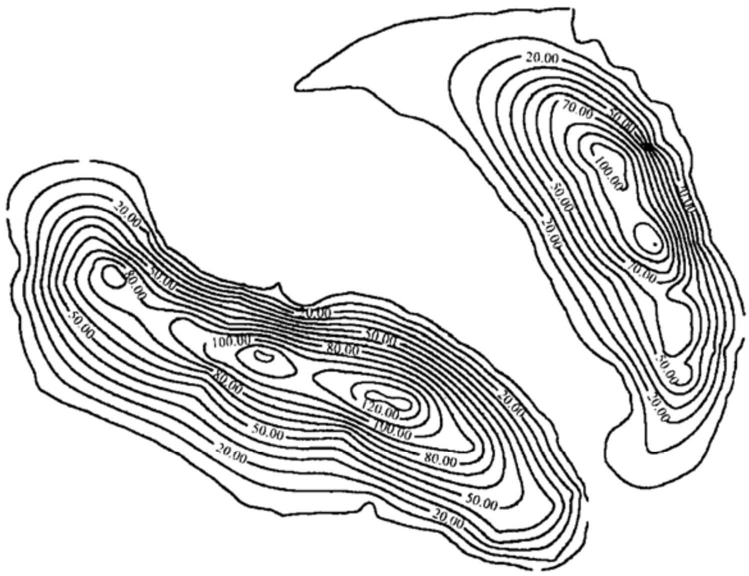

Fig. 4. Map of Glacier No. 1 Ice Thickness.

Table 1. Results of average ice thickness and ice volume calculation of Glacier No. 1

Parameters	East branch	West branch
Average ice thickness (m)	58.77	44.84
Ice volume (m^3)	51.87×10^6	20.21×10^6

From table 1, we can find that the average ice thickness of east branch is 58.77 m, which is The ice volume of east branch is 51.87×10^6 m^3, which is 2.6 times greater than that of west branch. We used the precise glacier mapping carried out in 1994 to determine glacier boundary positions, as this is the most recent map of Glacier No. 1. The values in table 1 may have some error caused by the change of the glacier surface area and its boundary positions since 1994. Considering that the glacier is shrinking slowly and is thin at its margins, the error caused by the changes of the glacier surface area and its boundary positions will be limited.

4 Discussion

The key to using radar to determine glacier thickness and subice topography is the penetrating power in glacial ice and the high resolution capability of imaging the ice-bedrock interface. The results of the current radar survey show that radar can clearly define the ice-bedrock interface and glacier thickness data. As for error analysis in radar thickness determination, it's similar to those in seismic and sonar methods. On the 2-D radar image, the thickness data are derived from vertical axis radar wave two-way travel time, that is to say, ice thickness (h):

$$h = \frac{t_s}{2} \times v$$

Where t_s is radar wave two-way travel time, v is the velocity of radar signal in glacier ice.

The accuracy of radar thickness data is dependent on the accuracy of radar wave travel time and velocity. We set our radar data sampling interval at 0.8 ns, so radar sampling interval error is negligible, for it won't exceed 0.8 ns. As for the value of radar wave velocity in glacier, extensive studies from previous work (Glen and Paren 1975; Drewry *et al.* 1982; Thompson 1992; Nolan *et al.* 1995; Moore *et al.* 1999; Ramirez *et al.* 2001) indicate that radar wave travel velocity in glacier in the range of 0.167 to 0.171 m/ns. In this paper, we set this value at 0.169 m/ns. The above analysis shows that the relative error of our radar thickness (h) can be calculated by this equation:

$$dh/h = dv/2v = 1.2\%$$

The morphological characteristics of subglacial valley reflect both glacial dynamics and boundary conditions such as bedrock lithology and structure. Subice topography has a direct impact on the processes of glacier dynamics. It's one of the basic parameters in glacier numerical modeling research. Glacier No. 1 is frozen to bedrock and the glacier moves mainly in the form of ice deformation (Huang *et al.* 1994). The ice is assumed to behave as a perfectly plastic material. The ice thickness (h) on the main glacial ice-flow line can be reasonably simplified as:

$$\mathrm{h} = \frac{11}{F \times \sin\alpha}$$

where F is morphology parameter of glacier valley cross-sections, α is the slope of glacier surface. This equation shows that ice thickness is decided by the values of F and α. The value of α can be easily calculated on the basic glacier contour map. The value of F reflects the impacts of glacier valley sides on glacier dynamic characteristics. Theoretically, the value of F is in the range of 0.5 to 0.9 and changes according to the geometric morphology of glacial valley cross-sections.

In the past, people could only make simple assumptions on this value, or set this value according to evidence drawn upon periglacial morphology or an empty glacier valley. Postglacial freezing-thawing weathering can make it very difficult to truthfully describe glacier valley cross-sections. However, with radar images we can obtain accurate morphology characteristics of glacier valley cross-sections (Li *et al.* 2001).

The topographically modified radar image of glacier main ice-flow line gives visual information on the undulation of glacier surface and bedrock surface. The undulation shapes of glacier surface and bedrock surface differ from each other, which means that perturbations produced by Glacier No. 1 bedrock undulations are damped out before they reach the surface. Hutter (1983) predicted the undulated wavelengths of the bedrock as three to five times as the glacier thickness must be present to perturb the ice surface topography; the bedrock undulation won't impact the surface topography when its wavelength is too long or too short. Our radar results confirm Hutter's theory, and this shows that Hutter's theory about glacier surface undulation is applicable to Glacier No. 1, in Tien Shan.

The sensitivity of glacier to climate change is mainly reflected by the change of ice thickness and ice volume. The calculation of ice volume is very important to determining water reserves in this largely glacier-dependent arid region in far western China. The conventional ice volume calculation method is of using glacier average thickness values multiplied by glacier acreage is not very accurate. The calculation method used in this paper is more reliable. Furthermore, its application will contribute greatly to studies of glacier changes. If we repeat the radar survey at regular time intervals, the differences between two survey results can accurately indicate glacier mass balance changes. Compared with conventional stake observation and isoline calculation method, radar survey method is more convenient and accurate.

5 Conclusions

As our study shows, the GPR radar survey method works well on alpine glaciers in low latitude, high altitude China. Very clear bedrock echoes were observed in radar images. The images produced from GPR clearly show the continuity of bedrock echoes. The undulation of the bedrock surface, indicates that GPR radar survey provides for fundamental data on glacier thickness, subice topography and ice volumes, which can contribute new knowledge and better understanding of glacier dynamics, glacier fluctuation and climate change, glacial erosion processes as well as providing estimates of glacier water reserves.

Radar results show that the maximum ice thickness of Glacier No. 1 is 133 m, the average thickness of east branch is 58.77 m and that of west branch is 44.84 m. And ice thickness along east branch main ice-flow line of Glacier No. 1 averages at 85.3 m and ice thickness along west branch main ice-flow line of Glacier No. 1 averages at 66.5 m. Based on the map of ice thickness, we know the thickest part of the glacier lies near the main flow line in the central area of the glacier.

Ice volume calculations based on radar data provide support to the studies of glacier fluctuations and estimation of the glacial water reserves. For Glacier No. 1, in Tien Shan, the ice volume of east branch is 51.87×10^6 m^3, which of west branch 20.21×10^6 m^3.

Subglacial topography features revealed by glacier radar images show that bedrock is more undulating than the glacier surface topography, indicating that the amplitude of the bedrock undulation decreases with increasing distance above the bedrock. The surface relief does not vary with that of the bedrock on Glacier No. 1. The morphologies of glacier valley cross-sections differ greatly in different parts of the glacier, which helps us to understand the impacts of glacier valley cross-sections on glacier motion.

Acknowledgments We would like to thank Wu Yunbo and Qian Songlin for their help with the fieldwork. Funding for this work was provided by the National Natural Science Foundation of China (No. 40071022), the Ministry of Science and technology, the People's Republic of China (No. 2001DIA50040), Tien Shan Glacier Station Research Foundation and Laboratory foundation of Ice Core and Cold Region Environment, Cold and Arid Regions Environmental and Engineering Institute, Chinese Academy of Sciences (No. BX2001-04).

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