An extensive subglacial lake and canyon system in Princess Elizabeth Land, East Antarctica

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ABSTRACT

The subglacial landscape of Princess Elizabeth Land (PEL) in East Antarctica is poorly known due to a paucity of ice thickness measurements. This is problematic given its importance for understanding ice sheet dynamics and landscape and climate evolution. To address this issue, we describe the topography beneath the ice sheet by assuming that ice surface expressions in satellite imagery relate to large-scale subglacial features. We find evidence that a large, previously undiscovered subglacial drainage network is hidden beneath the ice sheet in PEL. We interpret a discrete feature that is 140 × 20 km in plan form, and multiple narrow sinuous features that extend over a distance of ~1100 km. We hypothesize that these are tectonically controlled and relate to a large subglacial basin containing a deep-water lake in the interior of PEL linked to a series of long, deep canyons. The presence of 1-km-deep canyons is confirmed at a few localities by radio-echo sounding data, and drainage analysis suggests that these canyons will direct subglacial meltwater to the coast between the Vestfold Hills and the West Ice Shelf.

INTRODUCTION

Subglacial drainage beneath the Antarctic ice sheet (AIS) is important because basal water can affect the flow of overlying ice (Stearns et al., 2008), may influence ice sheet mass balance (Bell et al., 2011) and, where it meets the ocean, may locally enhance rates of basal melt beneath ice shelves (Le Brocq et al., 2013). The pattern of subglacial drainage reflects not only the ice conditions and geothermal flux (Schroeder et al., 2014), but is strongly controlled by subice topography (Rose et al., 2014).

Only seven long-distance (e.g., >100 km) subglacial hydrological networks have been identified beneath the AIS, some of which flow within a clearly channelized bed topography (Flament et al., 2014; Fricker et al., 2010; Gray et al., 2005; Schroeder et al., 2013; Wingham et al., 2006) and two that represent ancient subglacial drainage (Jordan et al., 2010; Rose et al., 2014). In addition, more than 400 Antarctic subglacial lakes have been identified (Siegert et al., 2016), some of which are located in significant topographic basins linked to these large subglacial hydrological networks.

In this paper we present satellite remote sensing and radio-echo sounding (RES) evidence for a vast, previously unrecognized subglacial canyon and lake system extending from the ice sheet interior to the coast in the interior of Princess Elizabeth Land (PEL) in East Antarctica (70–105°E and north of 77°S; Fig. 1). Here, there are few direct measurements of ice thickness; parts of PEL are more than 200 km from the nearest ice thickness measurement, and therefore sub-ice topography is poorly resolved (Fretwell et al., 2013).

APPROACH: MAPPING LINEAR FEATURES AT THE ICE SHEET BED

Three satellite-derived mosaics (Fig. DR1 in the GSA Data Repository[1]) of the AIS surface, the RADARSAT-1 Antarctic Mapping Project (RAMP) Antarctic Mapping Mission (AMM-1) synthetic aperture radar (SAR) image mosaic of Antarctica (RADARSAT; Jezek et al., 2002), the Moderate Resolution Imaging Spectroradiometer (MODIS) 2009 Mosaic of Antarctica (MOA) (Haran et al., 2014), and a digital elevation model (DEM) generated from European remote sensing (ERS) satellite ERS-1 and NASA Ice, Cloud, and Land Elevation Satellite (ICESat) data (Bamber et al., 2009), consistently reveal a series of large-scale linear features that cross PEL sub-perpendicular to present-day ice flow.

A significant component of the variability in RADARSAT and MODIS data is caused by ice flow over topography (Jezek, 1999) and variations in snow and ice reflectivity relating to ablation and accumulation patterns around consequent low-amplitude ice surface undulations (Welch and Jacobel, 2005). Thus, by analyzing contrasts in satellite ice surface data, patterns can be detected that reflect subglacial relief (Ross et al., 2014).

We map obvious linear features in these data over PEL assuming that variations are linked to subglacial topography. Results are constrained by independent RES data, where available. In addition, subglacial hydraulic gradients are calculated using both Bedmap2 bed elevation data (Fretwell et al., 2013) and a modified version of the bed to which simple and conservative geometrical representations of the mapped features are added (see the Data Repository). By applying hydrological flow routing algorithms to both bed models, and the present-day ice surface, we test the influence of the features upon subglacial water flow.

RESULTS

Two distinct but connected linear ice surface patterns are apparent in PEL (Fig. 2).

Subglacial Basin Morphology

In the interior of PEL, an elongate, extensive, relatively featureless zone of the ice sheet surface is apparent in MOA and RADARSAT imagery (Fig. 1B; Fig. DR1). We interpret this as a region of low basal friction, and therefore the possible surface manifestation of a large subglacial lake. The zone is ~140 × 20 km in size, covers an area of ~1250 km^2 (Fig. 2A), and would be the second largest subglacial lake by length after Lake Vostok (Kapitsa et al., 1996) and the fourth largest by area in Antarctica after Lakes Vostok, 90°E, and Sovetskaya (Bell

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[1]GSA Data Repository item 2016022, additional detail on the methodology involved in mapping the subglacial channel and lake system, and on the derivation and analysis of subglacial and subaerial drainage pathways, and supplemental figures, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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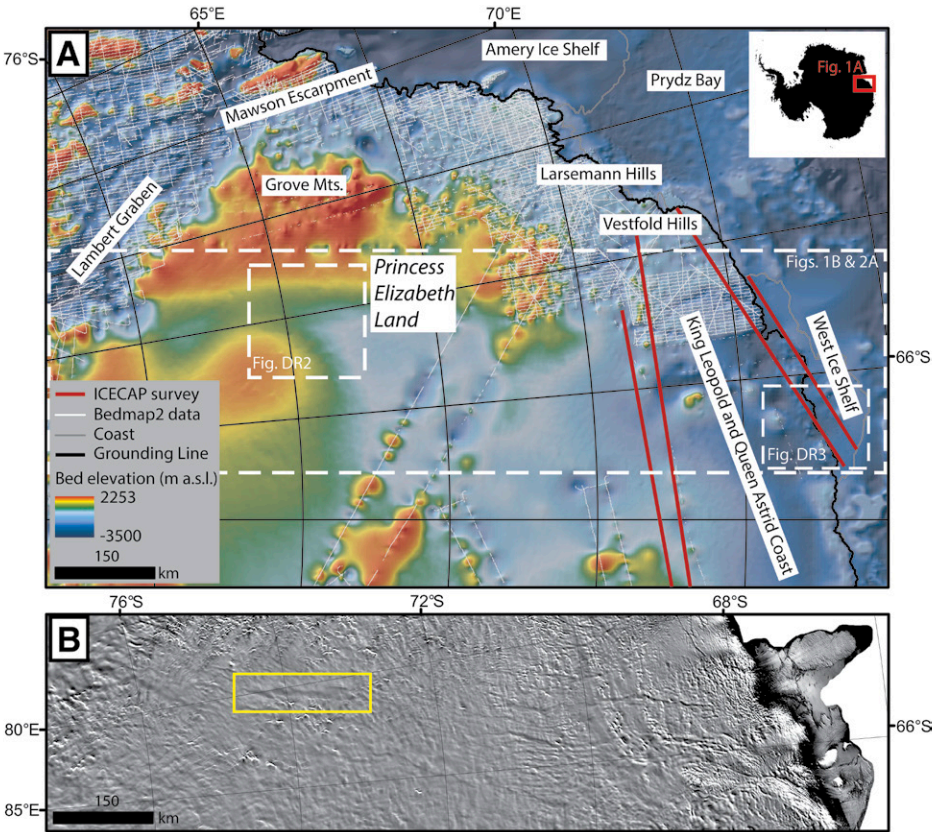

Figure 1. Bed elevation (a.s.l.—above sea level) and ice surface morphologies in Princess Elizabeth Land, Antarctica. A: Bedmap2 digital elevation model (Fretwell et al., 2013) illustrating the locations of direct measurements and highlighting the areas without direct measurements. Grounding line data are from Scambos et al. (2007). ICECAP—International Collaborative Exploration of the Cryosphere through Airborne Profiling program. B: Moderate Resolution Imaging Spectroradiometer (MODIS) mosaic of Antarctica 2009 (Haran et al., 2014) showing north-south–trending linear features and an elongate and relatively featureless zone on the ice sheet surface (yellow box).

et al., 2006). The ice surface above the feature shares characteristics with those of large subglacial lakes previously identified from the same data sets (Bell et al., 2006, 2007). Specifically, the surface has (1) low slopes, whether along flow or along the lake axis (<0.3° versus 0.5°–1° in the surrounding area); (2) a smooth textural appearance; (3) a pronounced ridge in the ice sheet surface at the downflow margin of the feature; and (4) sharply defined boundaries on its long-axis margins that are oriented perpendicular to regional ice flow (Fig. 2A; Figs. DR1 and DR2). The latter two characteristics are key reasons why water can pool in large volumes (Siegert, 2004). The presence of a basin or lake is also supported by a negative gravity anomaly measured by the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite (Forsberg et al., 2011). However, a RES survey is required to identify and measure the ice-water interface before the presence and characteristics of the potential lake can be unambiguously confirmed.

Subglacial Canyon Morphology

The second morphology observed in PEL is a series of subparallel, narrow, and long features (Fig. 2A), which individually extend to 545 km in length and are up to ~10 km wide; we interpret them as representing a series of large canyons in the bed. Some of these begin beneath, or adjacent to, the main ice divide (~72°S, 82°E) and extend northward toward the coast. Others originate at the divide and extend past, or into, the proposed subglacial lake before continuing south toward the main trunk of the Lambert Glacier. As the canyons near the coast, where they were previously mapped as structural geological lineaments (Golynsky and Golynsky, 2007), they gradually diverge from one another. The start and endpoints of the two sets of canyons align with only small gaps between them.

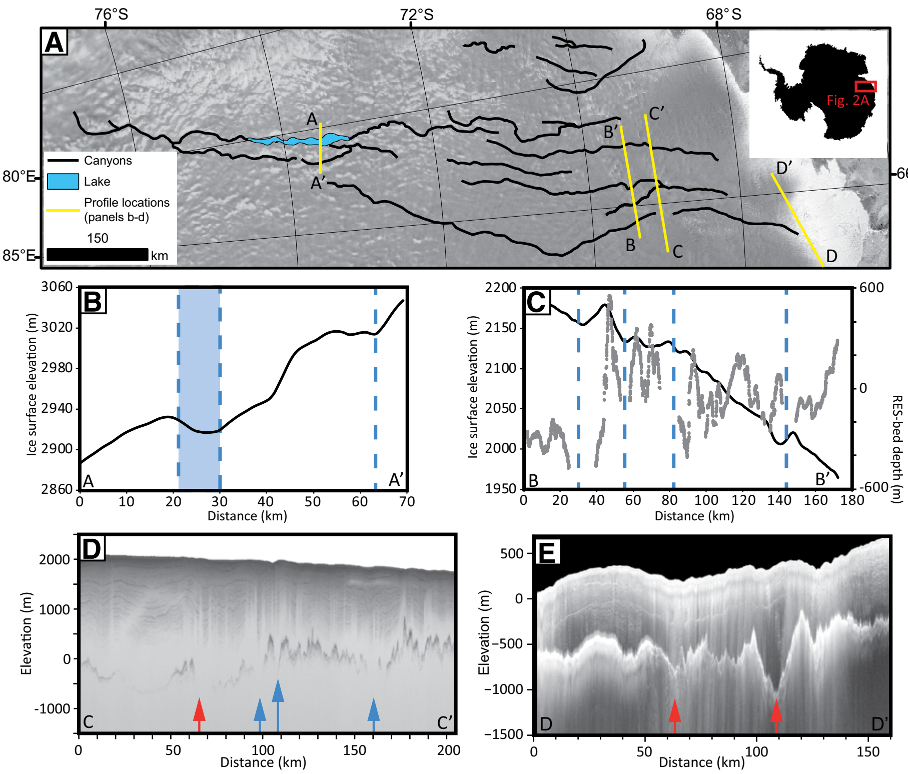

Figure 2. Subglacial topographic features in Princess Elizabeth Land, Antarctica. A: Mapped features overlain on RADARSAT ice surface morphology data (Jezek et al., 2002). B, C: Cross profiles of ice surface elevation (black) and, in C, direct measurements of bed depth (gray) from International Collaborative Exploration of the Cryosphere through Airborne Profiling (ICECAP) radio-echo sounding (RES) data indicating loss of bed signal (i.e., deep bed) over mapped canyons (blue dashed lines). Blue box in B indicates lake location. D: Focused RES data for profile C-C′ confirming the presence of canyons at the mapped locations (blue arrows) and a canyon (red arrow) that links endpoints of separately mapped canyons (see text). C-C′ is on ICECAP line ASB/JKB2h/R22Wa. E: Focused RES data for profile D-D′, which confirms deep canyons immediately inland of the grounding line. D-D′ is on ICECAP line PEL/JKB2h/Y16a.

Ground Truthing from RES Data

Four airborne RES profiles, collected by the International Collaborative Exploration of the Cryosphere through Airborne Profiling (ICECAP) program, cross the proposed canyons (Fig. 1A). Narrow, steep-sided, v-shaped subglacial canyons (Figs. 2B and 2C) are present exactly where our mapping suggests (Fig. 2A), revealing that, in places, they are >1 km below sea level. Furthermore, an unmapped channel imaged in the RES data (profile C-C′; Fig. 2D) confirms a connection between the endpoints of two separate features, indicating that the chain of canyons spans more than 1100 km. One channel, ~200 m below sea level, is also apparent in the Bedmap2 data near the coast, having been covered by a dense grid of radar survey data collected adjacent to the West Ice Shelf by Russia's Polar Marine Geosurvey Expedition in 2010 (Fig. 1). In addition, in two RES profiles acquired in central PEL (Göller, 2014), several gaps, coincident with our mapped canyons, occur where the bed is too deep to be recorded (Fig. 1). RES data from a Russian traverse confirm that the bed topography is rough and reveal multiple ~500-m-relief v-shaped features in the interior of PEL (Popov et al., 2010). The extension of the canyons to the coast is confirmed by an ICECAP RES profile a few kilometers inland of the grounding line, which contains two deep subglacial canyons (profile D-D′; Fig. 2E), the smaller of which we map further inland.

SUBGLACIAL DRAINAGE

We interpret the features identified in the satellite-derived ice surface imagery as surface expressions of long, deep subglacial canyons linked to a major subglacial basin containing a lake. The question of whether the system is currently active cannot be answered definitively without a targeted RES survey. However, ICECAP RES data over the West Ice Shelf show undulations in the ice shelf base (see the Data Repository and Fig. DR3) that could be the result of erosion by meltwater as it exits the mapped canyons (Le Brocq et al., 2013). However, we cannot be certain because warm ocean waters may also be melting the underside of the ice shelf (Pritchard et al., 2012).

Regardless of the evidence for active water flow, the length and depth of these features inland (Fig. 2) suggest that they will be the primary control on regional hydrologic routing where basal water is present, acting as a drainage bar and capturing water in the lake or diverting it toward the West Ice Shelf. In acting this way, we suggest that the canyons and lake reduce the likelihood of rapid ice flow in this region both at present and in the past. This is because rather than focusing water at one point and enhancing basal sliding, they capture it so it cannot lubricate the ice-bed interface over wide areas.

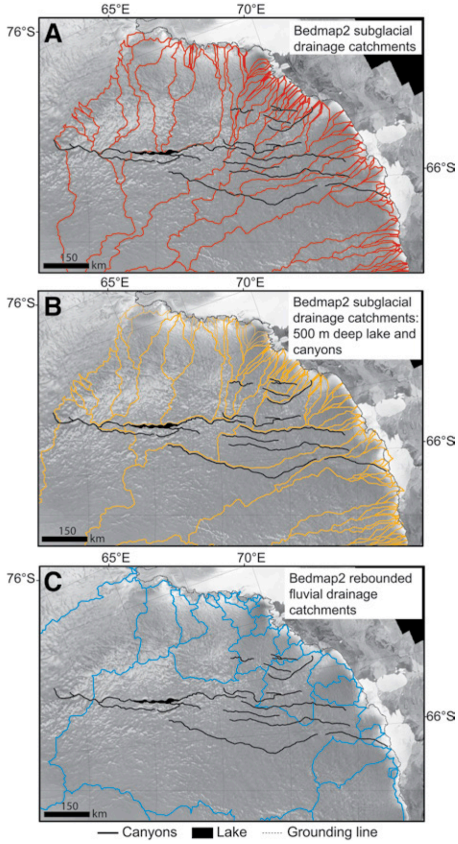

Figure 3. Drainage patterns across Princess Elizabeth Land, Antarctica, with and without canyons and lake superimposed. A: Bedmap2 (Fretwell et al., 2013) subglacial hydraulic potential drainage catchments. B: Canyonized Bedmap2 (see the Data Repository [see footnote 1]) subglacial hydraulic potential drainage catchments. C: Ice-free Bedmap2 fluvial drainage catchments. Both A and B have been calculated without the lake and canyons being taken into account. The underlying satellite imagery is from RADARSAT (Jezek et al., 2002).

Calculation of the hydraulic potential using the Bedmap2 bed and ice surface data (see the Data Repository) shows that subglacial drainage would transport water from central PEL toward the Lambert-Amery region (Fig. 3A). However, hydraulic potential calculated over a modified bed that has conservative 500-m-deep, 5-km-wide canyons included (see the Data Repository) shows how water originating from the easternmost canyons and lake could, instead, be steered east to the King Leopold and Queen Astrid Coast (Fig. 3B).

Given that modern subglacial meltwater production is likely in PEL (Pattyn, 2010), we suggest that the lake and canyons are conduits for subglacial water. Furthermore, there is little evidence for substantial change in ice sheet form in PEL during at least the past 5 m.y., with only minor ice margin fluctuations during the Quaternary (Mackintosh et al., 2014) and longer (Pollard and DeConto, 2009), and even slight thickening during the Pliocene (Yamane et al., 2015). Consequently, the subglacial channel system is likely to have influenced basal water flow over millions of years.

CANYON EVOLUTION

Where measured in RES data, the canyons are below any past or present sea level (Fig. 2), even when glacioisostatic adjustment is accounted for. Measurements of modern ice flow (Fig. 2) (Rignot et al., 2011) and models of past ice flow (Pollard and DeConto, 2009) and erosion (Jamieson et al., 2010) are inconsistent with the direction necessary to overdeepen most of the canyons by glacial erosion. Our calculations of pre-glacial fluvial drainage (see the Data Repository) over an ice-free landscape (Fig. 3C) suggest that canyon orientations are instead consistent with the direction of river flow, which could have cut these features to base level. Following the onset of continental-scale glaciation, erosion by the action of subglacial water may have significantly deepened their profiles.

The canyon network and lake are aligned with north-south–trending large, deep, and elongate subglacial lakes (Lakes Vostok, 90°E, and Sovetskaya) that are controlled by large-scale extensional tectonics (Bell et al., 2007). They are also aligned with extensional structures developed as part of the East Antarctic rift system (Ferraccioli et al., 2011) and structures relating to the amalgamation of East Antarctica (Aitken et al., 2014). Thus, the scale and orientation of the mapped features suggest an overarching tectonic control.

CONCLUSIONS

Princess Elizabeth Land in East Antarctica is one of the largest unsurveyed land surfaces on Earth. We use satellite imagery, validated with RES data, to identify and map an extensive linear series of subglacial canyons in PEL. Given the likelihood of parts of the bed being at pressure melting point, and the likely influence of the canyons on hydraulic potential, they may also compose the largest sub-ice drainage network identified beneath a modern ice sheet. Their subparallel and extensive nature implies that they are tectonic in origin and their depth suggests that they may have been modified by subglacial water flow. Linked to the canyons, a large subglacial lake may exist that may be the last remaining large (>100 km in length) subglacial lake to be discovered in Antarctica. To confirm and characterize the features in detail, new RES surveys are required.

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