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Evaluating Marie Byrd Land stability using an improved basal topography

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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

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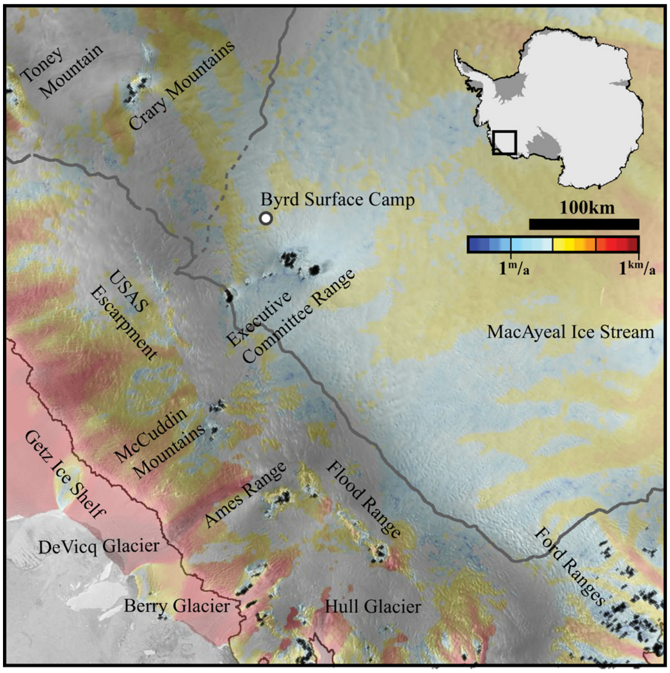

Fig. 1. Radarsat imagery of Marie Byrd Land (Jezek and RAMP Product Team, 2002) with rock exposures marked in black (Fretwell et al., 2013). MEaSURES ice velocities (plotted on a logarithmic scale) are provided to highlight the glaciers in the region (Rignot et al., 2011), with major ice divides in grey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

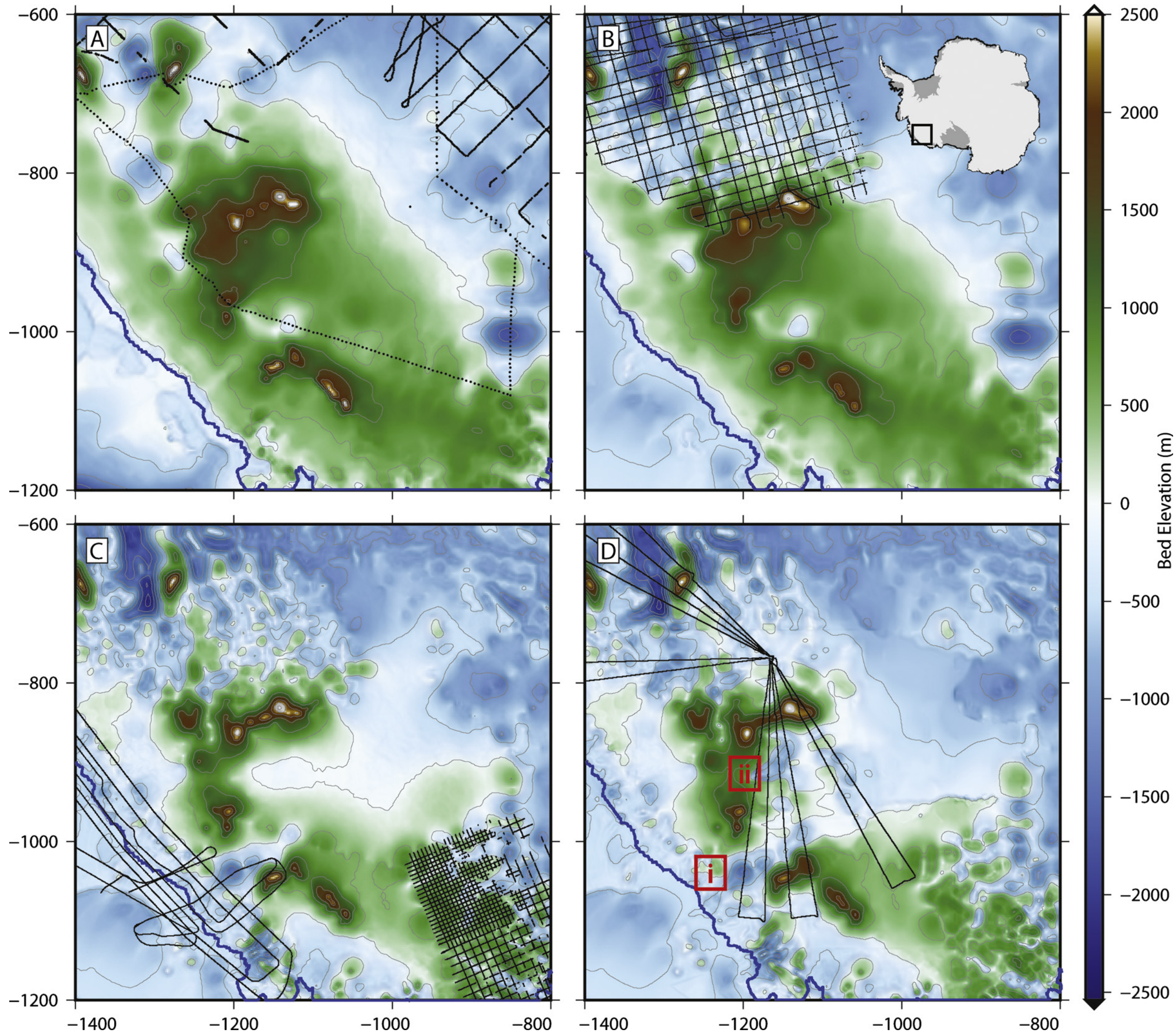

Fig. 2. Maps (A)–(D) illustrate our evolving understanding of Marie Byrd Land topography. Starting with (A), each map shows the location of new geophysical data in black, the updated topography contoured at 250 m intervals, and the modern grounding line in blue (Bohlander and Scambos, 2007). As more data are incorporated into the underlying grids, the inferred bed topography becomes deeper and more rugged, indicating discrete volcanic ranges as opposed to a regional dome. (A) shows the data from the 1959/60 IGY traverse as well as the NSF-SPRI-TUD surveys plotted in black, which were used to create the BEDMAP bed topography of Antarctica contoured behind (Lythe et al., 2001). Plotted in (B) are the AGASEA data collected over Thwaites and Pine Island Glaciers overlaying ALBMAP, the gridded bed topography those data generated (Vaughan et al., 2006; Holt et al., 2006; Le Brocq et al., 2010). (C) shows the 2009–11 Operation Ice Bridge data collected along the margin of the continent, the Western Marie Byrd Land grid flown in 1998–99 (Luyendyk et al., 2003), and the effect of enhanced interpolation methods used to produce Bedmap2 (Fretwell et al., 2013). (D) *shows the map generated by this study*, using the 2009–10 CReSIS radar data to update the bed topography between the Executive Committee and Flood Ranges. The two major features discussed in this paper are marked in red, where (i) is the DeVicq Trough and (ii) is the Executive Committee Basin.

ded topography produced with those data. The consistent trend across these maps is that new data always indicated a more incised bed than was previously estimated. The Marie Byrd Land plateau indicated by BEDMAP (Lythe et al., 2001) has disappeared in favor of isolated volcanic ranges. But even the most recent published bed topography (Bedmap2, Fretwell et al., 2013) has the Executive Committee Range, the USAS Escarpment, the McCuddin Mountains, the Ames Range, and the Flood Range connected by high basal topography, despite almost no geophysical data between them.

To fill the data gap in Marie Byrd Land, the Center for Remote Sensing of Ice Sheets (CReSIS) collected over 4600 km of airborne radar data during the 2009–10 Antarctic field season. Based out of Byrd Surface camp, the data were collected on a Twin Otter platform using the CReSIS Multi-Channel Coherent Radar Depth Sounder/Imager (MCCoRDS/I) with a frequency range of 140–160 Hz. We used an EM wave speed in ice of 168.5 m/μs to determine ice thickness, chosen using crossover locations between our data and the AGASEA data set (Holt et al., 2006; Vaughan et al., 2006). The relative range resolution for this radar system in ice is 5.6 m (Rodríguez-Morales et al., 2013); however, additional uncertainty introduced by surface and bed picks (∼15 m), firn correction (∼8 m), and in the dielectric profile of the ice (0.5% of ice thickness) results in ice thickness measurement uncertainties of ∼35 m (Dowdeswell and Evans, 2004). Using these data, we generated the bed topography in Fig. 2D.

The quality of the bed topography we produced is limited by the available data, but we believe it represents the best product currently available for this area of Marie Byrd Land. A simple, nearest-neighbor interpolation scheme was used; however, the large data gaps between lines (up to 40 km), and areas where there are no data (most notably between the Executive Committee Range and McCuddin Mountains), make any simple numerical scheme insufficient. In areas where our survey did not provide new information, we deferred to Bedmap2. In areas where our data overlapped surveys used in the previous topographies, the grid

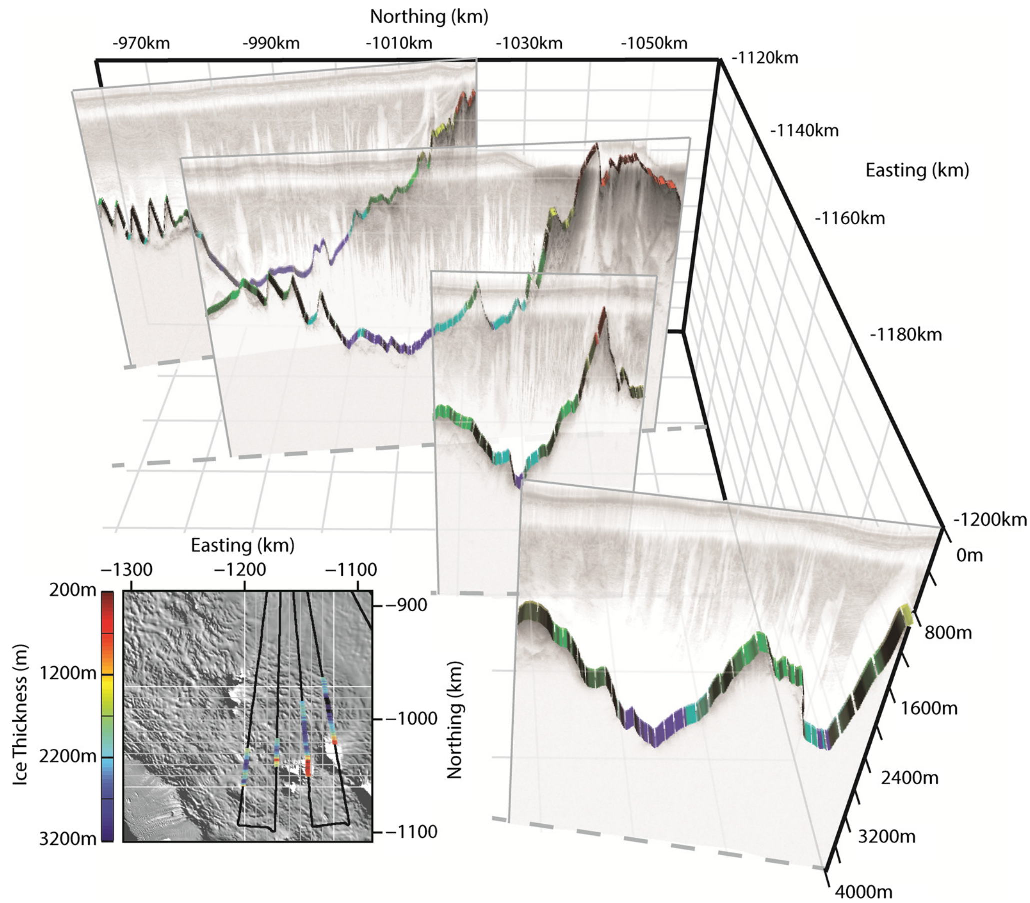

Fig. 3. 3D rendering of the radar profiles used to constrain the topographic trough underlying DeVicq Glacier, West Antarctica. Ice thicknesses are calculated using 168.5 m/μs as the radar wave speed in ice. The 2009–2011 Operation Ice Bridge data collected near the grounding line indicated the presence of a deep outlet; however, the size and inland extent of the trough were not well constrained previously.

was reinterpolated using all available data. Discretionary smoothing was performed to optimize the integration of Bedmap2 into sub-regions in which there were no geophysical data, subject to the condition that the resulting bed topography must be true to the collected data. Despite any limitations in its development, our new grid is faithful to all surveys, and highlights two dramatic features that are reasonably well-characterized in the new data and that deserve discussion in detail: the trough underneath DeVicq glacier, and the deep feature grid-south of the Executive Committee Range.

2.1. DeVicq Glacier

The most striking, and potentially important, feature discovered in these data is the trough underlying DeVicq Glacier (Fig. 2D.i). Fig. 3 shows the four radar profiles used to constrain the trough, and their relative orientation to the coast. Limitations in our interpolation scheme are responsible for the string-of-pearls look of the trough in plan view; additional data collected between the radar lines presented here will test the assumed continuity of the feature along its axis.

The deepest measured point in the trough lies between the Ames Range and McCuddin Mountains, where the bed is roughly 1000 m below sea level. The trough axis rises to 300 m below sea level at the grounding line. This trough is easily correlated between the individual radar lines, extending over 200 km inland from the Getz Ice Shelf. The current ice divide routes half of the ice in this trough toward the Getz Ice Shelf and ultimately the Southern Ocean, while ice to the south of the McCuddin Mountains flows south and west into the Ross Sea (Fig. 1). There is also a clear indicator of historic alpine glaciation in these data, seen on the most inland profile of Fig. 3, where several steep-walled U-shaped valleys appear to have been cut into the plateau adjacent to the McCuddin Mountains.

2.2. Executive Committee basin

The other notable feature in the data is the extremely deep basin (∼1 km below sea-level) immediately adjacent to the Executive Committee Range (Fig. 2D.ii). Satellite gravity data used in the production of Bedmap2 detected the trough, but the long-wavelength nature of the satellite data and the non-uniqueness of gravity inversion smoothed the feature over a much larger area. If the basin exists in the form presented by Fig. 2D, it likely indicates a period of alpine glaciation and overdeepening along the flanks of the Executive Committee Mountains. Alternatively, it is possible that this trough penetrates through the highland between the Executive Committee and McCuddin Mountains, where there are currently very few data. In order to better understand the geometry and historic flow regime of the ice on the Executive Committee Mountains, more geophysical data are required. As a result, the region between these mountain ranges should be a target for future data collection.

To determine the full implications of this new basal topography, we use it as a boundary condition for ice flow modeling in the next section.

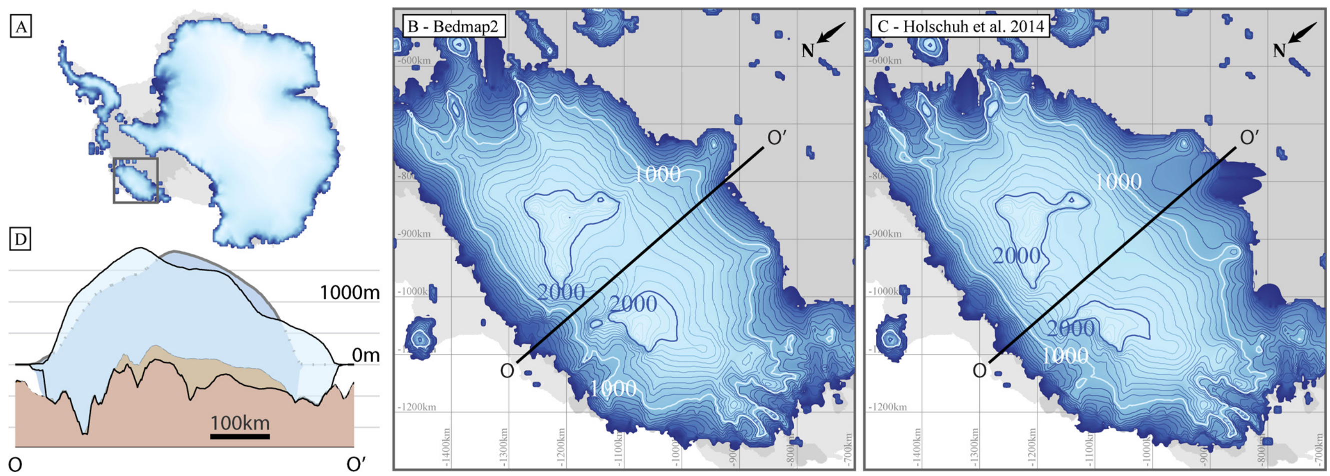

Fig. 4. Modeled ice surface elevations for the average continental run (A), the nested run using Bedmap2 as a boundary condition (B), and the nested run using the topography generated in this study as the boundary condition (C). Modeled ice surfaces (in blue) are contoured every 100 m and overlie shaded indications of the modern grounded (dark grey) and floating (light gray) ice areas. Cross-sections of the two modeled ice sheets along the DeVicq trough are provided in (D), with the cross-section from (B) behind (C). Despite complete loss of the Getz Ice Shelf, there is not significant retreat of the grounded ice along the ocean margin using either topography. The updated bed topography has a greater impact on ice dynamics on the southern side, lowering the steady-state ice surface elevation.

3. Model and experiment setup

Parametric uncertainties (Applegate et al., 2012) and variability in climate projections (Bindschadler et al., 2013) have been formally treated in model studies of the Greenland and Antarctic ice sheets, but uncertainty in the bed topography has been difficult to quantify. This is in part because models are often tuned using remote sensing data, adjusting basal friction and flow law parameters to recreate the relatively well surveyed ice surface (Pollard and DeConto, 2012a). As a result, errors in the bed can be offset by unrealistic values for other unknowns to reproduce the modern observations. While these confounding errors will result in a seemingly realistic spin-up, they are unlikely to result in accurate depictions of the past and future of the ice sheet.

Significant modeling work has been conducted for the West Antarctic Ice Sheet, indicating Marie Byrd Land has maintained a stable ice cap through the glacial/interglacial cycles of the Quaternary (Pollard and DeConto, 2009), and likely played a role in the initial glaciation of West Antarctica sometime during the late Eocene or Early Oligocene, although the exact timing and mechanism are still uncertain (Sorlien et al., 2007; Rocchi et al., 2006; Barker et al., 2007). The new bed topography derived in this study calls MBL stability into question, as the characteristics that result in WAIS collapse (a bed below sea-level with retrograde slope) are now found to extend deep into the Marie Byrd Land interior. Our experiment is designed to determine whether the evolution of the West Antarctic Ice Sheet as simulated by previous studies is correct (i.e. an ice-cap persists on MBL), or if our understanding of the extent of collapse and mechanism for regrowth needs to be revised in light of these new geophysical data.

Few models are well suited for problems of this scale; computational restrictions limit the time and spatial domains possible for higher-order models. As a result, we chose to use the model of Pollard and DeConto (2012b), which has demonstrated its ability to make long-term paleoclimatic runs for Antarctica (Mackintosh et al., 2011; DeConto et al., 2012; Gomez et al., 2013), and can provide direct comparison to the previous studies of WAIS referenced above (Pollard and DeConto, 2009; Deconto et al., 2008). The ice dynamics in this model are a combination of (i) internal shearing flow (Shallow Ice Approximation, SIA) for grounded ice, and (ii) stretching flow (Shallow Shelf Approximation, SSA) for ice shelves, coupled using a boundary-layer treatment of ice flux across grounding lines after Schoof (2007) that captures grounding-line migration reasonably accurately without very fine resolution in the grounding zone (e.g., Gladstone et al., 2010, 2012). The model for bedrock deformation beneath grounded ice follows Huybrechts and de Wolde (1999) and Ritz et al. (2001), with local asthenospheric relaxation towards isostasy below an elastic plate representing non-local lithospheric deformation. The model has no explicit basal hydrology, and sets basal sliding velocity to zero where the basal temperature is sufficiently below the pressure melting point.

The experiment is conducted in three steps for each bed topography examined:

1. An inversion is performed by the methods of Pollard and DeConto (2012a) from the bed topography and ice surface elevations to determine the basal sliding coefficients for each of the 40 km grid cells that make up our continental domain.
2. Full Antarctic runs are performed using a 40 km grid and the basal sliding coefficients from step 1 to calculate the steady-state ice sheet under modern climate conditions, and under a West-Antarctic-collapse scenario (ocean temperatures 2 °C above modern, chosen as a realistic collapse temperature from paleo-oceanic reconstructions (Dowsett et al., 2009)).
3. The coarse continental runs provide boundary conditions for a higher resolution (5 km) nested run over MBL, in an effort to resolve the effects of smaller scale features including the newly discovered DeVicq trough.

4. Model results

By increasing the mean ocean temperature 2 °C, most of WAIS thins, accelerates, and retreats. This results in the open sea-way spanning the Weddell, Amundsen, and Ross Seas (Fig. 4A). The continent-wide model runs produce nearly identical ice configurations for the regions outside of MBL, indicating no large changes in the dynamics of the system.

Fig. 4B–C present the final, steady-state ice surface over Marie Byrd Land generated by the nested model runs. Fig. 4B shows the results when using Bedmap2 as a boundary condition while 4C is the ice surface generated using our bed topography. The large features of the system are quite similar; kilometer-thick ice persists over the majority of the region. Retreat from Thwaites Glacier evacuates ice from between Toney Mountain and the Crary Mountains, where an ice tongue and glacier remain post-collapse. For both topographies the Getz Ice Shelf is lost, but there is no significant retreat of the grounding-line along the former shelf boundary. The primary differences between Figs. 4B and 4C can be seen on the south side of the remaining ice cap.

A subglacial peak south of the Executive Committee Mountains stabilizes the retreat of the ice sheet. This region is fed by ice flowing between the region spanning the Executive Committee and Flood Ranges, the broadest area of change between the two bed topographies. As indicated by Fig. 4D, the average ice-surface elevation is lower in this region when using the deeper bed we present here as a boundary condition, but the overall ice area is lower when using Bedmap2. This is due to dynamic effects of a deeper bed: the thicker ice has a higher driving stress, carrying away ice from the interior of the continent and drawing down the ice surface. This faster flowing ice is able to ground at a subglacial ridge farther away, expanding the overall ice area despite maintaining a similar volume.

In Fig. 4C a prominent ice tongue flows grid east toward the present day Ross Ice Shelf, with ice velocities greater than 100 m/a extending over 200 km into the interior. In contrast, ice velocities are much slower in this region when using Bedmap2, with velocities dropping below 100 m/a less than 50 km from the ice margin. When modeling the ice cap using our bed topography, the increased ice thickness results in higher southward driving stress through the ice cap interior. To bring the system into balance, there is a forced steepening and migration of the divide toward the DeVicq grounding line.

Changes to the topography of the DeVicq Glacier trough posed a significant potential threat to MBL stability. We observe that 2 °C of ocean warming is insufficient forcing to drive DeVicq Glacier back into the imaged portion of its trough. Even when modeled with a 4 °C ocean warming, dynamic retreat did not occur. As indicated in Fig. 4D, the post-collapse grounding line is downstream of the major overdeepening. This suggests that even if we better image the trough in the ice sheet interior, it will likely have little impact on our predictions of the long-term stability of the region. We do see a difference in the ice thickness and flow velocities here, with a steeper ice profile generated using the updated bed; however, this is mostly due to dynamic changes on the southern margin.

In total, our model results predict greater sea level rise when using the updated bed topography, with a difference between the two predictions of 8 cm. When using Bedmap2 as a boundary condition, there was a total of 3.35 m of sea level rise after WAIS collapse, while the new topography resulted in 3.43 m.

5. Discussion

With the new understanding that much of the ice in Marie Byrd Land rests below sea-level, we hypothesized that a warmer ocean would drive the ice margin deep into its interior; however, our modeling suggests otherwise. One of the instability criteria described by Weertman (1974) has a retrograde slope. When the ice reaches a critical thickness at the grounding line, there is a greater ice flux to the ocean than there is supplied to the grounding line, leading to drawdown of the ice surface and retreat of the grounding line. For a retrograde bed (one that deepens upglacier), ice retreat *must* result in thicker ice at the grounding line, increasing the ice flux and driving further retreat. For prograde slopes, retreat means thinner ice at the grounding line. Therefore, with a prograde bed, retreat of the ice will eventually lead to grounding line thicknesses below the critical value for dynamic retreat, and the ice sheet will stabilize.

While the trough under DeVicq glacier is a major feature of the subglacial landscape, the deepest part of its bed is upstream of the grounding line. The thickness of the ice at the grounding line (and therefore the ice flux) is not sufficient to drive retreat into the imaged overdeepening. Therefore, the trough geometry (in the form presented by this study) will not destabilize the ice cap spanning the McCuddin Mountains and the Flood Range. Loss of the Getz Ice Shelf would have large local effects on the ice velocities of the Glaciers flowing into the Southern Ocean, but DeVicq glacier would remain intact. We found that the region around DeVicq maintains a stable configuration even with 4 °C ocean warming, indicating that no reasonable ocean forcing can force DeVicq retreat using the physics of this model. Marie Byrd Land is instead more sensitive to topography changes near the Siple Coast ice streams, where we see significant ice loss during WAIS collapse.

Our bed topography also provides new geologic insight into the region. According to Rocchi et al. (2006) there is a notable change in the elevation of the correlated erosional surface between the Ames Mountains and the McCuddin Mountains. This likely indicates the presence of a fault, which would most likely be colocated with the DeVicq trough. There is, however, no significant elevation change in this surface between the USAS escarpment, Executive Committee Range, and McCuddin Mountains. This corroborates the idea that the deep feature we referred to as the Executive Committee Basin is erosional and not tectonic in origin. We further note that the highlands of MBL appear to have experienced extensive erosion by alpine glaciation, creating spectacular valleys that are still preserved in places, akin to those reported for the Gamburtsev Mountains (Rose et al., 2013).

The results of this study should provide guidance for future geophysical surveys of the region. Flights along the DeVicq trough axis would provide a more complete picture of its length and depth. A grid to the west of the Executive Committee Mountains would better define the region where we saw the greatest change in model results. This would also better resolve the hanging valleys we see near the DeVicq trough that are probable indicators of alpine glaciation. Finally, a survey to determine the southern extent of the Executive Committee Basin would help to better understand this feature, and determine to what degree it separates the Executive Committee Mountains from the USAS escarpment and McCuddin Mountains.

6. Conclusions

Notable uncertainties exist in the basal topography of many parts of Antarctica, and are not explicitly accounted for in assessments of ice-sheet stability. These uncertainties were previously as large as 1000 m in Marie Byrd Land (Fretwell et al., 2013), and yet their implications for projections of future sea-level rise were not evaluated. Predicted ice losses in stable regions like MBL scale with the depth of the bed, so systematic underestimation of ice thickness results in consistently low estimates of long term sea-level rise. As a result, accurate bed elevations are required everywhere to quantitatively model the future of the West Antarctic Ice Sheet, not just regions susceptible to the marine ice sheet instability.

We show that, despite the presence of previously unknown deep features near the Executive Committee Mountains and a pronounced trough under DeVicq glacier, the ice cap on Marie Byrd Land is stable under forcing sufficient to deglaciate the deep interior basins of WAIS. The MBL ice is relatively insensitive to our prescribed changes in the bed. While these results do not dramatically change our understanding of West Antarctic dynamics, they provide renewed confidence in previous modeling efforts, and refine our estimates of sea-level rise in response to a warming ocean.

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