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GPR Surveying in the kernel area of Grove Mountains, Antarctica

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Abstract The Grove Mountains, located between the Zhongshan Station and Dome A, are a very important area in inland Antarctic research. China has organized five investigations of the Grove Mountains, encompassing the geological structure, ancient climate, meteorites, ice-movement monitoring, basic mapping, meteorological observations, and other multi-disciplinary observational studies. During the 26th Chinese National Antarctic Research Expedition in 2010, the Grove Mountains investigation team applied specialized ground-penetrating radar (GPR) to survey subglacial topography in the eastern kernel area of the Grove Mountains. In this paper, we processed GPS and GPR data gathered in the field and drew, for the first time, two subglacial topographic maps of the Grove Mountains kernel area using professional graphics software. The preliminary results reveal the mystery of the nunatak landform of this area, give an exploratory sense of the real bedrock landforms, and indicate a possible sedimentary basin under the Pliocene epoch fossil ice in the Grove Mountains area. Additionally, it has been proven from cross-sectional analysis between Mount Harding and the Zakharoff ridge that the box-valley shape between two nunataks has already matured.

Keywords **Grove Mountains, GPR, subglacial topography, surveying**

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1 Introduction

The Grove Mountains area is a bare horn mountain area located in Princess Elizabeth Land of the East Antarctica. Its area is about 8 000 square kilometers, which includes 64 separate nunataks. The geographical location is confined within 72°20′–73°10′S and 73°50′–75°40′E, which is approximately 400 km to the Chinese Antarctic Zhongshan Station[1]. The Grove Mountains area is not only on the expedition route that must be traversed when traveling from Zhongshan Station to Kunlun Station or Dome A, but also an important research region that has been investigated by the Chinese National Antarctic Research Expedition, including research on its geological structure, environment, blue ice, and meteorites[2-6]. The Grove Mountains are full of ice cracks causing complex terrain, which is hazardous to people and vehicles working in the area. The position of Grove Mountains is alternative locations under consideration by China for establishing research stations. which gives added significance to the importance of surveying and mapping the area[7]. China has organized four investigations, including surveying, and geological and glaciological analyses, and has collected 110 square kilometers of topographical data on the kernel of the Grove Mountains, together with satellite imagery, digital elevation models, and information on the distribution of blue ice using various resolution optical and SAR images[8-12]. Preliminary research on ice cracks has been performed based on these surveys. However, limited by the terrain, weather, and technology, these initial surveys did not include ground-penetrating radar (GPR). The subglacial topography of the Grove Mountains has been mapped simply as part of the small-scale geographic map of Antarctica in its entirety[13], which means there has been no large-

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scale subglacial topographic map available for the Grove Mountains area before now. Recent research on the geology and paleoenvironment has proven that liquid lakes may exist beneath the ice or ancient glacial sedimentary basins[2]. The lack of relevant subglacial topographic data has affected the understanding of the tectonic origins of the Grove Mountains, which reinforces the imperative of conducting a surveying and mapping campaign in this area.

During the 26th Chinese National Antarctic Research Expedition, the Grove Mountains expedition (2009–2010) used professional GPR equipment to collect sounding data from the kernel area in the east of the Grove Mountains region. This area, between Mount Harding and the Zakharoff Ridge, encompasses an area of 50 square kilometers. Meticulously obtained GPR data were used to map the Grove Mountains kernel subglacial topography for the first time and revealed the landforms underneath the ice of this region. This has significance for further studies on the basement landforms and on the possible existence of a Pliocene ancient sedimentary basin underneath the ice of the entire area. This paper, using the field-measured data and mapped subglacial topography of the kernel area of the Grove Mountains, produces an exploratory analysis of the cross-sectional morphology of the subglacial terrain.

2 Data collection and data processing

2.1 Field data collection

Equipment used in the field data collection included: pulseEKKO PRO GPR (Canada Sense and Software Company, Canada), a smart-v1 integrated GPS receiver (Canada Novatel, Canada), a set of wooden sleds, and snowmobiles. The GPR hosts, receiving antennas, and GPS receivers are placed on the leading sleds and the transmitting antennas are placed on the rear sleds (Figure 1). The frequency of the antenna is 100 and 25 MHz. Given that the ice thickness in the survey area can exceed 1 000 m, the 25-MHz antenna is used for collecting the data. The two sleds are connected by a plastic pipe and held in fixed relative positions. The step size of the sending and receiving antennas is set to 6 m, the surveying overlay count is 8, and the radar wave velocity is set to 0.167 m·ns^{-1}[14]. Considering the antenna step, the formula for the calculation of depth is as follows:

$$D = \frac{1}{2}\sqrt{(V \times T)^2 - X^2}$$

where V is the radar wave velocity, T is the round-trip time of the radar wave, and X is the antenna step.

In January 2010, the expedition team collected field data from Mount Harding, Zakharoff Ridge, and the Gale Escarpment using snowmobiles to pull the wooden sleds. The sample interval (moving step) was 50 m, which produced large amounts of GPR data and GPS points over the course of the survey routes that reached almost 100 km, within the survey area of 50 km^2. The detailed survey routes are shown in Figure 2. For convenience in drawing subglacial topographic maps, the study area was divided into two parts: part 1, located southeast of the Zakharoff Ridge, and part 2, located northwest of the Zakharoff Ridge, as shown in Figure 2.

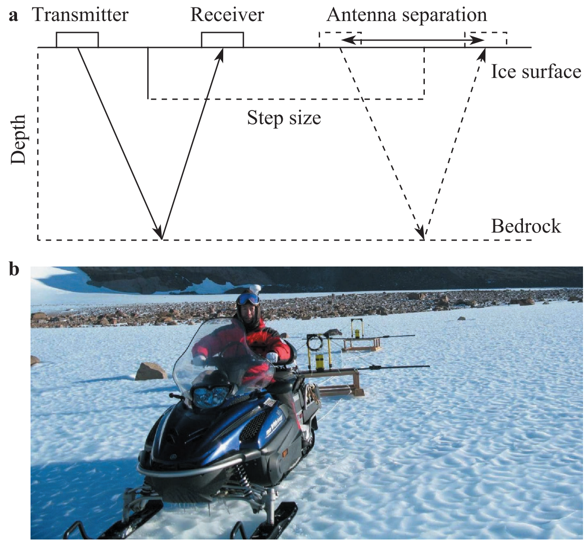


Figure 1 **a,** GPR sounder working schematic; **b,** field survey work.

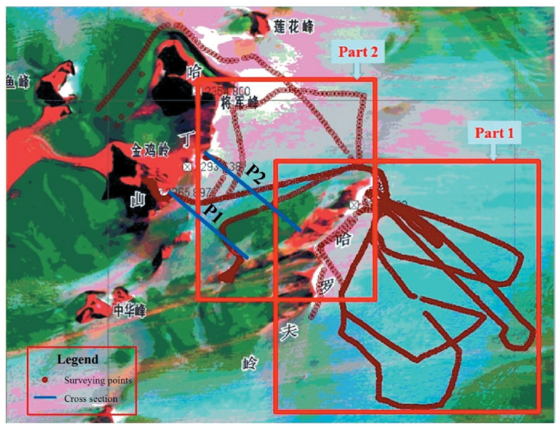


Figure 2 Route of subglacial topographic surveys in the kernel area of the Grove Mountains.

2.2 Field data processing

Longitude, latitude, and elevation data were extracted from the original survey data using our own bespoke software Then, survey points were projected onto a plane using a Gauss Projection, such that 3D coordinates (x_i, y_i, H_i) of the survey points were obtained. x_i, y_i are the horizontal coordinates of the GPS points and H_i is the altitude of the ice surface. GPR data were processed using EKKO software, which is the radar data processing software matched with the pulseEKKO PRO GPR. The process includes basic operations (such as data editing, filtering, and gain-adjustment), advanced operations, and visual representation[15]. After each survey route was processed with the EKKO software, it was possible to obtain clear radar cross-sectional diagrams of the subglacial topography in the

Grove Mountains area (Figure 3). Then, we extracted the depth (D_i) of the survey points and assigned GPS coordinates to each GPR point based on trace numbers using GPRead software, which was developed by the authors of this article based on Visual C++ 6.0. Thus, we obtained the subglacial altitude (E_i) of each survey point with the ice surface altitude (H_i) of each survey point reducing its depth (D_i).

The operating principle behind the GPS survey was point positioning with filtering, the accuracy of which is about 3–5 m. When surveying with the ice radar, we used the 25-MHz antenna, for which the transmitted pulse width is 80 ns. A conservative estimate of the accuracy is 1/10 of the pulse width; therefore, the accuracy is 8 ns, which is less than 1 m when converted to the surveyed ice depth. The established speed of radio waves in ice is between 0.165 and 0.170 m·ns^{-1} and thus we adopted 0.167 m·ns^{-1} as the speed. The maximum survey depth was about 800 m and we adopted a value of 1% as the error; therefore, the depth error caused by the error in the speed of radio waves in ice should be less than 8 m. Consequently, the accuracy of altitude is about 10 m, which illustrates that the survey results can be used for drawing topographic maps with 50-m contour internals.

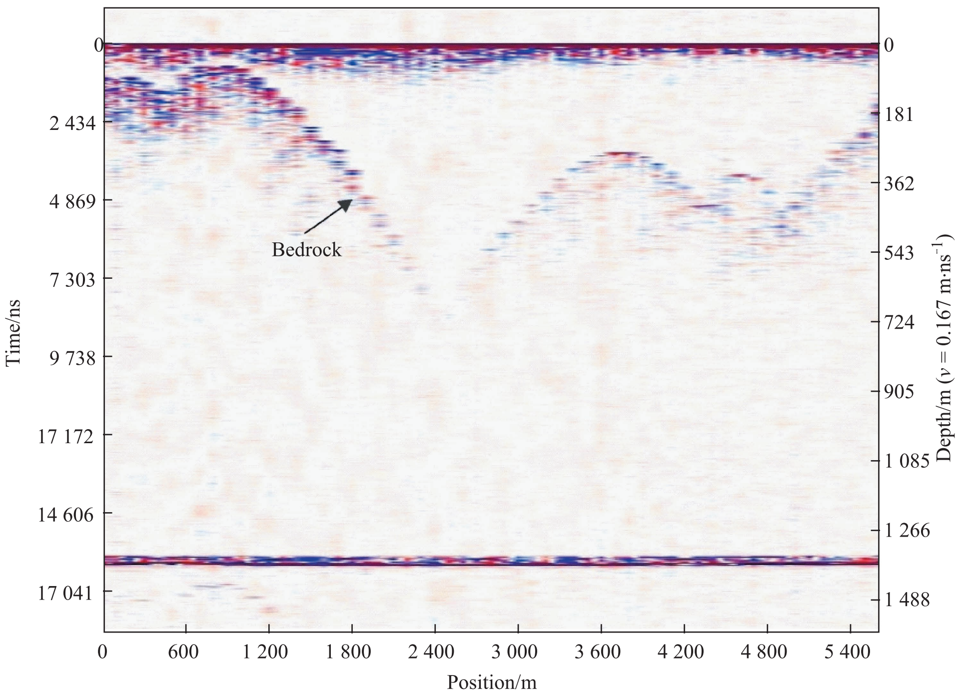


Figure 3 Radar cross-sectional diagram.

2.3 Drawing of subglacial topographic map

Surfer (Golden Software Inc., USA) is the contouring and 3D mapping software that is used widely in many areas, including geography, geophysics, hydrology, archaeology, and oceanography[16]. In this paper, Kriging interpolation within Surfer was used for the spatial interpolation of subglacial elevations within the kernel area of the Grove Mountains, from which regular grid data and contour maps were generated. Based on those, we mapped the 3D surface diagrams in the kernel area of the Grove Mountains, as shown in Figure 4.

Following that, we used CorelDraw X5 to map the 3D surface diagrams of the kernel area of the Grove Mountains. After converting the data formats for subglacial contours, altimetric points, and elevation data collected in the ice rock interface of the Grove Mountains[7], we imported them into CorelDraw X5 and completed the mapping using vector tracking and map borders. When mapping the subglacial topographic maps, we adopted a Gauss-Kruger projection using a WGS-84 coordinate system. The central meridian is

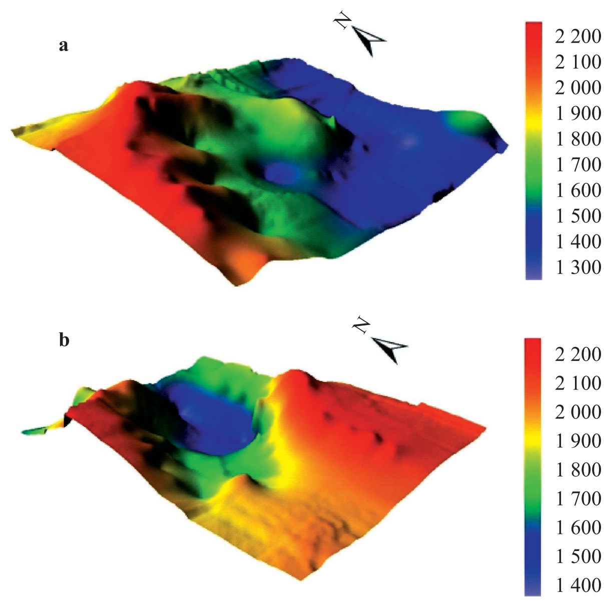


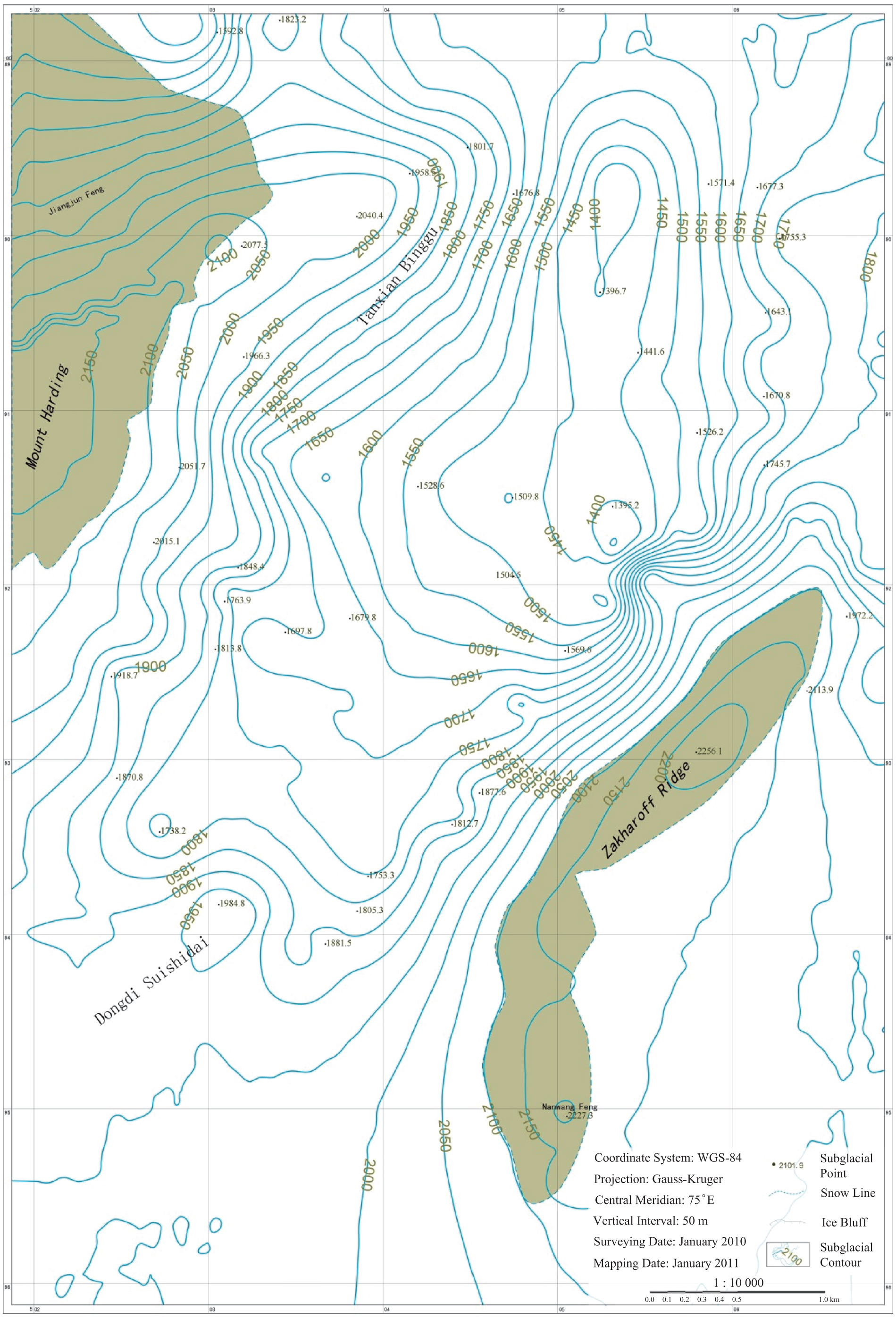
Figure 4 3D surface diagrams in the kernel area of the Grove Mountains: part 1 (**a**), southeast Zakharoff Ridge; part 2 (**b**), northwest Zakharoff Ridge.

75°E, the contour interval is 50 m, and the scale is 1:10 000. Taking the Zakharoff Ridge as the dividing line, we drew the subglacial topographic maps of the areas to the northwest and southeast of the Zakharoff Ridge (Figure 5).

3 Discussion

Following the four comprehensive investigations of the Grove Mountains, we found there had been large-scale ablation before the early Pliocene on the ice sheet of East Antarctica, and the forefront continental glaciers retreated into the Grove Mountains, which is 400 km from the current edge of the ice sheet[17-18]. Thus, it can be inferred that in the past, the Grove Mountains were at the edge of the East Antarctic ice sheet, and that the end of the ice tongue of Dome A would have formed numerous terminal moraine embankments in this region. It is easy to form frontal glacial lakes via the stacking and blocking effects of terminal moraine embankments. However, these glacial lakes were concealed by the subsequent advancing ice,

a Northwest Zakharoff Ridge subglacial topography



b

Southeast Zakharoff Ridge subglacial topography

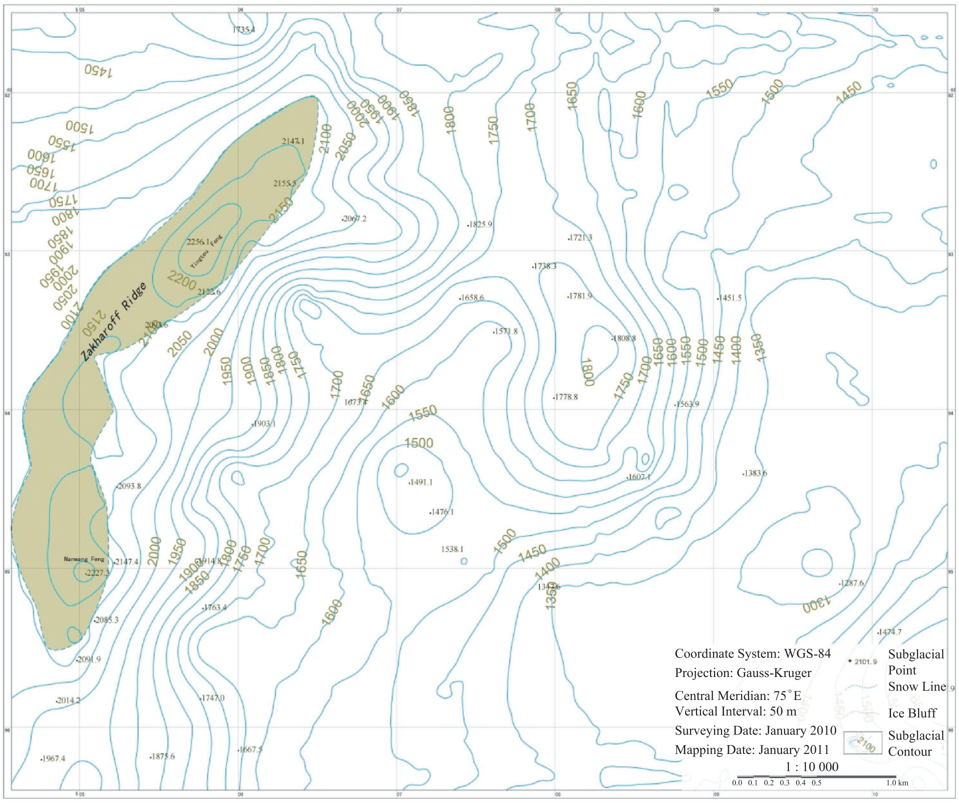


Figure 5 Subglacial topographic mapping in the kernel area of the Grove Mountains: northwest Zakharoff Ridge subglacial topography (**a**), southeast Zakharoff Ridge subglacial topography (**b**).

which has resulted in today's ancient subglacial sedimentary basin (ancient subglacial lake). Although the existence of liquid water cannot be discerned from the radar reflection waveforms from the GPR surveying work performed in the kernel area of the Grove Mountains, it can be seen clearly that there exist many sunken basins within the Grove Mountains' subglacial topography, and that these illustrate that numerous frontal glacier lakes existed in the past.

As the nunataks of the Grove Mountains have a barrier effect on the watershed of Dome A in East Antarctica, the Grove Mountains region has become an equilibrium line between zones of ice accumulation and ablation[2]. Through observations of the mass balance of the ice cap over many years, domestic scholars have established that the material balance line in the Grove Mountains is near Mount Harding. Foreign scholars believe that ice flow is fastest near the mass balance line[19], and remote sensing has revealed that there exist complex ice flows within the Grove Mountains and that the velocity is rapid. Rapid ice flow velocity and lateral ice scraping result in steep cliffs on the mountains on both sides of the ice flow. Through glacial geological and geomorphological observations, it has been found that the surface of the ice sheet of the Grove Mountains had oscillated frequently over time and that previously, the ice was about 100 m above its current position. This is evidenced by the polished surfaces and scratches on the rocks of these steep cliffs above the ice sheet. However, whether the rocks under the ice exhibit the same steepness as those shown by the Grove Mountain nunataks has not been explored previously. In this paper, we used the ice radar data between Mount Harding and the Zakharoff Ridge to generate a qualitative analysis of the valley's cross-sectional morphology between the two nunataks (Figure 6).

Valley morphology can reflect the characteristics of glacial erosion along a glacier, and it has important significance when studying glacier dynamics. Generally, mature valley morphology displays a U-shape, characterized by a wide, deep valley cross section and steep valley walls[20]. Figure 6 shows that the valley cross-sectional morphology between Mount Harding and the Zakharoff Ridge is U-shaped, and Figure 5 shows that the subglacial valley walls are very steep. Thus, we think that the morphology of the valley cross section is very mature.

4 Conclusion

The GPR survey conducted in the kernel area of the Grove Mountains is the first attempt by the Grove Mountains investigation team to obtain subglacial topographic data during the 26th Chinese National Antarctic Research Expedition. In this paper, we use GPS/GPR data gathered in the field to produce two subglacial topographic maps of the

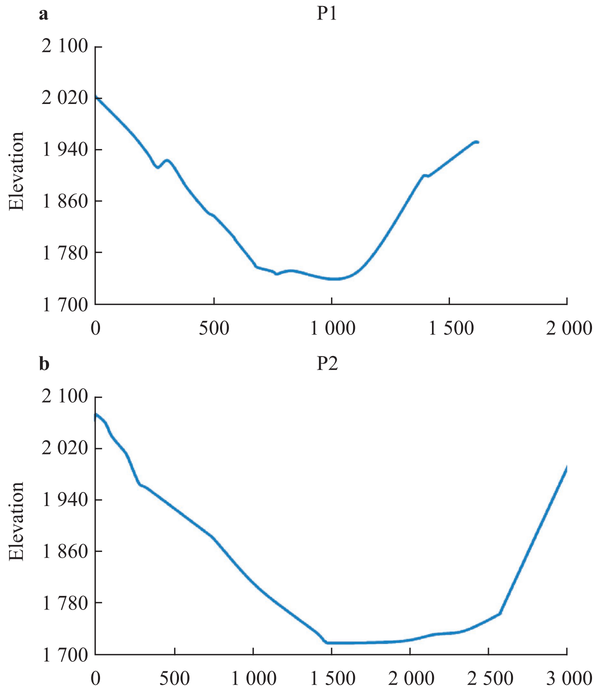


Figure 6 Cross sections between Mount Harding and the Zakharoff Ridge (m).

Grove Mountains kernel area. This is the first time that the topographical features under the ice cap have been revealed, and it represents a pilot study for the future large-scale GPR surveying of this area. From the derived subglacial topographic maps, we find that this region has numerous sunken basins, indicating that in the past, many glacier frontal lakes may have existed. We suggest that the Grove Mountains were once at the edge of East Antarctic Ice Sheet. Furthermore, valley morphological studies between Mount Harding and the Zakharoff Ridge indicate that the valley cross sections have developed a mature U-shape.

Because of severe climatic conditions, dense crevasses, widespread rubble zones, and deeper ice thicknesses, it was difficult for us to undertake the subglacial topographic survey work in the Grove Mountains area. Fortunately, we successfully completed the field survey work, collected precious data, and were able to draw 1:10 000-scale subglacial topographic maps. However, the number of effective measuring points was few, and insufficient to produce large-scale maps and to find liquid lakes. In future, we suggest organizing intensive GPR surveys in the Grove Mountains area to determine the ice characteristics and to establish whether subglacial lakes exist.

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