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Towards bridging the gap between Antarctic subglacial boundary conditions and ice-sheet model parameterization

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Abstract. The geology of Antarctica exerts a first-order control on ice-sheet dynamics by shaping the subglacial landscape and regulating basal friction, thermal profile, hydrology, and sediment distribution. These bed conditions influence where ice flows, how fast it moves, and how it responds to a changing climate. Yet most ice-sheet models incorporate geologic information only indirectly, typically as smoothed topography and simplified representations of basal processes. This incomplete capturing of geological information in ice-sheet models can be attributed to observational gaps, an incomplete community understanding of subglacial processes, and the need to simplify processes in ice-sheet models. As such, there is an opportunity to enhance communication and translation between geology and modeling disciplines, which will help improve our understanding of the thresholds and instabilities in Antarctic ice-sheet dynamics. Here, we discuss key subglacial geological conditions and processes and how they are used (or not used) in ice-sheet models. We highlight the disconnect between geological and

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physical interpretations of subglacial conditions and discuss possible strategies that will help bridge the gap between these disciplines as part of investigations of changing ice-sheet behavior.

1 Introduction

The mass loss from the Antarctic ice-sheet (AIS) (Rignot et al., 2019; Otosaka et al., 2023) and the possibility of marine ice-sheet instability (Schoof, 2007) underscore the need for high-fidelity ice-sheet models and sea-level-rise projections. These projections remain highly uncertain (Masson-Delmotte et al., 2021), partially because subglacial boundary conditions and processes are poorly constrained (e.g. Berends et al., 2023). Here, we refer to the physical boundary between the ice-sheet and the underlying geological substrate as the ice-sheet bed interface zone (IBIZ). Ice-sheet models currently rely on quantitative descriptions of the IBIZ over which the ice flows in order to calculate the pattern and speed of ice flow, and to simulate the response of Antarctic ice to changing environmental conditions. The basal conditions generally described in ice models include, at a minimum, topography, and optionally geothermal heat flow, basal hydrology, and some approach to describing the basal friction, which may or may not incorporate a representation of deformable subglacial sediment. In reality, these basal boundary conditions are determined by both present day conditions (i.e., ice thickness, hydrology, and erosion, illustrated in Figure 1), which can shift over relatively short time periods, and the geological evolution of the Antarctic continent, which was built over billions of years within diverse tectonic environments – from ancient cratons and orogenic belts to active rifts and volcanic zones (Boger, 2011; Jordan et al., 2020b; Stål et al., 2019) (Figure 2). This long and complex lithospheric evolution both records and influences ice-sheet behavior (e.g. Whitehouse et al., 2019; Paxman et al., 2020; Li et al., 2022; Reading et al., 2022). Despite their critical role in governing the past, present, and future behavior of the ice-sheets, we have had very few opportunities to directly observe basal conditions (Bentley and Koci, 2007). As such, there remain fundamental unknowns around the physical processes acting at the bed to control overlying glacier and ice-sheet dynamics (Stearns and Van der Veen, 2018; Joughin et al., 2019).

As a consequence, the representation of the IBIZ in ice-sheet models remains fundamentally limited. For example, while large-scale topographic features that steer ice flow are generally known, smaller-scale variations that can strongly affect grounding-line stability are often unresolved (Morlighem et al., 2020; Frémand et al., 2023; Pritchard et al., 2025). Likewise, geothermal heat flow is also poorly constrained due to limited knowledge of Antarctica's geological evolution and the scarcity of direct measurements (Fisher et al., 2015; Burton-Johnson et al., 2020; Reading et al., 2022). In ice-sheet models, these incomplete bed constraints are often combined with observations of the ice-surface via inversion to infer the basal conditions that control ice motion (Morlighem et al., 2010). However, because the data are sparse and surface signals integrate many processes, these inversions often absorb unmodeled processes and bed uncertainties (e.g. Joughin et al., 2019). Consequently, the basal friction coefficient inferred through inversion often acts as a tuning parameter that absorbs uncertainties in ice viscosity, temperature, subglacial topography, and the assumed ice flow law, meaning that different parameter combinations can reproduce the same present-day state but can lead to divergent ice-loss trajectories (e.g. Berends et al., 2023).

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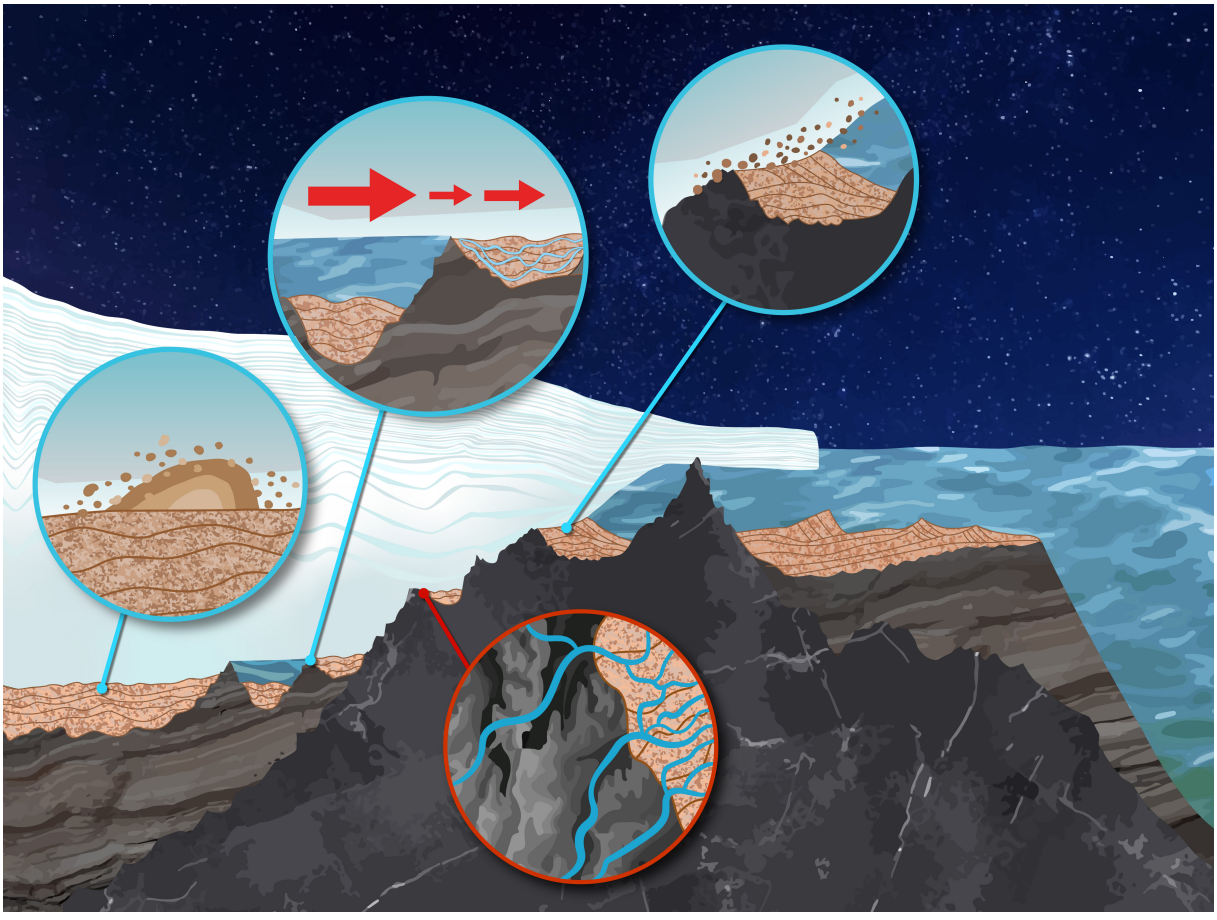


Figure 1. Cross section highlighting the interplay between complex geological boundary conditions and ice-sheet dynamics. The circles show zoomed in processes. The red circle is a bird's eye view of subglacial water flowing over a bedrock to sediment transition. The blue circles, from left to right, show 1) subglacial morphological processes including drumlin formation; 2) changes in basal sliding velocity (red arrows) over a subglacial lake, bedrock, and water-saturated sediment; and 3) grounding line sedimentation and development of a grounding zone wedge.

The limited direct representation of geological conditions in ice-sheet models is consequential because these properties exert a strong control on ice dynamics. Exposed glacial landscapes show that lithology influences bed topography and roughness (e.g., Gudlaugsson et al., 2013; Margold et al., 2015), which in turn governs subglacial water routing (MacKie et al., 2021), ice-flow steering (Winsborrow et al., 2010; McKenzie et al., 2023), basal slip (Law et al., 2023), and heat distribution at the bed (Willcocks et al., 2021). Where sediment is present, the bed may be weak and water-permeable, which enables deformation that can contribute substantially to ice motion (Evans et al., 2006). Despite this empirical knowledge of how geology exerts control on ice behavior in various ways, its inclusion in models of current ice flow is restricted to the imposition of large-scale topography (>500 m resolution in Antarctica), maps of modeled geothermal heat – often based on uncertain assumptions

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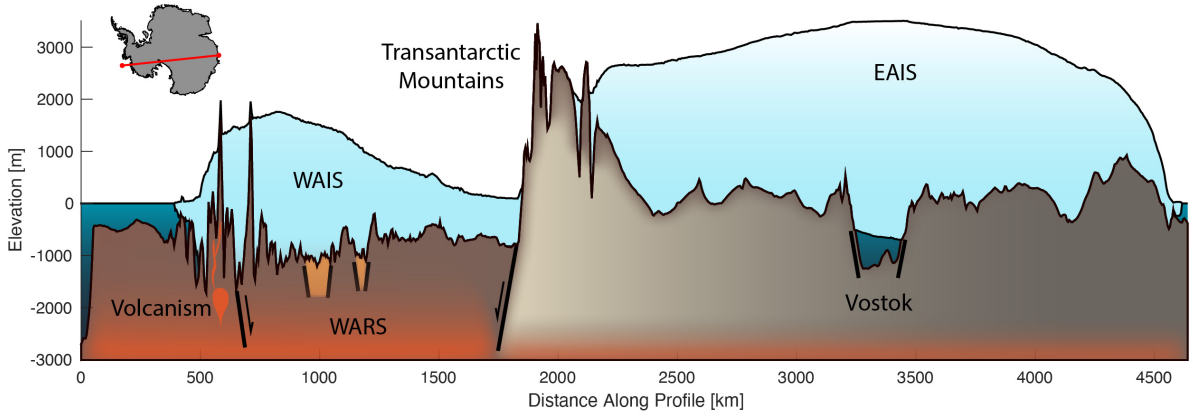


Figure 2. Cross section schematic of the West Antarctic ice-sheet (WAIS) and East Antarctic ice-sheet (EAIS) using BedMachine topography (Morlighem et al., 2020). Large-scale geologic conditions are highlighted, including subglacial volcanism, rift basins, the West Antarctic Rift System (WARS), the Transantarctic Mountains, and subglacial Lake Vostok.

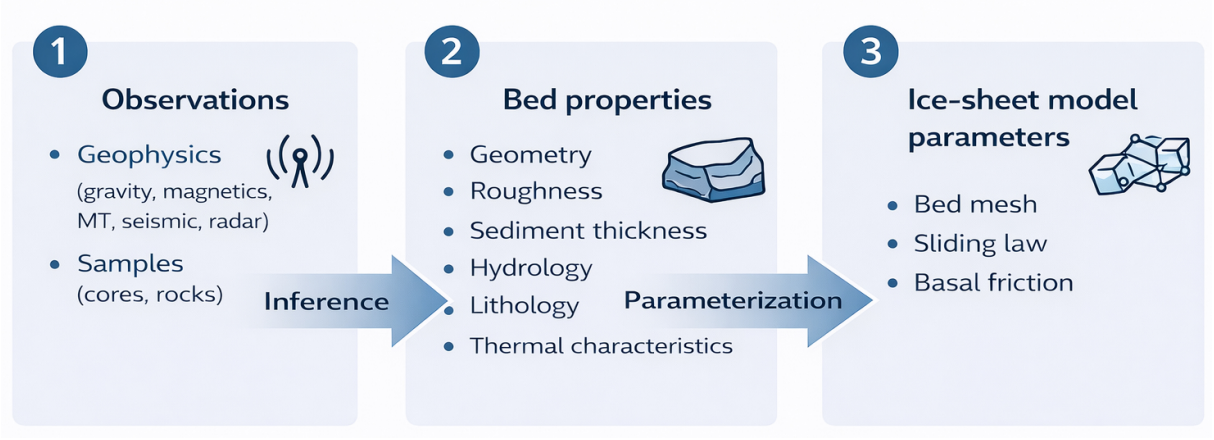


Figure 3. Conceptual workflow linking observations to ice-sheet model inputs. Our challenge is twofold: (1) *inferring* continental-scale estimates of basal conditions from (primarily) indirect observations, and (2) *parameterizing* these basal conditions into quantities that can be ingested by ice-sheet models.

(Lösing et al., 2020; Reading et al., 2022; McCormack et al., 2022a), and occasionally masks of inferred slipperier vs. stickier beds (Whitehouse et al., 2012). As such, there is a significant opportunity to improve the utilization of geological information in boundary conditions in ice-sheet models.

This paper aims to assess key geological boundary conditions and their role in driving ice movement. We pay particular attention to how geological boundary conditions translate into model parameters to highlight where geologic information is lost or missing from ice-sheet models. In doing this, we identify opportunities to bridge the gap between the geological

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understanding of Antarctica and simulations of ice-sheet evolution. Here, we define subglacial boundary conditions as any sub-ice geological process or pattern operating to influence the overlying ice sheet either directly or indirectly. We describe our knowledge of basal controls on ice-sheet dynamics, discuss how basal information is used (or neglected) in ice-sheet models, and highlight critical knowledge gaps. More precisely, in Section 2, we discuss the role of topography and its roughness at various scales; Section 3 describes deep Earth structure, bed lithology, and basal sliding and friction, including a statistical comparison of inversion-derived basal friction fields with observational estimates of bed conditions; and Section 4 describes geologic evidence of past subglacial conditions. In Section 5, we discuss future research opportunities to better integrate geologic knowledge with ice-sheet models.

2 Subglacial topography

2.1 The influence of topography on ice-sheet dynamics

One of the most obvious geologically controlled boundary conditions influencing ice sheets is topography. Both small- and large-scale subglacial topographic features fundamentally control ice-sheet geometry and dynamics through their influence on local climate and mass balance, ice thickness and elevation, and basal traction properties. In ice-sheet genesis, high altitudes typically have lower temperatures and higher precipitation rates and therefore promote accumulation, meaning that mountain regions are particularly favorable sites for the initiation and persistence of ice (Bo et al., 2009). This influence extends to both the growth and retreat of ice sheets. Ice-sheet models and geomorphological evidence suggest that topography played a key role in governing the location and extent of early East Antarctic Ice Sheet (EAIS) growth in the high-elevation Gamburtsev Subglacial Mountains, Transantarctic Mountains, and Dronning Maud Land at the Eocene–Oligocene Transition ca. 34 million years ago (DeConto and Pollard, 2003; Rose et al., 2013; Gernon et al., 2026). The coupling between topography and surface mass balance also influences ice surface elevation, and therefore the relative sizes of the accumulation and ablation zones, which affects the climate sensitivity and long-term stability of the ice-sheet (Noble et al., 2020).

At continental to regional scales, topography is critically important for the stability of Antarctica's marine-terminating glaciers. Ice-sheet models indicate that much of the West Antarctic Ice Sheet (WAIS) and the marine basins of the EAIS may be vulnerable to marine ice-sheet instability (MISI; Favier et al., 2014; DeConto and Pollard, 2016), owing to low-lying, retrograde (i.e. reverse-sloping) beds that deepen inland to more than 2000 m below sea level (Holt et al., 2006; Morlighem et al., 2020), provided that climate forcing thins the ice enough to initiate grounding-line retreat (Sergienko et al., 2026). For a marine-terminating glacier situated on a retrograde bed, retreat of the grounding line causes an increase in ice thickness at, and ice flux across, the grounding line. If this increased ice flux is not balanced by increased input (e.g. accumulation) over the basin upstream of the grounding line, the ice-sheet will thin, resulting in further retreat of the grounding line in order to retain hydrostatic balance (Schoof, 2007, 2012). Ice-sheet models demonstrate that this process can lead to runaway retreat of the grounding line into subglacial basins (e.g. Thwaites) until it has re-stabilized on higher terrain or pinning points (Joughin et al., 2014; Seroussi et al., 2017).

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At the scale of individual drainage basins and glaciers, deep valleys or troughs can facilitate ice stream onset by increasing ice thickness and driving stress, thereby increasing ice flux (Bentley, 1987; Bennett, 2003). This "topographic steering" results in thicker, faster ice flowing through topographic lows, which generates greater frictional heating and meltwater production and promotes enhanced basal sliding and erosion (Winsborrow et al., 2010). In contrast, the high topography on either side of the trough is likely to be overlain by thinner, cold-based ice, which promotes preservation of this topography adjacent to intense erosion within the trough (Truffer and Echelmeyer, 2003). This pattern of selective linear erosion (Sugden and John, 1976) enhances pre-existing topographic relief, and drives a positive feedback that leads to dramatic, steep sided fjords and troughs (e.g., Stern et al., 2005; Kessler et al., 2008). Numerous contemporary and paleo ice streams exhibit strong topographic control (Livingstone et al., 2012), including examples in the Transantarctic Mountains, western Greenland, and the northern and eastern margins of the Laurentide Ice Sheet (Margold et al., 2015; Stokes et al., 2016).

At km scales, local bed geometry can determine where retreat slows or accelerates. Although regional-scale bed geometry and slope are primary controls on ice-sheet stability, even glaciers grounded on retrograde slopes can maintain a stable grounding line under certain local geometric configurations (Gudmundsson et al., 2012) or climate conditions (Sergienko et al., 2026). Moreover, the timing and magnitude of grounding-line retreat are highly sensitive to the presence and geometry of $\sim$10 km scale bed bumps, ridges (Parizek et al., 2013; Koellner et al., 2019), and pinning points (Jones et al., 2021; Robel et al., 2022). Model behavior is consequently resolution-dependent: a grid spacing of 1 km or finer near the grounding line is needed to adequately represent ridges and pinning points that influence stability (Houriez et al., 2025; Williams et al., 2025). Uncertainty in bed geometry directly contributes to uncertainty in ice-loss projections. For example, Wernecke et al. (2022) found that using a small ensemble of stochastically simulated topographies for Pine Island Glacier increased projected ice-loss uncertainty by up to 25% by 2100 relative to the control beds, depending on the sliding law and climate forcing.

At finer scales (approximately one ice thickness and below), variations in basal roughness exert strong control on ice flow. A rough bed offers resistance to ice motion by increasing the normal component of stress opposing flow (e.g., Anandakrishnan and Alley, 1994), regardless of the specific properties of the ice–bed interface. Conversely, relatively smooth beds are often associated with active ice streaming, for example beneath the Siple Coast and Institute–Möller ice streams in West Antarctica (Siegert et al., 2004; Bingham and Siegert, 2009). Meyer and Creyts (2017) and Barndon et al. (2026) show that Moffatt eddies can form where ice crosses depressions, and that the steep adverse slopes on the downstream side of these depressions greatly increases the maximum resistance to ice flow. Small-scale topographic variations ($\leq$1 km) can also facilitate the development of a deforming temperate layer at the ice-sheet bed (Law et al., 2023; Liu et al., 2024) and soften the ice rheology (Minchew et al., 2018). These effects provide mechanisms through which topography at scales too small to be explicitly represented in many ice-sheet models can nevertheless influence large-scale ice dynamics.

Subglacial topography also controls ice dynamics indirectly through its influence on basal hydrology and geothermal heat flow. Specifically, the bed topography determines the flow of subglacial water (Shreve, 1972; MacKie et al., 2021; Shackleton et al., 2023) and distribution of subglacial lakes (MacKie et al., 2020). Topography also influences geothermal heat flow at the base of the ice sheet (see Section 3.1.2). In particular, topographic features at scales of $\sim$1–20 km can focus or diffuse heat

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flow and create localized anomalies (Willcocks et al., 2021; Reading et al., 2022). As such, the bed geometry and its spatial variability are crucial for representing the basal hydrology and thermal state.

The basal topography is similarly important beneath floating ice shelves. Sub-ice-shelf topography is critical to our understanding of sub-ice-shelf ocean circulation and ice shelf melt rates (Jacobs et al., 2011; Steig et al., 2012; Seroussi et al., 2017; Milillo et al., 2019; Tinto et al., 2019). Recent observations by an underwater vehicle suggest that even small-scale topography influences ice shelf melt patterns and rates (Schmidt et al., 2023). Large-scale sub-ice shelf topography exerts significant control on interactions between the base of the ice shelf and sub-ice shelf ocean water masses (Jacobs et al., 2011; Dutrieux et al., 2014). Together with variations in ice shelf thickness, sub-ice shelf topography controls variations in water column thickness that steer the circulation of ocean water masses and the distribution of heat beneath the ice shelf. Deep bathymetric troughs can provide pathways for relatively warm modified Circumpolar Deep Water to flow from the continental shelf toward the grounding line, whereas shallow sills or ridges can block or restrict this access and limit basal melt. Grounding line melt rates depend on both temperature and velocity of water flow, and are highly sensitive to patterns of sub-ice shelf circulation (Rignot and Jacobs, 2002; Burgard et al., 2022).

2.2 Parameterization in ice-sheet models

2.2.1 Digital Elevation Model construction

The important role of topography in ice-sheet dynamics has motivated the collection of millions of line kilometers of bed topography data through a combination of ice-penetrating radar (e.g. Frémand et al., 2023), multi-beam echo-sounding bathymetry (e.g. Nitsche et al., 2013), airborne gravity (Cochran et al., 2015; Scheinert et al., 2016), seismic (e.g. Muto et al., 2024), and autonomous underwater vehicles (e.g. Jenkins et al., 2010; Schmidt et al., 2023) surveying. Recent Bedmap data release efforts have made this record publicly available (Frémand et al., 2023). Despite this large volume of data, measurement gaps of up to multiple tens of kilometers remain which require interpolation. This interpolation can be performed with a variety of methods such as kriging (Bamber et al., 2001), spline approaches (Fretwell et al., 2013), or streamline-based methods that impose a greater degree of topographic continuity in the along-flow direction (Morlighem et al., 2020; Pritchard et al., 2025).

While the purely data-driven nature of the Bedmap data products makes them well-suited for a variety of scientific applications, they are not directly suited to ice-sheet modeling applications. Conventional interpolation approaches such as kriging and spline interpolation produce physical inconsistencies in ice-sheet models (Seroussi et al., 2011). Specifically, the ice would have to lose or gain mass at unrealistically high rates to match ice velocity measurements. To address this issue, topography can instead be estimated via a mass conservation inversion, where ice flow constraints are used to invert for bed topography such that ice mass is conserved when modeling ice flow (Morlighem et al., 2011; Bamber et al., 2013). The mass conservation approach is technically not an interpolation technique, but rather an estimation technique which may produce elevation estimates that deviate by up to hundreds of meters from radar bed measurements. The inversion procedure minimizes a cost function that penalizes mass flux divergences, deviations from bed measurements, and steep bed gradients. This method relies on the assumption that measured ice-surface velocity is a good approximation of the depth-averaged velocity, making it less

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effective in slow-flowing regions where internal deformation contributes to a greater proportion of surface ice velocity. As such, the mass conservation technique was used to map topography in fast-flowing ($\gtrsim$ 50 m/yr) regions in the BedMachine digital elevation model (Morlighem et al., 2020) (Figure 5). BedMachine's mass conserving nature makes it the preferred DEM for ice-sheet modeling applications.

An alternative approach is geostatistical simulation, which is used to generate multiple non-unique realizations that reproduce the variability of measurements and are constrained by observations (e.g. Deutsch et al., 1992). These stochastic methods can produce DEMs with a greater degree of "geological realism" or morphological accuracy (MacKie et al., 2021). This improved roughness information is useful for characterizing subglacial hydrological conditions (MacKie et al., 2020), estimating geothermal heat (Shackleton et al., 2023), and modeling complex sliding behavior (Law et al., 2023). The simulation of an ensemble of topographic realizations is particularly useful for quantifying uncertainty in hydrological (Neven et al., 2021; Yin et al., 2022) and ice-sheet model outputs, like sea level rise (Wernecke et al., 2022; McCormack et al., 2026). Geostatistical simulation does not account for mass conservation, making it poorly suited to ice-sheet modeling efforts. However, recent developments in geostatistical inversion have yielded geostatistical bed simulations that also conserve mass (Shao et al., 2026), as shown in Figure 5.

Sub-ice-shelf topography (bathymetry) presents a related estimation problem. Because direct observations are limited, bathymetry is often inferred through gravity inversions informed by airborne gravity surveys (e.g. Boghosian et al., 2015; Muto et al., 2016; Tinto et al., 2019; Jordan et al., 2020a; Eisermann et al., 2024; Charrassin et al., 2025). Gravity inversion is inherently non-unique because gravity observations reflect both bathymetric relief and variations in subsurface density, which requires assumptions about the geological density structure and other constraints (An et al., 2019; Jordan et al., 2020a; Charrassin et al., 2025). Most existing inversions produce a single deterministic estimate of bathymetry, although emerging Bayesian approaches instead generate probabilistic estimates that explicitly characterize uncertainty (Field et al., 2026).

2.2.2 Topography representation in ice-sheet models

Bed topography is typically interpolated onto an ice-sheet model grid or mesh as part of the model initialization. Typically, large-scale ice-sheet models used to project future sea level rise (e.g. Seroussi et al., 2011, 2024) have meshes that range from kilometers to 10s of kilometers. The main consideration influencing the choice of model mesh resolution is the trade-off between computational expense and the resolution required to capture ice-sheet dynamics in areas of interest or over certain timescales of interest. To balance computational cost with the need to accurately capture critical regions, some ice-sheet models employ adaptive mesh refinement (e.g., the Bidimensional Anisotropic Mesh Generator, BAMG; Hecht, 2006). In these models – such as the Ice Sheet and Sea-level System Model (ISSM) and Elmer/Ice – the computational mesh is refined as a function of a model field, typically the ice-sheet surface flow, refining the mesh resolution in areas where flow is fast, including grounding zones and fast-flowing outlet glaciers. In contrast, the slower-moving ice-sheet interior is typically modeled at a coarser resolution, reducing overall computational expense while preserving accuracy where it matters most. In models with fixed grids, topography variation within a model grid cell (e.g., the sub-grid standard deviation of bathymetry) is commonly used to modulate parameterizations of sub-grid pinning points, basal melt, and basal sliding (e.g., Pollard and

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DeConto, 2012a). The bed topography also provides the geometric foundation upon which other ice-sheet model parameters, including basal friction coefficients and ice rheology, are inferred or tuned. Consequently, choices about the bed (and its representation in the ice-sheet model) have cascading effects across model setup and simulation (Berends et al., 2023).

Ice-sheet models resolve variations in topography at the resolution of its grid or mesh, rather than the resolution of the original bed topography product. This can have a substantial influence on the accuracy of the bed topography morphology (e.g., shape and curvature) and texture (including spatial gradients in topography and roughness) realized in the ice-sheet model. To illustrate this, we generated an ensemble of 54 ice-sheet model meshes for Antarctica using constant meshing (resolutions of 1, 2, 5, 10, 15, and 30 km) and adaptive meshing using BAMG (ranging from a maximum resolution of 50 m to a minimum resolution of 50 km and across a range of meshing parameters). A summary of the approaches underlying each mesh ensemble member is provided in appendix A (Table A1). We interpolate the BedMachine v4 bed topography (Morlighem et al., 2020) onto each mesh. We then consider variations in the bed topography for each model mesh on eight transects, two at each of Thwaites Glacier, Totten Glacier, Siple Coast, and the Ronne-Filchner Ice Stream, aligned approximately across- and along-flow (Figure 4a).

The bed topography for the model ensemble defined on the transects varies by $>$1000 m (figure 4b-i) depending on the meshing technique. The adaptive meshes generally show the lowest absolute variations from the original BedMachine bed, particularly in regions where the mesh is highest resolution. By contrast, the lowest resolution uniform meshes produce the largest deviations from the BedMachine bed, particularly in regions of high spatial gradients in bed topography. These differences highlight that the fidelity of the interpolated bed to the underlying observational product is closely tied to mesh resolution and approach, which should be taken into consideration when designing a meshing strategy for both observational products used in ice-sheet model studies, and for ice-sheet model domains themselves, especially in areas of complex bed topography.

Simulations of paleo ice-sheet behavior, especially those exploring ice masses multiple millions of years ago or older, must account for changes in bed topography through time, as past topography may have differed substantially from the modern bed geometry (Paxman, 2023). Numerical modeling studies show that past ice-sheet behavior is sensitive to topography across a range of spatial scales, making paleotopographic reconstructions important for simulating ice-sheet responses to climate and ocean forcing during past warm periods (e.g., Wilson et al., 2013; Gasson et al., 2015; Halberstadt et al., 2021). These reconstructions are generated by "restoring" eroded material to the landscape by filling in valleys and troughs with thicknesses of rock constrained by offshore sediment volumes (Paxman et al., 2019; Hochmuth et al., 2020). However, reconstructed paleotopographies tend to be substantially and unrealistically smoother than modern landscapes. This smoothing has implications for simulated paleo ice-sheet behavior because the reconstructions lack bed roughness on dynamically important scales (e.g., Gasson et al., 2015), including valley geometry for steering ice, and pinning points that are important for the grounding lines of marine-terminating glaciers.

2.3 Gaps in topographic knowledge

The bed resolution in ice-sheet models is typically coarser than the along-track spacing of RES data but finer than the survey line spacing. As such, there will always be some degree of interpolation, inversion, and/or gridding that is required to translate

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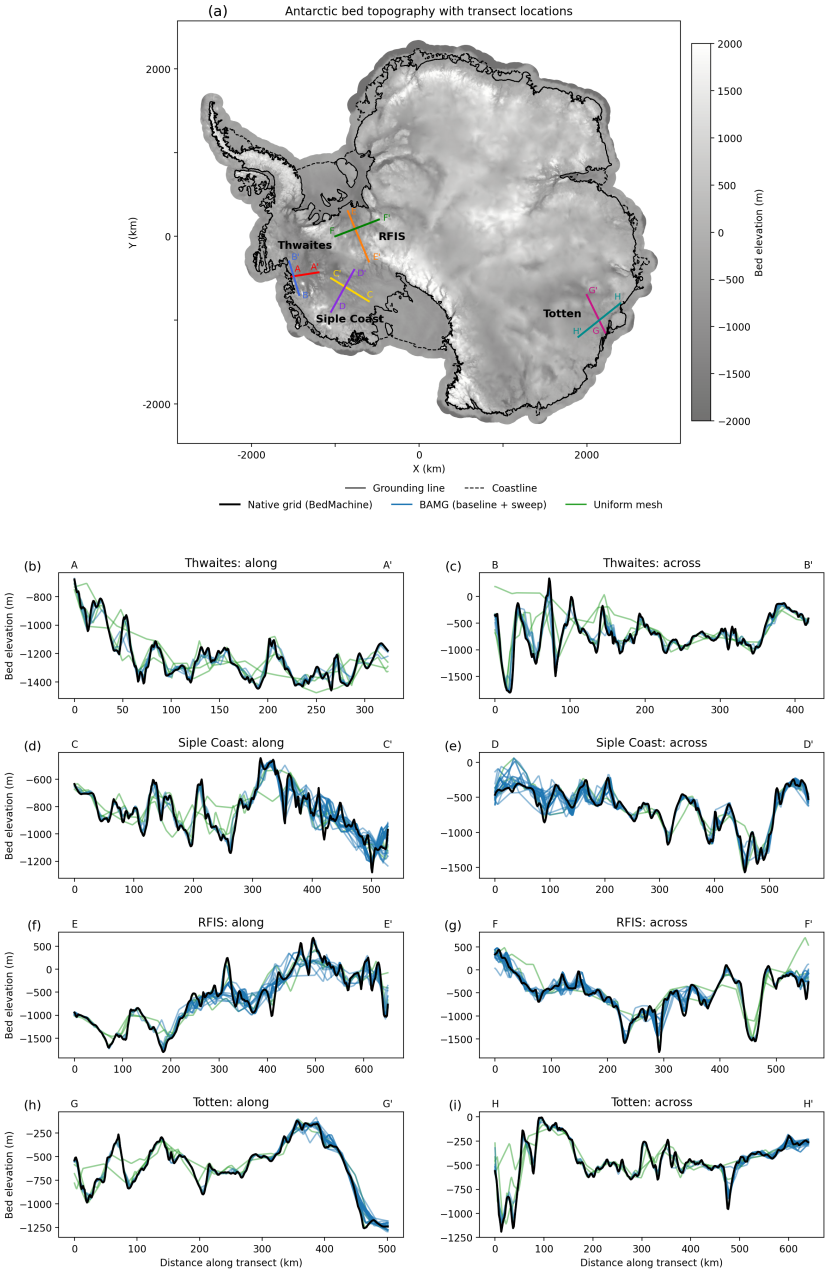


Figure 4. Realizations of bed topography on 54 ice-sheet model meshes. (a) BedMachine Antarctica v4 bed topography (Morlighem et al., 2020) with the locations of along-flow and across-flow transects from panels (b)-(i). (b)-(i) Bed topography realizations from 54 ice-sheet model meshes (appendix A) on transects shown in panel (a), with the BedMachine bed (black), adaptive mesh beds (blue), and uniform resolution mesh beds (green). RFIS is the Ronne-Filchner Ice Stream.

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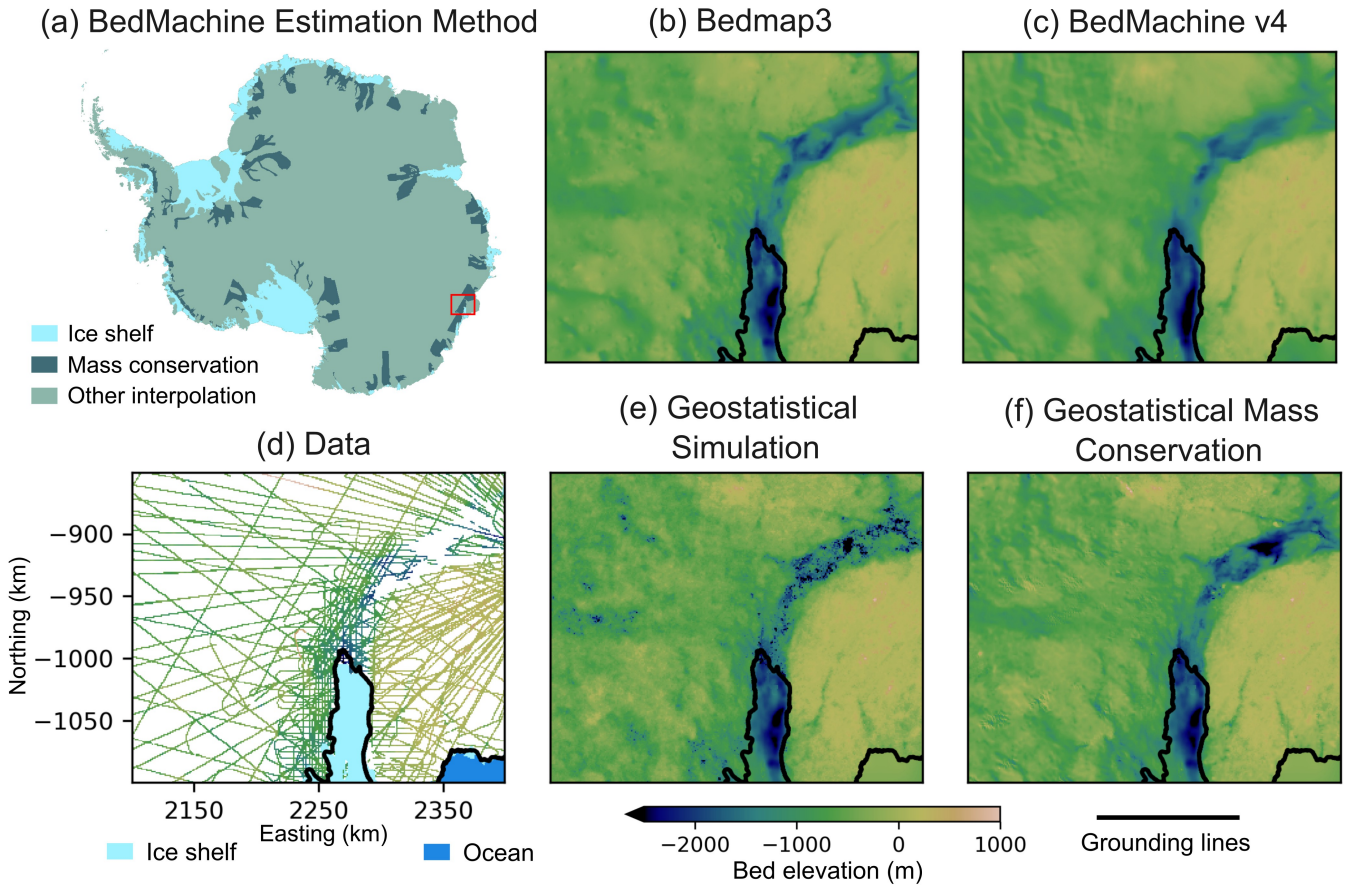


Figure 5. Representations of subglacial topography depend sensitively on the interpolation method used. (a) Mask showing the topography-estimation methods used in BedMachine Antarctica (Morlighem et al., 2020). (b) BedMap topography at Totten Glacier derived using streamline-based interpolation and modified thin-plate spline interpolation. (c) BedMachine topography at Pine Island Glacier derived using mass conservation and streamline diffusion. (d) Radar measurements of subglacial topography at Totten Glacier. (e) One topography realization generated by geostatistical simulation. (f) One topography realization generated by geostatistical mass conservation inversion from Shao et al. (2026)

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RES observations into model parameters. While mass-conserving topography is essential for running physically consistent ice-sheet models, this inversion is under-determined and does not have a unique solution. Regularization is therefore required (Morlighem et al., 2011), which suppresses steep topographic gradients and produces beds that are smoother than observations (MacKie et al., 2021). This means that, at least currently, increasing the resolution of bed mapping surveys yields diminishing returns, as the mass-conserving inversion suppresses the small-scale texture resolved in RES data. This smoothing also limits our ability to investigate the effects of roughness on ice flow and makes it difficult to quantify uncertainty in ice-sheet model

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behavior with respect to topographic uncertainty. Shao et al. (2026) demonstrated that this smoothing can be avoided via a geostatistical mass conservation inversion (e.g. Figure 5f). Their stochastic ensemble for Denman Glacier contained bed elevations that differed from BedMachine by up to 1500 m, despite both approaches imposing mass-conservation constraints. Such discrepancies highlight the deep uncertainty in inferred bed geometry even when physical constraints are imposed. This DEM reconstruction uncertainty is compounded by uncertainty in the underlying observations. Specifically, RES crossover errors can exceed hundreds of meters (e.g. Bamber et al., 2001), yet measurement uncertainty is not routinely propagated through DEM construction workflows.

Uncertainty in sub-ice-shelf bathymetry is similarly underrepresented. With the exception of emerging Bayesian inversion approaches that explicitly quantify uncertainty (Field et al., 2026), gravity inversions for sub-ice shelf bathymetry are typically deterministic. The gravity inversion problem is highly under-determined due to limited constraints on the bathymetry and subsurface density, and therefore requires simplifications and assumptions. For example, inversions typically rely on simple density assumptions (An et al., 2019; Jordan et al., 2020a; Charrassin et al., 2025) and state fixed uncertainties across entire surveys. Depending on the availability of additional constraints and knowledge of the local geological density structure, bed elevation uncertainties can be up to hundreds of meters (Bird et al., 2025; Charrassin et al., 2025; Field et al., 2026). These deterministic approaches tend to reflect the along-track resolution of the observations and produce overly smooth bathymetry, that may fail to capture critical roughness features influencing sub–ice shelf ocean circulation, and they do not provide a means by which to propagate bathymetric uncertainty into ocean circulation or melt-rate simulations.

Incorporating subglacial topography into ice-sheet models poses several challenges. Due to computational constraints, topography – even when available at 500 m resolution (i.e. BedMachine) – is interpolated onto much coarser grids that may exceed tens of km in resolution (e.g., Seroussi et al., 2020, and Section 2.2.2 above). Adaptive mesh refinement can concentrate computational resources on regions of fast flow or large gradients in velocity (Cornford et al., 2013; Dos Santos et al., 2019). However, determining where refinement is needed depends not only on the topographic variability – something that is poorly resolved – but on the scientific question. For projections of sea-level contribution, the priority is typically to resolve bed topography at fine scale within the grounding zone and the region within which it retreats over the course of the simulation period (Nowicki and Seroussi, 2026); for evolution of subglacial hydrological routing, the regions requiring refinement – for example, along subglacial channels or drainage divides – may differ substantially. The loss of fine-scale topography through the meshing approach also has implications for the representation of basal stresses. For example, Kyrke-Smith et al. (2018) and Hoffman et al. (2022) show that increasing topographic fidelity can decrease locally inferred basal traction because a greater proportion of resistance is supplied by normal stresses against bed obstacles. Overall, this suggests that roughness can significantly complicate the near-basal stress state and flow fields. At present, this behavior is not explicitly represented in sliding relationships used in large-scale ice-sheet models.

Several ice-sheet modeling studies have examined how precisely the bed should be resolved to constrain uncertainty in sea-level projections (Castleman et al., 2021; Caillet et al., 2026). For Thwaites Glacier, 2 km horizontal and 8 m vertical resolution in bed topography is needed to constrain projected sea-level contributions to within ± 2 cm over 200 years (Castleman et al., 2021). Using error estimates reported in BedMachine Antarctica, Caillet et al. (2026) show that bed topography affects the

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Antarctic contribution to sea level by more than 40 cm in 2150 and 1 m by 2300, which is comparable to the uncertainty in projections resulting from different emission scenarios. The impact of bed uncertainties is larger on regional- and glacier-scale simulations that have higher resolution meshes, which typically lead to greater variation in grounding line positions and mass change (Williams et al., 2025).

However, propagating uncertainty in subglacial topography through ice-sheet models remains difficult more broadly. The relationship between bed geometry and ice dynamics is highly non-linear, meaning that small differences in topography can lead to large and sometimes unpredictable changes in ice flow (Gasson et al., 2015; Robel et al., 2022; Sergienko and Wingham, 2022; Wernecke et al., 2022). Moreover, topography interacts with other poorly constrained basal properties, including sliding laws (Kyrke-Smith et al., 2018; Hoffman et al., 2022), geothermal heat flow (Shackleton et al., 2023), subglacial hydrology (MacKie et al., 2021), and climate variability (Christian et al., 2020; McCormack et al., 2021). Exploring these coupled uncertainties requires large ensemble simulations (e.g. Albrecht et al., 2020), which are computationally intensive (and are thus currently computationally prohibitive for models that use adaptive-mesh ice sheet simulations). Critically, McCormack et al. (2026) show that the choice of synthetic bed-generation method itself, independent of data sparsity, can shift projected sea-level contributions by tens of percent, indicating that interpolation methodology is a first-order, and currently under-acknowledged, source of uncertainty in ice-sheet projections.

Due to the nature of the reconstruction process, paleotopographic models fail to capture important small-scale roughness. Moreover, large uncertainties remain in the spatial and temporal variation of erosion rates through time, which means it is difficult to robustly reconstruct paleotopographic evolution at high temporal resolution. Currently, reconstructions exist only for a small number of time intervals (e.g., ca. 34, 23, 14, and 3.5 Ma) where offshore sediment volumes are broadly known (Paxman et al., 2019; Hochmuth et al., 2020). The evolution of topography due to tectonic deformation and mantle dynamics is also poorly constrained and only incorporated into reconstructions in a limited way (Paxman, 2023).

3 Subglacial material

3.1 The influence of geologic properties and processes on ice-sheet dynamics

The IBIZ layer may include several different materials including clean ice, sediment-laden ice, liquid water, wet deformable sediment, compacted or lithified sediment, and crystalline rock of various lithologies (Knight, 1997; van der Meer et al., 2003; Kleman and Glasser, 2007). This boundary layer sometimes, but not always, accommodates basal sliding. Its properties and their development under changing glacial conditions are therefore critical boundary conditions for modeling ice-sheet flow (Law et al., 2026). The IBIZ thus serves as a critical, highly variable layer where deep Earth processes couple with the overlying cryosphere (Whitehouse et al., 2019). In this section, we briefly review the properties of this interface and its influence on ice-sheet dynamics.

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3.1.1 Glacial erosion and sediment transport

Glacial erosion, sediment entrainment, transport, and deposition continuously modify the material properties of the IBIZ. The base of the ice can range from a sharply defined boundary to a more gradual transition across a basal debris zone including entrained sediment. Several mechanisms have been proposed for sediment entrainment, including glaciohydraulic supercooling (Alley et al., 1998; Bell et al., 2011; Licht and Hemming, 2017; Meyer et al., 2023). Alternatively, ice may infiltrate into porous sediments below and thus entrain sediment within the base of the ice through regelation (Iverson and Semmens, 1995; Christoffersen and Tulaczyk, 2003; Rempel, 2008). Direct observations of this basal debris zone remain sparse (Gow et al., 1979; Engelhardt and Kamb, 2013; Luthra et al., 2017; Winter et al., 2019; Priscu et al., 2021; Franke et al., 2023). Modeling studies suggest that the actively deforming or entraining zone may be meters to decimeters in thickness, while till accumulations can reach thicknesses of tens of meters (Christoffersen and Tulaczyk, 2003; Rempel, 2008), particularly downstream of regions of active erosion (Winter et al., 2019; Hooke et al., 2013). The rheology of sediment-laden ice differs substantially from that of both clean ice and unconsolidated sediment and depends strongly and nonlinearly on water content (Moore, 2014; Hansen et al., 2024).

Erosion and sediment transport can modify ice dynamics by changing the substrate encountered at the bed. The fundamental influence of different geologic substrates on ice-sheet behavior has long been recognized (e.g. Wellner et al., 2001). At a large scale, slower and more topographically controlled ice flow occurs across crystalline bedrock substrates, whereas fast ice streaming is associated with sedimentary substrates and deformable till (e.g. Alley et al., 1987; Anandakrishnan et al., 1998). The presence of easily erodible material, particularly in sedimentary basins, may be important for generating and sustaining a continuous till layer downstream (Bell et al., 1998; Li et al., 2022). Sediment produced through erosion can be entrained, transported downstream, and subsequently deposited, thereby allowing the mechanical properties of the IBIZ to evolve.

Over longer timescales, this coupling means that the IBIZ experienced by the ice-sheet is itself a product of past and evolving ice-sheet behavior. For example, the progressive erosion of the Antarctic interior and deposition of sedimentary strata on the prograding outer continental shelf has fundamentally altered ice-sheet behavior across million-year timescales (Colleoni et al., 2018a). These processes alter both topography (Section 2.1) and the distribution and properties of material at the ice-bed interface. Simulations of past (and future) ice-sheet evolution must therefore account not only for changes in topography, but also for the evolving substrate characteristics across glacial cycles.

3.1.2 Geologic controls on basal thermal state

The basal thermal state is fundamental to ice sheet dynamics, as it controls basal temperature, ice rheology, the distribution of frozen versus thawed bed conditions, and basal melt rates (Llubes et al., 2006; Pattyn, 2010; Dawson et al., 2022; Reading et al., 2022). Accurately characterizing the basal thermal state requires knowledge of the total heat budget at the IBIZ (Leysinger Vieli et al., 2018), with major contributions from frictional heat generated by basal sliding, heat associated with hydrological and hydrogeological flow, and geothermal heat flow. Although frictional heating can be the dominant component

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beneath fast flowing regions, the latter two contributions are geologically controlled and remain non-negligible (Larour et al., 2012), becoming dominant beneath slow flowing regions (Pittard et al., 2016a, b).

Geological controls on basal thermal state operate across multiple scales. At the largest scales, the deep Earth and mantle provide the long-wavelength contributions to the geothermal heat budget. For Antarctica, the broad-scale patterns in the crustal contribution to geothermal heat flow have been indirectly inferred although these patterns vary (Lowe et al., 2024b; Li and Aitken, 2024; Stål et al., 2024). At the continental scale, geothermal heat flow varies in a range from 40 mW m^{-2} in stable cratonic regions to over 100 mW m^{-2} in tectonically active areas like the West Antarctic Rift System (Stål et al., 2021).

The shorter wavelength crustal contribution is superimposed from non-steady state processes and radiogenic heat production associated with rocks enriched in potassium, uranium, and/or thorium (Reading et al., 2022; Burton-Johnson et al., 2020). Radiogenic heat production can produce localized heat-flow anomalies depending on the distribution of heat-producing rock units (Carson et al., 2014), while variations in near-surface rock thermal conductivity can further modify heat transfer to the ice-sheet bed (Willcocks et al., 2021). Volcanism, hydrology, and hydrogeology (Gooch et al., 2016) can locally enhance heat transfer by an order of magnitude or more, and shallow geological boundary conditions, such as bedrock topography and sediments, can lead to thermal focusing or de-focusing (Willcocks et al., 2021), therefore directly influencing the local thermal regime (Reading et al., 2022). High heat flow anomalies typically occur where multiple influences combine. For example, the anomaly at the Thwaites Glacier basin coincides with elevated mantle heat, likely crustal-scale faulting, and topographic effects (Reading et al., 2022). Sparse direct measurements in subglacial environments have also revealed exceptional values, such as 285 ± 80 mW m^{-2} at Subglacial Lake Whillans (Fisher et al., 2015; Begeman et al., 2017). These local scale processes are currently beyond the resolution of continent-wide heat flow models and remain poorly constrained. However, ice-sheet model simulations that include fine-scale heat flow anomalies show enhanced basal melting, particularly where the basal ice temperature is close to the pressure melting point (McCormack et al., 2022a), with implications for broader basal meltwater generation and feedbacks between ice flow and basal sliding.

3.1.3 Geologic controls on hydrology and hydrogeology

Bedrock lithology and structure exert important controls on subglacial hydrology through their influence on porosity and permeability and, consequently, the capacity of the substrate to store and transmit water. Relatively unfractured crystalline formations, such as granites, may provide an impermeable bedrock that allows little opportunity for either fluid-exchange or enhanced erosion to occur. Structures in the rocks including joints, bedding planes and schistosity, are important for glacial erosion (Hooyer et al., 2012; Lane et al., 2015). The orientation (dip and strike), length, thickness and spacing, as well as compositional competency contrasts of these fabrics can be important factors in the susceptibility to erosion (Krabbendam and Glasser, 2011) – and resultant fabric which influences sliding. In contrast, high-porosity sedimentary rocks, as well as heavily fractured volcanic or crystalline rocks, allows for water exchange with deep-seated groundwater systems. Modeling studies suggest that these aquifer systems can store and release water over long timescales, including in response to glacial–interglacial cycles (Person et al., 2012; Gooch et al., 2016). Crucially, experiments with realistic permeabilities shows that the rate of release is contingent on the rate of ice-sheet unloading, and that fast retreat may lead to discharge to the bed at rates

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comparable to modeled basal melt rates (Li et al., 2022). As rates of ice-sheet unloading increase, deep groundwater discharge may therefore constitute a substantial and potentially growing component of the subglacial hydrologic budget (Li et al., 2022; Robel et al., 2023), depending on the substrate.

The configuration of the subglacial drainage system, which is controlled amongst other things by topography, substrate and geothermal heat, influences ice dynamics. Distributed hydrological systems can maintain high basal water pressures and promote basal sliding, whereas efficient channelized drainage can lower basal water pressure and reduce lubrication (e.g. Walder and Fowler, 1994). Evidence for active subglacial hydrological systems in the past are preserved in relict subglacial channel systems mapped on the seafloor (Wellner et al., 2006; Simkins et al., 2022). The impact of these channelized subglacial hydrologic systems on ice dynamics can be difficult to ascertain from the landform record, although Simkins et al. (2017) demonstrate the co-evolution of grounding-line retreat and episodic meltwater drainage events. The activity and influence of past subglacial hydrologic systems are also recorded in the sediment record by meltwater plume deposits, indicating episodic pulses of sediment-laden subglacial meltwater, associated with marine grounding line retreat (Witus et al., 2014). Previous studies have leveraged both radio echo sounding and sedimentology to reconstruct subglacial hydrological systems in both the past (Witus et al., 2014; Prothro et al., 2018; Lepp et al., 2024) and present (Schroeder et al., 2013). Thus, constraining the subglacial plumbing systems of past and current ice-sheets is important for understanding how basal hydrology influences ice-sheet dynamics.

3.1.4 Geologic controls on basal sliding

Geologic controls on basal sliding are classically separated into the influence of "soft" (usually non-lithified sediment) and "hard" (usually crystalline basement rock) beds – both of which are pervasive in different areas of the Antarctic Ice Sheet (Anandakrishnan and Alley, 1994; Smith et al., 2013; Muto et al., 2019). However, as our understanding of Antarctic geology becomes more granular, it also becomes apparent that there are, in addition, areas featuring both bed types in close proximity to one another which may complicate these simple classifications or juxtapose bed processes. This includes Thwaites Glacier (Schroeder et al., 2014b; Muto et al., 2019; Jordan et al., 2023; Zeising et al., 2026), Pine Island Glacier (Bingham et al., 2017), Rutford Ice Stream (Smith and Murray, 2009; Schlegel et al., 2022), and large parts of East Antarctica (Liebsch et al., 2025). With the role of bed roughness – itself a function of geology (Siegert et al., 2005; Glasser and Ghiglione, 2009; Cooper et al., 2019) – in ice-sheet sliding also potentially large, though poorly quantified (Koellner et al., 2019; Law et al., 2023; Barndon et al., 2026), this pushes a previously binary distinction into a multi-dimensional parameter space.

The processes of soft- and hard-bed sliding in isolation are covered in depth in Cuffey and Paterson (2010), Jager et al. (2026), and Law et al. (2026) among others, but we briefly outline them here before considering more specific cases of geologic controls on basal sliding in Antarctica. In the case of water-saturated sediment, fast ice flow can be accommodated by deformation within an upper layer of subglacial till. Such till may be several meters thick, though the deformation horizon itself typical occupies only the upper centimeters (Evans et al., 2006; Halberstadt et al., 2018) making precise and accurate constraint challenging from surface geophysics alone. Experiments considering subglacial till in isolation consistently retrieve plastic failure (Clarke, 2005), while shear-ring experiments featuring ice overlying sediments indicate a regularized-Coulomb

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type relationship in these settings (Zoet and Iverson, 2020), where resistance is first provided through viscous ice deformation around embedded clasts, and then by the plastic failure envelope of the underlying sediment when the embedded clasts begin to shear through the uppermost layer of sediment. Where sediments are sufficiently thick, they may form a compacted horizon beneath the actively deforming layer (Evans et al., 2006). Although this lower layer may contribute little directly to basal motion, it can influence basal conditions by providing a reservoir for subglacial groundwater (Christoffersen et al., 2014), and a sustained source of subglacial sediments over longer timescales (Evans et al., 2006). The continuity of this till layer, particularly water-saturated and rheologically-weak sediments, is consequential for basal sliding. A continuous, water-saturated, rheologically weak bed can facilitate fast flow and allow ice-stream behavior to extend farther upstream, whereas discontinuities in weak sediment, rigid bedrock obstacles, or locally under-saturated sediments can form "sticky spots" that increase basal resistance (Alley et al., 1987; Engelhardt and Kamb, 2013).

Basal motion over hard beds is described through a different set of processes. Classical hard-bed sliding theory relates basal shear stress to sliding velocity through a power-law relationship arising from regelation and enhanced creep around bed obstacles (Weertman, 1957) (Table 1). Budd et al. (1979) and Budd et al. (1984) expanded upon this experimentally and empirically to include effective pressure, N (Table 1). Power-law sliding relationships remain widely used in large-scale ice-sheet models, typically with sliding exponents of (m=3) or (m=4) (Goelzer et al., 2020; Seroussi et al., 2020). This sliding relationship has been suggested to be effective in Alpine glacier settings (Gimbert et al., 2021; Gilbert et al., 2023) and for parts of Antarctica (Gudmundsson, 2007, 2011; Gillet-Chaulet et al., 2016), though with a higher sliding exponent than suggested in original theoretical papers. However, the physical basis of classical Weertman-type sliding has long been questioned because it does not represent the development of subglacial cavities or the influence of water pressure on basal traction (Lliboutry, 1979; Barnes and Gudmundsson, 2022). These limitations motivated the development of cavitation-based sliding theories, beginning (in English language) with Lliboutry (1968) and developed further by Iken (1981), Schoof (2005), and Gagliardini et al. (2007) among others. In these formulations, increasing sliding velocity promotes the growth of water-filled cavities downstream of bed obstacles and progressively reduces ice–bed contact. Basal shear stress initially increases with sliding velocity, but reaches a maximum as cavities expand; beyond this point, some formulations predict rate-weakening behavior, in which further increases in sliding velocity reduce basal resistance. Such rate weakening can produce unrealistic or unstable behavior when implemented in large-scale ice-sheet models. However, this issue is largely resolved through Helanow et al. (2021), which demonstrates that realistic three-dimensional bed topography geometrically limits cavity growth. Basal traction for cavitating hard beds at scales $\lesssim$25 m therefore approaches an upper bound without necessarily decreasing at higher sliding velocities. The resulting behavior resembles regularized-Coulomb sliding inferred for soft beds (Zoet and Iverson, 2020), although the characteristic transition velocity (u_t; Table 1) may be substantially lower in the case of hard beds ($\lesssim 30$ m yr^{-1}). At the same time, the continued empirical utility of power-law relationships in some observational studies (e.g. Maier et al., 2021; Gilbert et al., 2023) indicates that important gaps remain between process-based descriptions of basal mechanics and the effective sliding relationships inferred at ice-sheet-model scales.

In practice, there are also *general* trends in surface velocity and inferred sliding velocity dependent on bed type at the local/regional scale (below, with some exceptions) and at the continent scale (Section 3.3). Considering the onset of fast (>100

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m/yr) flow, Anandakrishnan et al. (1998); Bell et al. (1998) find that the onset of ice streams B and C on the Siple Coast corresponds with a transition from dense crystalline rocks to sediments, as inferred by surface geophysics. Peters et al. (2006) extends this with seismic reflection surveys for ice streams C and D, finding a discontinuous transition from a crystalline to sedimentary bed and from slow to fast flow, respectively, which is further supported by airborne magnetic data (Tankersley et al., 2022). Across the Antarctic Peninsula, Bingham and Siegert (2007) and Siegert et al. (2016) find a similar story for the Institute and Möller ice streams, with the inception of the Institute Ice Stream coinciding with a subglacial lake and a sharp transition to a zone of weak subglacial sediment. These studies all hail from (or in close proximity to) the West Antarctic Rift System (Behrendt et al., 1991; Karner et al., 2005), forging a clear link between continent-scale geology and ice flow. At Recovery Ice Stream, Langley et al. (2014) identify a similar transition in bed roughness but emphasize the role of subglacial lakes in initiating fast flow.

Geological variations may influence the position of ice-stream shear margins and the flow of ice-stream trunks. Geophysical observations reveal heterogeneous basal conditions beneath Thwaites Glacier (Jordan et al., 2023), yet MacGregor et al. (2013) find that local bed topography and other bed properties do not strongly control the position of its eastern shear margin. Elsewhere in West Antarctica, geophysical observations indicate the presence of porous, deforming sediment beneath many ice streams (Blankenship et al., 1986; Alley et al., 1987; Engelhardt et al., 1990; Holschuh et al., 2020), potentially consistent with a bounded, regularized-Coulomb sliding law (Hank et al., 2026). However, substantial variations in basal traction and velocity, including stick-slip behavior, occur even within seemingly homogeneous ice streams (Hudson et al., 2023). While topography clearly bounds some ice streams, such as Rutford Ice Stream (King, 2009), others exhibit more complex interactions between bed properties and subglacial hydrology (van der Wel et al., 2013; Kyrke-Smith et al., 2015; Perol et al., 2015). Jager et al. (2026) proposes two general sliding regimes across Antarctica: a power-law regime controlled by basal velocity that is applicable across much of the ice sheet, and a regularized-Coulomb regime influenced by subglacial water pressure beneath fast-flowing ice streams and outlet glaciers. Their findings suggest that a single sliding law may not adequately represent the range of basal conditions across Antarctica.

The choice of sliding law and its parameters has important consequences for modeled ice-sheet evolution. Different representations of basal rheology produce significant differences in ice-stream and grounding-line stability (Ritz et al., 2015; Brondex et al., 2019), and depending on initialization can influence projected mass loss by around 100% (Brondex et al., 2017; Åkesson et al., 2021). For example, Parizek et al. (2013) demonstrated that Thwaites could achieve stability if modeled with a plastic flow law, but retreats under power-law conditions. Similarly, Barnes and Gudmundsson (2022) and van den Akker et al. (2026) found that the ice-sheet response to different sliding exponents varies regionally. Together, these findings highlight the need to improve our process-based understanding of sliding, account for variations in sliding processes across Antarctica, and quantify the uncertainty that their misrepresentation introduces into sea-level rise projections.

3.1.5 Geologic controls on topographic evolution

The geology plays an important role in shaping and modifying Antarctic topography. Topography is a temporally-variable boundary condition over glacial-interglacial cycles and has evolved substantially, at least in parts of Antarctica, since ice-sheet

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Table 1. Common basal sliding relationships and their mathematical forms. τ_b = basal shear stress. u_b = basal sliding speed. C = friction coefficient. m = sliding exponent. N = effective pressure. Note that these relationships are vectorized in model applications.

Sliding Law	**Equation**
Linear	$\tau_b = C\,u_b$
Plastic	$\tau_b = C$ (independent of u_b)
Power-law (Weertman or Weertman-type)	$\tau_b = C\,u_b^{1/m}$
Budd (Velocity + Effective Pressure dependent)	$\tau_b = C\,u_b^m\,N^{-p}$
Regularized Coulomb	$\tau_b = C\left(\frac{u_b}{u_b + u_0}\right)^{1/m}$

inception. Topographic relief has been exaggerated by glacial erosion, which has incised troughs with depths of up to ∼3000 m below sea level (Frémand et al., 2023). In between the troughs, mountain peaks and summit plateaus have been uplifted by as much as ∼1 km due to the flexural response to erosional unloading (e.g., Stern et al., 2005; Paxman et al., 2017). Areas of low-lying, reverse-sloping topography have become more widespread since AIS inception due to the combined effects of glacial erosion (Jamieson et al., 2010), thermal subsidence (Wilson and Luyendyk, 2009), ice loading (Paxman et al., 2022), and dynamic topography (Austermann et al., 2015). This topographic evolution means that the sensitivity of the AIS to climate forcing has also evolved through time (Wilson et al., 2013; Paxman et al., 2020).

In regions experiencing ice sheet loss, topography can rebound due to glacial isostatic adjustment (GIA) (Whitehouse et al., 2019). The rate and magnitude of GIA are controlled by lateral variations in lithosphere thickness and viscosity contrasts. Mantle viscosity beneath Antarctica spans several orders of magnitude and deviates significantly from global averages due to variations in both temperature and composition (Pappa et al., 2019; Hazzard et al., 2023; Ivins et al., 2023; Li et al., 2025). The tectonic origin of these deep variations stems from contrasts between cratonic and non-cratonic mantle domains. East Antarctica's Precambrian cratonic roots are characterized by cold, depleted, chemically buoyant compositions and thick elastic lithosphere that promote high viscosities and slower GIA response, whereas West Antarctica's Phanerozoic tectonic history has produced a thinner, fertile mantle with enhanced thermal gradients that facilitate rapid viscous flow (Wiens et al., 2023). Even within East Antarctica's cratonic interior, substantial lithospheric heterogeneity should be expected (Boger, 2011; Stål et al., 2019). Such contrasts underly the pronounced spatial variations in GIA response observed across Antarctica, where recent ice loss triggers rapid uplift in West Antarctica while East Antarctica responds more slowly to both historical and contemporary ice mass changes (Kaufmann et al., 2005; Whitehouse, 2018; van der Wal et al., 2023).

The upper mantle is variable in both temperature and composition, leading to lateral variations in lithosphere thickness and to viscosity contrasts beneath Antarctica that span several orders of magnitude from global averages. This viscosity variation exerts a fundamental control on the rate and magnitude of glacial isostatic adjustment (GIA) in Antarctica and therefore the subglacial landscape development. The tectonic origin of these deep variations stems from contrasts between cratonic and

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non-cratonic mantle domains. East Antarctica's Precambrian cratonic roots are characterized by depleted, chemically buoyant compositions and thick elastic lithosphere that promote high viscosities and slower GIA response, whereas West Antarctica's Phanerozoic tectonic history has produced a thinner, fertile mantle with enhanced thermal gradients that facilitate rapid viscous flow (Wiens et al., 2023). Such contrasts underlie the pronounced spatial variations in GIA response observed across Antarctica, where recent ice loss triggers rapid uplift in West Antarctica while East Antarctica responds more slowly to both historical and contemporary ice mass changes (Kaufmann et al., 2005; Whitehouse, 2018; van der Wal et al., 2023). Where mantle material is present at shallow depths (Moho depth), an elevated heat flow contribution is expected. Thermal and compositional variations can be inferred through gravity (satellite) data (Pappa et al., 2019), seismic tomography (Shen et al., 2018; Lloyd et al., 2020), magnetotelluric data (Hill, 2020), or magnetic data (e.g. Martos et al., 2017; Lowe et al., 2023; Dziadek et al., 2021).

3.2 Parameterization in ice-sheet models

With less than one percent of the Antarctic continent exposed, direct geologic observations are sparse and difficult to incorporate explicitly into ice-sheet models. Furthermore, many of the geologic, hydrologic, and small-scale mechanical processes that influence basal motion cannot be resolved at the spatial scales of continental ice-sheet simulations. Consequently, their combined effects are typically subsumed within a basal traction coefficient inferred through ice-sheet model inversion (Joughin et al., 2009; Morlighem et al., 2010). In these inversions, spatial variations in basal traction are estimated by minimizing the misfit between modeled and observed quantities, most commonly ice-surface elevation or velocity. The resulting traction field allows the model to reproduce the observed present-day ice surface flow under its assumed stress balance, rheology, geometry, and sliding relationship. However, agreement with present-day surface velocity does not necessarily imply that the inferred basal traction represents the true physical properties of the bed. If the assumed sliding relationship or other model physics are incorrect (e.g., ice rheology; McCormack et al., 2022b; Rathmann and Lilien, 2022), the inversion can compensate through adjustments to basal traction (Berends et al., 2023), potentially leading to divergence between modeled and actual behavior when the ice sheet is subjected to different forcing.

The inverted basal traction field therefore provides an important parameter for ice-sheet simulations, not only at the point of initialization, but throughout a simulation, but its physical interpretation is ambiguous. In particular, it is generally not constrained by direct observations of bed geology or basal mechanical properties. Although inferred patterns of basal traction can be relatively insensitive to model resolution in some settings (Morlighem et al., 2013), this behavior is not universal (e.g. Kyrke-Smith et al., 2013), and there is currently no widely adopted methodology for relating the inferred traction coefficient directly to observational constraints on lithology, sediment properties, hydrology, or bed roughness. Instead, basal traction can effectively act as a "catch-all" parameter that compensates for unresolved or incorrectly represented processes not only at the ice–bed interface, but also elsewhere in the model, including uncertainties in ice rheology and mass-balance forcing when basal traction is the primary adjustable parameter. Geological controls on basal motion may therefore be embedded implicitly within the inverted traction field without being separately identifiable.

This problem is amplified in simulations of past ice-sheet evolution, for which basal conditions are even more poorly constrained. In the absence of information about spatially-varying paleo basal sliding, many model simulations of past ice sheet

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evolution derive a basal slip field by inverting or interpolating from the modern ice surface thickness or velocity. Because the basal slip inversion product can only provide information about modern grounded ice, modelers must make assumptions about the basal slip value across continental shelves where ice was grounded during past during glacial maxima. This value is a commonly varied parameter for deglacial model simulations (e.g., Pollard et al., 2016). Some ice sheet model simulations of deeper-time targets have used a simple two-value basal slip field based on whether bed topography is above or below sea level (Gasson et al., 2016; Halberstadt et al., 2021), with friction reduced below sea level on the assumption that deformable sediment is present and is water-saturated.

An alternative to the fixed sliding coefficient is the "till friction angle" module implemented within the Parallel Ice Sheet Model, which uses a Mohr-Coulomb yield stress scheme that considers effective stress via till pore-water content (Winkelmann et al., 2011; Martin et al., 2011; Albrecht et al., 2020). This ties basal strength to subglacial hydrology, which is not considered explicitly in a fixed sliding coefficient. Till friction angle parameters are tuned to reproduce present-day ice stream patterns, so both fixed sliding coefficients and till friction angle parameters are ultimately fit to the modern ice sheet, just through different optimizations. Although till friction angles can be measured from sediment cores and used to constrain palaeo and modern simulations, the lack of observations mean they are only infrequently used, with values instead being tuned to match known ice flow patterns or past ice flow extents. Such constraints can be more easily applied at a catchment scale (Jamieson et al., 2012).

3.3 Gaps in knowledge

Despite decades of geophysical surveys, our understanding of Antarctic subsurface geology remains limited. Direct sampling of the grounded bed is rare (Talalay et al., 2025). As such, nearly all inferences about lithology, sediment thickness, hydrology, and geothermal properties must be made indirectly from geophysical proxies including radar, active and passive seismic (Shen et al., 2018; Lloyd et al., 2020), magnetotellurics (Hill, 2020), gravity, and magnetics (Martos et al., 2017; Lowe et al., 2023; Dziadek et al., 2021; Aitken et al., 2023). Each of these techniques is fundamentally constrained by data sparsity and the non-uniqueness of their interpretations. For example, radar data encodes information on the basal roughness, lithology, and hydrology at both the macro-scale and wavelength-scale, but cannot easily be used to isolate specific material properties (Schroeder et al., 2014a; Christianson et al., 2016; Jordan et al., 2017; Winter et al., 2019; Franke et al., 2023). Seismic, magnetotellurics, gravity, and magnetic surveys each sense different physical properties (i.e. velocity, conductivity, density, and magnetization), but none uniquely identifies geology without strong prior assumptions. Even when multiple datasets exist, they are rarely co-located, are often acquired decades apart, and are subject to large uncertainties. Another major challenge is that geophysical methods resolve the bed at scales that are mismatched with the processes we care about. Some techniques (e.g. seismic reflection, receiver functions) are sensitive to the physical interface itself (Anandakrishnan and Winberry, 2004; Luthra et al., 2017). Others sample the volume of material below the bed, and allow the capacity to characterize thick accumulations of sediment and the bedrock beneath (Aitken et al., 2023), or use of seismic ambient noise created by processes such as ocean waves, to detect areas of sediments beneath the ice (Kelly et al., 2026) but some of these measures only resolve conditions at spatial resolutions that are coarse compared to the scales relevant to basal sliding. This mismatch leaves a large interpretive

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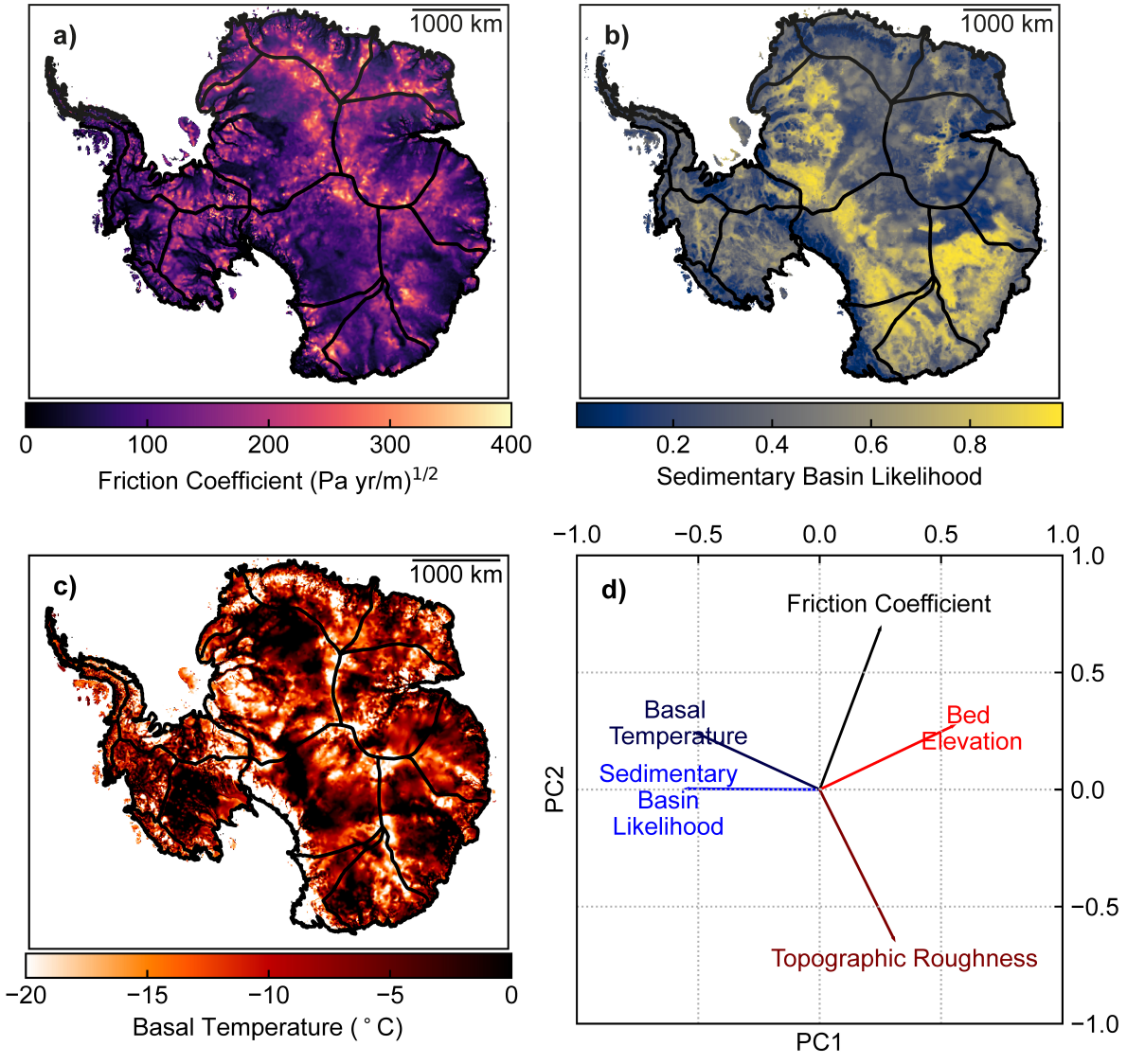


Figure 6. a) Basal friction coefficient derived from an ice-sheet model (Dawson et al., 2022); b) Sedimentary basin likelihood representing the geological classification in Antarctica (Li et al., 2022); c) Basal temperature relative to the pressure melting point (Dawson et al., 2022), estimated from an ice-sheet model using a geothermal heat flow model (Shen et al., 2020); d) Biplot showing the first two principal components of basal conditions, with bed topography sourced from the BedMachine Antarctica dataset (Morlighem et al., 2020). Its variation is estimated using a 30x30 km window.

gap between what geophysics can resolve and the conditions that are relevant to basal sliding. These limitations mean that even where datasets exist, the basal boundary conditions remain only loosely constrained.

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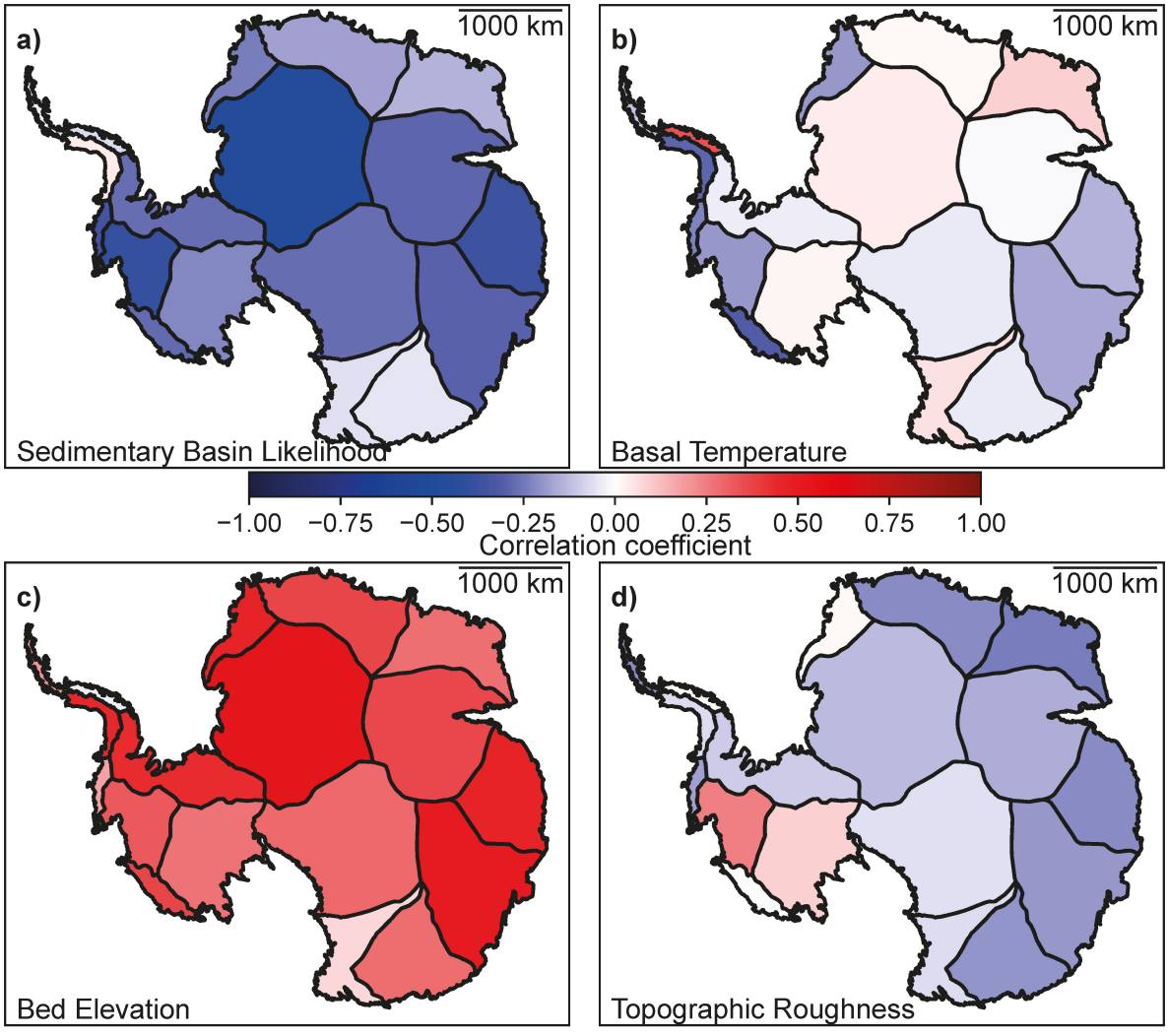


Figure 7. Correlation coefficient between basal friction coefficient and different bed variables by catchment. (a) Correlation between sediment basin likelihood and basal friction (high likelihood of sediment basin is negatively correlated with basal friction, which means that sediment is associated with low friction).

While the aforementioned observational challenges mean that basal friction inversions are important for parameterizing ice-sheet models, this inversion is under-determined and relies on uncertain topography. Additionally, the inverted friction parameters are sensitive to the ice flow law selection (e.g. Pollard and DeConto, 2012b; Morlighem et al., 2013; Barnes et al., 2021) and uncertainty in bed geometry (Zhao et al., 2018). These friction parameters may not evolve well in time as they are tuned to modern ice-surface velocities and the grouping of geological and hydrological slip influence into a single friction parameter, which makes it difficult to distinguish between the effects of hydrologic and geologic conditions, as well as other

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model uncertainties (Berends et al., 2023). Transient (time-evolving) basal slip calibrations may improve on some of these issues (Badgeley et al., 2025), but are not yet widely applied.

Furthermore, the subglacial hydrology can change on short time scales. For example, a study by Riel et al. (2021) found that basal friction inversion results vary with the tide, and a study by Das et al. (2023) found that there is no apparent correlation between basal friction estimates and radiometric reflectivity at Thwaites using a power-law sliding relationship. As a result, the basal friction inversion process used in models does not produce a meaningful representation of subglacial geological and hydrological conditions, making it difficult to investigate geologic controls on ice-sheet projections. Smith-Johnsen et al. (2020) instead estimated basal friction through a linear relationship with bed depth and were able to successfully model ice flow at the Northeast Greenland Ice Stream without using a friction inversion. This study underscores how even simple geological information can provide valuable insight into ice-sheet model parameters but also that there is a significant process gap that exists between geological understanding and the numerical simulation of ice behavior in Antarctica.

This disconnect between observed basal conditions and their representation in model parameterizations is illustrated in Figures 6 and 7. Figure 6 presents a biplot analysis comparing a basal friction coefficient with several estimates of basal properties. In a biplot, the loadings of the first two principal components (PCs) for each variable are plotted as vectors. Parallel vectors indicate a strong linear relationship, whereas orthogonal vectors indicate little or no correlation. We performed a principal component analysis (PCA) using: (1) a basal friction coefficient estimate from Dawson et al. (2022), (2) basal temperature relative to the pressure melting point from Dawson et al. (2022), (3) BedMachine bed elevation (Morlighem et al., 2020), (4) BedMachine bed roughness calculated from Li et al. (2022), and (5) a machine-learning-based sedimentary basin likelihood from Li et al. (2022), derived primarily from gravity and magnetic data.

The resulting biplot (Figure 6d) shows that the friction coefficient is strongly aligned with bed elevation but has only weak relationships with bed roughness, sedimentary basin likelihood, and basal temperature. To complement this, we computed correlation coefficients between the friction coefficient and each bed property within individual catchments (Figure 7). The results show a strong, continent-wide positive correlation between bed elevation and basal friction. Sedimentary basin likelihood consistently shows a negative correlation (i.e., areas with a high probability of sedimentary basins tend to have low friction). Basal temperature and roughness are weakly correlated to basal friction–positive in some catchments and negative in others. These analyses suggest that basal conditions may have some relationship to basal friction, albeit a weak one, and the strength and direction of these relationships can vary by catchment. This ambiguous connection between basal conditions and the friction field highlights the extent to which the friction field acts as a tuning parameter that compensates for multiple unresolved processes and therefore cannot be interpreted as a direct representation of the physical or geologic properties of the bed.

A fundamental limitation in ice-sheet modeling is that the appropriate form of the basal sliding relationship remains uncertain. This uncertainty is compounded by spatial variations in basal geology. Large-scale models commonly apply the same sliding relationship across the model domain (e.g. Seroussi et al., 2020), despite transitions between hard bedrock, deformable sediment, and mixed or discontinuous sedimentary beds that may support different modes of basal motion. While spatially varying friction coefficients can reproduce heterogeneous present-day flow, they do not account for spatial variations in the

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underlying sliding physics. A major knowledge gap is therefore both determining which sliding relationships best represent different basal environments and identifying where those environments occur beneath the ice sheet. This is additionally not helped by the lack of appropriate subglacial hydrological representations in ice sheet models although better physical representations are being developed despite the challenges of doing so (Haseloff et al., 2025).

4 Paleo constraints on basal boundary conditions

In the previous sections, we explored how subglacial geological conditions strongly influence ice-sheet movement and its response to climate forcing. However, it is important to note that the subglacial conditions can themselves act as a record of past ice sheet evolution. In this respect, they are underutilized in ice-sheet models, but there is an opportunity to further link landforms, sediment, and hydrologic conditions more physically in models to both control and constrain simulations.

4.1 Evidence for past basal conditions

As ice-sheets retreat, they reveal landforms created by ice flow and sediment movement which can be interpreted to reconstruct past ice dynamics (Pearce et al., 2017). Glacial landforms are perhaps the most numerous and spatially extensive constraint on past ice-sheet behavior, providing information on past ice flow direction, flow speed and the presence of ice streams, basal thermal regime, hydrology, and retreat pattern. Despite their ubiquity, glacial landforms are underutilized in model-data comparison, partially due to the scale difference between individual landforms and ice-sheet model grids (Ely et al., 2021). The useful landform record is found largely, though not completely, in the marine realm. For example, subglacial lineations – streamlined elongate ridges formed beneath the ice, composed of sediment (Ely and Clark, 2016), and usually occurring in fields of similar morphology with parallel conformity – are present in most glacial troughs across the continental shelf in Antarctica. These linear features (ranging from Rogen moraines to drumlins to mega-scale glacial lineations) are well-recognized ways of defining the presence of fast ice flow relative to neighboring non-lineated areas (e.g. Stokes and Clark, 1999). In Antarctica, the distribution of mega-scale glacial lineations has been used to define the margins of paleo ice streams (e.g., Livingstone et al., 2012; Cofaigh et al., 2014). For much of the deglaciated Antarctic seafloor, topographic troughs funneled ice flow (e.g. Bingham et al., 2012; Cofaigh et al., 2014), although more complex ice flow directional variations have been recorded in lineations on the floor of the Ross Sea (Greenwood et al., 2012; Halberstadt et al., 2016). Lineated bedforms are also known to be forming under present day ice streams, as demonstrated by geophysical surveys of the Rutford Ice Stream (King, 2009; King et al., 2016). Ice marginal landforms, such as moraines and grounding zone wedges, also contain information about past ice margin position, shape, and potentially retreat speed. For instance, the closely-spaced and relatively small ice marginal ridges reported by Batchelor et al. (2023) indicate rapid ice retreat, whilst larger, more infrequently spaced grounding zone wedges indicate slowdowns or pauses in marine based retreat (Jamieson et al., 2012; Bart et al., 2017). The presence of water has also been inferred on the beds of some Antarctic ice streams (e.g. Dow et al., 2022). This is often evidenced by channels eroded into hard crystalline bedrock over multiple glacial cycles (e.g. Smith et al., 2009; Wellner et al., 2006)

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as well as channels preserved in soft sediments that were active during the final stage of the last deglaciation (Simkins et al., 2017, 2021).

Finally, characteristics of glacially eroded sediment (e.g. provenance and sedimentary structure) are a significant geological indicator of past ice behavior. Sediment provenance analysis, which traces the geological fingerprint and transport pathways of glacially eroded material (e.g. Licht and Hemming, 2017) reflects sediment transport processes, and changes in sediment source are commonly identified using isotopic tracers. For example, warming basal conditions will increase basal hydrological activity (e.g. Hayden et al., 2025) enhancing erosion and flushing that sediment from inland regions to the margin. These proxy records enable reconstruction of former erosive ice-sheet margins, providing constraints on the timing and extent of ice-sheet retreat and advance. Beyond provenance, the structure, makeup and age of sub-seafloor sediments record glaciations since the Eocene-Oligocene Transition (Naish et al., 2001; Pollard and DeConto, 2020; McKay et al., 2022). These records have formed the core of our understanding of long-term ice sheet evolution in Antarctica and alongside individual drill-core records from the continental shelf and beneath the ice shelves, circum-Antarctic compilations of seismic stratigraphy (Huang et al., 2014; Hochmuth et al., 2020) help make the link between past ice behavior and climate. Changes in the geometry and geography of landmasses and ocean basins lead to first-order ocean current distribution and marine sedimentation patterns.

4.2 Use of geological constraints in ice-sheet models

The most commonly used geological constraints for modeling the paleo evolution of Antarctica are estimates of ice-sheet volume derived from paleo sea level or present-day rebound data. However, if used in model-data comparison alone, then an issue with equifinality arises because models with incorrect ice extents and thickness can produce reasonable fits to sea level data (Bradley et al., 2023). To circumvent this issue, direct constraints on the timing and amplitude of ice thinning come from ice-proximal geochronological data pertaining to when landforms or landscapes became ice free. For example, the dating of nunatak exposure provides constraints on ice thickness (e.g., Bentley et al., 2006; Small et al., 2019), which if spaced along a vertical transect have been used as constraints in models to provide target information on past thinning (Stutz et al., 2021; Jones et al., 2021; Halberstadt and Balco, 2026). Ice margin position and flow directions through time can be similarly inferred by dating landforms and investigating sediment cores. These seafloor data provide geomorphic constraints on modeled ice-sheet margin positions and flow directions (Ely et al., 2019, 2021; Archer et al., 2023), as well as informing model basal sliding zones where they have often been used to apply masks delineating lower vs. higher basal friction zones (Whitehouse et al., 2012). Both geochronologic and geomorphic data have been used to constrain model simulations of ice-sheet retreat since the Last Glacial Maximum (Pollard et al., 2016; Whitehouse et al., 2012; Lecavalier and Tarasov, 2025; Briggs et al., 2014; Albrecht et al., 2020; Pittard et al., 2022; Halberstadt and Balco, 2026; Halberstadt et al., 2026).

Sediment proxy records have been used to assess the geological likelihood of ice-sheet simulations from past warm periods in the geologic past (e.g., Halberstadt et al., 2024). For example, retreated ice-sheet states documented from changing isotopic compositions of sediment on the East Antarctic margin during warmest Mid-Pliocene and Pleistocene 'super' interglacial climates (Williams et al., 2010; Cook et al., 2017; Wilson et al., 2018) have influenced a number of ice-sheet modeling studies that suggest a dynamic ice sheet margin in the Wilkes Subglacial Basin (Crotti et al., 2022; DeConto and Pollard, 2016;

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Golledge et al., 2021). Recent advances in modeling of subglacial sediment production and transport systems are helping make the link between ice behavior and provenance so that simulations are more geologically-testable (e.g., Marschalek et al., 2025; Aitken and Urosevic, 2021; Hergarten, 2021; Aitken et al., 2024). Sedimentary evidence from syntheses of marine seismic data, constrained by geological evidence from terrestrial outcrops and drill cores, has been critical in simulations testing the role that paleotopography has played on Antarctic ice-sheet history (e.g., Colleoni et al., 2018b; Paxman et al., 2020).

4.3 Gaps in knowledge

In the northern hemisphere, the relationship between relatively common landforms and ice dynamics, combined with the availability of model-data comparison tools (Ely et al., 2021; Archer et al., 2023) has led to a recent uptake in the use of subglacial lineations and ice marginal landforms as model constraints for other paleo-ice-sheets (Patton et al., 2017; Ely et al., 2021; Gandy et al., 2021). However, in Antarctica, the scale difference between landforms and model grids has led to landforms most frequently being used to simply confirm the presence or absence of a slippery vs. sticky bed (e.g. to define basal friction conditions and thus enable ice stream flow (Whitehouse et al., 2012)); to qualitatively verify the accuracy of model output (Golledge et al., 2013); or to quantitatively compare model output against a regional-scale synthesis (Bentley et al., 2014) of past ice margin position or thickness over time (e.g., Briggs et al., 2014). The development of a circum-Antarctic landform database that incorporates all landforms (not just marginal constraints) and is granular rather than taking a timeslice approach (as has been common until now), would enable two things: First, modelers could use the spatial and temporal distribution of landforms to more clearly constrain not only the ice margin and past flow directions, but the basal conditions for Antarctic-scale simulations. Such an approach would move beyond the catchment scale use of landforms that has been possible in some simulations (e.g. Jamieson et al., 2014). Additionally, such a database could be used with existing tools for quantitative comparison of model skill against both lineations and ice marginal features (Ely et al., 2019; Archer et al., 2023; Halberstadt et al., 2026). Second, having a dataset with consistent coverage would enable modelers to not only have a landform-based friction map, but to begin exploring more process-based rules that relate ice behavior to geological processes, subglacial friction being one obvious example. Crucially, the development of such community databases of landforms and chronology of ice extent, thickness and flow dynamics would only be useful when it is up-to-date; therefore, to make the most of ongoing geological data collection, any database would need to be quality-checked and curated on an ongoing basis.

5 Discussion and future research opportunities

Our understanding of Antarctica's subglacial landscape has advanced rapidly, driven by improved geophysical mapping (Jordan et al., 2020b; Gustafson et al., 2022; Aitken et al., 2023), geological characterization (Sanchez et al., 2021; Cox et al., 2023), improved isotopic fingerprinting of bedrock exposures and detritus that allow inland geology to be inferred from the provenance of coastal samples (Flowerdew et al., 2012), and the growing use of machine learning approaches to classify multi-observable datasets (e.g. MacKie et al., 2020; Lösing and Ebbing, 2021; Li et al., 2022; Liebsch et al., 2025). Yet a central challenge remains: translating diverse geological observables – which includes physical properties such as density, conductivity, seismic

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velocity, or geological classifications – into parameters that ice-sheet models can meaningfully use. Addressing this need requires (1) a framework for converting geologic observations into proxies for bed properties that influence ice flow (Figure 3, Challenge 1), and (2) a mechanism for translating geologic conditions into parameters that ice-sheet models can ingest (Figure 3, Challenge 2). Developing both pieces is essential for moving from improved geological understanding to improved basal boundary conditions in next-generation ice-sheet models.

5.1 Inference of subglacial conditions

5.1.1 Geological observations and datasets

Geological observations of outcrops above the ice sheet (Cox et al., 2023) and subglacial sediments collected as part of drilling expeditions (e.g. Tulaczyk et al., 1998; Kamb, 2001) demonstrate the heterogeneity of Antarctic geology over a range of scales. Although scarce, these geological data will remain invaluable for ground-truthing geophysical data and interpolations (Aitken et al., 2023). Measurements of thermal, physical, and chemical properties from Antarctic geology can be used in/compared to regional crustal inversions (e.g. Lowe et al., 2024a; Lösing et al., 2025). Such measurements can best be taken as part of projects that access the bed beneath grounded ice (e.g. Tulaczyk et al., 2000; Priscu et al., 2021; Braddock et al., 2025), which will require technology development for drilling (e.g. Rack et al., 2014; Boeckmann et al., 2021; Makinson et al., 2021), sampling (e.g. Rosenheim et al., 2023), and observing (e.g. Fisher et al., 2015; Siegfried et al., 2023) the subglacial environment. Beyond sampling and observation efforts, investment in long term curation of geological sample archives from Antarctica (e.g. Polar Rock Repository, 2015) and databases (e.g. Sanchez et al., 2021) is key to enabling these insights. Overcoming outcrop-bias towards erosion resistant lithologies demands that bed-access technologies improve (U.S. Ice Drilling Program, 2024), as well as the ability to use glacially transported debris to characterize the bed beneath fast-sliding ice.

The sparse and biased nature of Antarctic data limits the ability to develop regional proxies for geological characteristics. This challenge can be mitigated by learning from elsewhere, such as leveraging data from Antarctic conjugate margins in Gondwana to train interpretations. For example, Lösing et al. (2025), crustal heat production was predicted using Australian rock-property and high-quality geophysical data to provide the missing knowledge in Antarctica. The mapping of other properties may, in principle, be trained similarly. For instance, the extensive studies of geomorphology and geology conducted in formerly glaciated regions of the Northern Hemisphere ice-sheets might be leveraged to develop better parameterizations of basal processes suitable for Antarctic data conditions (Kleman and Hättestrand, 1999; Stokes and Tarasov, 2010; Margold et al., 2015).

5.1.2 Geophysical imaging and analysis

Geophysical surveying methods–such as radar, seismic, gravity, magnetics, and magnetotellurics – have each proven effective in constraining bed conditions (e.g. Wannamaker et al., 2004; Ruppel et al., 2018; Morlighem et al., 2020; Jordan et al., 2023; Guy et al., 2024; Lowe et al., 2024b; Pritchard et al., 2025; Lösing et al., 2026; Manassero et al., 2026; Zeising et al., 2026). However, these techniques are individually limited by data sparsity and the non-uniqueness of their interpretations.

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For example, radar reflectivity is influenced by a combination of basal roughness, lithology, and water content (Peters et al., 2005), making it difficult to infer specific basal properties from bed power alone. More broadly, each geophysical method is sensitive to multiple bed parameters and at different spatial scales, resulting in substantial uncertainty in the interpretation of basal conditions. Future observational efforts should therefore prioritize complementary, multi-method geophysical surveys that enable information from one technique to reduce ambiguities inherent to another. These efforts should be accompanied by rigorous quantification of uncertainties associated with integrating datasets that differ substantially in spatial coverage, resolution, and sensitivity.

Joint analysis and inversion of geophysical datasets provide an important pathway to reducing the non-uniqueness of geophysical observations. The extensive coverage of gravity and magnetic airborne data in Antarctica has driven a surge in joint inversion studies, which link the inverted density and susceptibility distribution to Antarctic petrophysical rock property catalogs such as PetroChron (Sanchez et al., 2021) to constrain and identify geological provinces (Jordan et al., 2023; Lösing et al., 2023; Lowe et al., 2024b, a; Lösing et al., 2025). Utilizing magnetotelluric (MT) data in joint inversion approaches has been proven outside of Antarctica to provide important lithospheric insights such as fluid and melt distribution, mineral composition, structural architecture and thermal state of the lithosphere (e.g. Moorkamp, 2022). Although comparable MT-based studies are currently absent in Antarctica due to the limited availability of MT surveys, acquiring such data would fill a critical gap. MT observations can constrain deep crustal and upper-mantle properties and illuminate shallow subglacial conditions, including sediment water content, thereby improving our understanding of how solid Earth processes at multiple depths interact with the cryosphere (Hill, 2020; Manassero et al., 2026).

Bed topography remains the most essential input basal condition for ice-sheet models and serves as a basis for investigations of other basal properties including geothermal heat flow, geology, traction, and hydrology. While its large uncertainty is challenging to quantify and propagate into downstream analyses, geostatistical simulation (MacKie et al., 2021, 2023) and Bayesian inversion approaches (Field et al., 2026; Lösing et al., 2026; Shao et al., 2026) provide an opportunity for representing this uncertainty through ensembles of plausible bed configurations. Future efforts should move beyond single deterministic data products and towards probabilistic representations that enable the identification of regions where bed uncertainty contributes most strongly to uncertainty in ice-sheet model projections and other geophysical analyses. In addition, Ockenden et al. (2026) demonstrate the potential of using ice surface texture to infer bed topography and fill gaps between surveys. These approaches can help prioritize observational campaigns by identifying where improved bed constraints would provide the greatest scientific benefit.

Ice-penetrating radar remains the primary tool for capturing large-scale observations of the ice-bed interface, and is critical to ongoing bed mapping efforts (Matsuoka et al., 2026). As the radar gaps of the continent are filled in, bed elevation uncertainty due to measurement uncertainty will increasingly dominate over interpolation uncertainty. As such, a more rigorous treatment of measurement uncertainty is needed. Surveys that prioritize gap-filling will have increasingly diminishing returns, particularly for smooth areas of the bed where additional data will add little value to geostatistical simulations and mass conservation inversions. Future surveys should therefore prioritize complex and rough topography. Swath radar (Holschuh et al., 2020) will be particularly valuable in these settings and for interpreting geological processes at the bed. Although radar cannot uniquely

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characterize the material properties of the bed, multi-frequency systems have the potential to reduce ambiguity in reflected signals and better constrain basal characteristics (Broome and Schroeder, 2021).

Installing and maintaining a greater density of long-term seismic stations would lead to significant improvements in constraining the structure of the deep Earth and lithospheric mantle across Antarctica. Obtaining greater detail in Antarctica's magnetic and gravity constraints through airborne geophysics surveys, in particular with denser flight line spacing remains a high priority. Such datasets will help identify shallow crustal features such sediments and geological provinces but also help, in combination with satellite potential field data, to reveal major heterogeneities in lithosphere architecture (e.g. Ebbing et al., 2018; Pappa et al., 2019; Haeger et al., 2022; Pappa and Ebbing, 2023; Lowe et al., 2024b; Lösing et al., 2025). Such observations would provide an opportunity to jointly interpret and invert complementary geophysical datasets across Antarctica. For example, joint inversion of magnetotelluric and gravity field data has yielded new insights into the lithospheric properties beneath Yellowstone (Moorkamp, 2022). It is a high priority to survey key outlets of subglacial basins, and to characterize the nature of subglacial sediments (as sedimentary rock or unlithified sediments) using seismic data (Zeising et al., 2026). It is now possible to do so through on-ground passive seismic transects, which afford a cost-effective means of covering relatively large distances in the Antarctic interior (Shen et al., 2018).

Integrating geophysics with geological constraints requires the development of both quantitative models and qualitative geological narratives. Machine learning applications combine seismic wavespeed models, gravity, and magnetic information, while radar datasets combined with passive seismic constraints offer new pathways to systematically characterize subglacial properties while maintaining geological interpretation that respects sparse direct observations. Such coupled approaches, linking deep Earth structure through crustal architecture to ice-bed interface processes, represents a frontier in ice-sheet dynamics understanding, where Antarctic research innovations continue to advance methodological boundaries. Such models require the foundation understanding of geological evolution, and ongoing Earth-ice processes. In all cases, the limitations posed by sparse data must be respected, but may be addressed through careful interpolation, effective use of uncertainty metrics, and use of subsurface boundary conditions in ensemble-based modeling.

5.1.3 Temporal evolution of subglacial conditions

Subglacial conditions relevant to ice sheet behavior include parameters that influence the friction of the ice sheet (e.g., the distribution and characteristics of water, sediment, rock, and heat) as well as the shape of the subglacial landscape as it evolves and thus alters ice flow and climate interactions. In this regard, understanding the tectonic and glacial history of Antarctica becomes crucial because it directly influences the above characteristics and their evolution over all timescales. However, observations of, and constraints on, evolving subglacial conditions are sparse in Antarctica due to the challenges associated with gaining repeat observations in the modern era and acquiring constraints on long-term change from the geological record. As a consequence, past research has tended to rely on (1) numerical models to infer the evolution of conditions at the bed, including, for example: subglacial water flow (Dow, 2022), sediment transport (Pollard and DeConto, 2020; Aitken et al., 2024), and mantle flow (Austermann et al., 2015); and (2) reconstructions of the past onshore and offshore geometry of Antarctica (Wilson and Luyendyk, 2009; Wilson et al., 2012; Paxman et al., 2019; Hochmuth et al., 2020).

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Further priorities for future work could include the following: First, developing and improving maps of subglacial geology and topography to understand the evolution of the continent and the ice that overlies it, which includes subglacial rock sampling to constrain tectonic deformation (e.g., Daczko and Halpin, 2025; Halpin et al., 2026), long-term uplift (e.g., Fitzgerald, 1992), subsidence (e.g., Wilson and Luyendyk, 2009), denudation (e.g., Thomson et al., 2013), and paleo-environment (e.g., Coenen et al., 2020). In particular, constraining the evolution of major basins (Maritati et al., 2016; Jordan et al., 2020b; Armadillo et al., 2026) and mountain ranges (Ferraccioli et al., 2011; Eagles et al., 2018) will improve understanding of physiographic features that exert a major influence on ice sheet behavior. Second, assembling a database of circum-Antarctic sediment properties and provenance and more robust understanding of transport pathways will facilitate improved understanding of linkages between onshore and offshore erosion and deposition (e.g., Licht and Hemming, 2017; Sanchez et al., 2021; Marschalek et al., 2025). And third, conducting repeat measurements to constrain patterns and rates of change in topography and sediment (e.g., King et al., 2016) and flows of water (e.g., McMillan et al., 2013) will help enhance understanding of the scale, pattern and importance of sort-term changes at the present day. All of the above priorities would benefit significantly from further improvements to our knowledge of the current bed topography, measurement of which remains spatially heterogeneous and subject to uncertainty related to methodological choices in the gridding approach (Fretwell et al., 2013; Morlighem et al., 2020; Pritchard et al., 2025).

5.2 Translating bed properties to ice-sheet model parameters

Improving constraints on bed properties is critically important – particularly if that information can be meaningfully incorporated into ice-sheet models (Figure 3, Challenge 2). While continent-scale datasets now exist for key geological variables such as heat flow, sedimentary basin extent and type, volcanic provinces, and even structural fault maps derived from existing datasets, integrating this information into ice-sheet models remains a major challenge. The reliance of ice-sheet models on inverted parameters and simplified sliding law assumptions results in a workflow that largely bypasses geologic datasets, leaving much of the available information underutilized. To address this gap, a dedicated effort is needed to make geologic data accessible in model-ready formats and to develop tools that allow this information to be incorporated directly into sliding law choices and friction parameterizations. Doing so will enable models with improved "geological realism", ultimately enhancing our ability to understand and project ice-sheet behavior.

More formal quantification of uncertainties associated with the numerous basal parameters involved in ice-sheet models (e.g., topography, geothermal heat flow) is a key step towards providing more realistic predictions of ice-sheet dynamics in both the past and future (e.g., Caillet et al., 2026). Probabilistic future sea level rise projections consider various types of uncertainties associated with future scenarios or model parameters (Coulon et al., 2025; Seroussi et al., 2020); but the geologic uncertainty associated with bed conditions is not often provided in a format that can be formally propagated into future sea level projections. Providing modelers with multiple realizations of basal fields that realistically represent spatial uncertainty – rather than perturbing each grid point independently, which can produce spatially and physically inconsistent fields – will improve the characterization of uncertainty in ice-sheet evolution associated with various basal fields. However, ensemble sizes

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would likely increase significantly if bed topography and thus inverted basal friction parameter spaces were to be systematically explored.

Geostatistical simulation, particularly mass conserving geostatistical simulation (Shao et al., 2026), offers a powerful means to generating realistic topography and quantifying associated uncertainties. Given that bed topography underpins inversions for basal friction and ice viscosity, ensembles of rough topographies could be used to assess uncertainties in these parameters, improve model initialization, and evaluate model sensitivity. Resolution is another critical factor. Future work should investigate how model sensitivity varies with both topographic roughness and grid resolution. In particular, mesh refinement strategies may need to account for roughness, with rougher terrain potentially requiring finer resolution. Given the wide range of meshing approaches used across the ice-sheet modeling community, and our demonstration that common interpolation to these meshes can produce bed topography differences exceeding 1000 m depending on the meshing resolution and approach (Section 2.2), alternative interpolation approaches that are adaptable to the model mesh provided and better preserve the spatial character of bed topography may also need to be explored. Ultimately, ensembles of geostatistical simulations could inform how bed uncertainty propagates through ice-sheet models (e.g. McCormack et al., 2026) and help identify priority regions for targeted radar surveys.

Process-level model experiments could be used to establish links between local scale bed properties and model-scale parameters. Models with coarse resolution meshes that rely on sub-grid scale parameterizations or that require the tuning of a number of model parameters in order to match modern observations may be ill-suited for investigating basal sliding and deformation at a fundamental level. In contrast, process-based models can be used to run simulations at a meter resolution and have a simpler initialization process, and could be fundamental to developing a connection between geology and model processes/parameters (Law et al., 2023). Synthetic experiments could be used to study the impact of roughness and model resolution on sliding behavior, and examine how changes in roughness influence shear heating and ice stream onset (Liu et al., 2024). Synthetic experiments could also be used to answer the question, “At what spatial scale is topography geometry, and at what point does it become roughness?” Answering this question could help with parameterizing basal friction.

A persistent disconnect between geologic information and the selection of sliding relationships and friction parameterizations limits our ability to model basal influences on ice-sheet dynamics (e.g. Law et al., 2026) and to understand how uncertainties at the bed propagate into ice-sheet model predictions. To better represent the evolving basal state, ice-sheet models require geologically informed parameterizations that are less dependent on model-specific assumptions. Ideally, sliding relationships would vary spatially (and temporally) based on bed conditions, with basal friction coefficients constrained by observable properties such as bed roughness, hydrology, sediment presence/absence and bedrock lithology, or even glacial landforms characteristic of bed conditions. While these coefficients must remain physically consistent with ice-sheet model formulations, they should also be grounded in empirical relationships between bed properties and basal frictional processes. Developing these links remains an important direction for future research. Experimental data will remain critical to informing physical behaviors at the ice bed (e.g. Zoet and Iverson, 2015, 2016).

The process of translating sparse and uncertain observations into bed properties–and then into model parameters–is both technically challenging and time-consuming, especially when parameters must be updated as new data become available. To

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support modelers, every effort should be made to streamline and simplify this workflow. Full-stack, open-source pipelines and easily interpretable and accessible data products will be essential for this effort. Such tools would enable the seamless integration of spatially consistent geologic datasets with robust uncertainties into ice-sheet models, facilitate the generation of tailored parameter fields, and support more effective hypothesis testing and uncertainty quantification. By bridging the gap between observations, geologic interpretation, and model implementation, these workflows would help unify the disparate components of ice-sheet modeling into a more coherent, accessible, and reproducible system.

6 Conclusions

Antarctica's geological boundary conditions and processes are a critical but incompletely resolved and modeled component of ice-sheet behavior. Bed topography continues to be a critical though not fully quantified source of uncertainty in ice-sheet models. Field campaigns must continue to address Antarctica's observational gaps. At the same time, future interpolations and representations of bed topography must better quantify uncertainty and improve the morphological representation or geological realism of the landscape. Complex interactions between topographic roughness and geological conditions warrant further exploration.

Bridging the gap between geological knowledge and ice-sheet model parameterization is essential for making effective model projections. Future research should prioritize the assimilation of basal observations into the model parameterization process. This effort is important for improving the geological realism of ice-sheet model input parameters and mitigating the circular reasoning that is often encoded in ice-sheet model setup. Ideally, deriving frictional and sliding parameters independently of ice-sheet models would better facilitate hypothesis testing, improve our understanding of ice-sheet sensitivity to uncertainties in basal conditions, and aid in the perpetual search for a universal sliding law. Theoretical, experimental, and process-scale modeling experiments will remain vital to this effort.

While improving the treatment of the basal friction coefficient is an important pursuit, Antarctica's subglacial geology is more than just a frictional interface. Nor is this basal environment static. Future generations of ice-sheet models must consider the full vertical extent of geological conditions and processes, along with their interaction with the overlying ice. Simultaneously, observational studies must continue to investigate links between deeper geological features and conditions at the ice/bed interface. By integrating advanced observational techniques with improved model parameterizations, future research can better capture the dynamic interplay between geological and ice-sheet processes, which will ultimately strengthen our ability to project Antarctica's future.

Appendix A: Mesh generation

To investigate the impact of meshing approach on bed topography interpolation into an ice-sheet model mesh, we generated 54 unique meshes. Meshes fall into two categories, uniform or adaptive resolution, with the latter generated using BAMG (Bidimensional Anisotropic Mesh Generator; Hecht, 2006). For the adaptive meshes, we defined a baseline mesh configuration

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and then varied one parameter at a time. The parameters spanned core meshing parameters (initial resolution and minimum and maximum vertex length, applied overall and beneath ice shelves) and BAMG algorithm controls (error threshold and gradation). Each BAMG adaptive refinement was simulated for either one or two iterations. For the uniform resolution meshes, we applied a single uniform vertex length across the domain, with no adaptive refinement, across a range of resolutions. A summary of the parameters used in the mesh generation is provided in Table A1.

Data availability. All datasets used in this study are publicly available and include Bedmap topography (https://doi.org/10.5285/2d0e4791-8e20-46a3-80e4-f5f6716025d2), BedMachine topography (https://doi.org/10.5067/POJQI54A45HX), the Li et al. (2022) sedimentary basin likelihood map (https://doi.org/10.5281/zenodo.6611940), the Dawson et al. (2022) model of basal temperature relative to the pressure melting point (https://doi.org/10.5281/zenodo.6870567), the Shen et al. (2020) geothermal heat flow model (https://cmr.earthdata.nasa.gov/search/concepts/C1833336298-SCIOPS.html, and geostatistically simulated topography (https://doi.org/10.15784/601927). No new data sets were produced in this study.

Author contributions. E.J.M. was responsible for writing, experimental design, editing, figure making, analysis, and conceptualization. L.L. was responsible for experimental design, editing, figure making, and analysis. A.R.H. was responsible for writing and analysis. S.S.R.J. was responsible for writing, editing, and conceptualization. R.L. was responsible for writing and editing. M.L. was responsible for writing and editing. F.S.M. was responsible for writing, editing, figure making, and analysis. G.J.G.P. was responsible for writing and editing. A.A. was responsible for writing, editing, and conceptualization. E.D. was responsible for writing and editing. J.E. was responsible for writing and editing. M.F. was responsible for writing and editing. J.A.H. was responsible for writing and editing. D.H. was responsible for writing and editing. Y.M.M. was responsible for writing and editing. S.N. was responsible for editing and conceptualization. A.R. was responsible for writing, editing, and conceptualization. N.S. was responsible for writing, editing, and figure making. T.S. was responsible for writing and editing. K.T. was responsible for writing and editing. R.V. was responsible for writing and editing.

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Table A1. Summary of the 54 mesh realizations generated for the resolution and BAMG sensitivity study. "Vertex length" refers to the target edge length of mesh elements. Maximum vertex length (fast flow) and minimum vertex length (ice shelf) were fixed at their baseline values of 1,500 m and 500 m, respectively, in all adaptive runs.

Parameter	Description	Baseline Value	Values Tested	Iterations Tested	Realisations	Group
Initial resolution	Initial vertex length used to seed the adaptive remeshing	10 km	10–50 km (step 10 km)	1, 2	10	Adaptive (BAMG)
Minimum vertex length (overall)	Lower bound on vertex length applied across the whole domain	50 m	100–500 m (step 100 m)	1, 2	10	Adaptive (BAMG)
Maximum vertex length (overall)	Upper bound on vertex length applied across the whole domain	50 km	10–50 km (step 10 km)	1, 2	10	Adaptive (BAMG)
Maximum vertex length (ice shelf)	Upper bound on vertex length beneath floating ice shelves	5 km	1–5 km (step 1 km)	1, 2	10	Adaptive (BAMG)
Baseline configuration	All parameters held at their baseline values	—	—	1, 2	2	Adaptive (BAMG)
Error threshold	BAMG interpolation error tolerance controlling local refinement	1.0	0.5, 1.0, 2.0	2	3	Adaptive (BAMG)
Gradation	BAMG parameter limiting the growth rate of vertex length between adjacent elements	1.2	1.1, 1.2, 1.5	2	3	Adaptive (BAMG)
Uniform resolution	Single vertex length applied uniformly across the mesh, with no adaptive refinement	—	1, 2, 5, 10, 15, 30 km	0	6	Constant

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created Figure 1. ChatGPT was used to format Figure 3. ChatGPT was used to create a script to query Crossref and add DOIs to references (all DOIs were manually checked).

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