Subglacial topography inferred from ice surface terrain analysis reveals a large un-surveyed basin below sea level in East Antarctica

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[1] A terrain analysis technique relating ice-surface plan curvature to basal topography is applied to the Antarctic Ice Sheet. The technique suggests complex bed topography and a large subglacial basin more than 1500 m below present day sea level under the Recovery Glacier and its catchment in East Antarctica. Despite the importance of accurate subglacial topography for understanding the nature of ice flow and for numerical modeling, available data in this region are sparse. The presence of a large area of ice grounded below sea level, flowing at elevated velocities could have significant implications for the potential stability of this region of East Antarctica, previously thought to contain only small areas of marine ice sheet. The catchment region alone contains an ice volume equivalent to 2.6 m of global sea level rise, therefore it is important that the nature of the basal conditions in this region are better understood.
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1. Introduction

[2] The morphology of an ice sheet and its level of stability are dependent on the nature of underlying basal conditions. When an ice sheet is grounded below sea level, it tends to have a low profile surface compared to a classical convex ice sheet surface profile. Surface drawdown is caused by fast flowing ice stream features flowing predominantly by basal sliding over deformable marine sediments [e.g., *Alley et al.*, 1986; *Tulacyzk et al.*, 2000]. *Vaughan and Bamber* [1998] compared an ice surface Digital Elevation Model (DEM) of the Antarctic Ice Sheet (AIS) with a modeled analytical ice surface (following *Vialov* [1958]). They identified nine low-profile regions where the measured ice surface was more than 500 m lower than the modeled ice surface (Figure 1). Eight of these regions correspond to areas where the ice sheet is known to be grounded below sea level (five of these in the West AIS (WAIS)), a configuration widely believed to be inherently unstable due to a grounding line feedback mechanism [e.g., *Weertman*, 1974; *Schoof*, 2007]. The continental East AIS (EAIS) is considered more stable, despite the existence of four low profile regions.

[3] Little is known directly about the basal topography in the ninth region, L9, encompassing the Recovery Glacier and its catchment, where the observed surface velocities indicate that fast flow occurs well inland [*Joughin and Padman*, 2003]. The BEDMAP dataset [*Lythe et al.*, 2001] contains very few measurements in this region; hence what is known is mainly derived from indirect methods. Data inversion methods indicate that Recovery Glacier may be grounded up to 1500 m below sea level [*Joughin et al.*, 2006] and there may be a large region in the interior well below sea level [*Warner and Budd*, 2000]. Ice surface analysis methods have been used to infer subglacial lakes in the low-slope region (slope <0.45 m km^{-1}, Figure 1, inset) at the onset of fast flow [*Bell et al.*, 2007]. Indirect magnetic evidence of a sedimentary basin up to 800 m below sea level has been found in a neighboring tributary region of Slessor Glacier (L7, Figure 1) [*Rippin et al.*, 2003; *Bamber et al.*, 2006], causing basal motion to dominate the flow in the tributary [*Rippin et al.*, 2006]. As a result of these findings, it is feasible that there are water saturated deformable sediments present in the Recovery Glacier catchment, causing enhanced flow and surface drawdown.

[4] Data on the basal topography are crucial for accurate numerical modeling of marine-based ice sheets and for understanding the response of an ice sheet system to sea level change. This paper utilizes a terrain analysis technique which relates ice surface plan curvature to the bed topography, using a recent ice surface DEM [*Rignot et al.*, 2008], in order to infer the bed topography in region L9.

2. Plan Curvature

[5] Across slope, or plan, curvature is a terrain analysis technique commonly used in hydrological applications to indentify convergent and divergent flow paths in catchments. *Rémy and Minster* [1997] first suggested a link between the plan curvature (PC) of an ice sheet surface and the bed topography. The link between PC and basal topography is first demonstrated here using an idealized circular ice sheet, existing at a pole, limited in extent by latitude (bed is an adjusted subset of BEDMAP, 5 km resolution).

[6] The PC of the ice sheet surface is derived using a terrain analysis software package, TAS (Terrain Analysis System [*Lindsay*, 2005]). The algorithm requires the fitting of a partial quartic equation to the nine elevation points making up a 3 by 3 window on the surface elevation grid. The PC is then a measure of the curvature transverse to the slope [see *Zevenbergen and Thorne*, 1987]. Negative values indicate convex PC, positive values indicate concave PC. Applying the PC technique to a 5 km resolution DEM leads to a spatially incoherent result (see auxiliary materials, e.g.,

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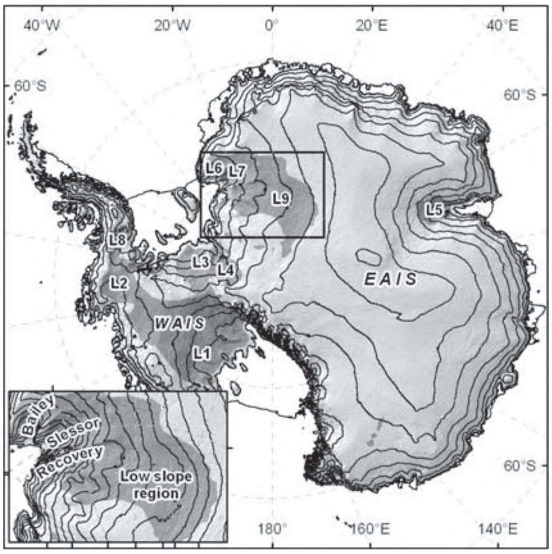

Figure 1. Regions (L1–L9, shown in dark gray) where the measured ice surface elevation is >500 m lower than the theoretical ice sheet surface (redrawn from *Vaughan and Bamber* [1998]) and 500 m surface contour intervals (EAIS dome is at 4000 m). Coastline is from Antarctic Digital Database v3. Inset surface contours at 200 m intervals.

Figure S1a, applied to whole AIS).[1] Longitudinal stresses within the ice tend to smooth out local scale variations in ice thickness over 10–20 times the ice thickness [*Kamb and Echelmeyer*, 1986], hence, at a 5 km scale, it is necessary to apply a variable size, variable weight filter, dependent on the ice thickness [following *Kamb and Echelmeyer*, 1986; *Le Brocq et al.*, 2006]. Otherwise, a grid resolution of 20 km or greater must be used (Figures S1a–S1d). The greater level of detail available in a higher resolution dataset leads to a 5 km resolution being employed here, using a smoothed ice sheet surface. As we do not have a reliable measure of ice thickness, we used the smallest filter that produced coherent features (30 km, Figures S1e–S1g).

[7] If the entire base of the idealized ice sheet, outlined above, was above sea level (henceforth, ASL ice sheet) and no deformable sediments were present (e.g., Figure 2a), the ice sheet would flow through two mechanisms; internal deformation [*Glen*, 1955] and classical Weertman sliding [*Weertman*, 1964]. These mechanisms are both considered to be driven by the basal shear stress, a function of surface slope and ice thickness (equivalent to the gravitational driving stress). As the ice thickness decreases towards the extremities of the ice sheet, the surface slope must increase in order to maintain the ice sheet in a state of balance, leading to the classical convex surface profile of, for example, *Vialov* [1958]. This will also lead to convex *plan* contours (e.g., Figure 2b, numerical model result where basal sliding is a linear function of the basal shear stress [e.g., *Payne*, 1998]) and, hence, convex PC values (Figure 2c). Where the relative basal topography is lower than its surroundings, ice flow will be concentrated into outlet glaciers which will have a greater ice thickness due to the troughs they flow through. As a result, these outlet glaciers would not require such a steep slope to maintain ice flux, hence, slightly concave plan contours will result (e.g., feature 1 on Figures 2a–2c).

[8] If areas of the bed beneath our idealized ice sheet were below sea level and deformable sediments were present (e.g., Figure 2d, henceforth BSL ice sheet), enhanced fast flow features can develop via sediment deformation. These enhanced flow features have a low basal shear stress, causing surface drawdown and strongly concave plan contours (Figure 2e, numerical model result where basal sliding is a function of both the basal shear stress and the effective pressure [e.g., *Budd et al.*, 1984]), and, hence, strongly concave PC values (Figure 2f). Inter-stream ridges, flowing by internal deformation only, will form between the fast flow features where relative bed elevations tend to be higher (cf. Siple Coast Ice Streams). Hence, these inter-stream areas will develop convex plan contours (Figure 2e). The resulting PC for the BSL ice sheet (Figure 2f) shows a good qualitative agreement with the basal topography (Figure 2d). Inter-stream ridges and ice divides complicate the picture, introducing highly convex values in areas where bed elevations are below sea level. Despite the potential difficulty in distinguishing between strongly convex plan contours caused by interstream ridges or an area with the bed above sea level, the PC of the ice surface has the potential to identify *relative* basal topography, but must be considered in the context of the setting (i.e., topographically constrained vs. non-topographically constrained).

[9] The above examples are very idealized; at a 5 km grid scale, strongly concave PC values will also be caused by small scale (<15 km), topographically controlled, convergent ice flow features with a steep slope (e.g., in the Transantarctic mountains). Therefore, some consideration needs to be given to the scale of the flow features which are discussed in section 4, as well as their overall morphology. At a 5 km scale, the shape of the ice sheet extent will not have a large impact on the PC values. Table 1 summarizes the key features of each idealized ice sheet, and the associated level of curvature for each feature.

3. Application to the Antarctic Ice Sheet

[10] The PC algorithm was applied to the smoothed AIS ice surface DEM (Figure 3a). PC values range from ~ -0.01 for highly convex areas to ~ 0.01 for highly concave areas, where 0 is rectilinear. The PC values generally correlate well with the basal topography in areas where the base of the ice sheet is below sea level and fast flow features are present, whether this is in a topographically constrained setting (e.g., Evans Ice Stream (inset 1, Figure 3)) or in a less constrained topographic setting (e.g., Siple Coast region (inset 3, Figure 3)). The existence of highly concave PC values largely corresponds to areas of bed that are below sea level, except for areas of extreme topographic relief causing strongly convergent flow (e.g., the Transantarctic Mountains).

4. Recovery Glacier

[11] Having established that the technique is reliable for regions of the AIS where bed data are available, the

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL034728.

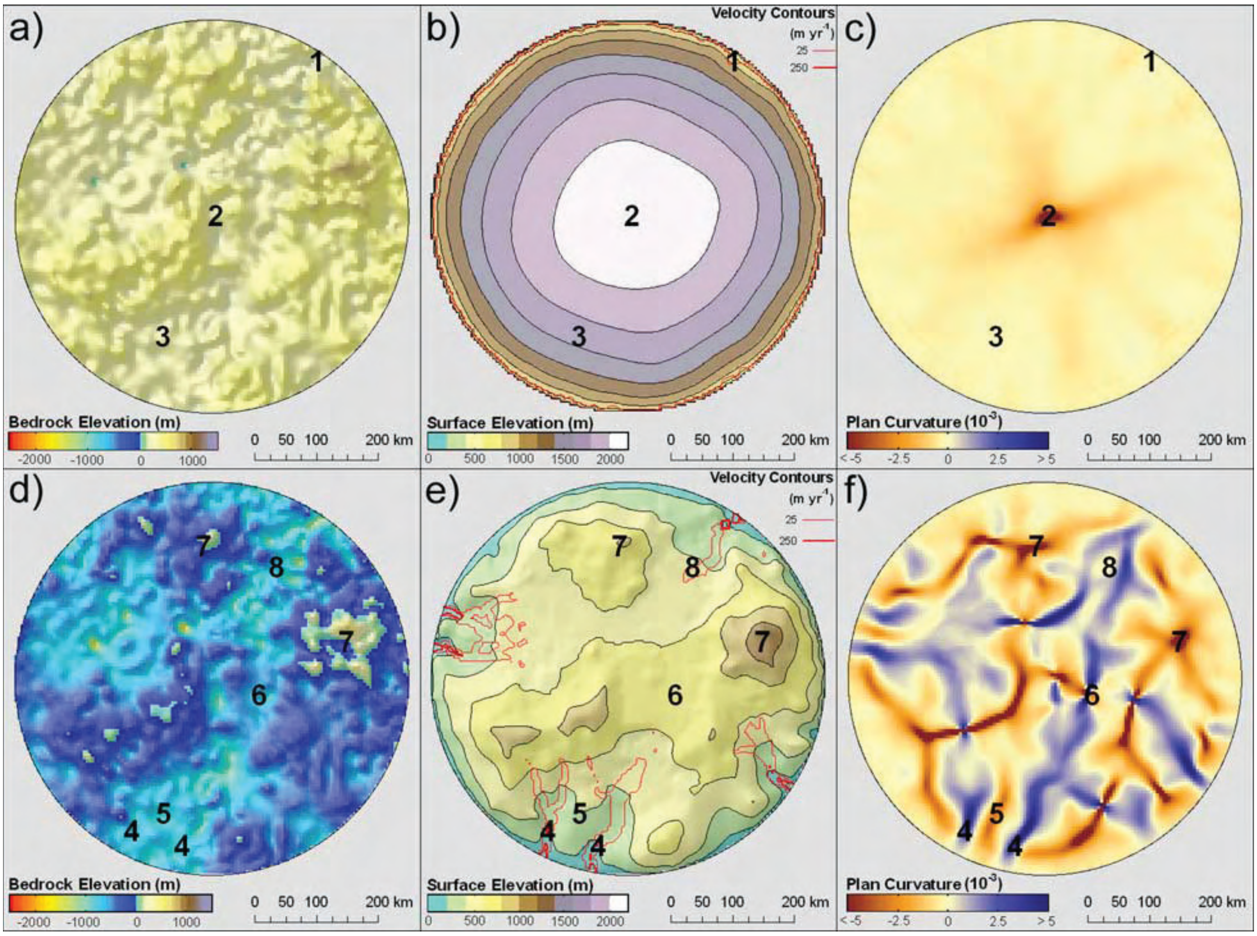

Figure 2. (a) ASL artificial bed, (b) example ice sheet surface resulting from ASL bed, (c) PC of smoothed ice sheet surface (from Figure 2b), (d) BSL artificial bed, (e) example ice sheet surface resulting from BSL bed and (f) PC of smoothed ice sheet surface (from Figure 2e). The numbers correspond to features discussed in the text (summarized in Table 1).

discussion now focuses on the Recovery Glacier region. Extracts from one basal topography transect available from the region [*Lythe et al.*, 2001] show a strong agreement with the PC analysis (Figures 4a and 4b). More recent data are available for an area covering the Slessor Glacier tributaries [*Rippin et al.*, 2003]; the correlation between an extract from this dataset and the PC is also good (Figure 4c). Figure 4b highlights the difficulty in distinguishing between areas of bedrock above sea level and areas which are likely to be frozen to their bed; between 175 km and 240 km along the profile, the measured bed is well below sea level, though it corresponds to a convex PC value.

4.1. Western Half of Recovery Glacier Catchment

[12] The western half of the Recovery Glacier catchment (Figure 3a, west of inset 2, nearest to the grounding line) displays a range of PC values similar to both the Evans Ice Stream and the Siple Coast region, with concave PC values up to ~0.01. This range of PC values is only found elsewhere in the WAIS and the Transantarctic Mountains. Such a large range is not found elsewhere in the interior of the EAIS (>450 km inland), except at Lake Vostok, where the presence of the lake significantly reduces the basal shear stress. The presence of highly concave PC values for flow features of the size observed in this region (>30 km, with a low surface gradient) indicates that there are areas where the bed elevation is well below sea level, and water-saturated deformable sediments may exist, which are facilitating enhanced localized ice flow.

[13] In order to determine the topographic setting in this region, it is important to first determine whether it is high relief or a differing thermal regime which is causing the

Table 1. Summary of Features and Their Associated Curvature Type[a]

	Type	Curvature (Smoothed Ice Surface)
	Above Sea Level	
1	Outlet Glacier/Complex Topography	Slightly convex and concave
2	Ice Dome	Highly convex
3	General bed above sea level	Slightly convex
	Below Sea Level	
4	Ice Stream	Highly concave
5	Inter-stream Ridge	Highly convex
6	Ice Divide	Highly convex
7	Topography above sea level	Highly convex
8	General bed below sea level	Slightly convex and concave

[a]Features discussed in the text and illustrated on Figure 2.

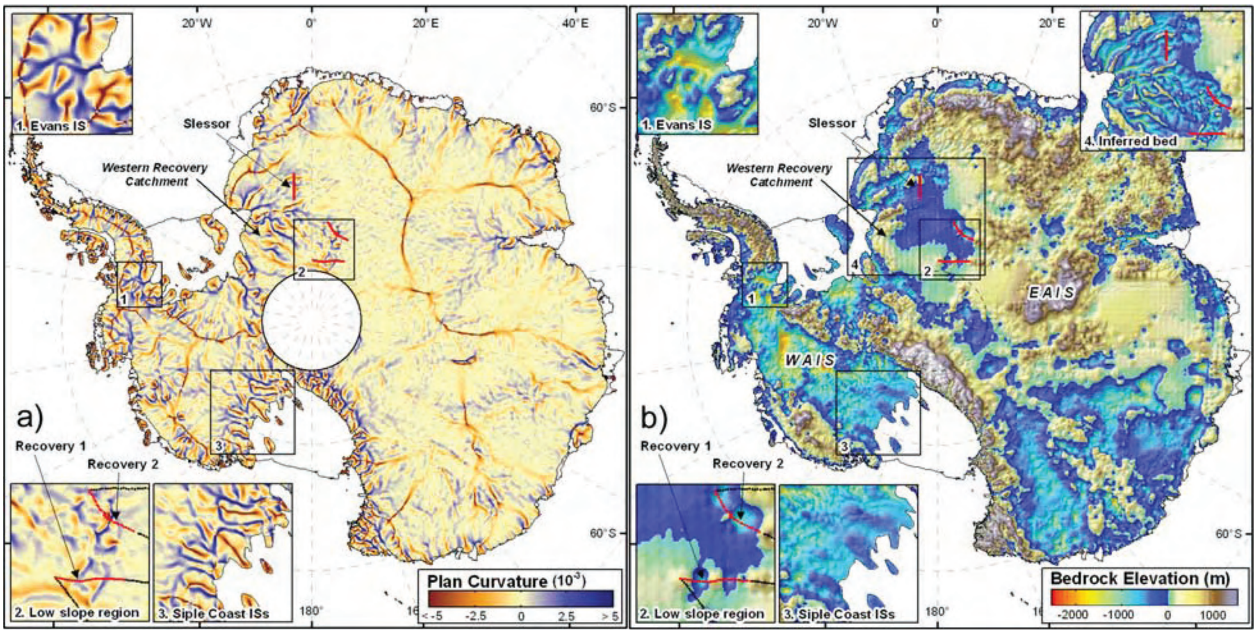

Figure 3. (a) PC of smoothed AIS ice surface DEM and (b) original BEDMAP dataset (inset 4 is the proposed bed). Red lines relate to profiles shown in Figure 4.

convex PC values. Elevation data from ice free areas and the general surface morphology indicate there are some areas of high relief in this region, hence, it is assumed that the convex PC values *are* due to high relief. The PC values in this area can therefore be compared to elevations found in Evans Ice Stream and neighboring ice streams. Based on this comparison, the bed could be up to 2500 m below sea level in the troughs.

4.2. Low-Slope Region

[14] In the interior low-slope region (Figure 3a, inset 2), the presence of highly concave flow features and a large low-slope region suggests that some, if not most, of the bed is well below sea level, despite the existence of slightly convex PC values. The convex PC values are less extreme than in the western half of the catchment (>−0.001), apart from some isolated values. The range of values is much

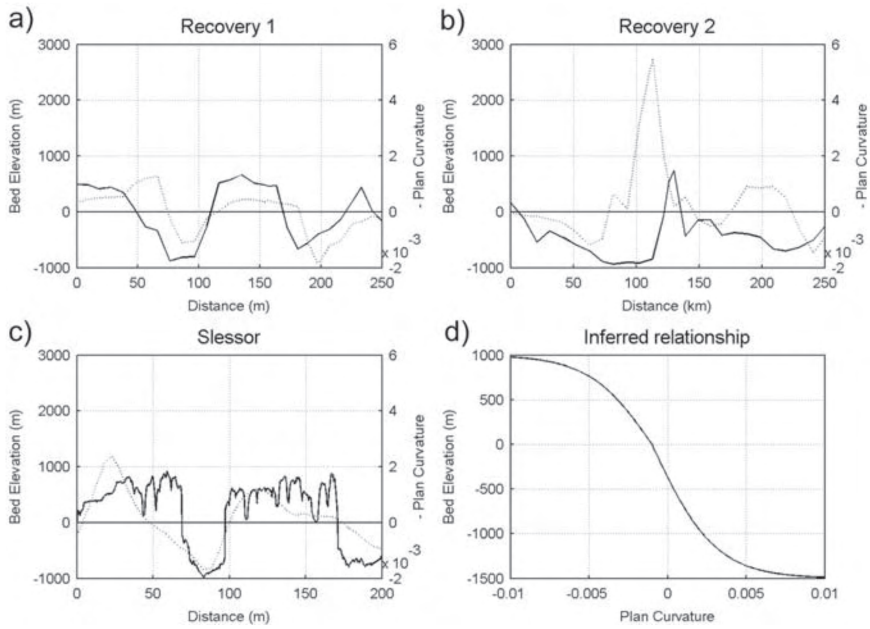

Figure 4. (a)–(c) Measured bed elevations (solid line) and PC values (dotted line) for three transects (marked in red on Figure 3). Note for display purposes the values plotted are negative PC (i.e., <0 is concave, >0 is convex). (d) Relationship between PC and bed elevation used to produce the modified BEDMAP dataset shown in Figure 3b (inset 4).

more similar to the interior of the WAIS, where the majority of the bed is below sea level. For an EAIS comparison, areas where the bed is well below sea level, for example in the Slessor tributaries (>800 m below sea level), correspond to *convex* PC values similar to that found beneath the low-slope region. Depths from the single BEDMAP transect which crosses the low-slope region also support basal topography up to 1000 m below sea level where convex PC values exist.

5. Inferred Topography

[15] Despite the good qualitative agreement between PC values and the known basal topography demonstrated in Figures 3 and 4, converting the PC values into a quantitative prediction of unknown basal topography is uncertain. The above analysis of the PC results for region L9 leads to an approximate relationship between PC and basal topography (Figure 4d). PC values greater than −0.001 (slightly convex values and all concave values) give bed elevations below sea level, with a minimum value of 1500 m below sea level (the lowest observed in the region). PC values less than −0.001 (highly convex) give bed elevations above sea level, up to a value of 1000 m above sea level. This relationship is therefore slightly biased to allow interior areas with slightly convex values to remain below sea level.

[16] The quantitative relationship (Figure 4d) results in a large region of the EAIS where the bed is significantly below sea level (inset 4, Figure 2b) with some significant relief in the western part of the catchment. The predicted topography should not be taken as a precise quantitative representation of the basal topography; however, it is a useful indication of the nature of the basal topography, as the determination of the qualitative topography is reasonably robust.

6. Conclusions

[17] This work has demonstrated the usefulness of terrain analysis techniques in understanding the nature of flow in an ice sheet, and the potentially useful data that can be inferred from the ice surface morphology. The presence of a significant area of the EAIS, in the region of Recovery Glacier, exhibiting enhanced flow with a low surface gradient, and PC values similar to the WAIS suggests that there may be a large basin with water saturated deformable sediments in the region, over 1000 m below sea level, with a plentiful supply of basal meltwater, connected to the coastal regions.

[18] The presence of a large area of subglacial sediment below sea level in this region would have implications for the stability of this sector of the EAIS, making it much more sensitive to oceanic forcing and possible grounding line migration. The predicted basal topography adds a further 1.0×10^5 km^3 of ice to the total volume of ice in Antarctica (previous estimate: 24.7×10^6 km^3 [*Lythe et al.*, 2001]). However, as most of the ice is below sea level, it will already have displaced seawater, so will not significantly increase the total contribution of Antarctica to potential future global sea level rise. As suggested by *Vaughan and Bamber* [1998], whether or not a large area of bed exists below sea level, with marine sediments, is of major importance. The ice volume above buoyancy in the basin region alone is 9.5×10^5 km^3, equivalent to 2.6 m of global sea level rise (compared to an estimated 5 m for the WAIS [*Lythe et al.*, 2001]). Ice outside of the basin region would also be impacted by the thinning, raising this total sea level rise significantly. If the same grounding line instability thought to be occurring in the WAIS also occurs in this basin, the region could contribute significantly to future global sea level rise.

[19] Therefore, it is imperative for understanding of the nature of the EAIS, and reliable predictive modeling, that basal topography is mapped in this area. The dataset presented here provides a useful guide to areas which require specific focus.

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