Earth and Planetary Science Letters 408 (2014) 362–369

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Evaluating Marie Byrd Land stability using an improved basal topography

N. Holschuh[a,*], D. Pollard[b], R.B. Alley[a,b], S. Anandakrishnan[a,b]

[a] *Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA*
[b] *Earth and Environmental Systems Institute, Pennsylvania State University, University Park, PA 16802, USA*

ARTICLE INFO

Article history:
Received 26 May 2014
Received in revised form 8 October 2014
Accepted 11 October 2014
Available online 4 November 2014
Editor: P. Shearer

Keywords:
Marie Byrd Land
DeVicq Glacier
geophysics
glaciology
ice-sheet modeling

ABSTRACT

Prior understanding of the ice-sheet setting in Marie Byrd Land (MBL) was derived primarily from geologic and geochemical studies of the current nunataks, with very few geophysical surveys imaging the ice covered regions. The geologic context suggested that the ice rests on a broad regional high, in contrast to the deep basins and trenches that characterize the majority of West Antarctica. This assumed topography would favor long-term stability for the West Antarctic Ice Sheet (WAIS) in MBL. Airborne geophysical data collected in 2009 reveal a much deeper bed than previously estimated, including a significant trough underlying DeVicq Glacier and evidence for extensive glacial erosion. Using these data, we produce a new map of subglacial topography, with which we model the sensitivity of WAIS to a warming ocean using the ice-sheet model of Pollard and DeConto (2012b). We compare the results to estimates of ice loss during WAIS collapse using the previously defined subglacial topography, to determine the impact of the newly discovered subglacial features. Our results indicate that the topographic changes are not sufficient to destabilize the northern margin of MBL currently feeding the Getz Ice Shelf; the majority of ice loss occurs from flow toward the Siple Coast. However, despite only slight dynamic differences, using the new bed as a boundary condition results in an additional 8 cm of sea-level rise during major glacial retreat, an increase of just over 2%. Precise estimation of past and future ice retreat, as well as a complete understanding of the geologic history of the region, will require a higher resolution picture of the bed topography around the Executive Committee mountains.

1. Introduction

Modern Antarctic ice-sheet behavior is influenced strongly by the ocean. As a result, understanding grounding line dynamics and the present state of the ice-sheet margin has been one of the primary research interests of the glaciological community. Recent studies have shown that the initiation of ice retreat from the Amundsen Sea Embayment has already begun (Joughin et al., 2014; Mouginot et al., 2014). With unstable retreat apparently now underway, researchers must turn their attention to the morphology and dynamics of the ice-sheet interior to determine the full extent of the risks posed by West Antarctic collapse.

The bed of the West Antarctic Ice Sheet (WAIS) is characterized by deep interior basins and trenches. These are flanked by regions with topography well above sea level, which are exposed as nunataks (Ross et al., 2014). Marie Byrd Land (MBL) is arguably the most prominent of these highland regions (Fig. 1). Cenozoic volcanoes pierce the ice surface (LeMasurier and Rex, 1989), providing easy access to the rock that underlies this part of WAIS. Away from the nunataks in MBL, however, our understanding of the composition and structure of the bedrock is poor. In this study, we use new radar data to supplement previous geophysical studies of the region and produce an improved bed topography for MBL. This new topography reveals previously unrecognized features near the Executive Committee Mountains and under DeVicq Glacier which have potential implications for ice-sheet behavior during WAIS retreat.

Understanding the subglacial topography of Antarctica is important for a number of reasons: the geometry of the bed is used to infer the tectonic history (Behrendt et al., 1991; LeMasurier et al., 1996) and paleotopography of the region (Wilson and Luyendyk, 2009; Vaughan et al., 2011; Jamieson et al., 2005), and is used to constrain modern gravity (Jordan et al., 2009; Muto et al., 2013; Riedel et al., 2012) and passive seismic surveys (Chaput et al., 2014; Winberry and Anandakrishnan, 2004). The bed is also a critical boundary condition for ice-sheet modeling (Hutter, 1982; Holt et al., 2006; Vaughan et al., 2006), with certain geometries

---

* Corresponding author. Tel.: +1 701 367 7472.
E-mail address: ndh147@psu.edu (N. Holschuh).

http://dx.doi.org/10.1016/j.epsl.2014.10.034
0012-821X/© 2014 Elsevier B.V. All rights reserved.

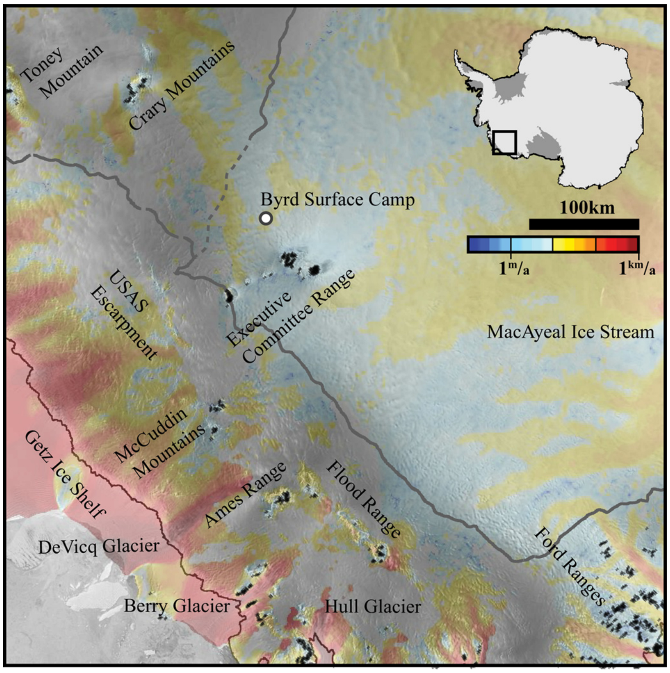

Fig. 1. Radarsat imagery of Marie Byrd Land (Jezek and RAMP Product Team, 2002) with rock exposures marked in black (Fretwell et al., 2013). MEaSURES ice velocities (plotted on a logarithmic scale) are provided to highlight the glaciers in the region (Rignot et al., 2011), with major ice divides in grey (modified from Zwally et al., 2012). Geologic and glaciological features discussed by name are labeled.

thought to precipitate unstable retreat of the ice (Weertman, 1974; Schoof, 2007). As a result, comprehensive seismic and radar surveys of the ice sheet are essential to both our geologic and glaciological understanding.

Prior to 1998, geophysical coverage of MBL consisted of data from only two International Geophysical Year traverses (Bentley and Chang, 1971) constraining the bed topography over ~150,000 km^2 (Fig. 2A). Much of our understanding of Marie Byrd Land was developed from geological and geochemical studies of the MBL nunataks. Structural studies found widespread block faulting in the region (LeMasurier et al., 1996). Correlation of a mid-Cretaceous erosional surface highlights the motion on these faults, indicating relative uplift around the Executive Committee Range (Hole and LeMasurier, 1994; Rocchi et al., 2006). Geochemical studies of the MBL volcanoes originally referred to the region as a unified volcanic province, but later studies found that complicated migration of magmatism through the region had contributed to geochemically distinct volcanoes (LeMasurier and Rex, 1989). The magmas show consistent alkaline character suggestive of a plume origin, and plumes are known to cause crustal doming (Hole and LeMasurier, 1994). The widespread volcanism, correlated erosional surface, and (poorly constrained) topographic high, led to the characterization of the “Marie Byrd Land Dome.”

Any topographic evidence for a dome has largely or completely been eroded, as shown by new data. In the 1998/99 field season, airborne radar surveys were conducted over the Ford Ranges in Western MBL (Luyendyk et al., 2003), followed by comprehensive surveys of the Thwaites and Pine Island Glacier catchments in 2004/05 (Vaughan et al., 2006; Holt et al., 2006). The resulting topographies generated from these data are plotted in Figs. 2C and 2B respectively. Each new data set has further undermined the assumption that MBL is a continuous highland, highlighting errors in the previous topography as new subglacial troughs were discovered. These surveys consistently found ice thicknesses equal to or greater than previous estimates, indicating a pervasive historical bias for a shallow bed in Marie Byrd Land.

Errors in the topography could have large implications for our understanding of the collapse and regrowth dynamics of WAIS. Growth of the East Antarctic Ice sheet (EAIS) is comparatively well understood; deep-sea $\delta^{18}O$ records indicate Antarctic ice-sheet growth in the late Eocene (Zachos et al., 2001), likely starting with alpine glaciation in the Gamburtsev Mountains (Rose et al., 2013) and growing into a full EAIS by the Eocene–Oligocene transition (Barker et al., 2007). Evidence for the timing and mechanism of growth of the West Antarctic Ice Sheet is sparse. Some seismic evidence indicates persistent West Antarctic glaciation as old as ~25 Ma (Sorlien et al., 2007), yet evidence from glacial erosion in Marie Byrd Land suggests that extensive ice sheet glaciation like that associated with modern conditions was not established until ~15 Ma (Rocchi et al., 2006). There is, however, some consistency; current theories rely on high elevations in MBL as well as the Ellsworth–Whitmore Block for the initiation and growth of a grounded ice sheet (Bentley et al., 1960; Ross et al., 2014).

Early efforts to model Cenozoic ice sheet growth using realistic orbital and CO$_2$ forcings for the Eocene–Oligocene transition resulted in little to no ice on Marie Byrd Land (DeConto and Pollard, 2003). This is in part due to the naive Eocene topography used. The deep troughs that characterize much of the bed under the West Antarctic Ice Sheet exist in relatively young crust, formed as a result of rifting during the breakup of Gondwana between 105 and 85 Ma (Fitzgerald, 2002). In contrast, MBL has been tectonically stable for much longer, with crust dominantly 1–1.2 Ga in age (Handler et al., 2003). Several studies argue that crust produced by the West Antarctic Rift System was likely above sea-level before the erosion and thermal subsidence of the late Cenozoic (Wilson and Luyendyk, 2009; Wilson et al., 2012). Modeling efforts using these reconstructions as boundary conditions show that WAIS may have extended to the continental shelf at the Eocene–Oligocene transition just like the East Antarctic Ice Sheet, indicating that the dynamics are extremely sensitive to the land area above sea-level (Wilson et al., 2013). To understand the Eocene landscape (and therefore faithfully model the dynamics of WAIS growth) an accurate modern topography is required, as any errors present in our understanding of the modern propagate through the paleotopographic reconstruction process.

The geologic and glaciological studies of MBL cited above highlight the need for accurate imaging of the subglacial structure. In this paper, we present a geophysical data set collected in the 2009/10 Antarctic field season that significantly changes our understanding of the current Marie Byrd Land topography, and investigate the implications of a revised topography for ice-sheet dynamics in West Antarctica.

2. Basal topography

Because of widespread glacial cover, our understanding of the Antarctic bed is incomplete. Geophysical data coverage of Antarctica is, however, increasingly comprehensive; in the current state-of-the-art bed topographic data set, there are only three regions where the distance to the nearest data point exceeds 100 km: Princess Elizabeth Land, Southern Coats Land, and Marie Byrd Land (Fretwell et al., 2013). Geophysical surveys in these regions have the potential to discover major unresolved subglacial features, infilling what are currently vast, smooth sections of Bedmap2 with a better representation of the actual topography.

As described in the introduction, the initial attempts to produce a topographic map of the bed using geophysical data led to a picture much different from the one we have today. Figs. 2A–C show the progression of our understanding as currently defined by the literature, with each map (starting with Fig. 2A) showing the new data used to constrain the bed, and the resulting grid-