Estimation of glacier ice thickness using Ground Penetrating Radar in the Himalayan region

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Glacier ice thickness estimation can provide vital information for the estimation of glacier-stored freshwater resources and numerous field-based techniques have been used for this. Determination of ice thickness is a challenging task in mountain glaciers like in the Himalayas, due to harsh climate and rugged terrain conditions. In the present study, Ground Penetrating Radar (GPR) survey was carried out to estimate the ice thickness at Chhota Shigri glacier in Himachal Pradesh, India. This GPR carries a multiple low frequency antenna. GPR surveying was done in discrete mode at 16 MHz frequency with 4 m antenna gap (transmitter and receiver) at 50 cm data-acquisition intervals along the glacier length at bare ice of the ablation zone. The bedrock reflection was distinctly observed in the profiles indicating ice thickness varying from 110 to 150 m with approximately 0.049 km^3 water equivalent for the surveyed area. The results also showed subsurface features like point reflector and a linear non-bed reflection within the ablation ice zone. Total volume of ice and water equivalent of Chhota Shigri glacier was found to be 1.20 and 1.05 km^3 respectively, using area–depth relationship for the Himalayan glaciers.

Keywords: Ablation zone, glaciers, Ground Penetrating Radar, ice thickness.

GLACIER ice presently covers almost 16 million sq. km of the earth's surface, most of which is contained within the Antarctic (13.5 million sq. km) and Greenland (1.74 million sq. km) ice sheets. The remaining 3% or 500,000 sq. km exists as ice caps, ice fields and glaciers located at high altitudes or in mountainous regions of the world[1]. Mountain glaciers possess freshwater resources (in the form of glaciers) which are the source of a perennial supply of water to the rivers originating from snow and glaciated terrains. Himalayan mountains hold the largest concentration of snow and glaciated area outside of the polar region, which is the source of water to the rivers in the Indo-Gangetic plains[2]. This makes the study of snow and glacier terrain vital to us. One of the key issues in Himalayan glaciology is the estimation of glacier ice thickness. This is an important parameter to assess the frozen water reservoirs which depends on geomorphology and areal extent of the glacier. The ice thickness of a glacier may vary from a few metres for small glaciers to a few hundred metres for large glaciers and ice sheets[3]. Change in glacier ice thickness can provide an important input to understand the effect of global warming on the glaciers.

The Fourth Assessment Report published by the Intergovernmental Panel on Climate Change[4] predicts a global warming of 0.2°C per decade for the next two decades, which could lead to thinning of glacier ice. In the past few decades, global climate change has had a significant impact on the high mountain environment[5]. Based on remote sensing observations, the glaciated region has shown an overall deglaciation of about 21% between 1962 and 2007 in the Himalayas[6]. Overall annual specific mass balance was found to be negative for the period 2002–2006 in the Chhota Shigri glacier, however, no specific trend was observed[7]. The glacier in Taram basin has shown overall retreat and shown a loss of 1307 sq. km from 1963 to 1999/2001 corresponding to a loss of ice mass of 87.1 km^3, equivalent to about 6.6% and 3.8% of the area and volume in the early 1960s (ref. 8). Berthier *et al.*[9] have reported a negative mass balance using field and remote sensing data showing rapid ice loss of glaciers in the Spiti/Lahaul region. This loss of ice in areal extent and volume leads to the thinning of the glaciers.

Numerous approaches like seismic, gravitational, electrical resistivity and magnetic methods have been used to estimate the depth of the glaciers in different parts of the world[10–13]. Besides these, Ground Penetrating Radar (GPR) has emerged as a recent technique to estimate the subsurface ice thickness[14], in addition to its role in other subsurface geological studies. GPR is a non-destructive technique which provides fast and accurate results and has been widely used in numerous applications including glaciological studies[15–18]. Radio waves penetrate deeper through the glaciers due to low dielectric constant of ice and gets reflected from the bedrock. A relationship was developed to estimate ice thickness of the Himalayan glaciers with respect to their areal extent[19]. Ice thickness measurements of Dokriani bamak (glacier) in the Himalayan region were carried out with GPR using 12.5 MHz radar frequency[20]. Snout and moraine thickness of the glaciers in Chandra Bhaga basin was estimated using GPR; however it failed to estimate snout thickness (35–40 m) at Samudra Tapu glacier at 50 MHz frequency[21]. Airborne survey has been used to estimate snow thickness and buried objects under the snow in the Himalayan region[22,23]. This study presents the results of the GPR survey for estimating glacier ice thickness of the bare ice ablation zone and subsurface features using 16 MHz frequency in the Himalayan region.

Chhota Shigri is a valley glacier and a part of the Chandra sub-basin in the Chenab basin located in the Lahaul–Spiti valley, Himachal Pradesh. The Lahaul–Spiti

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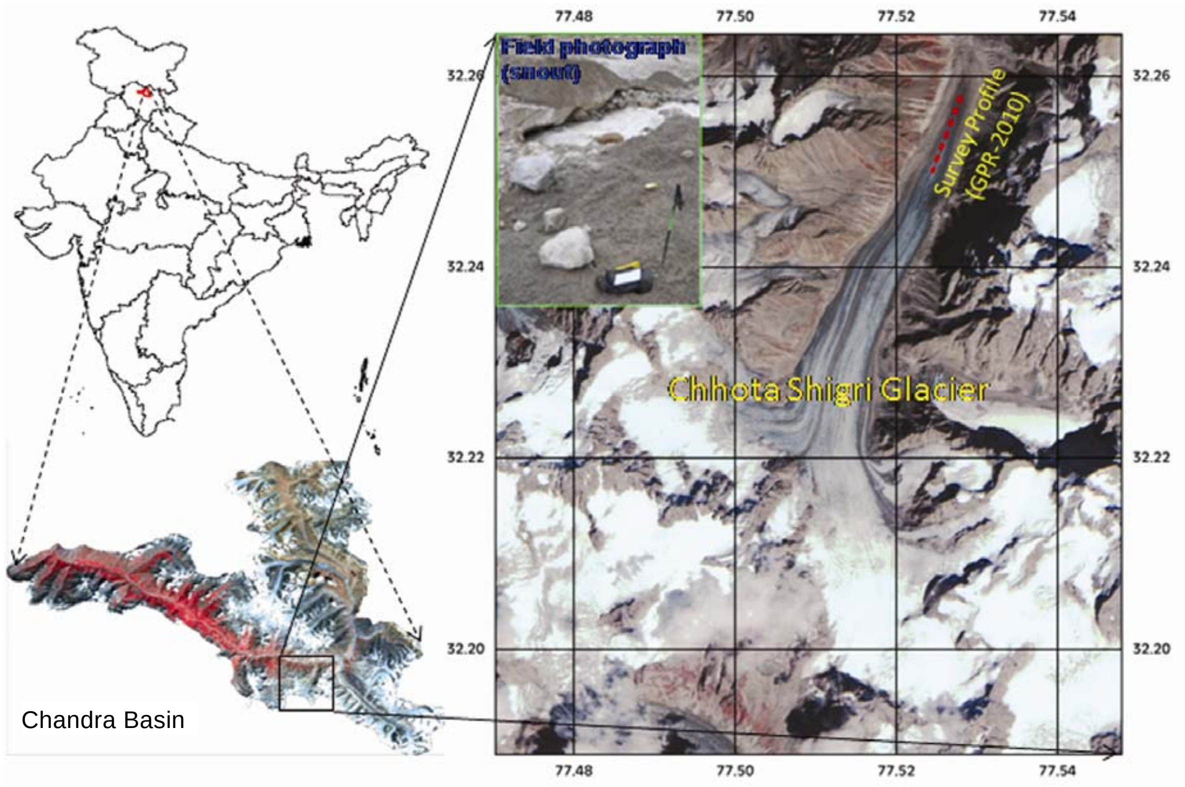

Figure 1. Study area and location of Ground Penetrating Radar (GPR) operation (marked with a red line on the ablation zone) along with field photograph of snout at Chhota Shigri glacier (satellite data: LISS IV FCC, 16 September 2006).

valley is considered to be a cold desert and does not possess any permanent vegetation due to snow and glacier-covered regions. The Chhota Shigri glacier lies within the crystalline axis of the Pir-Panjal range. This crystalline axis is comprised mostly of meso to ketazonal metamorphites, migmatites and gneisses. Figure 1 shows the location of the Chhota Shigri glacier (approximately 77.48–77.53°N and 32.19–32.28°E). GPR operation is marked with a red line on the ablation zone along with the field photograph of the snout. This glacier is oriented roughly NE–SW in its ablation area and has a variety of orientations in the accumulation area. Satellite data of AWiFS sensor for 2007 (10 July, 20 July, 30 July, 4 August, 18 August, 27 August, 1 September, 11 September, 15 September and 5 October) along with LISS IV (16 September 2006) and LISS III (27 August 2001) were used to identify different glacier features and the glacier boundary. Temperature variation between the maximum and minimum at the equilibrium line (4600 m) was found to be 10.5°C to –5.2°C, whereas near the snout a maximum temperature of 16°C and a minimum of 4°C have been recorded[24].

A field expedition was organized during 26 August–7 September 2010 using the Geophysical Survey System Inc. (GSSI) GPR system with SIR-3000 control unit and multiple low frequency (MLF) antenna. A 16 MHz frequency was used for the GPR survey during this field study. The SIR-3000 is a lightweight, portable, single-channel GPR system. It runs on intuitive and user-friendly DAQ GUI, and the radar parameters were set up in the field using the control unit of the GPR.

GPR of low-frequency antenna (16 MHz) of GSSI was used to estimate the ice thickness of the glacier in point mode. A field photograph and schematic diagram of the GPR layout is shown in Figure 2. The transmitter and receiver of GPR antenna extend an arm of 6 m each and connected with the control unit. The GPR survey parameters (like dielectric constant, scan, frequency, scan/unit, etc.) were set in the field using SIR 3000, as shown in Table 1. The distance between the transmitter and the receiver was fixed at 4 m interval while the step increase along the measurement line was 50 cm. A signal was triggered through the transmitter; data collection was confirmed through a beep at the control unit. A 50 cm step-wise movement of the antenna was carried out and the same process was repeated throughout the survey. The data were collected along the bare ice ablation zone during 0900–1600 h in September as the glacier ice was completely exposed. Four profiles were measured with a length of approximately 400 m, excluding profile 2. This profile was discarded during the operation due to poor signal. Figure 3 shows the operation of the GRP survey using MLF frequency. Figure 4 shows the raw field data and trace window (O scope) at Chhota Shigri glacier. The field data were collected along with three transect lines along the glacier. The weather was bad during the fourth profiling exercise and data could not be collected further. These data are raw and require other processing steps to improve and refine the collected observations. RADAN 6.5 software was used to open and process the GPR data[25]. This software has been developed by GSSI to display, edit, process and to generate output after advanced processing of the dataset.

Figure 5 shows the processing steps of the GPR data. Correct position adjusts the position of the ground surface while rectifying the direct arrival of signal passing through air/ground interface. This was done while adjusting time-zero in the ground-coupled bistatic antenna, so that the depth scale starts at the ground surface and not

Figure 3. Operation of the multiple low frequency antenna on the ablation zone of Chhota Shigri glacier.

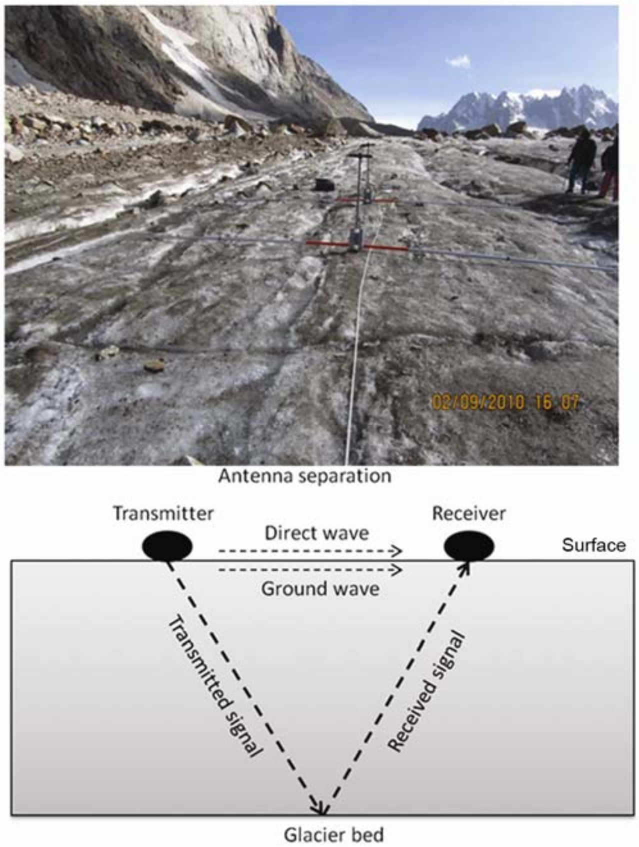

Figure 2. GPR set up on the ablation zone of Chhota Shigri glacier.

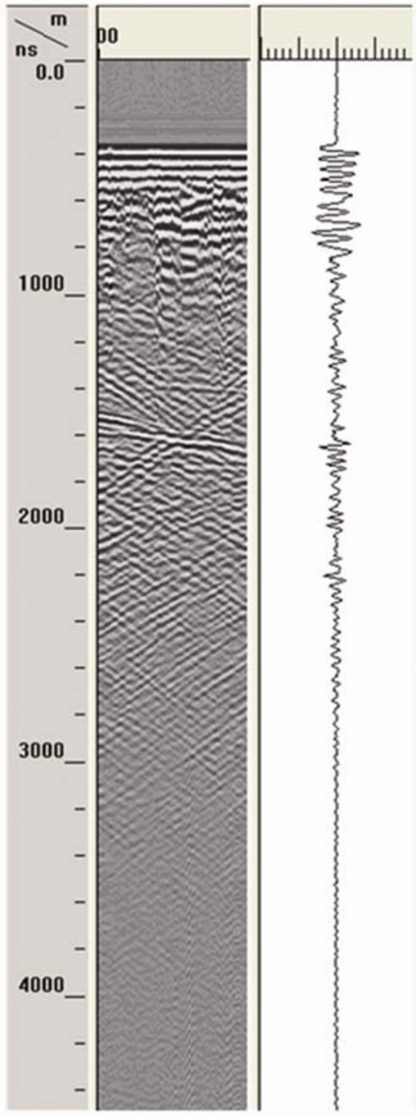

Figure 4. Field data collected through GPR and trace window (Line scan and Wiggle).

Table 1. Ground Penetrating Radar (GPR) parameters used in the survey

GPR input	Parameters
Frequency	16 MHz
Dielectric constant	3.1
Range	4500 ns
Samples/scan	2048
Scan/m	32

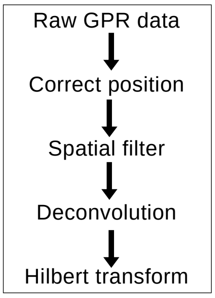

Figure 5. Processing step of the collected GPR data.

several nanoseconds before. One has to set the first positive peak of the direct wave to the top of the screen and this can be considered a close approximation of the ground surface. Spatial filtering (F–K filters) generates a two-dimensional matrix of phase and amplitude of various spatial waves and allows the user to develop a two-dimensional filter to attenuate the noise. Performing the inverse Fourier transformation of the product matrix from the transformed data and the filter yields data with reduced noise. The advantage of F–K filtering over successive vertical and horizontal one-dimensional frequency filtering is that it enables a better distinction to be made between the signal and the noise. The 2D filter is defined by four parameters: Radius, dRadius, Alpha and Delta Alpha (dAlpha). Deconvolution is the filtering method used to remove multiples or 'ringing' effect when the radar signal bounces back and forth between an object and the antenna, causing repetitive reflection patterns throughout the data and obscuring information at lower depths. RADAN uses a method called predictive deconvolution. Hilbert transform is used to display subtle properties of the earth. The phase information is sometimes more sensitive to important subsurface (dielectric) changes than the amplitude or geometric information. Hilbert transform will decompose a radar signal represented as a time series into its magnitude (via envelope detection), instantaneous phase, or instantaneous frequency components (the derivative of phase). The magnitude display is useful for indicating the raw energy reflected from an object or layer. The radar wavelet itself may not always be a clear indicator of energy levels because it consists of several cycles. The instantaneous frequency indicates how the earth is filtering the radar signal. Figure 6 shows the output after incorporating the processing steps as mentioned in Figure 5.

Similar trend in thickness was assumed for the cross-sectional ablation zone along the surveyed line of the GPR. This area was used to estimate the volume of ice for the surveyed bare-ice ablation zone. Continuous monitoring of the AWiFS sensor in the ablation season of year 2007 was carried out to determine the minimum snow cover data to identify the accumulation and ablation zones. However, the glacier boundary was delineated using LISS IV data (2006) to calculate the accumulation and ablation area in conjunction with LISS III of 2001. The Chhota Shigri glacier is approximately 9 km and covers around 11.95 sq. km total area and 3.1 sq. km accumulation area and ablation area 8.85 sq. km based on LISS IV (16 September 2006) based remote sensing data. Average thickness of the glacier was also estimated using empirical relationship developed for the Himalayan region as given below[19]

$$H = -11.32 + 53.21\,F^{0.3},$$

where H is the mean glacier thickness (m) and F the glacier area (sq. km).

Glacier thickness is an important parameter for various applications and GPR has been developed as a non-destructive technique for subsurface studies. GPR survey depends on many technical/logistic reasons restricting its utilization in the Himalayan region. At the same time, it has a constraint of rough terrain, harsh climate and limited time-window span (preferably ablation period) to conduct the experiment. Frequency of the antenna, dielectric constant of the medium (like snow, ice, debris), range to achieve the required depth, distance between transmitter/antenna for point mode antenna and sampling of observations are crucial for these studies.

GPR survey was carried out using a low-frequency antenna (16 MHz) of GSSI in the ablation zone of the Chhota Shigri glacier. The radio waves can penetrate through ice to interact with the bedrock and retrieve the depth information. Total profiling of the GPR survey was approximately 400 m along the glacier. Figure 6 shows the O-scope (raw data) of the survey. The processing steps (Figure 5) were used to remove the noise and improve the data information to estimate the thickness of ice. Figure 6 also shows the processed data depicting different glacier subsurface features. Any change in the dielectric constant within the subsurface medium shows a change in reflection (Figure 6 *b*). This continuous change in reflection along the bed, which is due to the change in dielectric constant of ice and rock, shows a small dipping bed signature. This change in reflectivity was used to derive the ice thickness information. GPR profiles have shown the ice thickness as 110, 130 and 150 m respectively. Vertical resolution of measurement was estimated 2.5 m using pulse width of transmitted signal and velocity of EM waves in glacier ice. An average depth of 130 m using GPR showed the volume of ice to be approximately 0.0572 km^3 (water equivalent 0.049 km^3) for the surveyed ablation zone section in the Chhota Shigri glacier.

Non-bed reflection may occur due to the entrained debris layer along a shear plane. A review has suggested that ice-density variations, ice crystallographic anisotropy and chemical variability may also cause internal reflections[26]. Another study suggested that during an ablation season, scattering of EM pulses can result from enhanced

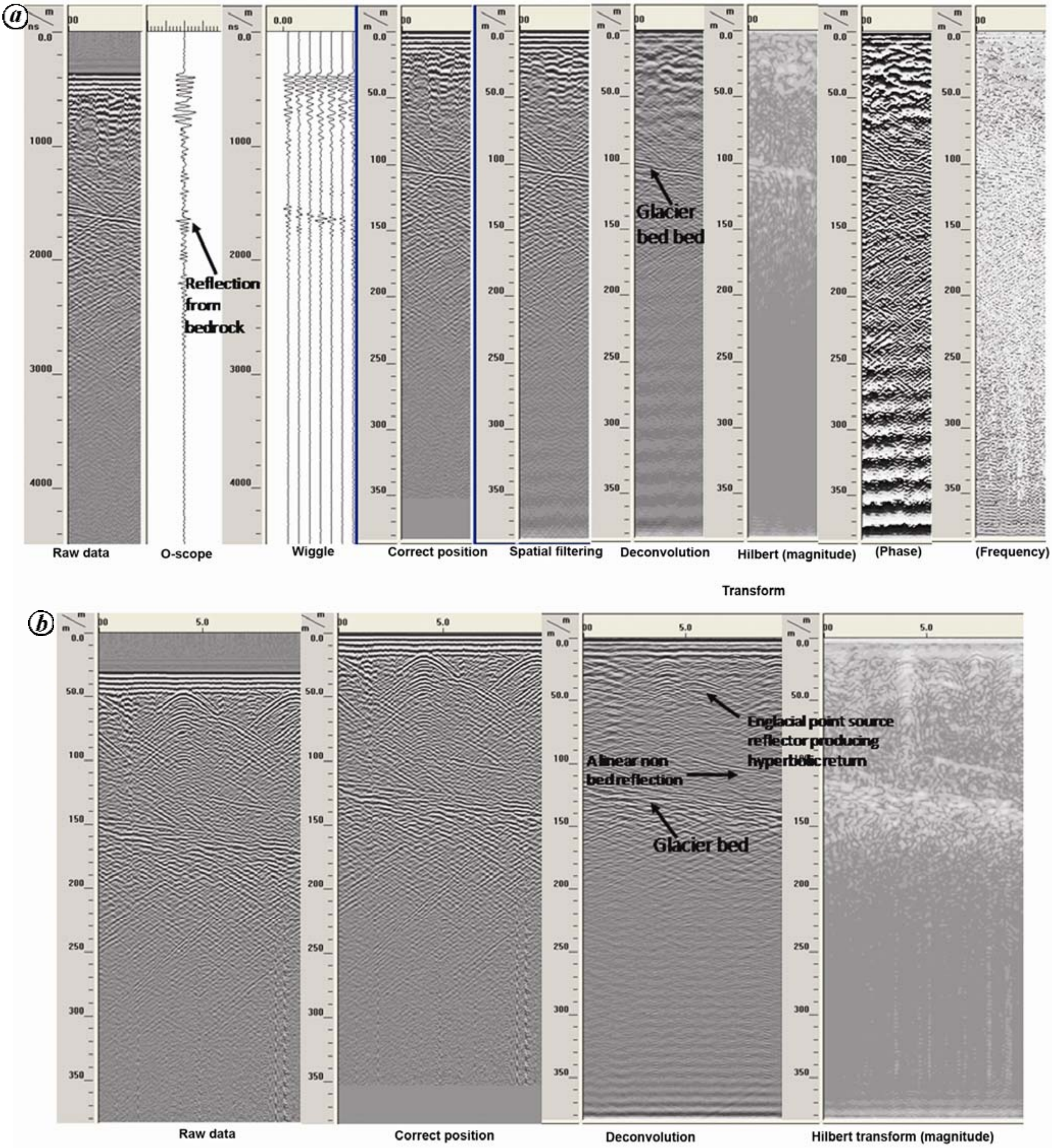

Figure 6. GPR-processed data over Chhota Shigri glacier. (***a***) Profile 1 and (***b***) Profile 3.

melting and/or refreezing leading to englacial heterogeneities[27]. Hyperbola shape represents the englacial object signature due to the presence of a point source of different dielectric permittivity like a rock (Figure 6 *b*). A non-bed reflector is present in profile 3. There is one vertical discontinuity (possibly structure) percolating water down below which leads to englacial heterogeneity due to melting/freezing of ice behaving as different dielectric material. Change in magnitude (Hilbert transform) clearly shows the presence of subsurface discontinuity; however, phase and frequency (Hilbert transform) could not pick up any such variability. Area–depth relationship was used to estimate the thickness of the glacier (~101 m) using the relationship of Chaohai and Sharma[19]. Total volume of ice and water equivalent of the Chhota Shigri glacier was found to be 1.20 and 1.05 km^3 respectively.

GPR is a non-destructive technique which has shown the potential to estimate ice thickness and identify englacial subsurface features in the Chhota Shigri glacier. A low-frequency antenna (16 MHz) was used in the present study and the survey has shown that the glacier thickness changed from 110 to 150 m across the 400 m profile length, as we move towards the equilibrium line. The presence of point reflector (hyperbola signature) and non-bed reflector (due to englacial heterogeneities) could be helpful to understand the subsurface glacier phenomenon. An average depth of 130 m of the surveyed ablation area showed a volume of 0.0572 km^3 (water equivalent 0.049 km^3). This study presents the application of GPR for ice thickness estimation and identification of subsurface features of the Himalayan glaciers. However, one has to take into account the various crucial parameters required for GPR survey especially in the Himalayan region.

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