East Antarctic Ice Sheet bed erosion indicates repeated large-scale retreat and advance events.

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With changing climate, ice sheet retreat and advance is a major source of sea-level change, but our understanding of this is limited by high uncertainties. In particular, the contribution of the East Antarctic Ice Sheet (EAIS) to past sea level change is not well defined. Several lines of evidence suggest possible collapse of the Totten Glacier catchment of the EAIS during past warm periods, in particular, during the Pliocene⁴−⁷, causing a multi-meter contribution to global sea level. However, the large-scale structure and long-term evolution of the ice sheet have been insufficiently well known to constrain retreat-advance extents in this region. Using aerogeophysical data⁵−⁶ we define the erosion of the ice sheet bed as an indicator of past ice sheet activity. We show that deep erosion exposing basement rocks is restricted to two regions: the head of the Totten Glacier, within 150 km of the present grounding line; and deep within the Sabrina Subglacial Basin, 350-550 km from the present grounding line. These regions demarcate the marginal zones of two distinct quasi-stable EAIS configurations corresponding to modern-scale and retreated ice sheets. Despite experiencing both regimes, the 200 to 250 km broad transitional region between the two is less eroded, suggesting a shorter-lived exposure to eroding conditions. Limited transition-zone erosion is well explained by repeated retreat-advance events driven between the quasi-stable states by ocean-forced instabilities. Representative ice sheet models indicate that the global sea-level increase from retreat in this sector can be up to 0.9 m in the modern-scale configuration, and is in excess of 2 m in the retreated configuration.

Satellite-based observations indicate that the margin of Totten Glacier may be experiencing greater ice loss than anywhere else in East Antarctica⁷−⁸. This, coupled with the presence of the 1.5 km deep Aurora Subglacial Basin upstream, means Totten Glacier and its drainage basin may be at risk of substantial ice loss under ocean warming conditions. Vulnerability of this region to change may be driven by access of warm modified circumpolar deep water to the ice-shelf cavity. At decadal timescales this access is controlled by a combination of polynya activity and bathymetric constraints⁹−¹⁰. Recent studies indicate that potential access pathways exist to access the cavity beneath the Totten Ice Shelf¹¹.

Totten Glacier also possesses an inland ice stream that extends far into the continental interior. This ice stream mostly overlies the Sabrina Subglacial Basin (SSB), which is a bowl-shaped depression bounded to the east by the Terre Adelie Highlands, to the south by Highland C and to the west by Highland B (Figure 1). The
SSB is underlain by an extensive sedimentary basin (the SSSB) of moderate but quite variable thickness (Figure 1c). This basin probably dates back to at least 40 Ma\(^6\), and therefore predates glaciation. Perhaps because of this sedimentary basin, this region has widely distributed subglacial hydrology\(^{12}\) and little large-scale topographic relief\(^{6,12,13}\), although the surface is quite rough at shorter wavelengths\(^{12}\).

Here we use geophysical data from the ICECAP program (extended data Figure 1) to define the erosion of the SSB due to the activity of the East Antarctic Ice Sheet (EAIS). We use 2D gravity modelling along flight lines, also including depth to magnetic basement estimates, to understand the thickness of sedimentary rocks in the SSB region. Representative ice-sheet models support the interpreted erosion regimes and provide complementary estimates of global sea level change.

**Figure 1: Interpretation of erosion in the Sabrina Subglacial Basin region:**

- **a)** Base-ice elevations. Data from ICECAP (bold) and Bedmap\(^{214}\) (muted). The Sabrina Subglacial Basin is the low-lying region bounded by Highland B, Highland C and the Terre-Adelie Highlands. VF – Vanderford Glacier; CG – Cape Goodenough.
- **b)** SSSB thickness (km) derived from gravity modelling. The SSSB is the centrally located basin of moderate thickness. Much thicker sedimentary basins occur in the Aurora Subglacial Basin and Vincennes Subglacial Basin (VSB).
- **c)** From these datasets we interpret regions of
differing erosion characteristics for the SSB. See text for further details of these regions. Inset shows the
study area location.

The gravity model results show the SSSB to extend southeast from the Totten Glacier for over 500 km. Its
base is as deep as -4000 m elevation (Figure 1b), but is typically much shallower. The basin base is tilted
towards the south or southeast, although several east-northeast oriented faults define smaller-scale
perturbations (Figure 2). Allowing for the subglacial topography (Figure 1a), the thickness of the SSSB is
defined (Figure 1c). The results suggest an initially broad and generally flat-based geometry, with a probable
pre-erosion thickness of approximately 3 km. Error analyses (Figure 2, extended data Figures 2, 4-7) indicate
the modelled SSSB thickness error is approximately ±500m. The ASB and VSB have larger uncertainties, up
to 2 km, and erosion patterns are not interpreted within these basins.

The thickness of the SSSB (Figure 1c) shows high variability within tectonic blocks; and also transgressions of
major tectonic structures (see extended data Figure 3, extended data Figure 8) and does not parallel the
tectonic structure of the region. Rather, the SSSB thickness defines distinct patterns that relate to the
erosion of the SSB by the East Antarctic Ice Sheet.

Glacial erosion occurs due to basal-sliding, which requires warm-based ice and a sufficiently high basal shear
stress to cause motion, and erosion-rate is primarily dependent on the basal velocity of the ice sheet. Regions with high erosion potential are typically found near the margins of an ice sheet, and may be
selective or distributed. Under selective erosion, deep troughs occur in regions with high lateral
convergence of ice flux, as well as high basal-velocity. These convergent zones are often topographically
focused within pre-existing valley systems. Thinner ice promotes stronger selective erosion because
highlands are often cold-based and are protected from erosion. The same highlands may be warm-based
under thicker ice cover. As a consequence, larger ice sheets are more likely to exhibit distributed erosion,
whereas smaller ice sheets are more likely to exhibit selective erosion.

For the SSB we interpret several regions of distinctive erosion (Figure 1d) that define two distinct quasi-
stable EAIS configurations. We identify a modern-scale configuration, with a marginal zone near the present-
day margin, and a retreated configuration, with a marginal zone located far inland. These configurations are
not time specific, although global climate and sea-level data suggest a retreated ice sheet was dominant in
the Oligocene to mid-Miocene, with a modern-scale ice sheet dominant since the mid-Miocene.

Cumulative glacial erosion is generally low in elevated coastal regions, including Law Dome, the Knox Coast
and the Cape Goodenough region. Erosion is also low on the highlands surrounding the SSB and ASB. Ice
sheet models suggest that the coastal highlands are either covered with slow-moving ice, or are ice free
(Figure 3; Extended data figure 9). Highlands A and C, the upper part of Highland B, Ridge B and Dome C
remain ice covered in all models, and it is likely that these highlands were also covered by the early ice sheet

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Figure 2: Gravity model along flight line R06Ea (location, Figure 1b). a) Observed and calculated gravity data, including model components from ice and topography, the deep crust and Moho, and the sedimentary basins. b) The model, also showing prior depth to magnetic basement estimates, the tensioned spline fit, and cross-ties with other models. The gravity disturbance was modelled at true observation elevations as indicated by the uppermost grey line c) SSSB thickness and current surface ice velocity (vertically flipped). Average error in ice sheet velocity on this line is 10.5 m/yr \(^{18}\). A|B, B|C and C|HC (HC-Highland C) indicate the locations of the boundaries demarcated in Figures 1 and 3. Note the thin to absent basin downstream of A|B, the sloped base from A|B to B|C, and the anti-correlation between basin thickness and ice-sheet velocity. Dashed lines indicate the inferred prior 3 km thickness of the SSSB, which has been almost entirely removed in Region A, and eroded in line with present-day ice velocity in Region B. See extended data figures 4 through 7 for additional representative models throughout the SSB region.

Region A surrounds the coastal glaciers, and is typified by a broad region with moderate elevation, cut by a number of smaller channels that are aligned with modern ice sheet flow (Figure 1a). The SSSB thickness is nil for much of Region A and rarely exceeds 1 km (Figure 1c). The A|B boundary is located near a topographic ridge that extends WSW from Cape Goodenough. The ridge is at ca. -200 m elevation, but is cut by channels...
as deep as -600 m elevation (Figure 1a). The ice-sheet bed within region A is ocean-sloping, with an average measured gradient along flight lines of +2 to +4 m/km.

Region B is defined by an almost linear inland-thickening trend to the base of the SSSB, with an upstream limit defined where this thickening trend ceases to be evident. Over ca. 200-250 km, the thickness of the SSSB increases in co-variance with the reduction in ice sheet velocity (Figure 2 and extended data Figures 4-7).

Non-selective and inland-reducing erosion within regions A and B points to the activity of an ice sheet with a modern-scale configuration. Under current climate conditions our ice sheet model indicates high basal velocities within Region A (extended data Figure 9a). With an air temperature, $dT_a=+4$°C and an ocean temperature, $dT_o=+1$°C, the model indicates a retreat of the ice sheet margin to the A|B boundary, with high basal velocities mostly within Region B (Figure 3a). These results indicate a history of repeated smaller-scale retreat and advance cycles within Region A. These are likely orbitally forced, with a typical length-scale of less than 200 km, and do not invoke collapse.

Region B comprises two subregions. Subregion B2 preserves only the modern-scale ice sheet erosion signature, and the SSSB is typically over 2 km thick. In Subregion B1, the SSSB is typically 1-2 km thick and, in addition to the modern-scale ice sheet signature, a muted dendritic pattern is evident (Fig 1). The ice sheet bed in Subregion B1 is beneath sea level and typically inland-sloping, with an average gradient of -1 to -3 m/km. Therefore, once the topographic ridge at the A|B boundary is reached, retreat into the inland SSB is subject to ocean-driven instabilities.

Ocean-driven instabilities include the marine ice sheet instability (MISI), moderated by ice-shelf buttressing, and ice-cliff failure augmented by hydrofracturing. From a modern-scale configuration, highly unstable ice sheet reconstructions for the Pliocene, especially those including ice-cliff failure, can breach the A|B boundary. Under similar climate conditions, more stable reconstructions typically fail to breach this boundary. This suggests that a significant degree of ice-sheet instability is necessary to cause retreat into the SSB interior under Pliocene conditions.

Following retreat into the SSB interior, a new ice sheet margin is established in front of Highlands B and C, in a more advanced location than a previous interpretation of the early ice sheet. Region C (Figure 1) is characterised by a well-developed dendritic erosion pattern, with sufficient erosion to expose basement. This region is consistent with the occupation of a fluvial valley network by a smaller-scale ice sheet. Highland C and the Terre Adelie Highlands are significant topographic highs extending well above sea level. Average measured gradient on their frontal slopes is ~+2.5 m/km. Consequently, these highlands are persistent barriers to further ice sheet retreat, even under highly unstable conditions.

Highland B, however, is pierced by three deep fjords providing access to the Aurora Subglacial Basin (ASB). This additional vulnerability limits the residence-time of an ice margin in front of Highland B and permits ice sheet retreat into the ASB. The B|C boundary links to the central fjord, suggesting that this fjord is the most significant for facilitating further collapse.

The erosion characteristics of regions B1 and C point to the activity of a retreated ice sheet. With $dT_a=+8$°C and $dT_o=+2$°C (Figure 3b) the ice sheet margin retreats to Subregion B1, with high basal velocities mostly within Subregion B1 and Region C. With $dT_a=+12$°C and $dT_o=+5$°C further retreat to the B|C boundary is indicated, with only Region C of the SSB being ice covered (Figure 3c). This retreat scenario is similar in
extent to a previous interpretation of the early ice sheet, prior to advance into the SSB, although the locations of the ice margins differ in location. With $dT_a=+15^\circ C$ and $dT_o=+5^\circ C$ full retreat into the ASB is indicated (extended data Figure 9b), with ice coverage only on inland highlands. This retreat scenario is somewhat more extensive than a previous interpretation of the early ice sheet, prior to advance into the ASB.

**Figure 3: Ice sheet models with differing climate forcing.** Ice sheet models showing ice sheet surface and bed elevations and basal velocity contours. Models were run with air ($dT_a$) and ocean ($dT_o$) temperatures above today’s. Sea level contributions including ice mass loss and isostatic rebound are estimated for all Antarctica ($dV_a$) and for the SSB/ASB sector ($dV_l$), indicated by the green area (inset). With $dT_a=+4^\circ C$ and $dT_o=+1^\circ C$ (a) the ice sheet margin is located near the A|B boundary and high basal velocities are focused in region B. With $dT_a=+8^\circ C$ and $dT_o=+2^\circ C$ (b) the ice sheet margin is located in region B and high basal velocities are focused in regions B1 and C. With $dT_a=+12^\circ C$ and $dT_o=+5^\circ C$ (c) the ice sheet margin is located near the
B|C boundary and high basal velocities are focused in region C and the ASB. Additional models are shown in extended data figure 9.

Overall, SSB erosion points to large periods of time with a modern-scale ice sheet, with similar structure to todays, and also large periods of time with a retreated ice sheet. Despite experiencing both regimes, Subregion B1 is less eroded than both regions A and C, suggesting that less time has been spent transitional between the two states. Thus, although Highland B is a significant barrier, retreat of the EAIS into the ASB is necessary to explain our observed erosion, and is a characteristic of a fully retreated ice sheet.

There is no direct evidence in the erosion record for Pliocene ice-sheet retreat events at Totten Glacier. Ice-rafted detritus from ODP site 1165 at Prydz Bay includes a detrital signature that matches closely both the detrital record in Totten-proximal sediment cores and the predicted basement geology of Region A. This suggests basement rocks were being eroded in Region A at 7 Ma and at 3.5 Ma. Therefore, the modern-scale ice sheet has been a regular feature of the EAIS at Totten Glacier since well before 7 Ma.

Nonetheless, a significant retreat here may be necessary to generate a sufficient EAIS contribution to Pliocene sea-level highstands of up to 20 m above present. Our representative ice sheet models provide guidance as to the contribution of this sector to global sea level, although it is important to note that different ice sheet models will resolve these pinning points with differing amounts of sea level contribution. In addition, transient effects, including the lag-time between ice removal and isostatic response, may generate short-term sea level fluctuations that we do not consider here.

With the bi-stable EAIS configurations we have defined, any Pliocene retreat event was likely restricted to within Region A (<150 km retreat from present) or involved over 350 km of retreat. A stable long-term ice sheet margin in the intervening zone is less likely, excepting transient pinning at Highland B. Numerical models suggest this transient period in front of Highland B may persist for several thousand years.

The largest retreat under the modern-scale ice sheet configuration (Figure 3a) is associated with a total Antarctic contribution to global sea level of 8.39 m, of which the SSB/ASB sector provides 0.89 m. Allowing for 7.3 m of sea level rise obtained from complete collapse of the Greenland ice sheet, this is insufficient to explain a 20 m highstand.

The retreated ice-sheet models (Figures 3b and 3c) are associated with a total Antarctic contribution to global sea level of 16.5 m and 21.5 m respectively, of which the SSB/ASB sector provides 2.18 m and 2.89 m respectively. Full retreat into the ASB (extended data Figure 9b) is associated with a total Antarctic contribution of 29.1 m, with 4.29 m being sourced from the SSB/ASB sector.

Therefore, the influence of Totten Glacier instability on global sea level is clearly significant, but for any particular warm period, it is also highly uncertain and subject to progressive instability. Our results suggest that the first discriminant is the development of sufficient retreat to breach the A|B boundary ridge. This causes an instability-driven transition from the modern-scale configuration to the retreated configuration. Under ongoing retreat, the breaching of Highland B causes further collapse into the ASB. Each of these changes in state is associated with a significant increase in both the absolute and proportional contribution of this sector to global sea level.

METHODS * To be redone*
Collection, processing, imaging, availability

GRAVITY MODELLING

UNCERTAINTIES ASSOCIATED WITH GRAVITY MODELLING

ICE SHEET MODELLING

CODE AVAILABILITY

The ice sheet surface and base were derived from laser and radar sounding as described in earlier ICECAP publications, interpolated by kriging. Gravity modelling used the Free-Air gravity anomaly corrected for latitude, instrument drift, elevation, aircraft kinematic accelerations and the Eötvös Effect. Modelling along flight lines used an iterative combination of forward modelling and inversion using a commercial two-dimensional code based upon the principles of Talwani. This code can successfully model 1D and 2D structures, but not complex 3D structures. Our approach is valid for the ice sheet surface and the SSSB base, but some topographic features are three-dimensional in form and cause localised errors. Only relative gravity differences can be modeled, and results were levelled to a common baseline. Cross-line differences were reduced by applying a constant value to a tensioned spline fit through the basin base on each line so as to minimise the misfit between that line and all cross-ties. Median cross line difference is 200 m, and the arithmetic mean is 300 m, with the highest values associated with rugged topography, certain flight lines, and the deepest basin regions. The central Sabrina Subglacial Basin provides consistently low cross-line differences (Extended Data Fig. 2). We imposed the following density structure: Ice sheet density 920 kg m\(^{-3}\), crystalline basement density 2670 kg m\(^{-3}\), lower crust density 2800 kg m\(^{-3}\), mantle density 3200 kg m\(^{-3}\). Sedimentary rock density was varied between a lower limit of 2200 kg m\(^{-3}\) and an upper limit of 2500 kg m\(^{-3}\) to create the ranges of sediment thickness shown in Fig. 2c and extended figures 4b-7b. The former was based on a reasonable maximum porosity of 25% given the thickness of ice and likely age of the rocks; the latter was defined by the limit where basin thickness departs considerably from magnetic depth to basement estimates. This uncertainty is the error shown in Figure 2. It varies linearly and predictably with density contrast, and has no influence on the pattern of basin thickness, only the magnitude. The Moho and a 13 km thick lower crust were defined by a flexural model that accounts for ice and topographic loads. An elastic thickness of 25 km was used, although due to the long-wavelength of the loads involved little variation in Moho structure is observed between 10 km and 50 km elastic thickness.

REFERENCES


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AUTHOR CONTRIBUTIONS

ARAA undertook data processing, analysis and modelling and wrote the paper. JLR, TVO, MJS, DAY, DDB, JSG coordinated the field program and/or undertook data collection, quality control and processing. N.R.G. Conducted the ice sheet modelling. All Authors contributed significantly to interpretation, discussion and manuscript preparation.
Extended Data Figure 1: Geophysical Data in the study region. Free-air gravity data (a) and magnetic intensity (b); also showing interpreted basement faults.

Extended Data Figure 2: Model intersection misfits for the gravity models. The dots show the tensioned spline fit after levelling. Levelling applied a constant value to each line to achieve optimal least-squares fit to the cross-ties.
Extended Data Figure 3: SSSB base morphology. This map also shows basement faults (thick dashed), and the locations for line R06Ea and additional representative model profiles along Y07b (Extended Data Figure 4), R03Ea (Extended Data Figure 5), R08Eb (Extended Data Figure 6) and GL0092a (Extended Data Figure 7).

Extended Data Figure 4: Gravity model along flight line Y07b (location, Extended Data Figure 3). a) Observed and calculated gravity data, including model components from ice and topography, the deep crust and Moho, and the sedimentary basins. b) The model, also showing depth to magnetic basement estimates, the tensioned spline fit, and cross-ties with other models. c) SSSB thickness and current surface ice velocity (flipped). Average error in ice sheet velocity on this line is 8.4 m/yr$^{18}$. 
Extended Data Figure 5: Gravity model along flight line R03Ea (location, Extended Data Figure 3). Observed and calculated gravity data, including model components from ice and topography, the deep crust and Moho, and the sedimentary basins. b) The model, also showing depth to magnetic basement estimates, the tensioned spline fit, and cross-ties with other models. c) SSSB thickness and current surface ice velocity (flipped). Average error in ice sheet velocity on this line is 9.7 m/yr$^{18}$. TAH - Terre-Adelie Highlands.
Extended Data Figure 6: Gravity model along flight line R08Eb (location, Extended Data Figure 3).

Observed and calculated gravity data, including model components from ice and topography, the deep crust and Moho, and the sedimentary basins. b) The model, also showing depth to magnetic basement estimates, the tensioned spline fit, and cross-ties with other models. c) SSSB thickness and current surface ice velocity (flipped). Average error in ice sheet velocity on this line is 8.6 m/yr\(^{18}\). HC - Highland C.
Extended Data Figure 7: Gravity model along flight line GL0092a (location, Extended Data Figure 3).

Observed and calculated gravity data, including model components from ice and topography, the deep crust and Moho, and the sedimentary basins. b) The model, also showing depth to magnetic basement estimates, the tensioned spline fit, and cross-ties with other models. c) SSSB thickness and current surface ice velocity (flipped). Average error in ice sheet velocity on this line is 10.6 m/yr$^{18}$. ASB - Aurora Subglacial Basin.
Extended Data Figure 8: Gravity models including basement density variations. a) line R03Ea, b) line R06Ea, c) line R08Eb. The models involve an attempt to generate the flattest basin topography with block-scale density contrasts. Long-dashed dashed lines indicate major faults. The dotted line indicates the basin structure with a homogenous basement density of 2670 kg/m$^3$. Blocks are changed within 25 kg/m$^3$ of this value. Differences are substantial in places but the overall pattern is preserved.
Extended Data Figure 9: Representative ice sheet models for retreat states. Each image represents the ice sheet extent and thickness after a long-term 20 ky run under consistent climate forcing. Each model has different air/ocean temperatures. a) with air/ocean temperatures of today (0/0°C), b) with air/ocean temperatures of 4/1°C above today's, c) with air/ocean temperatures of 8/2°C above today's, d) with air/ocean temperatures of 12/5°C above today's, e) with air/ocean temperatures of 15/5°C above today's. Stated values indicate the total Antarctic contribution and the component from western Wilkes Land.