MEASUREMENT OF DEFLATION OF A DEBRIS-COVERED GLACIER IN OPABIN BASIN, YOHO NATIONAL PARK

ADAMS, Kristyn[1], TENNENT, Christina[2], VALLIS, Vanessa[1], MENOUNOS, Brian[2], OSBORN, Gerald[1] (1) Geoscience, University of Calgary, Calgary, Alberta T2N 1N4, Canada, (2) Geography, University of Northern British Columbia, Prince George, British Columbia V2N 4Z9, Canada.

Introduction:

The Opabin Basin (Fig. 1) in the Lake O'Hara watershed in Yoho National Park is being extensively studied by a team of hydrogeologists and geophysicists from Canada and around the world. These studies are designed to gain an understanding of hydrological responses of alpine basins to climate warming. A large contributor to the basin's runoff is glacially derived, but this hydrologic component is complicated by the large lobe-shaped rock glacier adjacent to the Opabin Glacier (Fig.2). Ice contained in rock glaciers may have two possible configurations: (1) Interstitial ice is ice contained in the pore spaces between the boulders and debris of the rock glacier. This type of ice forms after the debris is deposited, and grain to grain contact is retained within the debris. (2) Rock glaciers can contain a core of pure ice that may be a continuation of clean ice up-valley, but with a cover of rock-fall debris from the valley walls. This type of rock glacier can also be referred to as a "debris-covered glacier".

There is disagreement about the nature of the ice under the surface debris of the Opabin rock glacier. Geophysical analyses of this rock glacier have suggested that there is no pure ice under large areas of this debris, but the rock glacier has been interpreted by geomorphologists to be composed of a pure ice core under a debris cover (i.e., a debris-covered glacier) because in two places melting has resulted in exposures of the interior, and these exposures show a thin layer of debris overlying pure ice.

An independent means of testing the subsurface distribution of ice is to determine if the surface elevation of the rock glacier has decreased over time. A significant lowering, or deflation, of the rock glacier surface would indicate the presence of a pure ice core. This study presents a method of (a) detecting the recent presence of massive ice under a debris cover; (b) roughly quantifying the lowering of the surface of this rock glacier over several decades, and therefore also estimating hydrologic discharge rates from this feature; and (c) illustrating the areal distribution of this deflation.

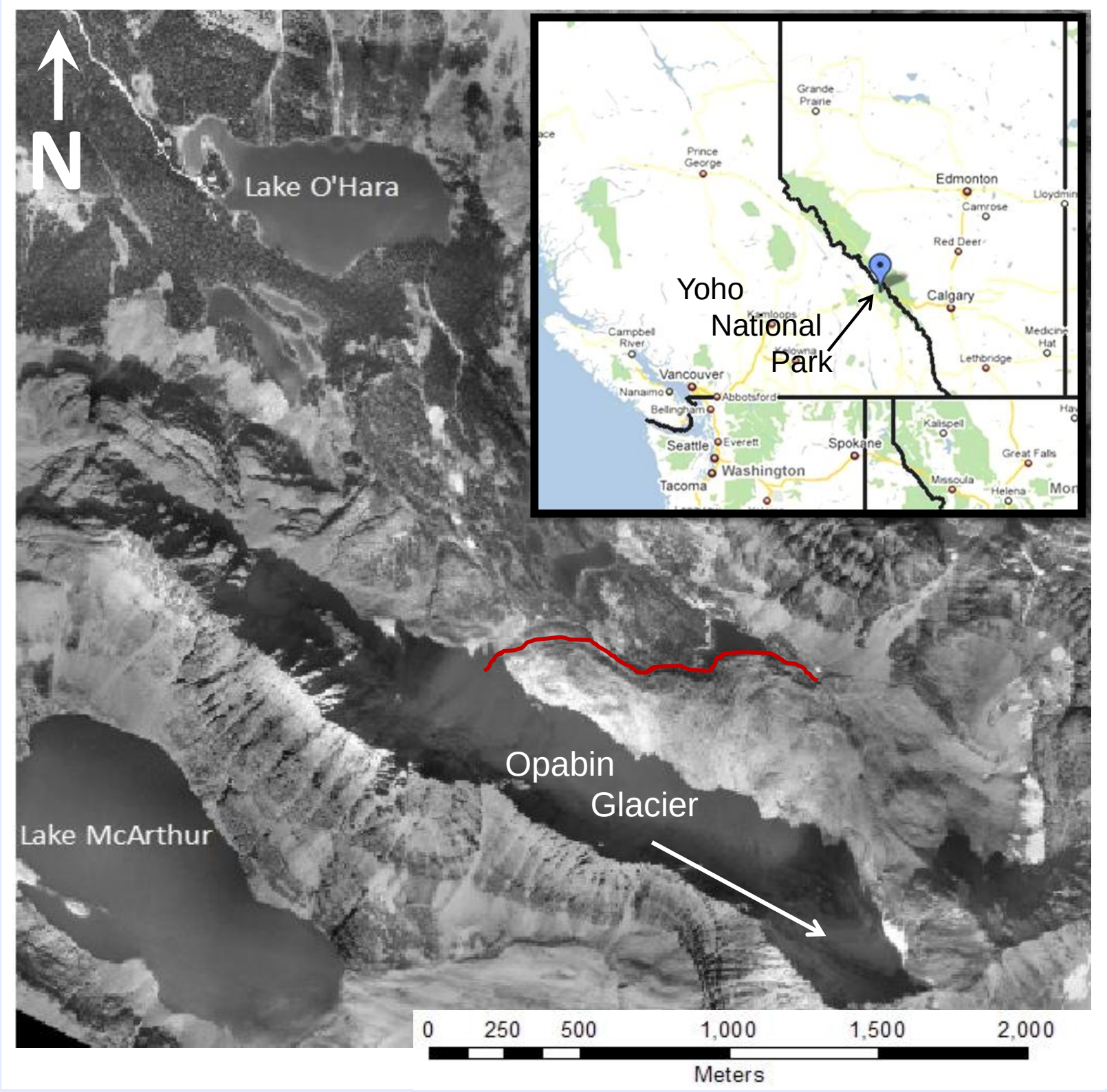

Figure 1: *Opabin Basin in Yoho National Park, showing the locations of Lake McArthur and Lake O'Hara. The extent of the rock glacier is outlined in red slightly north of the Opabin Glacier. Inset is a map that shows the location of Yoho National Park relative to the border between British Columbia and Alberta.*

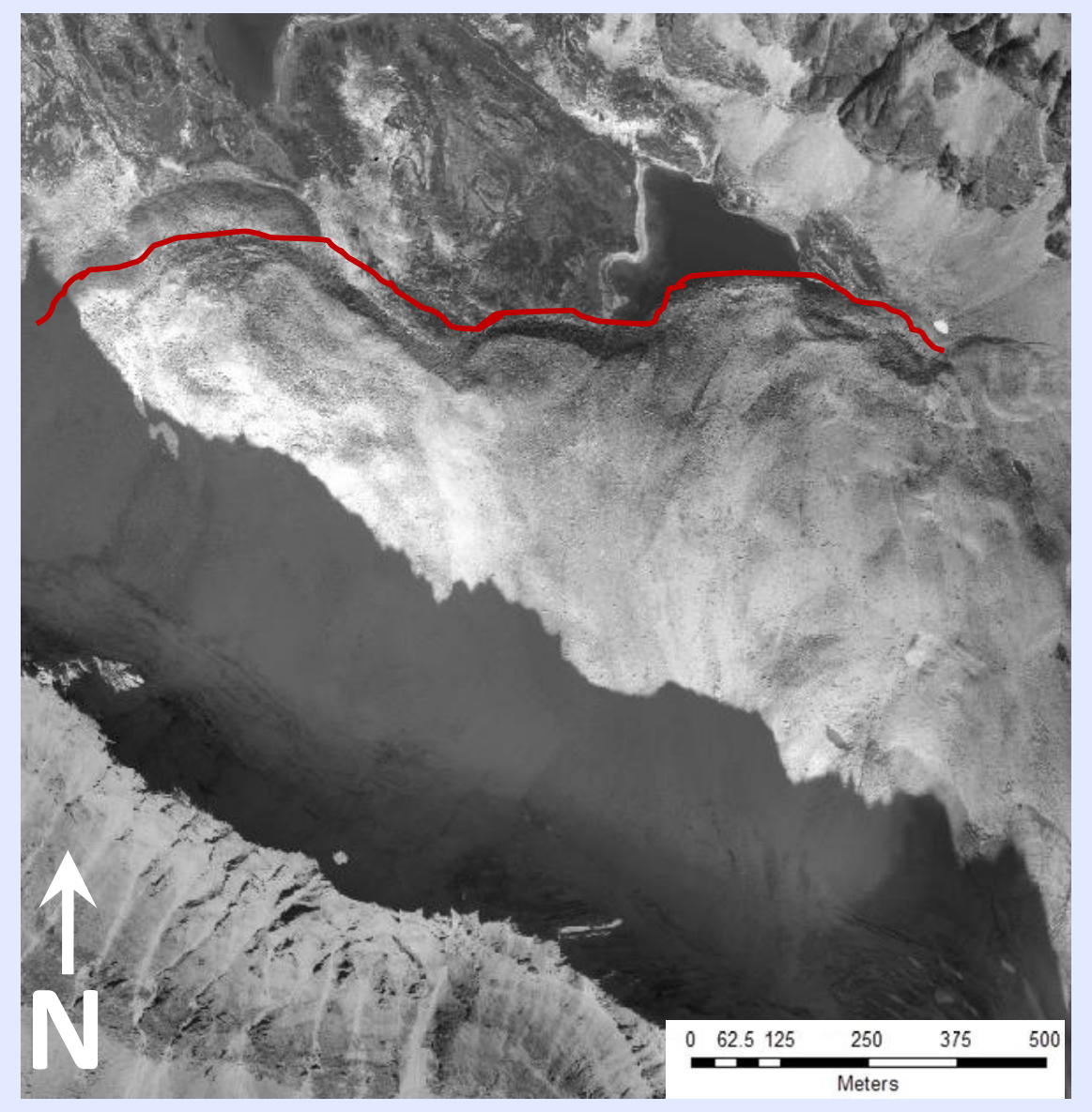

Figure 2: *Rock glacier, located slightly down-valley from the Opabin Glacier. The toe rock glacier is outlined in red.*

Methods:

In this study, photogrammetrically-derived digital elevation models (DEMs) of the rock glacier surfaces in 1962 and 2006 were compared to determine if there has been any lowering of the rock glacier surface. This is the first study in Canada that attempts to monitor a rock glacier with this methodology. Stereo pairs of aerial photographs from 1962 and 2006 were used to generate stereo images and DEMs with the photogrammetric software VRTwo (Cardinal Systems, LLC) and the GIS program ArcGIS. Five identical ground control points (GCPs) were collected from the 1962 and the 2006 air photos, distributed at varying elevations. A statistical test was completed to test the accuracy of the GCPs, specifically root mean square error which is the square root of the variance. Root mean square errors of the GCPs were X=0.692m, Y=0.304m and Z=0.011m, and were always below 1.1m; this is indicative of low error in the GCPs. Elevations of the rock glacier were collected manually for both years using a fixed grid of 10m. The DEM generated from the 2006 airphotos was subtracted from the 1962 DEM to generate a "difference model" that illustrates where deflation has occurred, and roughly quantifying it.

There were some limitations on the coverage of the DEM for the rock glacier surface in both the 1962 and the 2006 models. Although both sets of photographs were taken in the late summer, the 1962 photos had some snow cover that was patchy across the rock glacier surface, and continuous across the surface that is adjacent to the bedrock cliff in the southwest corner. The 2006 photographs have an extensive shadow in that same southwest region next to the bedrock cliff. Elevations could not be determined in areas of snow cover and the shadow because the contrast between pixels was not high enough to illustrate ground level. As a result, the difference model is not continuous over the entire rock glacier surface, and has no coverage next to the bedrock cliff in the southwest corner; the total area of the rock glacier with DEM coverage was 245,000m^2.

Accuracy of the rock glacier DEMs generated was verified by also collecting checkpoints from a stable bedrock surface near the rock glacier on a fixed 25m grid. These points were collected in photos from both years using the same model generated for the rock glacier analysis, and then the 1962 bedrock surface was subtracted from the 2006 bedrock surface to create a bedrock-difference model. This model would have ideally indicated no surface lowering of the bedrock in the 44 years. Deviations from this zero-change scenario provided information about the errors in the model. As can be seen in the difference DEM (Fig. 3), the error in the model appears to be systematic as opposed to random; a gradient from negative elevation change to positive elevation change from SW to NE appears to be present. Using Matlab, the plane of bias was found for the checkpoints (Fig. 4a), and the dataset for both the bedrock and the rock glacier were transformed so that this plane is horizontal (Fig.4b). The plane of bias was found have a strike of 329° and a dip of 0.4°SW. The data from the bias-corrected bedrock difference model was normally distributed about a defined mean of zero (Shapiro-Wilks, n=182, p>0.05), and had elevation changes ranging from -1.6m to 1.7m. This range suggests that there is an inherent error in the model of approximately ±2m.

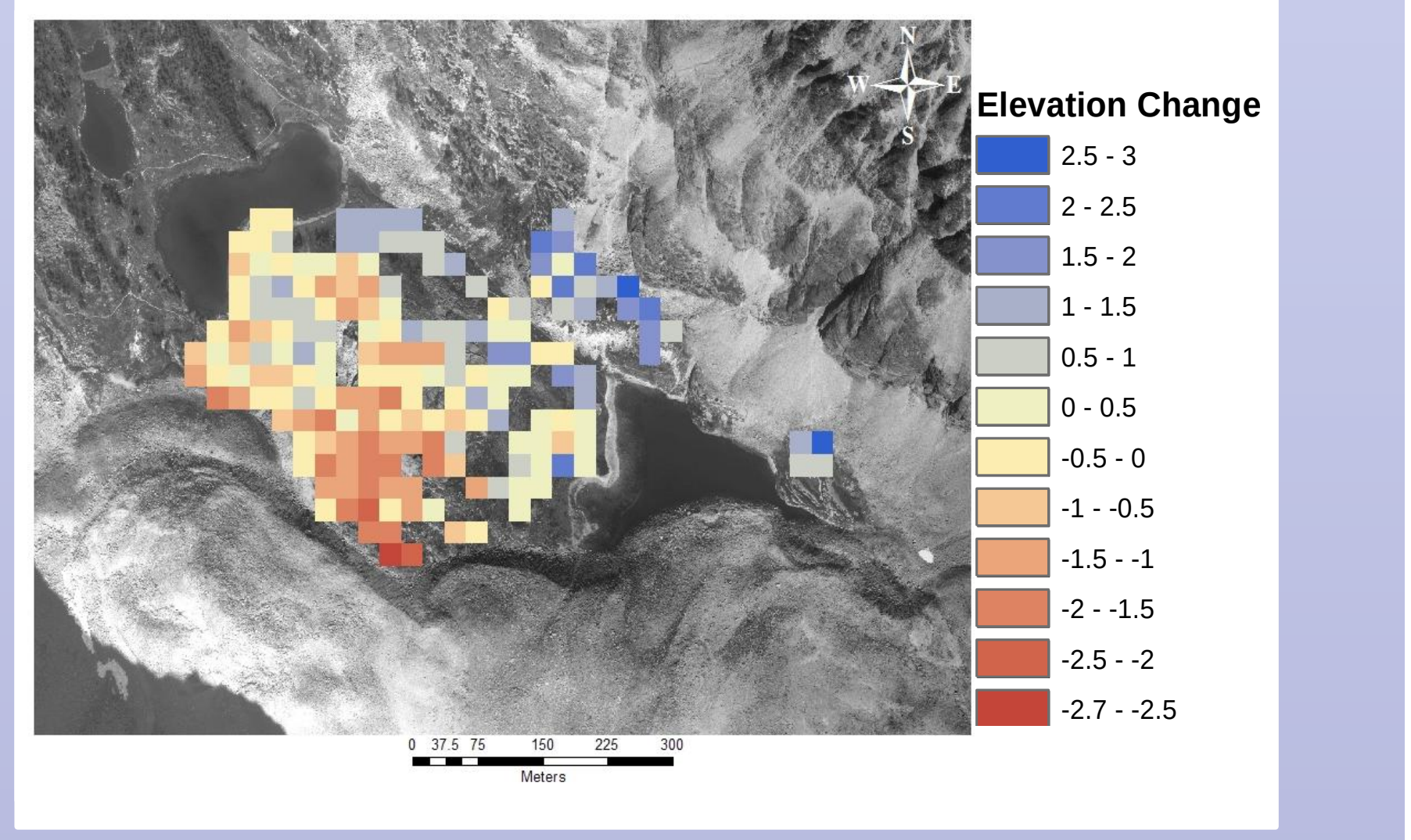

Figure 3: *Bias-corrected difference model for stable bedrock surface generated by subtracting 1962 surface from the 2006 surface. Positive elevation change is shown in blue and negative elevation change is shown in red. This image illustrates the systematic bias present in the data set; negative values in the SW grading to positive values in the NE.*

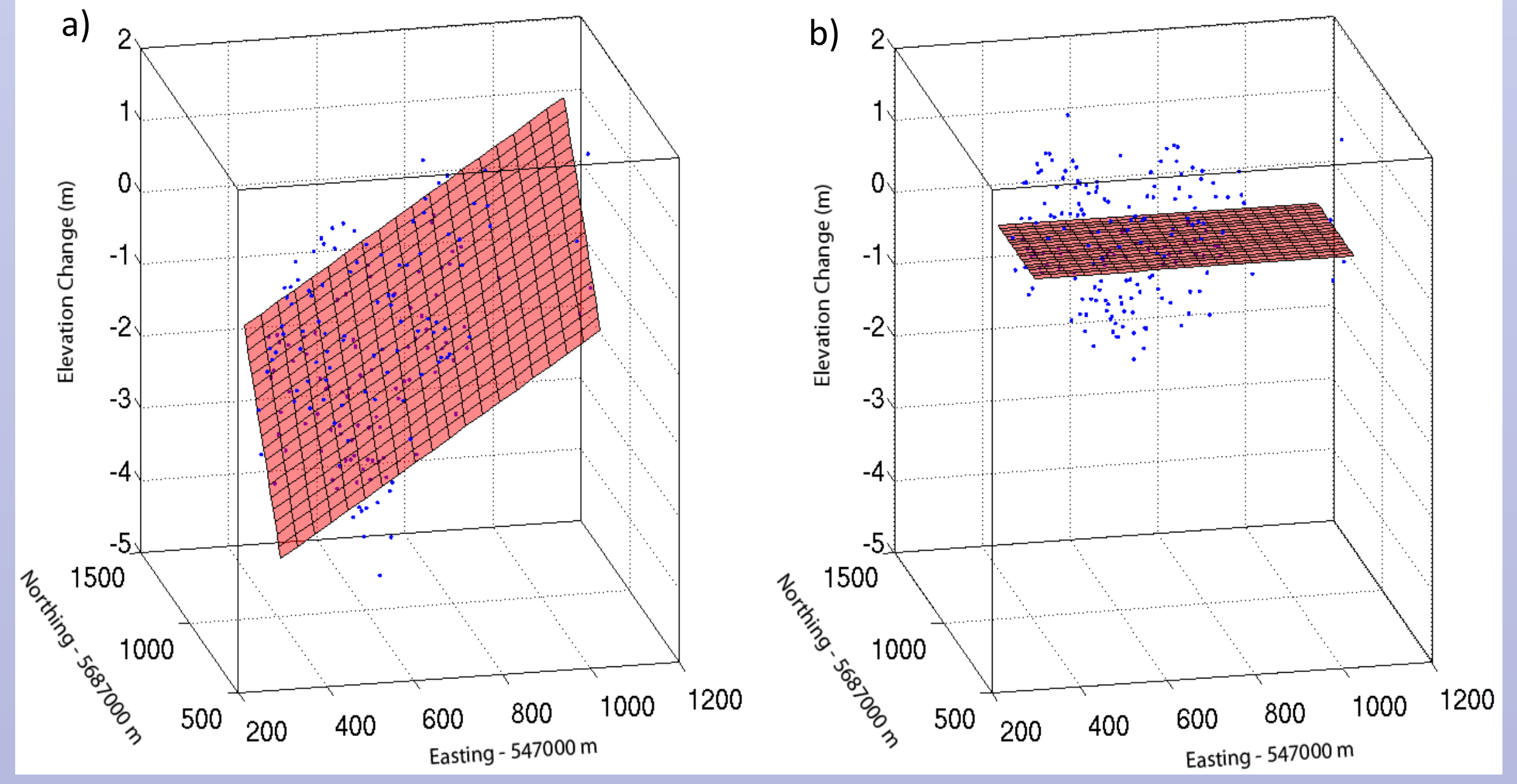

Figure 4: *(a) Bias plane found in bedrock checkpoints, and (b) the transformed data with the plane corrected to horizontal to represent zero elevation change.*

Results:

The difference model (Fig. 5) was generated for the rock glacier by subtracting the 1962 rock glacier surface from the 2006 rock glacier surface, and then correcting for the bias plane found with the checkpoints. Four cross sections were also analysed across the surface of the difference model. The locations of these cross sections are plotted on the difference model, lines A through D (Fig. 5).

The major findings of this experiment were:

- A mean surface deflation of -4.7±3m, which means that the surface lowered by ~5m over the 44 year period
- Elevation change ranged from +5.2m to -38.1m. The distribution of results for elevation change is displayed in Figure 6.

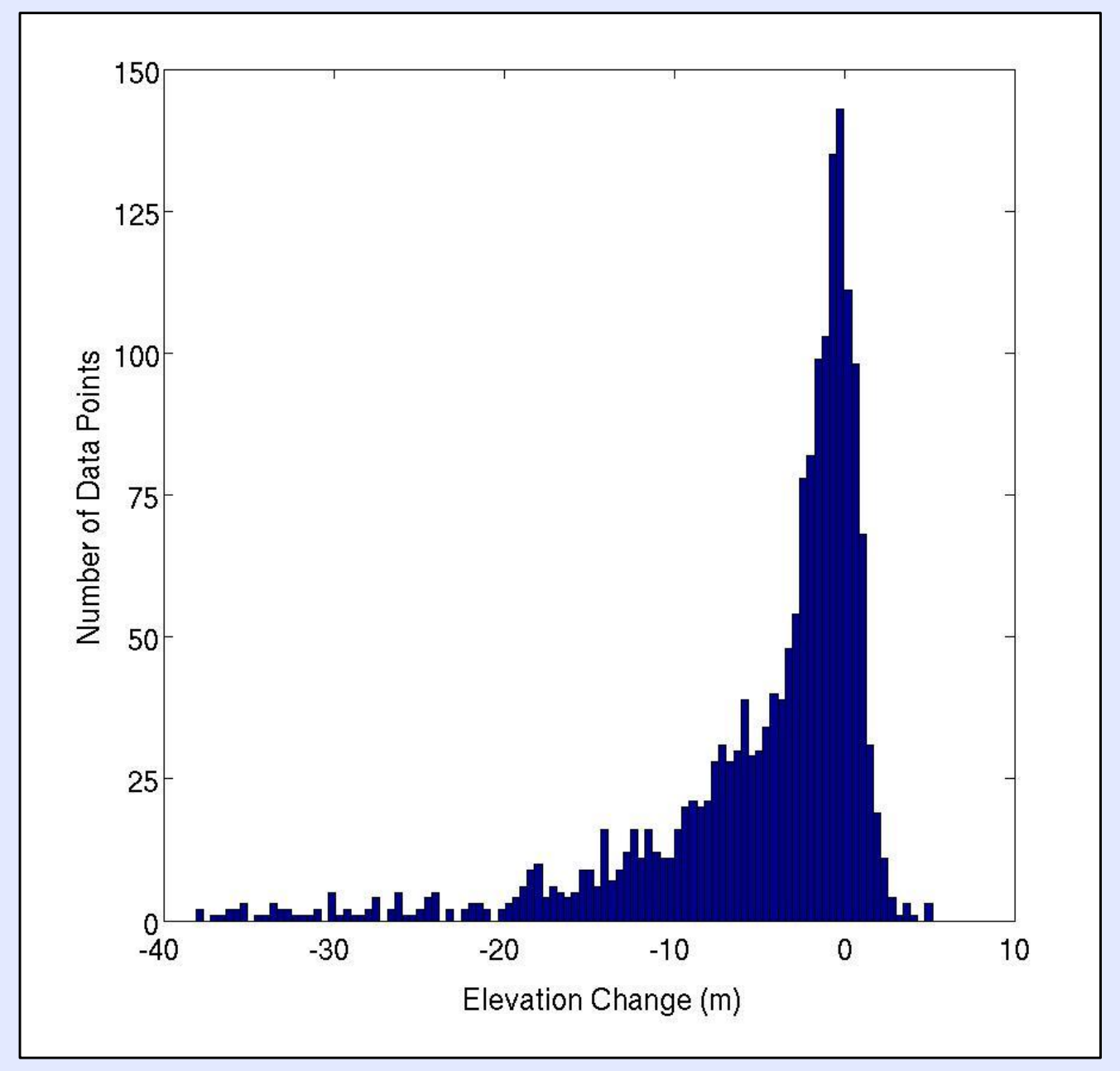

Figure 6: *Data distribution of elevation change from the rock glacier difference model.*

- The areas of most extreme elevation change occurred as localized depressions and are interpreted to be zones of local melting. These are represented by the orange and red pixels in Figure 5.
- There are also some areas of significant uniform melting, up to ~15m in magnitude, particularly along parts of the north-east edge of the rock glacier (Fig. 5).

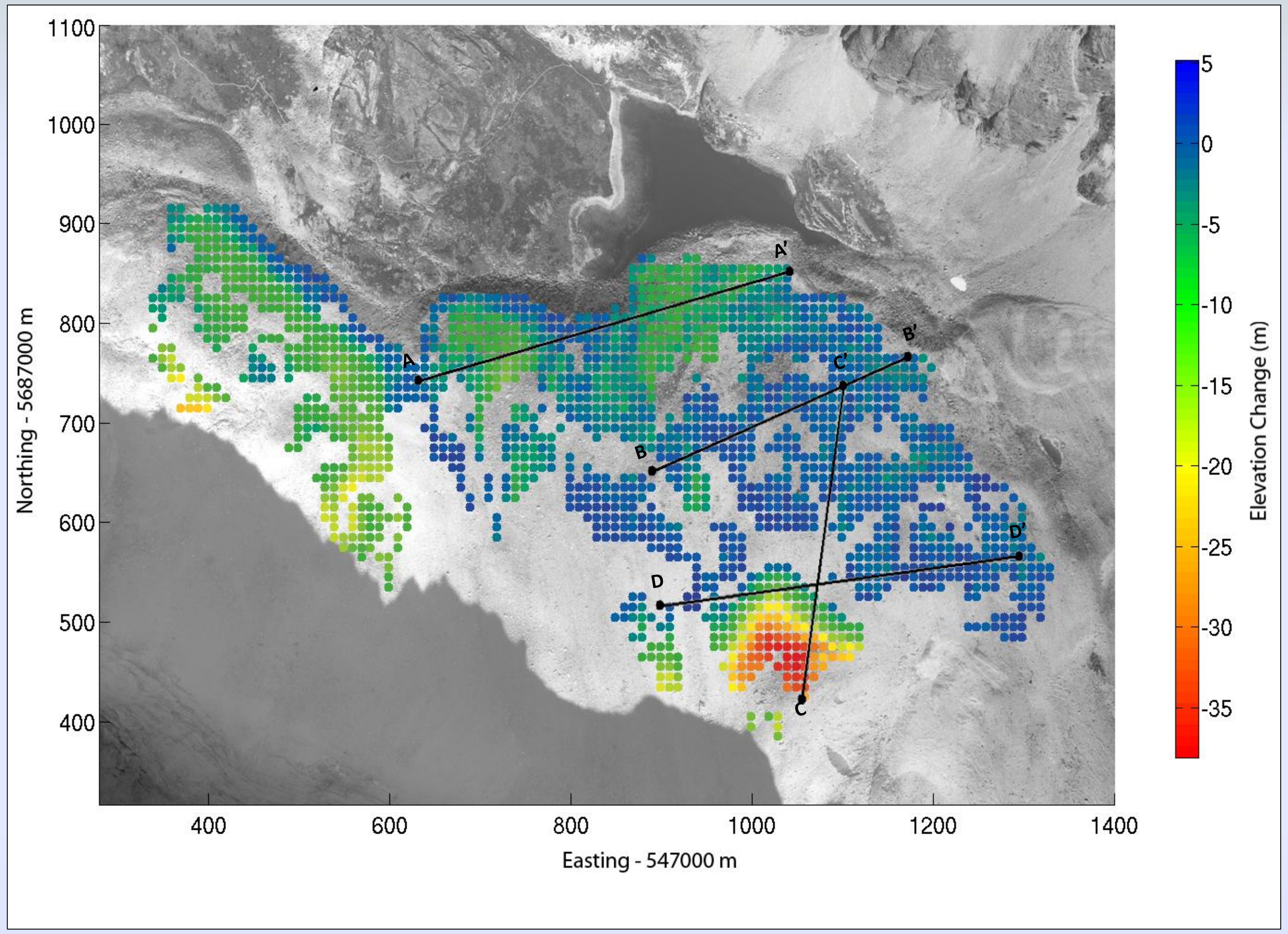

Figure 5: *Rock glacier difference DEM (2006-1962) with bias correction. Positive to zero elevation change is represented by blue colours, and maximum elevation change is represented by orange and red. Locations of cross sections A, B, C, and D are also shown.*

The cross sections are displayed below in Figure 7. Cross section A runs through the north-east edge of the rock glacier, and demonstrates an area of significant uniform melting. Cross sections C and D are examples of extreme elevation change as a result of localized melting zones. Because of the extreme melting demonstrated on the south end of the difference model, the vertical exaggeration for cross section C is set at half that of the other three cross sections. Cross section B is an example of an area where no significant deflation has occurred over the 44 year time interval.

Based on the results from this experiment, the ice volume lost over the 245,000 m^2 area of the rock glacier that was analyzed was 1 470 000m^3, which equates to 1.35 x 10^{9}L of water with a 0.92 ice to water density-conversion factor. If a 10 week melting period is assumed each year for the 44 year time interval, the approximate discharge that generated from the rock glacier is about 4.39 x 10^{5}L/day. This is about 1% of the total annual drainage in the basin.

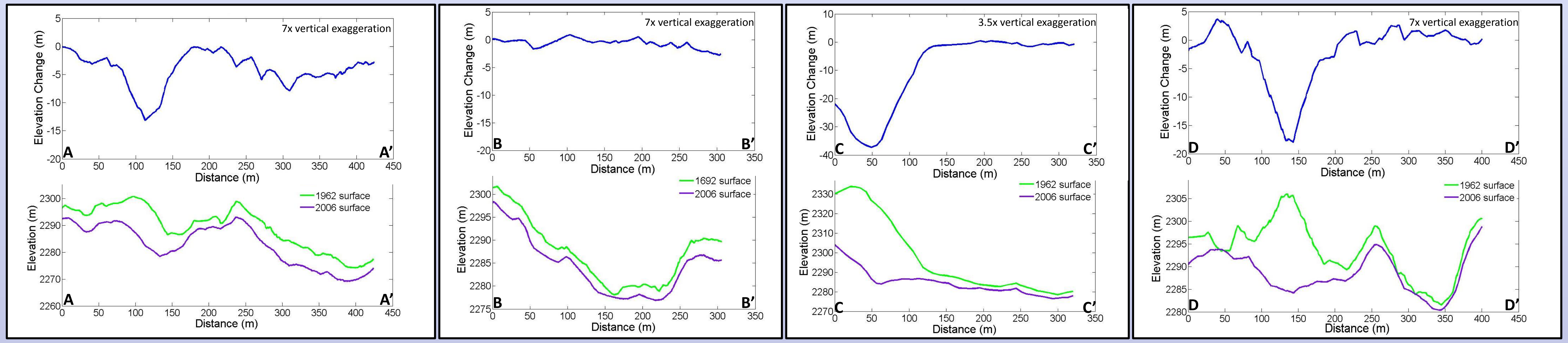

Figure 7: *Cross sections A, B, C, and D (Fig. 5). The blue line shown in the top graph for each pair illustrates the elevation change as found in the difference model. The bottom graphs with the green and purple lines represent the elevations of the 1962 surface and the 2006 surface, respectively.*

Conclusion:

This DEM experiment demonstrated that there has been significant deflation over the 44 year time interval, indicating the presence of pure ice. This project was successful in developing a method that can provide an independent test for the presence and nature of ice under a debris cover. Additionally, this experiment yielded a significant result that has not previously been recognized, that a debris-covered glacier can undergo uniform surface lowering over a large area, as opposed to only lowering in discrete localized melting zones.

The DEM comparison shows reasonable congruence with geophysical surveys completed for most areas of the rock glacier, although interpretations differ as to the nature of the ice at the toe: the results of the DEM comparison suggest the presence of pure ice, in contrast to geophysical interpretations which suggest interstitial ice. A possible explanation is that in the time interval between 1962 and 2006 an original ice core was completely melted, so that there was no pure ice left by the time the geophysical survey was completed.

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