~~The Antarctic Ice Sheet~~ Inferring the ice sheet sliding law ~~inferred~~ from seismic observations: A Pine Island Glacier case study

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Abstract. The response of the Antarctic ice sheet to climate change and its contribution to sea level under different emission scenarios are subject to large uncertainties. A key uncertainty is the slipperiness at the ice sheet base and how it is parameterized in glaciological projections. Alternative formulations of the sliding law exist, but very limited access to the ice base makes it difficult to ~~select among~~ validate them. Here, ~~we use satellite observations of ice flow, inverse methods, and a~~ the Viscous Grain-Shearing (VGS) theory of acoustic propagation in granular material, together with independent estimates of grain diameter and porosity from sediment cores, is used to relate the effective pressure, which is a key control of basal sliding, to seismic observations recovered from ~~Antarctica. Together with independent estimates of grain diameter and porosity from sediment cores, this~~ Pine Island Glacier, Antarctica. With basal shear stress and sliding speed derived through satellite observations of ice flow and inverse methods, the new Bayesian sliding law inference – VGS (BASLI–VGS) approach enables a comparison of basal sliding laws within a Bayesian model selection framework. The presented direct link between seismic observations and sliding law parameters can be readily applied to any acoustic impedance data collected in ~~a glacial environment~~ glacial environments underlain by granular material. For rapidly sliding tributaries of Pine Island Glacier, these calculations provide support for a Coulomb-type sliding law and widespread low effective pressures.

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1 Introduction

Large uncertainties accompany sea level rise projections for the 21st century. Relative to 1900, the estimates vary between ~ 50 and $> 100\ \mathrm{cm}$ (IPCC Core Writing Team, H. Lee and J. Romero (eds.), 2023). This uncertainty hampers the formulation of adaptation strategies. A key source of uncertainty is the slipperiness of the bed beneath regions of fast-flowing ice streams (Ritz et al., 2015; Brondex et al., 2017), particularly in the Amundsen Sea Embayment (e.g., Nias et al., 2018; Joughin et al., 2019;

20 Brondex et al., 2019). Despite over 60 years of research on basal sliding ~~(e.g., Brondex et al., 2017; Weertman, 1957; Lliboutry, 1958a, b, 1~~
    (e.g., Weertman, 1957; Lliboutry, 1958a, b, 1959; Budd et al., 1979; Iken, 1981; Iverson et al., 1998; Tulaczyk et al., 2000; Schoof, 2005;
    , the sliding law operating on large scales in Antarctica remains a matter of debate.

   For ice that slides over the bed, a no-slip boundary condition is inappropriate. Free slip is also unrealistic because basal drag
    provides significant resistance to sliding wherever the ice is not floating. Instead, a sliding law that relates basal shear stress
25 to sliding speed is needed. Alternative formulations of this sliding law have been proposed, applying to different subglacial
    circumstances (e.g., Fig. 1b-f). The frequently used Weertman-type power law (e.g., Weertman, 1957; Arthern et al., 2015; Ritz
    et al., 2015; Arthern and Williams, 2017; Brondex et al., 2017; Kyrke-Smith et al., 2017; Hank and Tarasov, 2024) considers
    ice slipping over a rough, hard bed, with ice deforming to pass around large obstacles while bypassing smaller obstacles by
    pressure melting and regelation (Fig. 1b; Weertman, 1957). In contrast, Lliboutry envisaged discontinuous ice contact with a
30 hard bed, separated by water-filled subglacial cavities (Fig. 1c; Lliboutry, 1958a, b, 1959). Later studies show this cavitation
    could lead to an upper bound for basal shear stress, even for fast-sliding glaciers (Iken, 1981; Schoof, 2005), and the upper
    bound was subsequently included in analytically derived sliding laws (Schoof, 2005; Gagliardini et al., 2007).
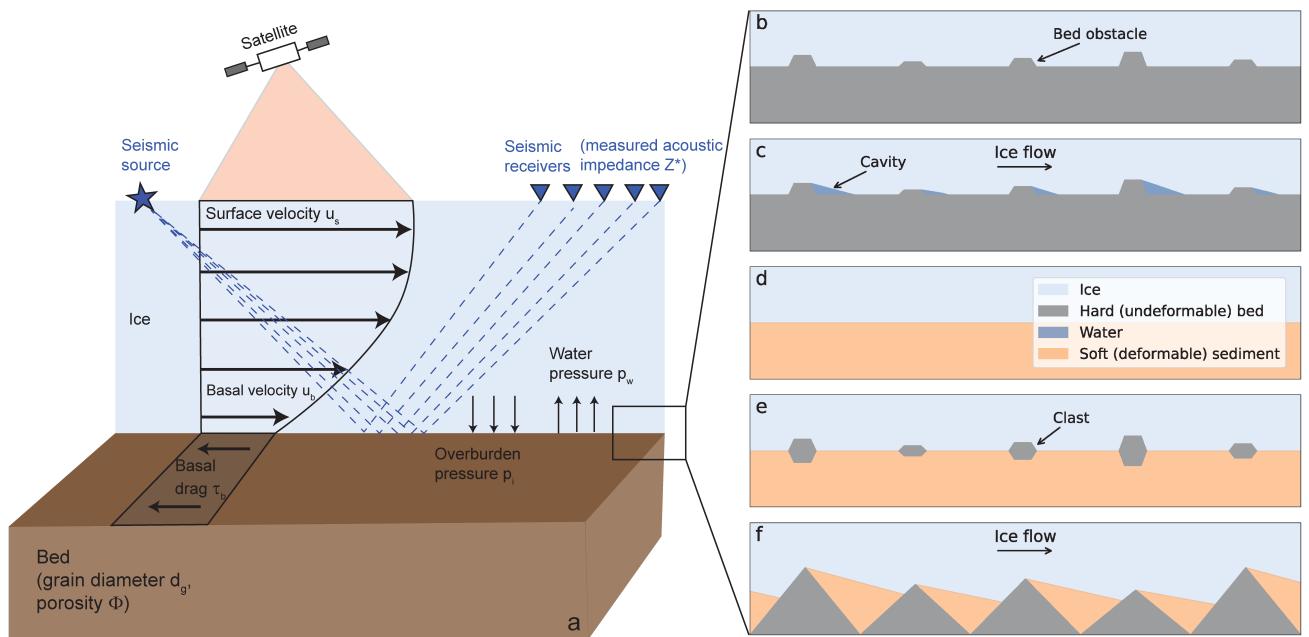
Figure 1. Experimental setup (a) and schematics of the bed considered for different sliding laws (b-f). The schematics are not to scale. Details
of the experimental setup are outlined in Fig. 2 and the text.

   Another type of basal drag law is based on sliding lubricated by a deforming layer of sediment that yields, either in a
    rate-dependent (viscoplastic) fashion or according to a rate-independent plastic law (Fig. 1d; e.g., Budd et al., 1979; Iverson
35 et al., 1998; Tulaczyk et al., 2000). One such boundary condition is a Coulomb sliding law, for which the basal shear stress
    is independent of sliding speed, but varies in proportion to the effective pressure, i.e. the difference between the weight of

the overlying ice and the subglacial water pressure. Higher effective pressures lead to greater compression within the granular sediment. In an alternative formulation, a modification of the Weertman-type power law that accounts for a strong dependence of the basal shear stress on effective pressure found in laboratory experiments has been proposed (Budd et al., 1979).

40   Ice loss projections, particularly of the Amundsen Sea Embayment, are sensitive to the applied sliding law, with sliding law parameters being a key source of uncertainty (e.g., Gillet-Chaulet et al., 2016; Brondex et al., 2017; Joughin et al., 2019; Brondex et al., 2019; Barnes and Gudmundsson, 2022). Previous approaches constraining the basal properties, i.e. the sliding law parameters, generally rely on remote sensing data and inverse methods (e.g., Arthern et al., 2015; Hoffman et al., 2018; Gudmundsson et al., 2019; Ranganathan et al., 2021) or seismic observations (e.g., Smith et al., 2013; Brisbourne et al., 2017)

45   but lack a direct link between observations and the representation of basal sliding in ice sheet models (Kyrke-Smith et al., 2017).

    Here, we present ~~a new methodology~~ the new BAyesian Sliding Law Inference – Viscous Grain-Shearing (BASLI–VGS) methodology, which enables the quantitative determination of the most appropriate basal sliding law by directly comparing the measured and predicted acoustic impedance, i.e. the product of the compressional wave speed and density of the subglacial

50   material (Fig. 2). The seismic reflection coefficient from the bed is sensitive to the contrast in acoustic impedance between ice and bed. Because the acoustic impedance of ice is known ($3.33 \pm 0.04 \cdot 10^6 \, \text{kg} \, \text{m}^{-2} \, \text{s}^{-1}$; Atre and Bentley, 1993), this allows the acoustic impedance of the bed to be recovered from seismic reflection surveys performed in the field (Fig. 1a). ~~A~~ The VGS theory of acoustic propagation in ~~sediment~~ granular material (Buckingham, 1997, 2000, 2005, 2007) relates the acoustic impedance to the effective pressure, providing a direct link to the basal sliding law: in most laws, low effective pressure, i.e.

55   high basal water pressure, is associated with fast ice sliding over slippery sediment. As basal water pressure has only been measured directly in a few locations via hot-water drilled boreholes (e.g., Engelhardt et al., 1990; Engelhardt and Kamb, 1997; Lüthi et al., 2002; Smith et al., 2021), it has been difficult to map effective pressure. The new approach provides effective pressure over a much wider area.

2   Methods

2.1   Linking seismic observations and basal sliding laws

60   The ~~six~~ sliding laws examined in this study (Sec. 2.2) are thought to represent sliding over different subglacial beds (Fig. 1b-f). To infer which of these sliding laws is most probable, we first derive the basal shear stress (τ_b) and sliding speed (u_b; Fig. 2 and S1) from inverse methods using the Wavelet-based Adaptive-grid Vertically-integrated Ice-sheet-model (WAVI; Arthern et al., 2015; Bradley et al., 2024, Sec. 2.3). The effective pressure (N) can then be estimated by rearranging the sliding laws. ~~As the~~

65   ~~Weertman-type power law does not directly depend on effective pressure (N), we instead use two endmember scenarios: a) ice~~ ~~at floatation everywhere ($N = 0 \, \text{Pa}$) and b) ice overburden pressure everywhere ($N = p_i$; further details in~~
    The VGS theory (Sec. ~~2.2.2).~~ .
    ~~The Viscous Grain-Shearing (VGS) theory (Sec. 2.4; Buckingham, 1997, 2000, 2005, 2007)~~ 2.4) provides a model of acoustic propagation in granular material. Substituting the estimated effective pressure into this model and using independent es-

timates for ~~the~~ grain diameter (d_g) and porosity (ϕ) from sediment cores (Engelhardt et al., 1990; Stone and Clarke, 1993; Smith et al., 2011; Kirshner et al., 2012; Smith et al., 2014, 2017; Clark et al., 2024, and Smith, unpublished data), provides an estimate of acoustic impedance for each sliding law. The predicted acoustic impedance is then compared to acoustic impedance measurements collected at five sites on Pine Island Glacier (PIG) in Antarctica (Fig. 4; Brisbourne et al., 2017) by calculating the misfit $\chi^2_{\Theta_i}$ according to

$$\chi^2_{\Theta_i} = \frac{1}{N_\mathrm{d}} \sum_j^{N_\mathrm{d}} \frac{\left(Z_{\Theta_i,j} - Z^*_j\right)^2}{\sigma^2_j}, \tag{1}$$

where $N_\mathrm{d} = 300$ is the number of data points (60 per site, 120 m apart), and $Z_{\Theta_i,j}$ are the acoustic impedance predictions under a given sliding law i and the model parameters Θ_i (grain diameter ~~, porosity, and maximum one additional sliding law parameter~~ and porosity, along with any additional sliding-law-specific parameters; further details in Sec. 2.2 and 2.5). Data points are treated as independent: a sub-sampled data set (every 10th data point) generally yields the same conclusions (Fig. S2 and S3). While there is evidence that PIG is largely underlain by deformable sediments (Muto et al., 2016; Brisbourne et al., 2017), the exact values of Θ_i are uncertain. Therefore, the misfit $\chi^2_{\Theta_i}$ is systematically assessed across what is considered to be a reasonable parameter space (Sec. 2.5). The model parameters do not vary spatially. Z^*_j and σ_j are the acoustic impedance observations and their uncertainties. As an example, all metrics involved in predicting the acoustic impedance and calculating the misfit $\chi^2_{\Theta_i}$ (u_b, τ_b, N, Z_{Θ_i}, Z^*, σ) are shown for one set of parameter values (~~$d_\mathrm{g} = 0.05\,\mathrm{mm}$~~ $d_\mathrm{g} = 0.063\,\mathrm{mm}$, $\phi = 0.43$, ~~transition speed without the dependence on effective pressure $u_\mathrm{t,noN} = 708.2\,\mathrm{MPa^{-1}\,m\,a^{-1}}$~~ Coulomb friction coefficient $\mu = 0.49$) and the ~~Zoet-Iverson~~ Coulomb sliding law in Fig. S4.

However, inferring the best-candidate sliding law based solely on the minimum misfit is inadequate, as it does not take into account any prior assessment of the probability of the parameter values used. Instead, we use Bayesian model selection (Sec. 2.5) to identify the most probable sliding law based on all misfits within the parameter space (likelihood function in Fig. 2). In this framework, the a priori probability of each model, and of particular parameter values within each model is specified by prior distributions. Using Bayes' rule, these prior probabilities are updated using seismic data, to provide posterior probabilities. Ultimately, this allows us to compute the normalized posterior probability of each sliding law, given the seismic observations collected on PIG (Eq. 20). An advantage of the Bayesian approach is that Occam's razor is automatically applied: overly flexible models with a large range or dimension of parameter space are penalized relative to simpler, less flexible models with fewer parameters or tighter bounds upon parameters.

2.2 Basal sliding laws

The effective pressure required as input for the VGS theory is determined based on the basal sliding laws described here. Usually, these laws are expressed so that basal drag is a function of sliding speed and effective pressure. To compute effective pressures, these relationships must be inverted, either by explicitly rearranging the equations or by numerical root-finding. For all sliding laws and sites, we ensure the effective pressure does not exceed the ice overburden pressure.
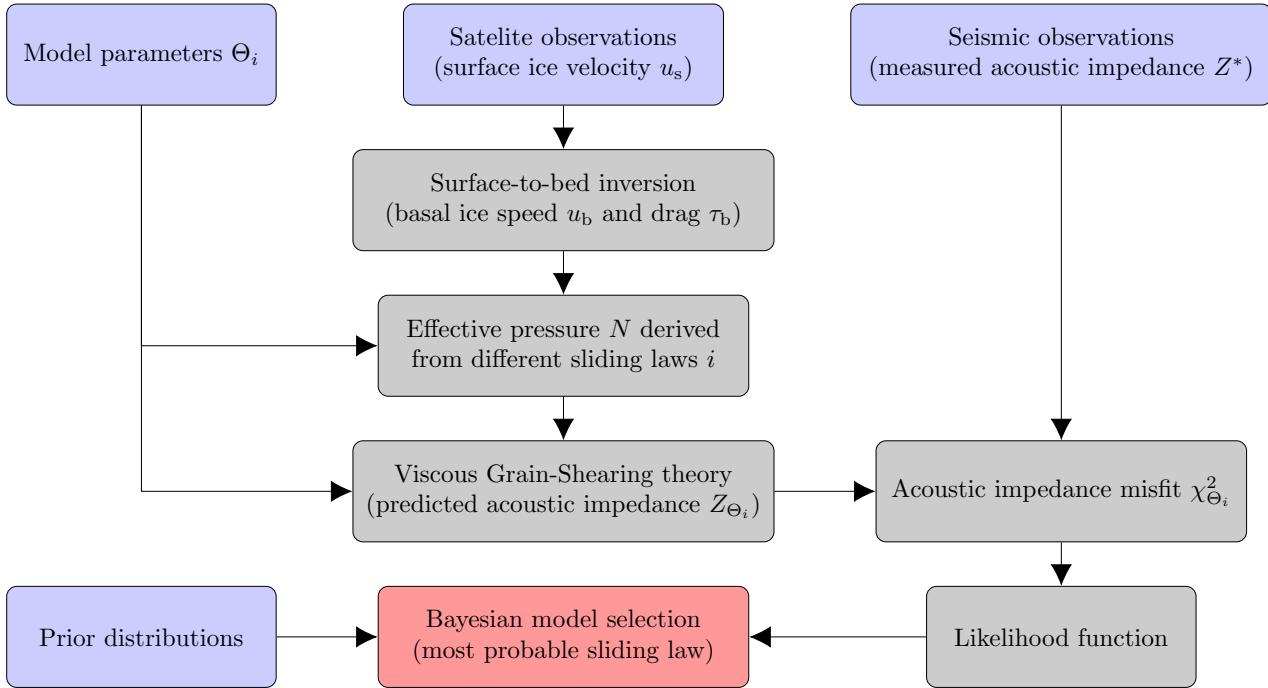
Figure 2. Flowchart of the presented BASLI–VGS methodology. Refer to the text for further details.

Strictly speaking, the VGS theory used to predict acoustic impedance only applies to granular material (Sec. 2.4). However, while the formation of cavities, for example, is most appropriate for undeformable bed protrusions, larger rock fragments embedded in granular sediment or even fine-grained deformable sediment might play a similar role (Schoof, 2007a, b; Fowler, 2009; Schoof . Therefore, whenever we are using a sliding law initially developed for hard bedrock (Sec. 2.2.3 and 2.2.6), we assume a

105   granular, relatively undeformable material that can not support tangential friction at its interface with the ice (here referred to as *rigid bed*).

2.2.1 Fixed effective pressure

The most straightforward approach for estimating the effective pressure (N) – one that does not require the specification of a sliding law – is to assume it is at a fixed fraction of the ice overburden pressure (p_i) everywhere. To contextualize and

110   constrain the results obtained using effective pressures derived from various sliding laws (Sec. 2.2.3 to 2.2.7), we compute the acoustic impedance corresponding to different fractions of the ice overburden pressure, including the two fixed effective pressure endmember scenarios; a lower bound $N = 0\,\mathrm{Pa}$ for which the ice is assumed to be at floatation everywhere, and b) an upper bound, $N = p_i$, for which the effective pressure is assumed equal to the ice overburden pressure everywhere. These

endmembers correspond, respectively, to situations where basal water pressure fully supports the weight of overlying ice or does not support any weight at all.

2.2.2 Weertman

The Weertman-type power law (Weertman, 1957) assumes that ice slides perfectly over a rigid bed. A thin water film separating the ice and undeformable bed, allows locally for free slip. The basal drag τ_{b} – resistance to basal motion u_{b} – is instead induced by form drag as the ice deforms around the bed obstacles (Fig. 1b). This leads to the relationship

$$\tau_{\mathrm{b}} = C_{\mathrm{W}} u_{\mathrm{b}}^{m}, \tag{2}$$

where C_{W} and $m = 1/3$ are, respectively, the Weertman friction parameter and exponent (often related to the creep exponent n in Glen's flow law, $m = 1/n$). As Eq. 2 does not directly depend on the effective pressure(N), , the Weertman-type power law can not be directly tested within this approach. Instead, we calculate the acoustic impedance for two endmember scenarios; a lower bound $N = 0$ Pa for which the ice is assumed to be at floatation everywhere, and an upper bound, $N = p_{\mathrm{i}}$, for which the effective pressure is assumed equal to the ice overburden pressure (p_{i}) everywhere. These endmembers correspond, respectively, to situations where basal water pressure fully supports the weight of overlying ice or does not support any weight at all. the Budd sliding law.

2.2.3 Budd

Laboratory experiments examining temperate ice sliding over bed surfaces with a wide range of roughnesses (e.g., Fig. 1b) indicate that τ_{b} exhibits a strong dependence on N (Budd et al., 1979). Consequently, the Weertman-type power law was modified to account for this dependence.

$$\tau_{\mathrm{b}} = C_{\mathrm{B}} u_{\mathrm{b}}^{m} N^{q}, \tag{3}$$

where C_{B} and $q = 1$ are the Budd friction parameter and exponent, respectively.

2.2.4 Coulomb

The Coulomb-type plastic rheology sliding law describes ice sliding over soft, deformable sediments (Fig. 1d; Iverson et al., 1998; Tulaczyk et al., 2000).

$$\tau_{\mathrm{b}} = \mu N, \tag{4}$$

where $\mu = \tan(\Phi)$ is the Coulomb friction coefficient and Φ the till friction angle.

2.2.5 Tsai-Budd

A simple sliding law describing basal motion as the combination of ice deformation around and across bed obstacles (Weertman) and deformation of the underlying sediment (Coulomb; Fig. 1e or f; Tsai et al., 2015) takes the form

$$\tau_{\mathrm{b}} = \min[C_{\mathrm{W}} u_{\mathrm{b}}^m, \mu N]. \tag{5}$$

As for the Weertman-type power law itself, Eq. 5 can not be tested in the context discussed here because the Weertman part of the sliding law has no dependence on the effective pressure~~(using the endmember scenarios for the Weertman part is inconsistent with the underlying assumptions of Eq. 5).~~. To overcome this issue, we replace the Weertman part of Eq. 5 with the Budd sliding law (Eq. 3):

$$\tau_{\mathrm{b}} = \min[C_{\mathrm{B}} u_{\mathrm{b}}^m N^q, \mu N]. \tag{6}$$

~~When varying C_{B}, we set $\mu = 0.5$. Similarly, when varying μ, we set $C_{\mathrm{B}} = 37.01 \, \mathrm{m}^{-1/3} \, \mathrm{s}^{1/3}$ (based on minimum misfit when varying C_{B}).~~

2.2.6 Schoof

Eq. 2 and 3 neglect Iken's bound induced by water-filled cavities ~~(upper bound of τ_{b}/N determined by the maximum up-slope angle of the~~ (upper bound of τ_{b}/N determined by the maximum up-slope angle of the bed in flow direction (β); Fig. 1c; Iken, 1981; Schoof, 2005; Ga . Thus, Schoof (2005) derived a new sliding law incorporating this upper bound. Strictly speaking, the Schoof sliding law only applies to linear ice rheology. Gagliardini et al. (2007) then numerically extended the relationship to non-linear rheologies. Here we use a generalized form of this sliding law (Brondex et al., 2017):

$$\tau_{\mathrm{b}} = \frac{C_{\mathrm{S}} u_{\mathrm{b}}^m}{(1 + (C_{\mathrm{S}}/(C_{\max} N))^{1/m} u_{\mathrm{b}})^m}, \tag{7}$$

where C_{S} is the Schoof friction parameter and $C_{\max} = \tan\beta$ represents Iken's bound (Iken, 1981; Schoof, 2005). ~~Initial experiments with $C_{\mathrm{S}} = 7.624 \, \mathrm{MPa} \, \mathrm{m}^{-1/3} \, \mathrm{s}^{1/3}$ (as suggested by Brondex et al. (2017)) show a high percentage of incompatible (can not be explained by Eq. 7) $u_{\mathrm{b}} - \tau_{\mathrm{b}}$ pairs, inhibiting the determination of a misfit (Fig. S15 and S16; see also Brondex et al., 2019) . As varying C_{S} has only minor effects on the misfit over the examined parameter range (1 to $1 \cdot 10^7 \, \mathrm{MPa} \, \mathrm{m}^{-1/3} \, \mathrm{s}^{1/3}$; Fig. S15) and to avoid this issue, we set $C_{\mathrm{S}} = 1 \cdot 10^3 \, \mathrm{MPa} \, \mathrm{m}^{-1/3} \, \mathrm{s}^{1/3}$ (closest to suggested value while ensuring low percentage of incompatible $u_{\mathrm{b}} - \tau_{\mathrm{b}}$ pairs when varying $C_{\max}$).~~

2.2.7 Zoet-Iverson

Based on experiments in which pressurized ice at its melting temperature is slid over a water-saturated till bed, Zoet and Iverson (2020) derived the following sliding law for glaciers on deformable beds (Fig. 1e):

$$\tau_{\mathrm{b}} = N\mu \left(\frac{u_{\mathrm{b}}}{u_{\mathrm{b}} + u_{\mathrm{t}}}\right)^{\frac{1}{p}}, \tag{8}$$

where the transition speed

$$u_{\mathrm{t}} = \frac{\left(\frac{1}{\eta(Ra)^2 k_0^3} + \frac{4C_1}{(Ra)^2 k_0}\right)(N_F N)}{(2 + N_F k)}, \tag{9}$$

$k_0 = \frac{2\pi}{4R}$, and the regelation parameter $C_1 = C_p \frac{K}{L}$. Slightly rearranging Eq. 8 and 9 allows us to numerically determine N

$$\tau_{\mathrm{b}} = N\mu \left(\frac{u_{\mathrm{b}}}{u_{\mathrm{b}} + u_{\mathrm{t,noN}} N} \frac{u_{\mathrm{b}}}{u_{\mathrm{b}} + C_{\mathrm{ZI}} N}\right)^{\frac{1}{p}}, \tag{10}$$

where

$$u_{\mathrm{t,noN}} C_{\mathrm{ZI}} = \frac{\left(\frac{1}{\eta(Ra)^2 k_0^3} + \frac{4C_1}{(Ra)^2 k_0}\right) N_F}{(2 + N_F k)} \tag{11}$$

is the transition speed coefficient (u_{t} without the dependence on N). All other parameters are listed in Table. 1.

Variable	Description	Value	Unit
p	slip exponent	5	-
η	effective ice viscosity	$3.2 \cdot 10^{12}$	Pa s
R	clast radius	~~0.0153~~ 0.015	m
a	fraction of clast radius that protrudes from bed surface	0.25	-
C_p	depression of the melting temperature of ice with pressure	$7.4 \cdot 10^{-8}$	K Pa^{-1}
K	mean thermal conductivity of ice and rock	2.55	W m^{-1} K^{-1}
L	volumetric latent heat of ice	$3 \cdot 10^8$	J m^{-3}
N_f	till bearing capacity factor	33	-
k	till strength reduction resulting from the ice pressure shadow in the lee of clasts	0.1	-

Table 1. Parameters used in Eqs. 10 and 11 (supplementary material of Zoet and Iverson (2020) and references therein).

While the mathematical form of the Schoof (Eq. 7) and Zoet-Iverson sliding law (Eq. 10) is very similar, the physical reasoning and interpretation differ. The Schoof sliding law is most applicable for ice sliding over a rigid bed (granular but relatively undeformable material), whereas the Zoet-Iverson sliding law aims to describe ice sliding over a water-saturated till bed (deformable). Similarly, the sliding-law-specific parameters μ and C_{max} represent distinct physical properties, and, may therefore differ significantly (Sec. 2.5).

2.3 Surface-to-bed inversion

Basal shear stress and basal sliding speed are derived using the ice sheet model WAVI, which is vertically integrated but retains an implicit velocity-depth profile (Arthern et al., 2015; Bradley et al., 2024). Data assimilation methods are used to initialise

the model into a present-day state (approximately 2015): spatially varying two-dimensional fields of ice stiffness and basal drag are calculated by matching modelled surface velocities with observations of surface velocities (Mouginot et al., 2022), accumulation rates (Arthern et al., 2006), and thinning rates (Smith et al., 2020). Internal ice temperatures are provided from a thermal solve of the BISICLES ice sheet model (Cornford et al., 2013). Full details of the inverse method are detailed in Arthern et al. (2015), and the resulting basal sliding speed and basal shear stress are shown in Fig. S1. In this inversion, the basal drag is identified using the Weertman sliding law. However, the sliding relationship that links basal drag and basal speed can be re-parameterised in terms of any of the selected sliding laws that we test here, as long as neither the basal speed nor the basal drag are altered in this process.

2.4 Viscous Grain-Shearing theory

The Viscous Grain-Shearing (VGS) theory (Buckingham, 1997, 2000, 2005, 2007) is used to relate seismic observations to effective pressure (Fig. 2). According to the VGS theory, the elastic deformation under effective pressure that generates frictional resistance also stiffens the sediment and increases the speed of propagation of sound waves. Changes in the speed of sound alter the acoustic impedance ($Z = \rho_{\rm s} c_{\rm p}$), the product of the compressional wave speed in the sediment ($c_{\rm p}$) and density ($\rho_{\rm s}$). In turn, the acoustic impedance controls the reflection coefficient of seismic energy from the base of the ice sheet. The acoustic propagation model predicts the compressional wave speed ($c_{\rm p} = \psi[N, d_{\rm g}, \phi, f_{\rm s}]$) as a function of effective pressure (N), grain diameter ($d_{\rm g}$), porosity (ϕ), and seismic frequency ($f_{\rm s}$). The link between the compressional wave speed and effective pressure predicted by the acoustic model provides an avenue to test whether a given sliding law applies at any location. All other parameters of the acoustic propagation model have been calibrated using acoustic observations of the ocean floor.

The governing equation for the compressional wave speed is

$$c_{\rm p} = \frac{c_0}{{\rm Re}\left[1 + \zeta \left(i\omega T\right)^q g\left(\omega\tau_{\rm p}\right)\right]^{-1/2}}, \tag{12}$$

where $c_0 = \sqrt{\frac{\kappa_0}{\rho_0}}$ is the sound speed in the absence of grain-to-grain interactions, $\kappa_0 = \left(\frac{\phi}{\kappa_{\rm p}} + \frac{1-\phi}{\kappa_{\rm g}}\right)^{-1}$ the bulk modulus of the medium, and $\rho_0 = \phi\rho_{\rm p} + (1-\phi)\rho_{\rm g}$ the bulk density of the medium. The dimensionless grain-shearing coefficient is

$$\zeta = \frac{\gamma_{\rm p} + (4/3)\gamma_{\rm s}}{\rho_0 c_0^2}, \tag{13}$$

where $\gamma_{\rm p} = \gamma_{\rm p0}\left[\frac{N d_{\rm g}}{N_0 d_{\rm g0}}\right]^{1/3}$ and $\gamma_{\rm s} = \gamma_{\rm s0}\left[\frac{N d_{\rm g}}{N_0 d_{\rm g0}}\right]^{2/3}$ are the compressional and shear rigidity coefficients, respectively. $N_0 = (1-\phi_0)(\rho_{\rm g} - \rho_{\rm p})g z_0$ is the reference effective pressure. The function

$$g\left(\omega\tau_{\rm p}\right) = \left(1 + \frac{1}{i\omega\tau_{\rm p}}\right)^{-1+q} \tag{14}$$

accounts for the effect of the viscosity of the molecularly thin layer of pore fluid between contiguous grains (ν). Molecularly thin films become progressively more viscous as they are squeezed, and, therefore, ν differs significantly from the viscosity

of the bulk fluid (Israelachvili, 1986; Luengo et al., 1996; Granick, 1999). The compressional viscoelastic time constant τ_p is defined as $\tau_p = \nu/E$, where E is a spring constant (Buckingham, 2005). The values of τ_p used in the VGS theory are visual fits to the *SAX99* experiments (Buckingham, 2007). However, the measurements were taken in 18 to 19 m deep water (Richardson et al., 2001). Therefore, the exerted overburden pressure is ~ 2 orders of magnitude smaller (less squeezed) than under PIG (ice thickness of 1500 to 2500 m in tributaries, e.g., Fretwell et al., 2013). While it is apparent that the viscosity of molecularly thin layers increases with the applied pressure (or loading) p_L, the exact relationship between p_L, the thickness of the thin film, and the viscosity ν is not straightforward (e.g., Israelachvili, 1986; Luengo et al., 1996; Yamada, 2003). Assuming $\nu \propto p_L$, we set $\tau_p = 0.012$ s (2 orders of magnitude larger than the value in Buckingham, 2007)). However, future studies should further explore the adaptation of the VGS theory from oceanographic to glacial contexts.

$\omega = 2\pi f$ is the angular frequency, $i = \sqrt{-1}$, and Re returns the real part of a complex number. All other parameters are listed in Table 2.

Variable	Description	Value	Unit
T	arbitrary time introduced to avoid awkward dimensions	1	s
q	strain hardening index	0.0851	-
κ_p	bulk modulus of pores	$2.374 \cdot 10^9$	Pa
κ_g	bulk modulus of grains	$3.6 \cdot 10^{10}$	Pa
ρ_p	density of pore fluid	1005	kg m^{-3}
ρ_g	density of grains	2730	kg m^{-3}
γ_{p0}	reference compressional coefficient	$3.888 \cdot 10^8$	Pa
γ_{s0}	reference shear coefficient	$4.588 \cdot 10^7$	Pa
d_{g0}	reference grain diameter	$1 \cdot 10^{-1}$ $1 \cdot 10^{-3}$	m
ϕ_0	reference porosity	0.377	-
g	acceleration due to gravity	9.81	m s^{-2}
z_0	reference depth in sediment	0.3	m
f_s	seismic frequency	100	Hz
τ_p	compressional viscoelastic time constant	0.012	s

Table 2. Parameters used in the VGS theory. The values for f_s and τ_p are based on seismic frequencies in a glaciological context and a scaling analysis of the value used in Buckingham (2007), respectively. All other values are adopted from Buckingham (2005).

2.5 Bayesian model selection

We compare the different sliding laws using Bayes' Rule:

$$P(M_i|D,I) = \frac{P(D|M_i)\,P(M_i)}{P(D)} \frac{P(D,I|M_i)\,P(M_i)}{P(D,I)}, \tag{15}$$

225 where D represents the data (acoustic impedance observations), I represents the inverted u_b and τ_b, and M_i represents the model for sliding law i ~~(together with VGS theory) and D represents the data (acoustic impedance observations)~~together with the VGS theory. However, the situation here slightly differs from the routine application of Bayes' rule for inferring model parameters within a single model and is more akin to Bayesian model selection. The main difference for the model selection framework is that the probability space is extended to cover multiple models, each of which has its own parameter space.

230 Since the number of parameters differs between models ~~, we~~ (e.g., two for the fixed effective pressure scenarios and four for the Zoet-Iverson sliding law) and we aim to compare the posterior probabilities of models $P(M_i|D,I)$, not the joint posterior probability of models and parameters $P(\Theta_i, M_i|D,I)$, we marginalize over the model parameters Θ_i to retrieve ~~$P(D|M_i)$:~~

$$P(D|M_i) = \int_{\Theta_i} P(D|\Theta_i, M_i)\, P(\Theta_i|M_i)\, d\Theta_i.$$

$P(D,I|M_i)$:

235
$$P(D,I|M_i) = \int_{\Theta_i} P(D,I|\Theta_i, M_i)\, P(\Theta_i|M_i)\, d\Theta_i \tag{16a}$$

$$= \int_{\Theta_i} P(D|I,\Theta_i, M_i)\, P(I|\Theta_i, M_i)\, P(\Theta_i|M_i)\, d\Theta_i. \tag{16b}$$

Assuming the error of the data follows a Gaussian distribution, the likelihood of the acoustic impedance data given the model~~and parameters~~, its parameters, and the inverted $u_\mathrm{b} - \tau_\mathrm{b}$ is calculated according to

$$P(D|I,\Theta_i, M_i) = \exp\left(-0.5\chi_{\Theta_i}^2\right). \tag{17}$$

240 Therefore, the posterior probability of each model M_i is

$$P(M_i|D,I) = \frac{\int_{\Theta_i} \exp\left(-0.5\chi_{\Theta_i}^2\right) P(\Theta_i|M_i)\, d\Theta_i\, P(M_i)}{\sum_{j=1}^{n} \int_{\Theta_j} \exp\left(-0.5\chi_{\Theta_j}^2\right) P(\Theta_j|M_j)\, d\Theta_j\, P(M_j)} \frac{\int_{\Theta_i} \exp\left(-0.5\chi_{\Theta_i}^2\right) P(I|\Theta_i, M_i)\, P(\Theta_i|M_i)\, d\Theta_i\, P(M_i)}{\sum_{j=1}^{n} \int_{\Theta_j} \exp\left(-0.5\chi_{\Theta_j}^2\right) P(I|\Theta_j, M_j)\, P(\Theta_j|M_j)\, d\Theta_j\, P(M_j)}. \tag{18}$$

The prior information from the inverted $u_\mathrm{b} - \tau_\mathrm{b}$ (not used to constrain $P(\Theta_i|M_i)$) can be directly incorporated into an updated prior using Bayes' rule:

$$P(\Theta_i|I, M_i) = \frac{P(I|\Theta_i, M_i)\, P(\Theta_i|M_i)}{P(I|M_i)}, \tag{19}$$

245 where $P(I|M_i) = \int_{\Theta_i} P(I|\Theta_i, M_i)\, P(\Theta_i|M_i)\, d\Theta_i$ is a normalization term. Eq. 18 can then be written as

$$P(M_i|D,I) = \frac{\int_{\Theta_i} \exp\left(-0.5\chi_{\Theta_i}^2\right) P(\Theta_i|I, M_i)\, d\Theta_i\, P(M_i|I)}{\sum_{j=1}^{n} \int_{\Theta_j} \exp\left(-0.5\chi_{\Theta_j}^2\right) P(\Theta_j|I, M_j)\, d\Theta_j\, P(M_j|I)}, \tag{20}$$

where we use a prior ~~$P(M_i) = 1/n$~~ $P(M_i|I) = 1/n$ that considers each sliding law equally probable, with n being the number of sliding laws considered.

Posterior probabilities calculated using $P(M_i) = 1/n$, i.e. without the normalization through $P(I|M_i)$ in Eq. 19, are shown in Fig. S6.

250

Finally, the prior distributions for all model parameters $P(\Theta_i|M_i)$ need to be defined. The prior distributions for all individual parameters are shown in Fig. 3. The combination of multiple individual priors creates a model's parameter space Θ_i and determines the model prior $P(\Theta_i|M_i)$. Since the parameter space differs between the models (number of individual parameters (dimensions) as well as number of tested parameter values), we ensure $\int_{\Theta_i} P(\Theta_i|M_i)\,d\Theta_i = 1$ for all models. ~~This~~

255 ~~normalization penalizes~~ This normalization reflects the fact that once a model has been chosen, the parameters of that model must lie somewhere within its parameter space with certainty. This is self-evident and automatically applies Occam's Razor, penalizing models with a larger parameter space compared to less flexible models. The key idea of Occam's Razor is that a balance between goodness of fit and model flexibility is desirable, but we emphasise that no special manipulations are required to enforce this balance in the Bayesian approach.

260 When constructing the parameter space Θ_i, the prior distributions of individual parameters are treated as independent of one another. Although physical relationships among some of these parameters have been described in the literature, the formulation of a coupled prior remains challenging, as these relationships are often convoluted by other properties. For instance, the porosity is generally inversely related to the mean (or median) grain size, but this relationship is convoluted by, e.g., the particle size uniformity (e.g., Wang et al., 2017; Atapour and Mortazavi, 2018; Gupta and Ramanathan, 2018; Díaz-Curiel et al., 2024). As

265 the Bayesian model selection framework already downweights extreme parameter combinations (e.g., high porosity and large grain size) through the chosen independent prior distributions, and because the minimum misfit and most probable parameters are generally consistent with, e.g., the porosity-grain size relationship described in the literature (e.g., Díaz-Curiel et al., 2024), we do not expect a significant change in the posterior probabilities.

Various literature estimates inform the examined parameter ranges and corresponding prior distributions. The porosity

270 prior (Fig. 3a) is derived from borehole data and seismic experiments from Ice Stream B and C, West Antarctica (Blankenship et al., 1987; Engelhardt et al., 1990; Atre and Bentley, 1993), borehole data from Trapridge Glacier, Yukon Territory, Canada (Stone and Clarke, 1993), marine sediment cores from the Amundsen Sea Embayment ~~(Smith et al., 2011, 2014, 2017)~~ (Table S1; Smith et al., 2011, 2014, 2017), sediment recovered from beneath Rutford Ice Stream, West Antarctica (Table S1; Smith, unpublished data), as well as the porosity of sands and glass beads used to validate the VGS (Buckingham, 2014; Lee

275 et al., 2016, and references therein). As the latter do not directly relate to a glacial context, we assign these higher porosities a lower probability. The porosity estimates from seismic experiments (Blankenship et al., 1987; Atre and Bentley, 1993) assume no significant dependence on effective pressure and are employed as an independent comparison rather than to directly inform the prior.

The grain diameter prior (Fig. 3b) is based on sediment cores collected in the Amundsen Sea Embayment, particularly Pine

280 Island Bay ~~(Kirshner et al., 2012; Smith et al., 2011, 2014, 2017; Clark et al., 2024)~~ (Table S1; Kirshner et al., 2012; Smith et al., 2011, 20 and the Rutford ice stream (Table S1; Smith, unpublished data). We differentiate between Clay ($< 1/256$ mm), Silt ($\geq$
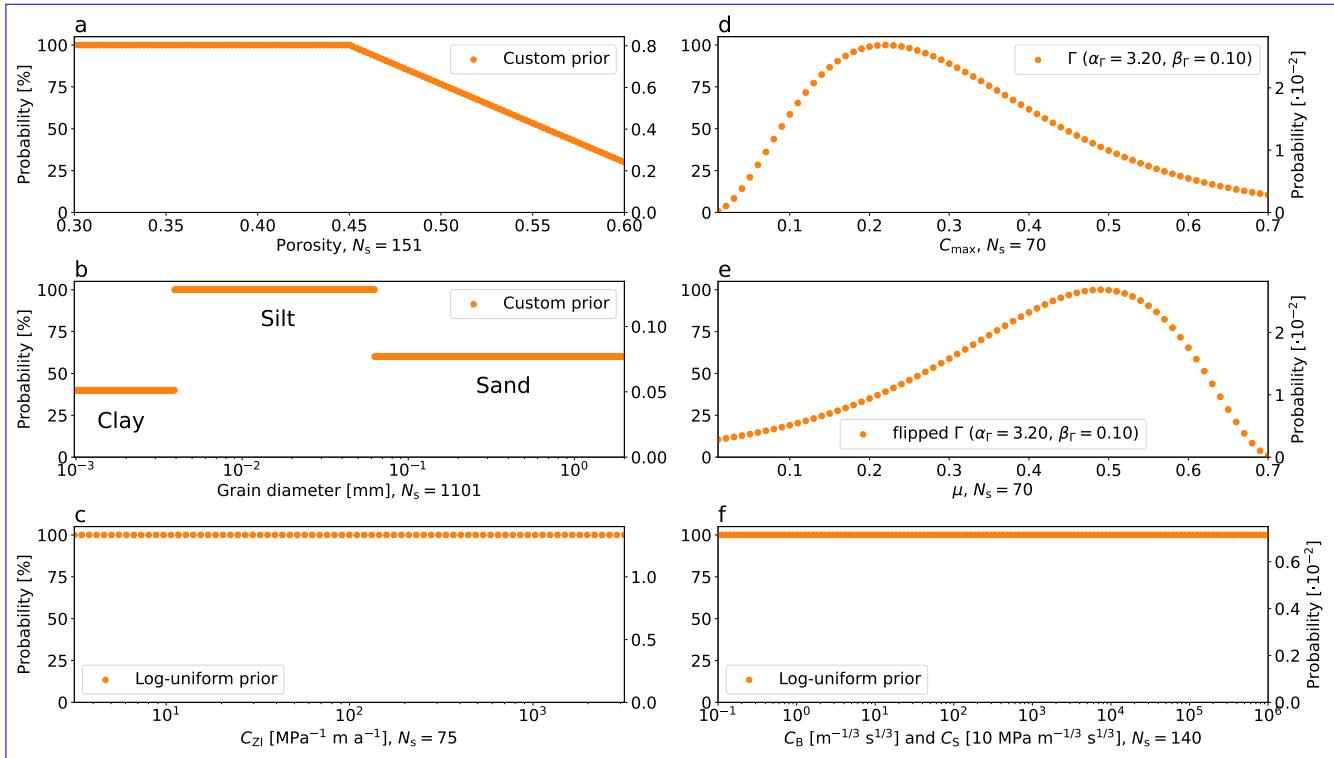
Figure 3. Prior distributions for all model parameters Θ. N_s is the sampling size. The left and right axes show the scaled probability (0 to 100 %) and actual probability used (depends on N_s), respectively.

1/256 mm and $\leq$ 1/16 mm), and Sand ($>$ 1/16 mm). ~~A log-uniform prior was chosen for $u_{t,noN}$ (Fig. 3c) as it is a positive scale that~~ The prior is then derived from the relative fractions of these grain-size classes.

The transition speed coefficient (C_{ZI}) values reported in the initial publication of the Zoet-Iverson sliding law range from
285 56.36 to 363.52 MPa^{-1} m yr^{-1} (Zoet and Iverson, 2020). A later study using the same bed material (Horicon till sourced from the same location) but with plowing clasts removed uses the same parameters (given in Table S1 of Zoet and Iverson, 2020) except for a smaller clast radius $R = 0.0045$ m (instead of $R = [0.015, 0.030]$ m), leading to $C_{ZI} = 1120.17$ MPa^{-1} m yr^{-1} (Fig. S4 in Hansen et al., 2024). Given these significant uncertainties and that C_{ZI} depends on several ~~uncertain parameters and no constraints beyond the initial publication are available (Zoet and Iverson, 2020).~~ other uncertain parameters, a log-uniform
290 prior covering the range 3.16 to 3155.76 MPa^{-1} m yr^{-1} was chosen (Fig. 3c).

The C_{max} prior (Fig. 3d) is based on bed topography beneath PIG retrieved from Bedmap2 data (Fig. S7 and S8; Fretwell et al., 2013) as well as autonomous underwater vehicle (AUV) data collected downstream of Thwaites Glacier (Graham et al., 2022) and under the Thwaites Eastern Ice Shelf (Wåhlin, unpublished data; Fig. S9 and S10). While shear resistance is most likely built at scales smaller than the resolution of Bedmap2, the bed roughness and therefore the actual relevant scale are
295 less clear and likely vary spatially. As these smaller scales are not explicitly represented by the basal drag derived from our

inversion, it is not straightforward to determine the $C_{\max}$ prior directly from the small-scale AUV data. Therefore, we align the highest probability in the $C_{\max}$ prior with the steepest Bedmap2 bed angles and incorporate even steeper bed angles at smaller scales through a more gradual decline towards higher $C_{\max}$ values (Sec. S6.2).

μ is a frequently used parameter and its prior (Fig. 3e) aims to capture the overall distribution within the glaciological community (e.g., Savage et al., 2000; Tulaczyk et al., 2000; Cuffey and Paterson., 2010; Iverson, 2010; Tsai et al., 2015; Brondex et al., 2017). Note that although $C_{\max}$ and μ serve similar roles in, e.g., the Schoof and Zoet-Iverson sliding law, they represent distinct physical properties and are thus assigned separate prior distributions (Sec. 2.2.7).

As C_{B} and C_{S} are positive scaling coefficients that may vary over several orders of magnitude, even within the same glacial catchment (Budd et al., 1984; Larour et al., 2012; Favier et al., 2014; Arthern et al., 2015; Brondex et al., 2017; Gladstone et al., 2017), a log-uniform prior was chosen for these parameters (Fig. 3f).

Due to the computational cost of the grid search, we currently limit the model parameter space Θ_i to 4D. For example, we do not consider variations in the exponents m, q, and p (Sec. 2.2). However, computationally more efficient methods, such as Monte Carlo algorithms, can be explored in future studies to simultaneously vary more than four parameters.

3 Results and Discussion

3.1 Minimum acoustic impedance misfit comparable for all sliding laws examined

Based on a previous study examining the same acoustic impedance data (Kyrke-Smith et al., 2017) and due to the smoothing effect of the inversion (1 km horizontal grid resolution), we do not expect to capture acoustic impedance variations for each individual data point but rather the general trend across the five data sites. Given this context, all sliding laws reasonably match the acoustic impedance observations when using the parameter values yielding the minimum misfit across all data sites (Fig. 4). However, for some sliding laws, the minimum misfit parameter values are at the limits of the likely range (e.g., extremely small grain diameter ($d_{\mathrm{g}} = 0.003$ mm) for the Budd sliding law). ~~As an example, Fig. ?? shows how the misfit varies with the three model parameters d_{g}, ϕ, and $u_{\mathrm{t,noN}}$ when using a Zoet-Iverson sliding law. The same plots for all other sliding laws are shown in Fig. S11 to S22.~~ While the minimum misfit might correspond to a rather unlikely parameter value, a narrow band of similarly small misfits spans a more reasonable parameter range, indicating some indistinctness in the selected minimum misfit parameter values. This is a key characteristic of the misfit distribution in all of our experiments. As an example, Fig. 5 shows how the misfit varies with the three model parameters d_{g}, ϕ, and μ when using a Coulomb sliding law. The same plots for all other sliding laws with a maximum 3D parameter space are shown in Fig. S11 to S22.

3.2 Ice dynamics of Pine Island Glacier governed by Coulomb-type sliding

To consider the misfit distribution across the entire parameter range and any prior assessment of the probability of the parameter values used ~~and the misfit distribution across the entire parameter range~~, we infer the best-candidate sliding law based on Bayesian model selection. The ~~Zoet-Iverson sliding law when varying $u_{\mathrm{t,noN}}$~~ Coulomb sliding law has the highest pos-
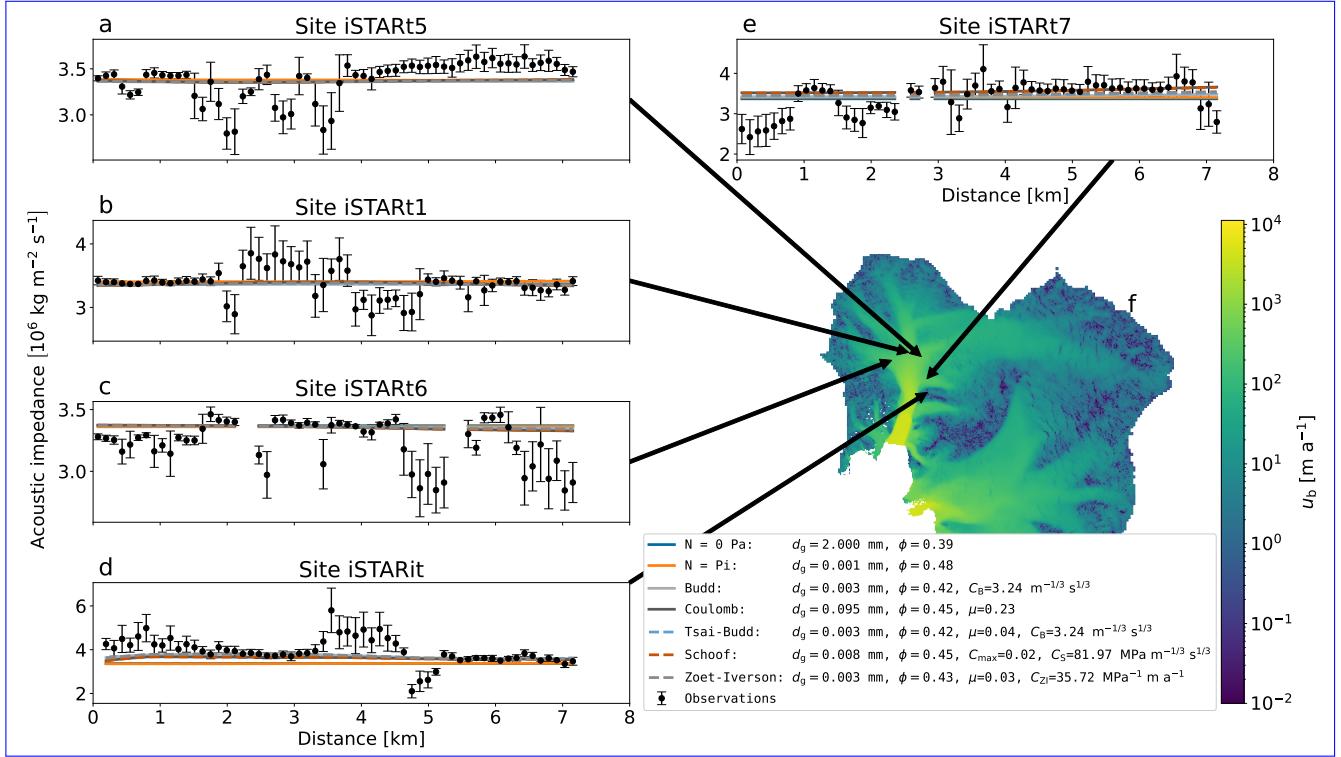
Figure 4. (a-e) Acoustic impedance observations (Brisbourne et al., 2017) compared with the model predictions based on different sliding laws when using the minimum misfit model parameters shown in the legend. The observational uncertainties are shown as error bars. The model parameters are grain diameter (d_g), porosity (ϕ), ~~Coulomb friction coefficient (μ),~~ Budd friction parameter (C_B), Coulomb friction coefficient (μ), Iken's bound (C_{max}), and transition speed ~~without the dependence on effective pressure N ($u_{t,noN}$~~ coefficient (C_{ZI}; see Sec. 2.2 for details). (f) Basal sliding speed in the Amundsen Sea Embayment (from inversion; Sec. 2.3). The arrows mark the location of the data sites. Except for site iSTARit, all data were collected on fast-flowing tributaries of PIG (Brisbourne et al., 2017).

terior probability of all sliding laws tested (increase of ~~22 %~~ 27.5 % relative to the prior; Fig. 6). ~~The Coulomb, Tsai-Budd, Schoof ,~~ However, the Schoof and Zoet-Iverson sliding laws ~~all show an increase~~ in probability relative to the prior. All of these ~~laws incorporate~~ show a similarly strong increase, hindering the determination of a single-best sliding law. The Tsai-Budd sliding law exhibits the smallest increase (4.8 %) out of all the laws incorporating a Coulomb friction term of the form μN or $C_{max}N$~~, suggesting~~. Nonetheless, the increase in posterior probability for all sliding laws incorporating a Coulomb friction term suggests this is a desirable property of a sliding law. In comparison, the Budd sliding law, without the μN modification of the Tsai-Budd law, performs worse (~~5.6 %~~ 0.8 % decrease). The ~~Weertman-type~~ fixed effective pressure endmember scenario that assumes $N = p_i$ everywhere performs worst of all, leading to the smallest posterior probability (~~84.2 %~~ 83.4 % decrease). The endmember scenario with $N = 0\,\mathrm{Pa}$ everywhere yields the highest posterior probability of all ~~sliding laws that do not incorporate a Coulomb friction term (1.1 % decrease; see~~ fixed effective pressure experiments (4.1 % increase; see also Fig. S23~~for the Weertman-type power law when using different fractions of the overburden pressure as effective pressure~~).
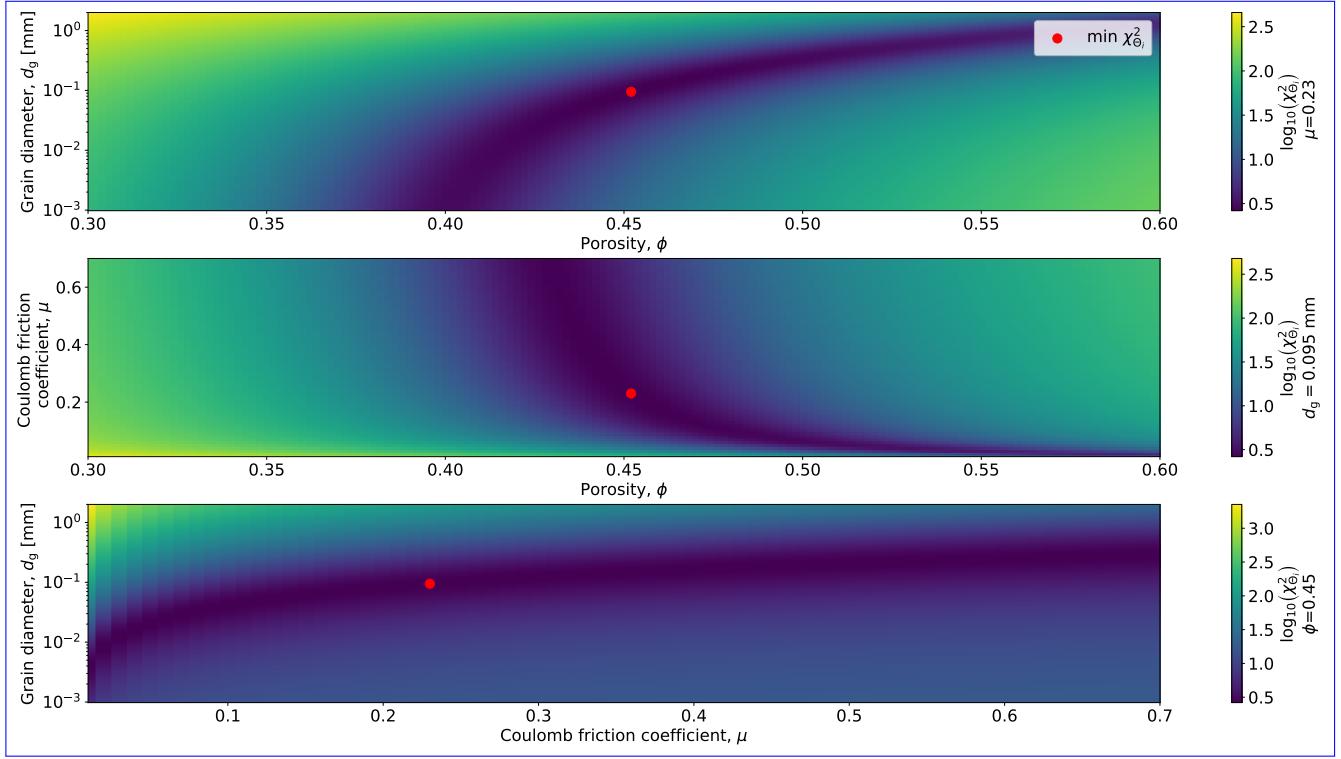
Figure 5. Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_{g}), porosity (ϕ), and ~~transition speed without the dependence on N ($u_{\mathrm{t,noN}}$)~~ Coulomb friction coefficient (μ) under a ~~Zoet-Iverson~~ Coulomb sliding law ~~(Coulomb friction coefficient μ fixed at 0.5; see Sec.~~ ~~2.2.7 for details).~~ For the parameter not shown, the value yielding the minimum misfit is used and denoted next to the colorbar of the corresponding panel. The red dots mark the minimum misfit.

The relatively high posterior probabilities of sliding laws incorporating a Coulomb friction term and the $N = 0$ Pa end-member scenario are consistent with the widespread occurrence of deformable sediment under the fast-flowing tributaries of
340   PIG (Brisbourne et al., 2017). Furthermore, the high probabilities of these sliding laws align with previous studies identifying (quasi-)plastic deformation of the underlying sediment as the primary mode of sliding for PIG (Gillet-Chaulet et al., 2016; Joughin et al., 2019). While the sensitivity of grounding-line retreat patterns and mass loss projections to the choice of sliding law is high (Brondex et al., 2019), determining the exact implications of using a (quasi-)plastic sliding law on glacier behaviour through prognostic simulations for all sliding laws and parameter values is out of the scope of this study. In general, sliding
345   laws representing a (quasi-)plastic rheology lead to higher sea level rise contributions (Ritz et al., 2015; Gillet-Chaulet et al., 2016; Brondex et al., 2019).
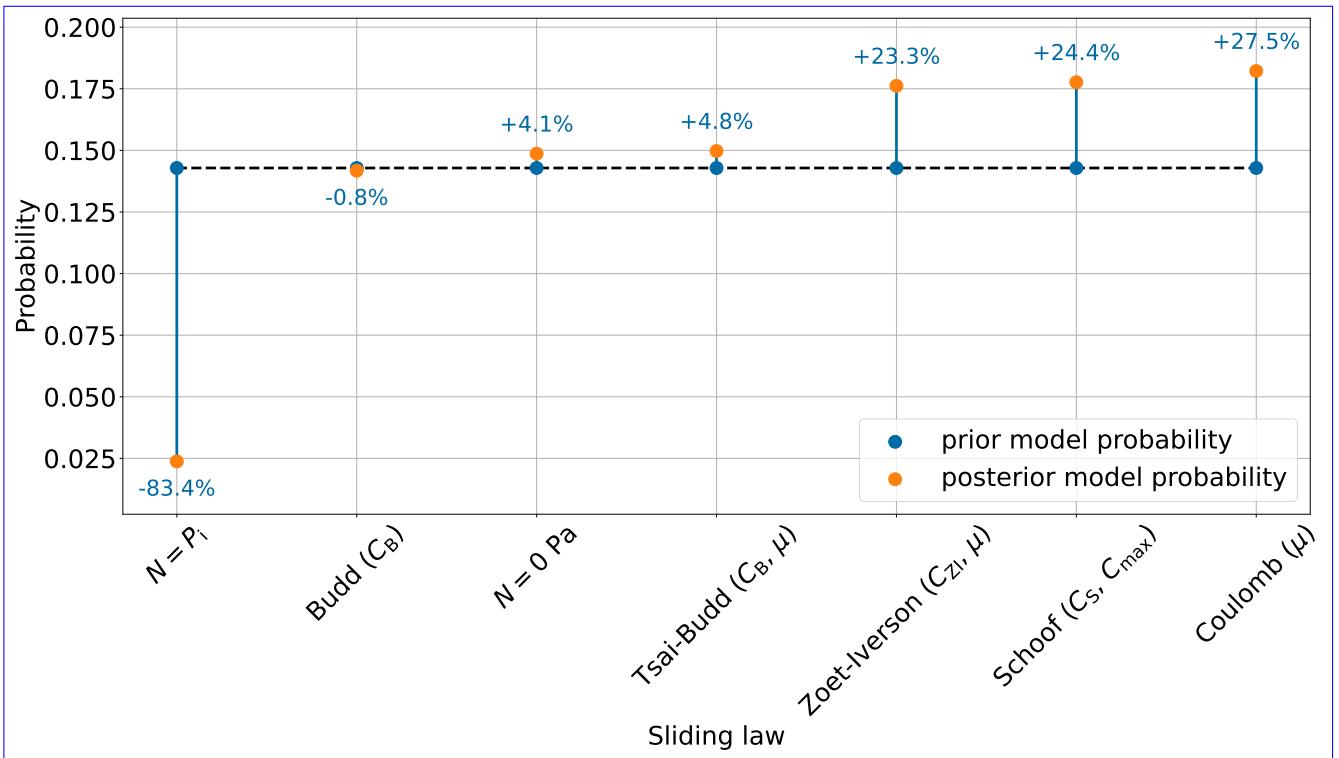
Figure 6. Normalized probabilities (Eq. 20) of all sliding laws examined in this study given the acoustic impedance observations collected on PIG. The prior model probability is $\cancel{P(M_i) = 1/n}P(M_i|I) = 1/n$, with n being the number of models examined (blue circles; dashed horizontal line visualizes equal prior probability). To obtain the posterior model probability, we marginalized over all corresponding model parameters Θ_i, encompassing the acoustic propagation model parameters (d_g and ϕ) and ~~varied sliding law~~ any additional sliding-law-specific parameters (denoted in brackets). No sliding law parameter was varied for the two ~~Weertman-type endmember scenarios as they use a~~ fixed effective pressure ~~(~~endmember scenarios $N = p_i$ and $N = 0$ Pa~~)~~. The prior distributions for all parameters are shown in Fig. 3. The blue vertical lines and numbers indicate the change in probability.

3.3 Effect of prior distributions on most probable model parameters

As for the minimum misfit model parameters, the predicted acoustic impedance under the model parameters with the highest posterior probability generally agrees with the observations within uncertainties for all sliding laws tested (Fig. S24). In the remainder of this paper, we refer to the model parameters with the highest posterior probability as the maximum a posteriori (MAP) parameters. When examining the MAP parameters in more detail (Fig. S24), the effect of the chosen prior distributions is evident. Although covering the full range within this size classification, the MAP grain diameter for all sliding laws is Silt-sized (highest prior probability; Fig. 3). The MAP porosities (0.39 to 0.44) are at the upper end of the high-prior probability range ($\phi = [0.3, 0.45]$) for all sliding laws except the ~~Weertman-type~~ fixed effective pressure endmember scenario $N = p_i$

355   ($\phi = 0.55$; Fig. S24), indicating comparatively porous sediments beneath PIG. Similarly, the MAP values of the unique sliding law parameters without a log-uniform prior distribution (μ and $C_{\max}$) are in the vicinity of the highest prior probability.

    Even if we use log-uniform prior distributions for scaling coefficients and uniform priors for other parameters, the sliding laws incorporating a Coulomb friction term still yield the highest probabilities (Fig. S25). This demonstrates the robustness of our key result against variations in prior distributions.

360   3.4   Low effective pressure across most of Amundsen Sea Embayment

    Excluding the ~~two Weertman-type endmember scenarios (fixed N)~~fixed effective pressure scenarios, the predicted effective pressure for the MAP model parameters is generally below 0.1 MPa (1 bar) for the 4 sites within fast-flowing tributaries (Fig. S26). The relatively high probability of the $N = 0$ Pa ~~Weertman-type~~ endmember scenario (Fig. 6 and S23) further supports a low effective pressure. This is in agreement with previous effective pressure estimates derived from, e.g., shear

365 wave velocities (Blankenship et al., 1987), borehole water level measurements (Engelhardt et al., 1990; Engelhardt and Kamb, 1997; Lüthi et al., 2002; Smith et al., 2021), and the widespread presence of active subglacial lakes (Gray et al., 2005; Fricker et al., 2007; Smith et al., 2009).

    Site iSTARit, located between two tributaries, has higher effective pressures (0.1 to 1 MPa), with the effective pressure derived from the ~~Zoet-Iverson~~ Coulomb sliding law being ~~~ 0.5 MPa~~~ 0.1 MPa. We hypothesize that the higher effective

370 pressure and resulting increased basal drag at this site hinder basal sliding.

    Retrieving the effective pressure for the ~~Zoet-Iverson ($u_{\mathrm{t,noN}}$)~~ Coulomb sliding law with the MAP parameters across the whole Amundsen Sea Embayment indicates the effective pressure is generally below 0.5 MPa (Fig. 7b). Being closely related to the basal drag, this map represents the slipperiness of the bed, with areas of low effective pressure being susceptible to fast retreat. However, the effective pressure map is based on a spatially uniform ~~$u_{\mathrm{t,noN}}$~~μ obtained from five sites in PIG and

375 does not capture (local) dynamic subglacial systems as, e.g., represented by a subglacial hydrology model. Furthermore, using only the ~~Zoet-Iverson ($u_{\mathrm{t,noN}}$)~~ Coulomb sliding law with the MAP parameters neglects the probabilities of other sliding laws and parameter values. Therefore, the provided effective pressure map should be used with caution. Following the Bayesian framework to ~~account for these probabilities and~~ determine the most probable effective pressure map by weighting the individual maps for all sliding laws and parameter values, ~~as well as using~~ incorporating spatially variable model parameters~~is out~~

380 ~~of the scope of this study. Therefore, the provided effective pressure map should be used with caution~~, as well as applying BASLI–VGS in regions characterized by higher basal heterogeneity (e.g., Thwaites Glacier), should be explored in future studies.

4   Conclusions

    In this study, we present ~~a new~~ the new BASLI–VGS approach that directly relates measured and predicted acoustic impedance

385 data~~to infer~~. Since the predicted acoustic impedance depends on the effective pressure, an ice sheet sliding law and ~~, subsequently, effective pressure~~ its parameters can be inferred, subsequently enabling the derivation of an effective pressure map. While the
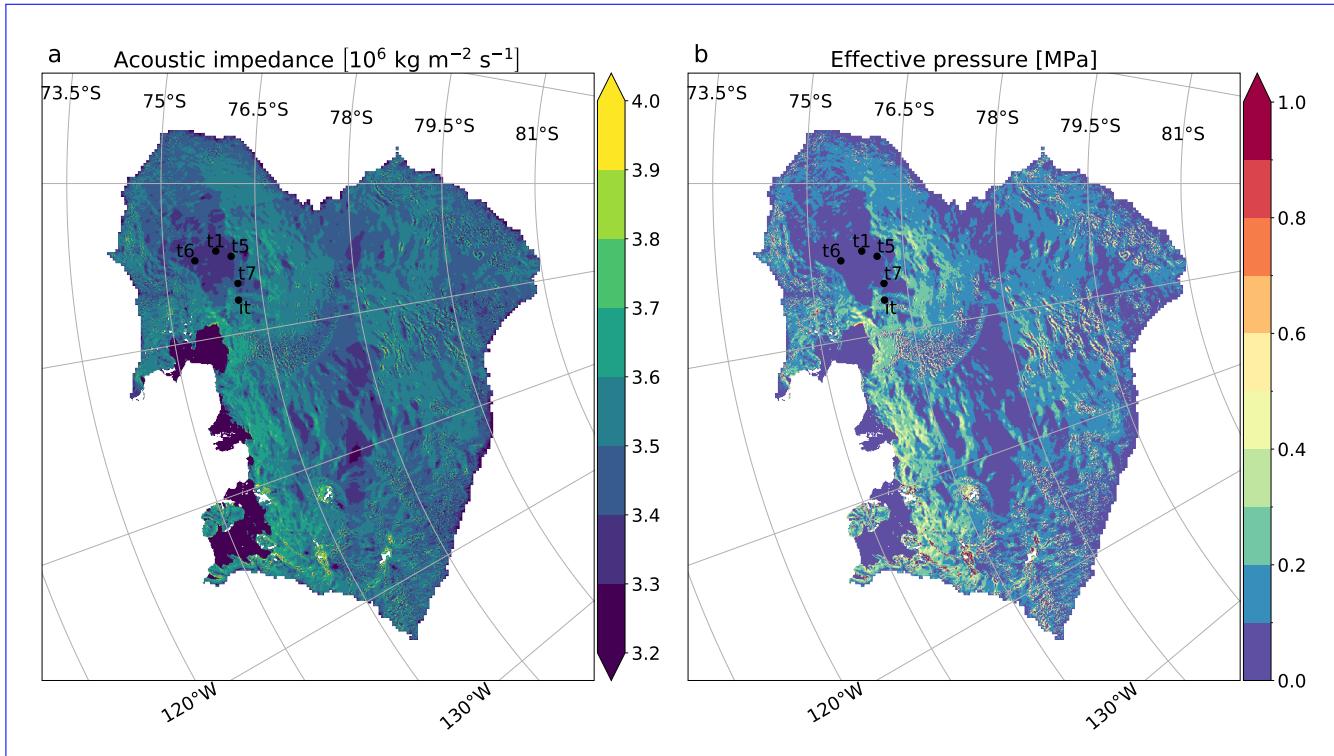
Figure 7. Predicted acoustic impedance (a) and effective pressure (b) in the Amundsen Sea Embayment when using a ~~Zoet-Iverson~~ Coulomb sliding law with the MAP (highest posterior probability) model parameters (~~$d_g = 0.05$ mm~~$d_g = 0.063$ mm, $\phi = 0.43$, and ~~$u_{t,noN} = 708.2$ MPa^{-1} m a^{-1}~~$\mu = 0.49$). The black dots mark the locations of the seismic observation sites.

current conclusions are primarily based on seismic data over soft sediments, the presented methodology can be readily applied to any acoustic impedance data collected in ~~a glacial environment~~glacial environments underlain by granular material. For the seismic data collected on fast-flowing tributaries of Pine Island Glacier, the acoustic propagation model predicts the observed acoustic impedance within uncertainties. Inferred effective pressures are generally below 0.5 MPa across most of the Amundsen Sea Embayment and below 0.1 MPa within fast-flowing tributaries of Pine Island Glacier. Bayesian model selection identifies Coulomb behaviour as the most probable mode of sliding, potentially increasing sea level rise contributions from the Amundsen Sea Embayment. To minimize uncertainties in sea level rise projections, the sliding law used in large-scale ice sheet models should, therefore, approach Coulomb behaviour in fast-flowing regions.

Code availability. The main code has been attached to the submission of this manuscript. After acceptance for publication, the code will be made available in a public archive.

Data availability. Data is available upon request from the corresponding author. After acceptance for publication, the data will be made available in a public archive.

Code and data availability. TEXT

Sample availability. TEXT

Video supplement. TEXT

Author contributions. KH, RJA, and CRW conceptualized the ideas behind this study. AMB, JAS, and AW prepared, respectively, the seismic data, sediment core data, and AUV data for use in this study. KH prepared the experimental design, ran the model, and analyzed the results with input from all authors. All authors contributed to the interpretation of the results and writing of the paper.

Competing interests. The authors have no competing interests.

Disclaimer. TEXT

Acknowledgements. The authors thank the members of the International Thwaites Glacier Collaboration (ITGC), particularly the ITGC Geophysical Habitat of Subglacial Thwaites (GHOST) team for fruitful discussion. We also thank Ronan S. Agnew and Kelly A. Hogan for their support in the interpretation of acoustic impedance and autonomous underwater vehicle (AUV) data, respectively. Finally, we thank two anonymous reviewers and the handling topic editor, Adam Booth, for their constructive comments.

This work was funded by the GHOST project, a component of the International Thwaites Glacier Collaboration (ITGC). Support from National Science Foundation (NSF: Grant PLR 1738934) and Natural Environment Research Council (NERC: Grant NE/S006672/1), with logistics provided by NSF-U.S. Antarctic Program and NERC-British Antarctic Survey. ITGC Contribution No. ITGC-142. Additional support was provided by the ITGC MELT project (NSF Grant 1739003 and NERC Grant NE/S006656/1) and Natural Environment Research Council (NERC: Grant NE/G014159/1 and NE/R016038/1). The Ran AUV was financed by Knut and Alice Wallenberg Foundation.

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S1 Basal ice speed and basal drag map
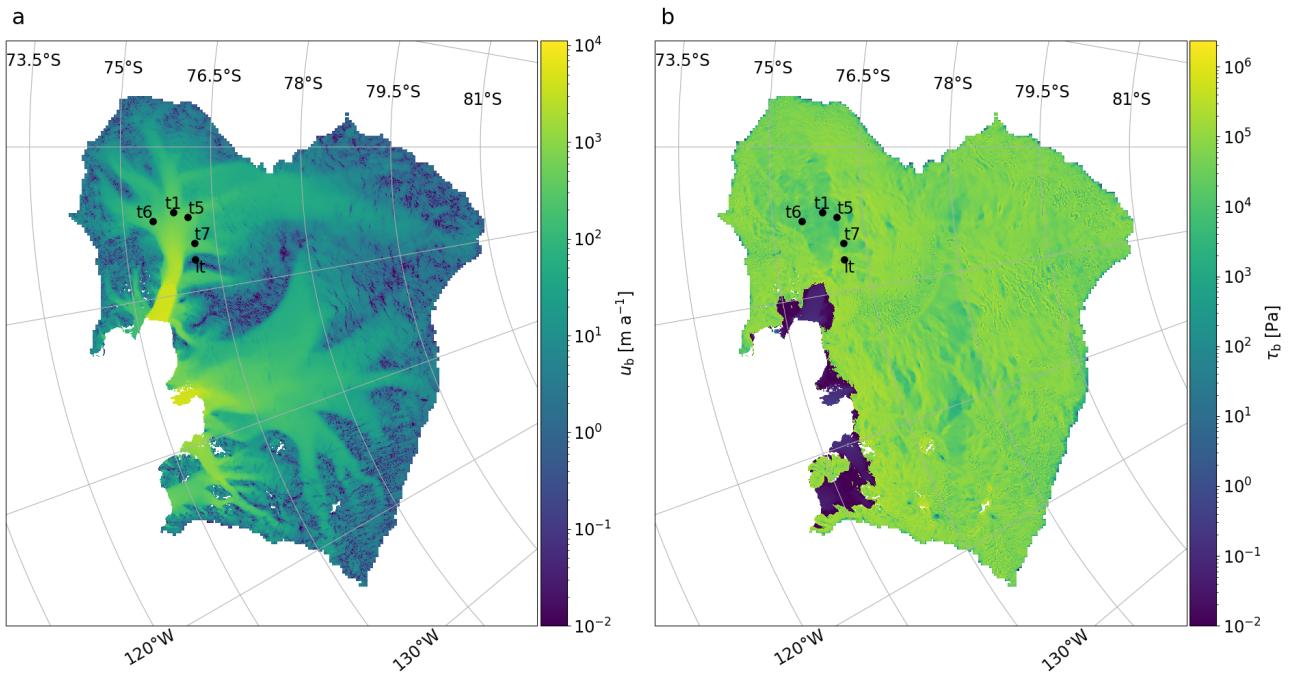
Figure S1. Basal sliding speed (a) and basal shear stress (b) in the Amundsen Sea Embayment retrieved from the surface-to-bed inversion. The black dots mark the locations of the seismic observation sites.

S2 Posterior probabilities when using sub-sampled data
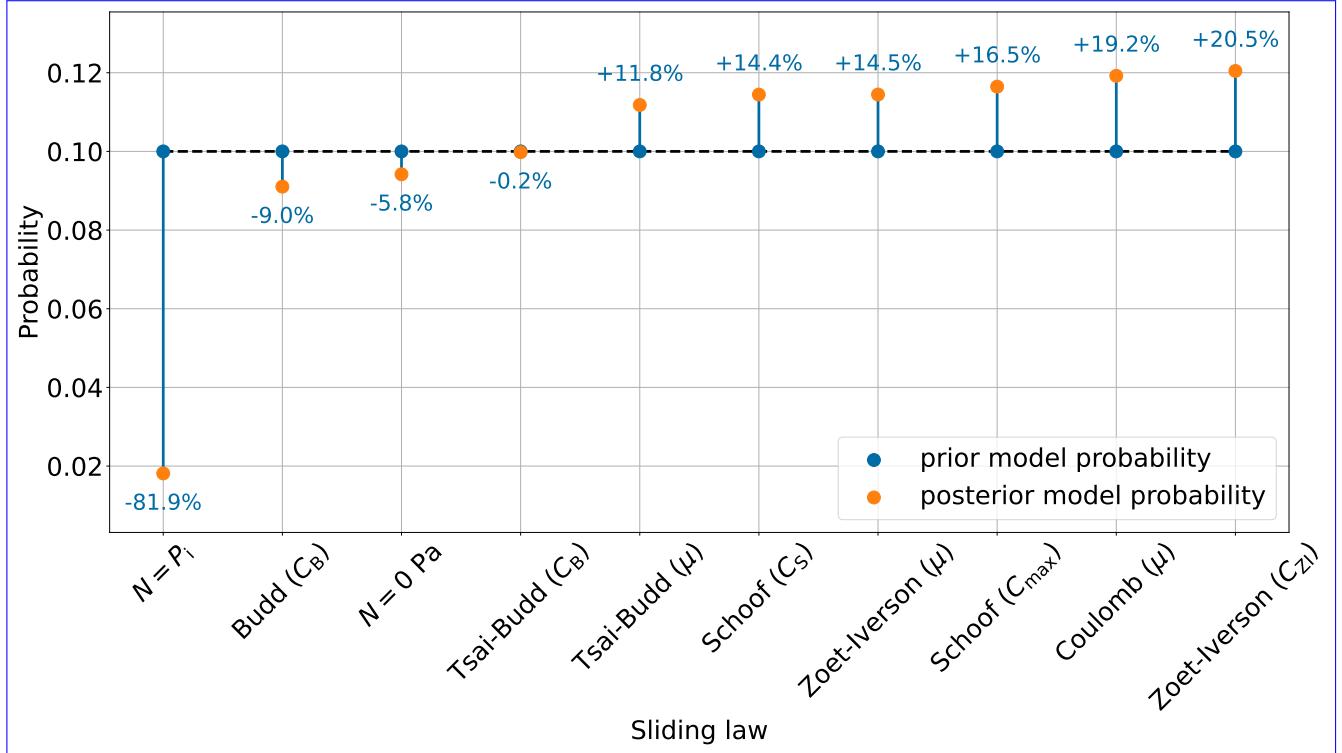
Figure S2. Normalized probabilities (Eq. 20) when using only every 10th acoustic impedance measurement collected on Pine Island Glacier (PIG). Due to the small changes in the posterior model probabilities (Fig. S3) but significant increases in computational cost, we did not run sub-sampled experiments for the 4D sliding laws. Limiting Θ_i to 3D leads to two different representations of the Tsai-Budd, Schoof, and Zoet-Iverson sliding law with one sliding law parameter fixed. The fixed parameters are $\mu = 0.5$ for Tsai-Budd (C_B), $C_B = 37.01 \, \mathrm{m}^{-1/3} \, \mathrm{s}^{1/3}$ (based on minimum misfit when varying C_B) for Tsai-Budd (μ), $C_{max} = 0.2$ for Schoof (C_S), $C_S = 1 \cdot 10^3 \, \mathrm{MPa} \, \mathrm{m}^{-1/3} \, \mathrm{s}^{1/3}$ (value closest to $C_S = 7.624 \, \mathrm{MPa} \, \mathrm{m}^{-1/3} \, \mathrm{s}^{1/3}$ suggested by Brondex et al. (2017) while ensuring low percentage of incompatible $u_b - \tau_b$ pairs; Sec. S5; Fig S15 and S16) for Schoof (C_{max}), $\mu = 0.5$ for Zoet-Iverson (C_{ZI}), and $C_{ZI} \sim 340 \, \mathrm{MPa}^{-1} \, \mathrm{m} \, \mathrm{a}^{-1}$ (as suggested by Zoet and Iverson, 2020) for Zoet-Iverson (μ). Unless indicated otherwise, these values correspond to the highest prior probability. Otherwise, as Fig. 6 in the main text.
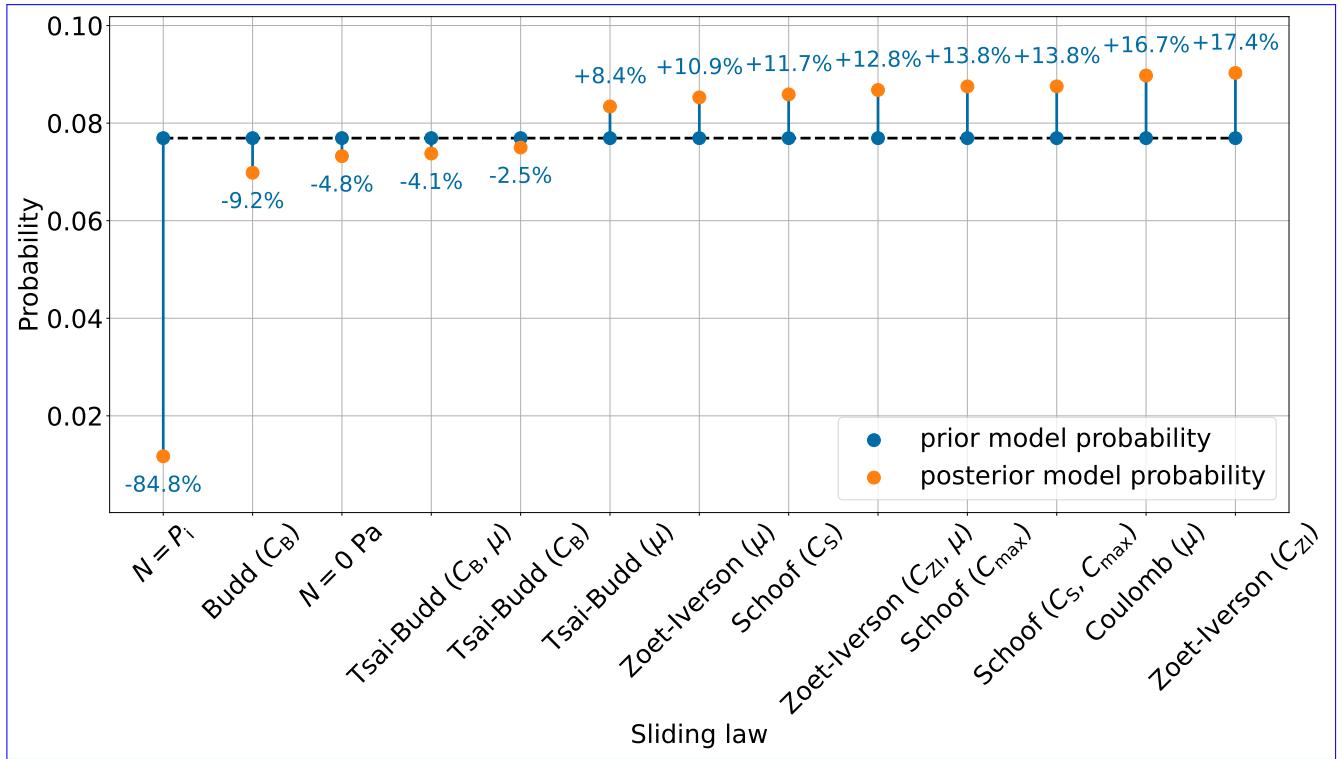
Figure S3. Normalized probabilities (Eq. 20) when limiting the model parameter space Θ_i to 3D compared to the full 4D results. Limiting Θ_i to 3D leads to two different representations of the Tsai-Budd, Schoof, and Zoet-Iverson sliding law with one sliding law parameter fixed. The fixed parameters are $\mu = 0.5$ for Tsai-Budd (C_B), $C_\mathrm{B} = 37.01 \ \mathrm{m}^{-1/3} \ \mathrm{s}^{1/3}$ (based on minimum misfit when varying C_B) for Tsai-Budd (μ), $C_\mathrm{max} = 0.2$ for Schoof (C_S), $C_\mathrm{S} = 1 \cdot 10^3 \ \mathrm{MPa} \ \mathrm{m}^{-1/3} \ \mathrm{s}^{1/3}$ (value closest to $C_\mathrm{S} = 7.624 \ \mathrm{MPa} \ \mathrm{m}^{-1/3} \ \mathrm{s}^{1/3}$ suggested by Brondex et al. (2017) while ensuring low percentage of incompatible u_b–τ_b pairs; Sec. S5; Fig S15 and S16) for Schoof (C_max), $\mu = 0.5$ for Zoet-Iverson (C_ZI), and $C_\mathrm{ZI} \sim 340 \ \mathrm{MPa}^{-1} \ \mathrm{m} \ \mathrm{a}^{-1}$ (as suggested by Zoet and Iverson, 2020) for Zoet-Iverson (μ). Unless indicated otherwise, these values correspond to the highest prior probability. Otherwise, as Fig. 6 in the main text.

S4 Metrics involved in determining the acoustic impedance misfit
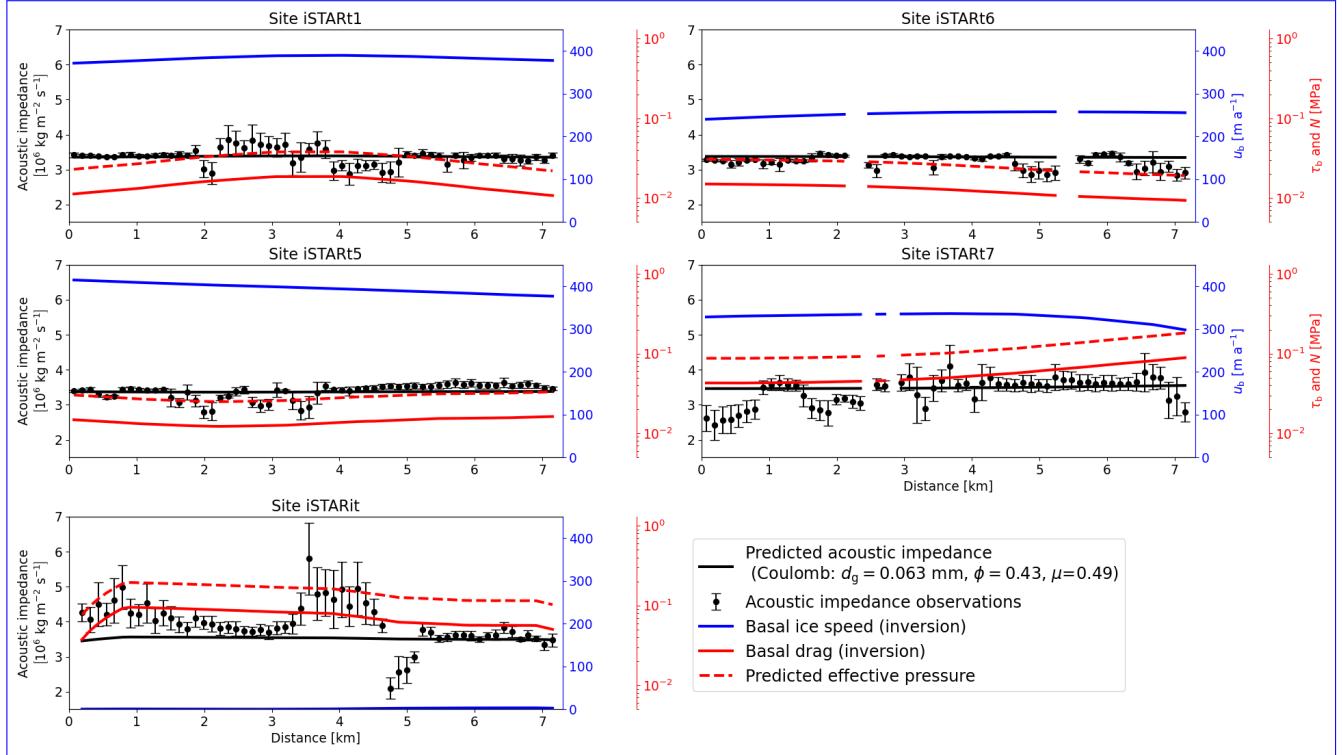
Figure S4. Metrics involved in predicting the acoustic impedance based on the Viscous Grain-Shearing (VGS) theory and calculating the misfit to the seismic observations. The black, blue, and red colours (lines, points, and axes) represent acoustic impedance, basal ice speed, and basal drag and effective pressure, respectively. The results are based on the ~~Zoet-Iverson ($u_{t,noN}$)~~ Coulomb sliding law with the maximum a ~~posterior~~ posteriori (MAP) parameter values.~~μ was fixed at 0.5.~~

When using the Schoof sliding law, C_S values smaller than $1 \cdot 10^3 \, \text{MPa} \, \text{m}^{-1/3} \, \text{s}^{1/3}$ (e.g., $C_S = 7.624 \, \text{MPa} \, \text{m}^{-1/3} \, \text{s}^{1/3}$ suggested by Bron show a high percentage of incompatible (can not be explained by Eq. 7) $u_b - \tau_b$ pairs, inhibiting the determination of a misfit (Fig. S5, S15, and S16; see also Brondex et al., 2019). As this information is available prior to applying the Bayesian model selection, but was not used to constrain the C_S prior, we update $P(\Theta_i | M_i)$ by incorporating the information from the inverted
10   $u_b - \tau_b$ using Bayes' rule (Eq. 19). However, the posterior probabilities without this normalization are shown in Fig. S6. Since the chosen parameter space Θ_i does not lead to incompatible $u_b - \tau_b$ pairs near the seismic data sites for any of the other sliding laws, their posterior probabilities are not affected. Note that their final normalized probabilities differ because of the change in the posterior probability of the Schoof sliding law.
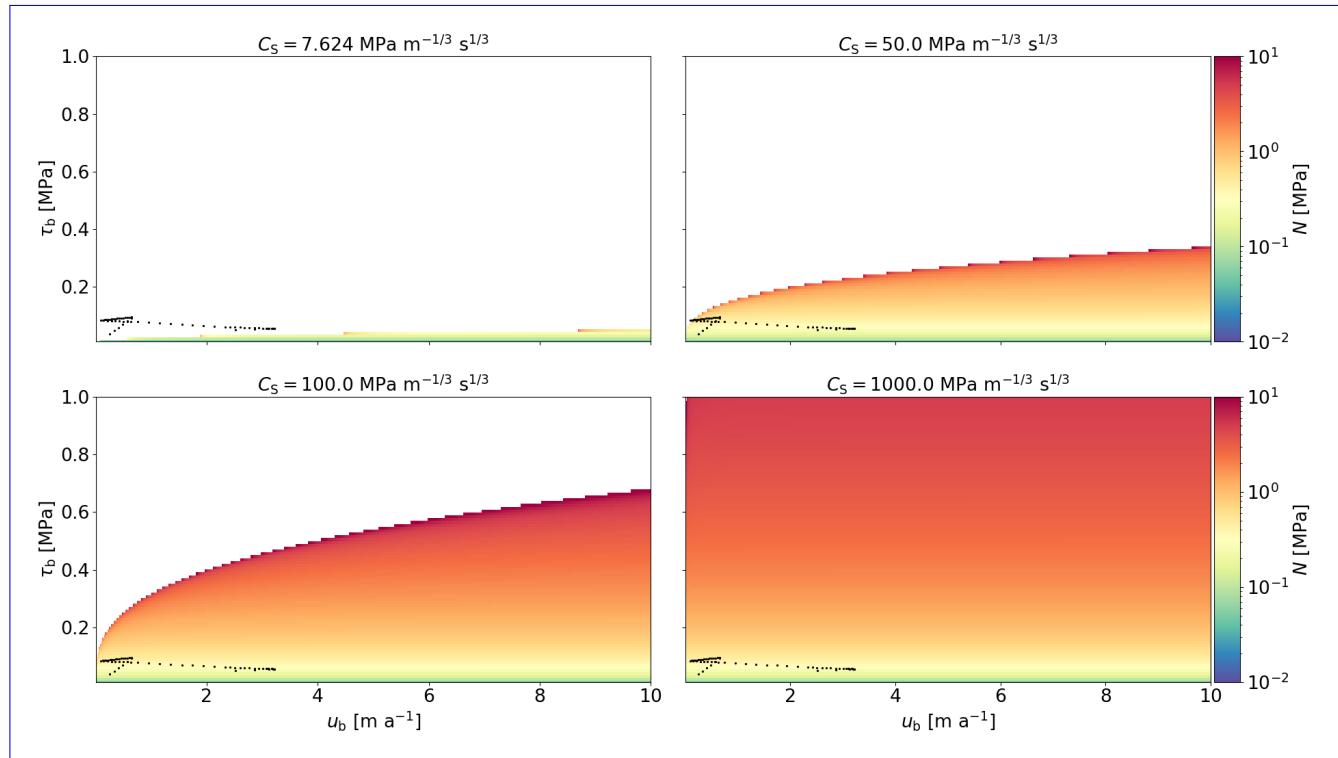
Figure S5. Simple toy experiment illustrating the $u_b - \tau_b$ pairs incompatible with Eq. 7 for different C_S values ($C_{\max} = 0.2$ and $m = 1/3$). Smaller C_S values, generally corresponding to smoother beds, lead to more incompatible $u_b - \tau_b$ pairs (larger white area). This issue primarily arises for small u_b and comparatively large τ_b values at site iSTARit located between two tributaries (black dots).
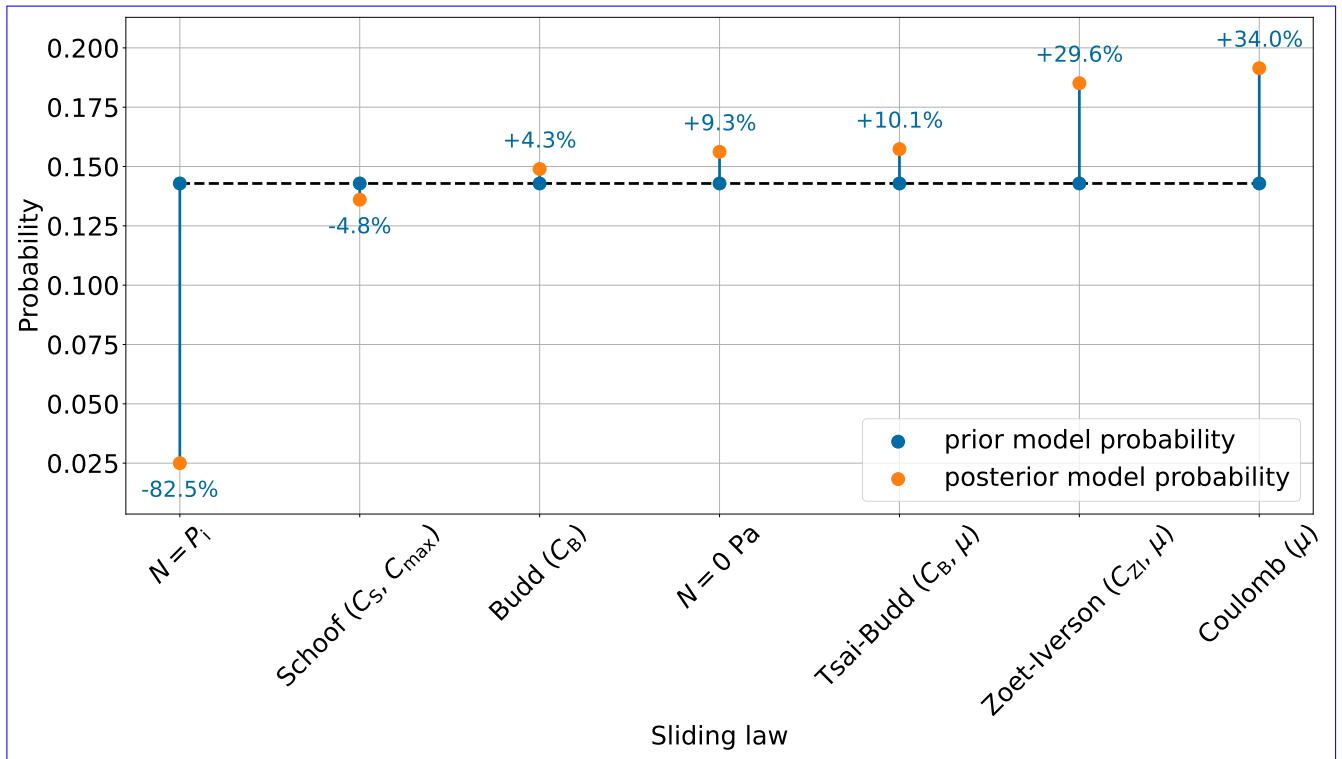
Figure S6. Normalized probabilities (Eq. 18) of all sliding laws examined in this study given the acoustic impedance observations collected on PIG. The prior model probability is taken as $P(M_i) = 1/n$, rather than $P(M_i|I) = 1/n$, and consequently, no normalization via $P(I|M_i)$ (Eq. 19) is applied. This leads to a significant reduction in the posterior probability of the Schoof sliding law due to an increasing number of incompatible $u_b - \tau_b$ pairs for C_S values smaller than $1 \cdot 10^3$ MPa m$^{-1/3}$ s$^{1/3}$ (see Fig. S5 for a simple toy experiment), resulting in overall 27 % of the likelihood being undefined (NaN), which is treated as zero likelihood here. Otherwise, as Fig. 6 in the main text.

S6 Prior distribution~~— Maximum up-slope angle of the bed and Iken's bound~~

S6.1 Porosity and grain diameter

Site	Porosity [%]	Clay [%]	Silt [%]	Sand [%]	Gravel [%]	Facies	Notes
BEAMISH	35	8	36	30	27	ST	Recovered from beneath Rutford Ice Stream (Smith, unpublished data)
PIGA	36	30	31	26	13	IT	Recovered from PIG ice shelf (Smith et al., 2017)
PIGB	39	28	28	33	11	IT	Recovered from PIG ice shelf (Smith et al., 2017)
VC415	34	3	46	36	14	ST	Deposited seaward of Dotson Ice Shelf during the Last Glacial Maximum (Smith et al., 2011)
VC417	35	3	51	37	8	ST	Deposited seaward of Dotson Ice Shelf during the Last Glacial Maximum (Smith et al., 2011)

Table S1. Porosity and grain diameter data used to determine the corresponding prior distributions. The facies are ice transitional sediment deposited at or close to the grounding line (IT) and subglacial till deposited at the base of the ice stream (deformation till; ST).

S6.2 Maximum up-slope angle of the bed and Iken's bound

The distribution of the up-slope angles of the bed in flow direction (β) and the corresponding Iken's bound ($C_{max} = \tan \beta$; Fig. S7) is examined for the center part of Pine Island Glacier (PIG; magenta box in Fig. S8). As the horizontal grid resolution of Bedmap2 is 1 km ~~Fretwell et al. (2013))~~(Fretwell et al., 2013), the maximum up-slope angle (and therefore C_{max}) on smaller scales might be significantly ~~larger~~ steeper than suggested by the distribution in Fig. S7. For example, autonomous underwater vehicle (AUV) data collected downstream of Thwaites Glacier (1.5 m horizontal resolution; Graham et al., 2022) and under the Thwaites Eastern Ice Shelf (2 m horizontal resolution; Wåhlin, unpublished data) indicate that the maximum $C_{max} > 0.7$ (largest value tested within this study; Fig. S9). However, as the horizontal resolution of the inversion used to derive the basal shear stress and sliding speed is much coarser (1 km; same as the Bedmap2 resolution), it is not straightforward to determine the C_{max} prior directly from the AUV data. Nevertheless, the chosen C_{max} prior aims to incorporate higher bed angles at smaller scales through a more gradual decline towards higher values while aligning the highest probability with the extreme values in Fig. S7.

Figure S7. C_{max} distribution in flow direction within the magenta box in Fig. S8. The Bedmap2 horizontal grid resolution is 1 km (Fretwell et al., 2013). The bin width is 0.02.
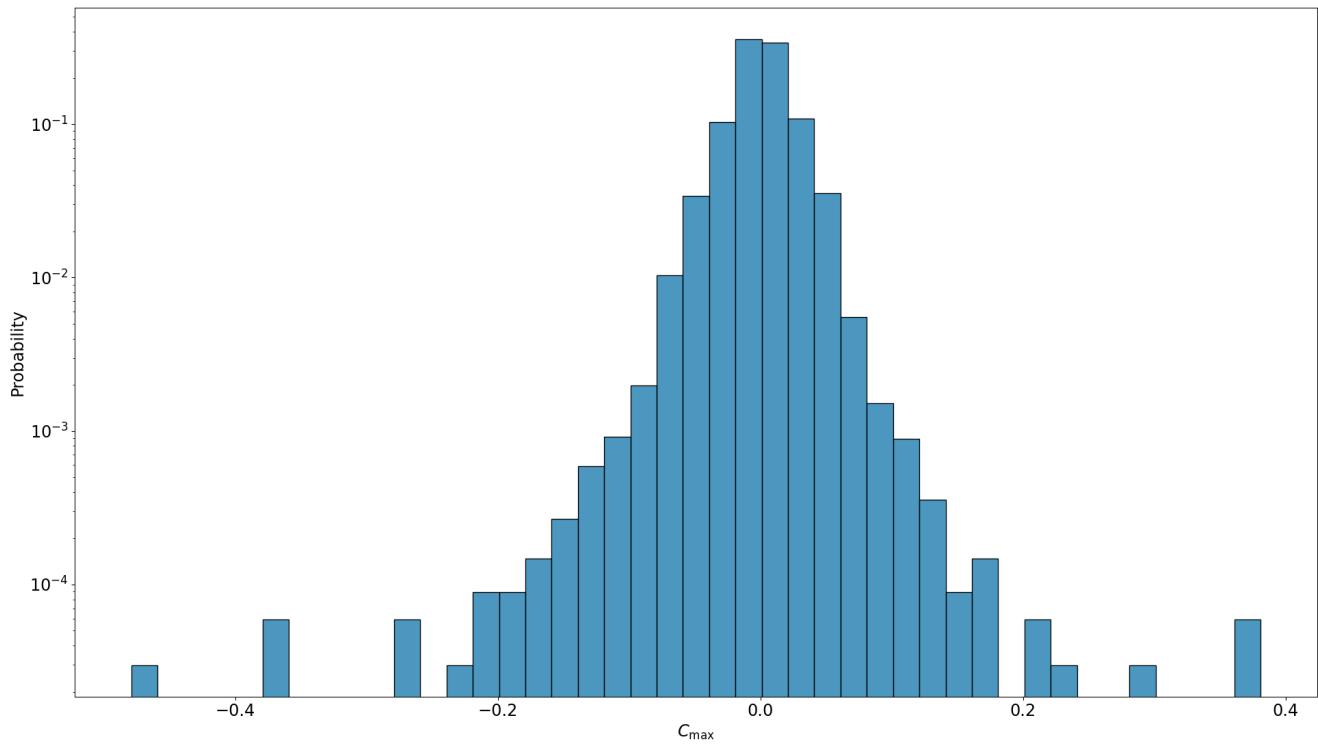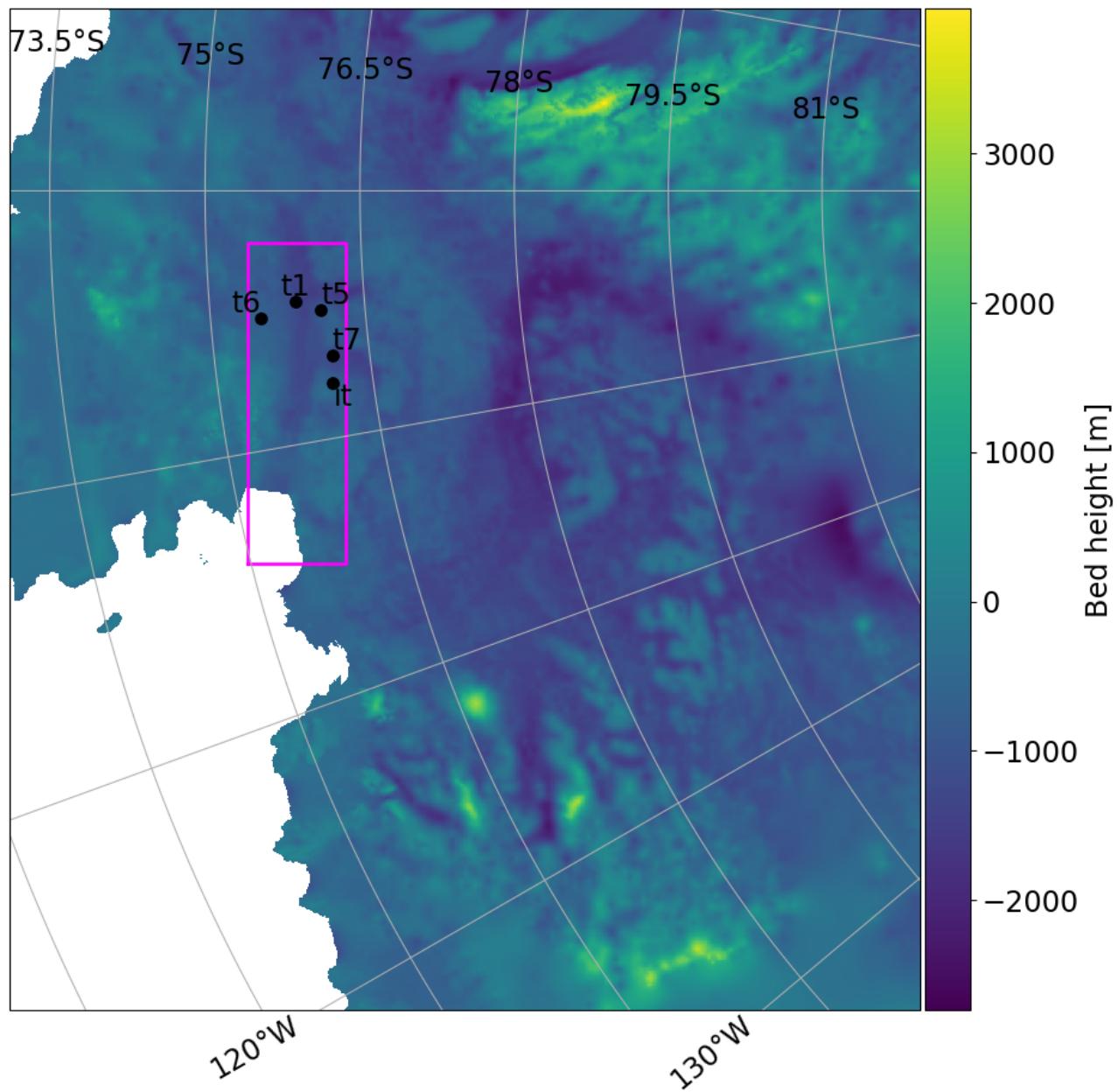
Figure S8. Bed height for areas with ice cover (grounded and floating; based on Bedmap2; Fretwell et al., 2013). The magenta box frames the main trunk of Pine Island Glacier (PIG) and the black dots mark the locations of the acoustic impedance data sites.
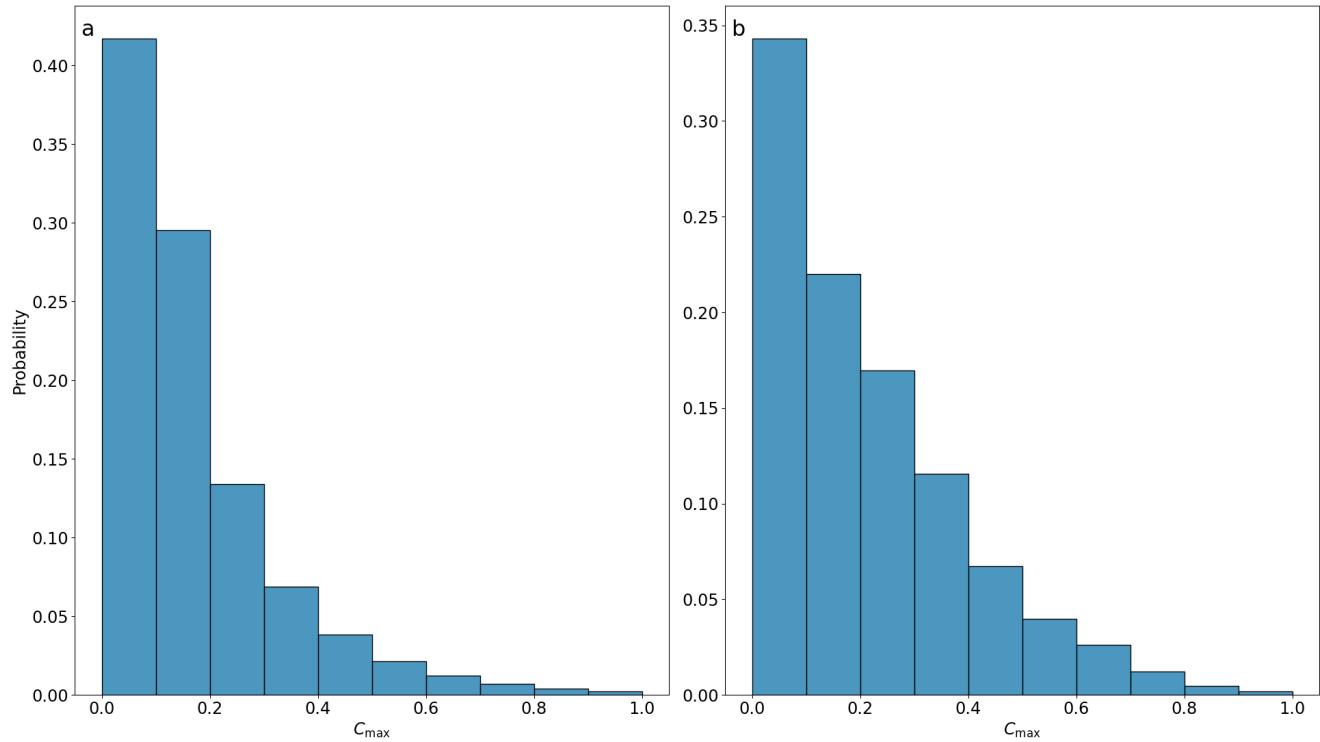
Figure S9. $C_{\max}$ distribution from autonomous underwater vehicle (AUV) data collected downstream of Thwaites Glacier (a; 1.5 m horizontal resolution; Graham et al., 2022) and under the Thwaites Eastern Ice Shelf (b; 2 m horizontal resolution; Wåhlin, unpublished data). The bin width is 0.1. $C_{\max}$ values > 1.0 are not shown here. The corresponding spatial distributions are shown in Fig. S10.
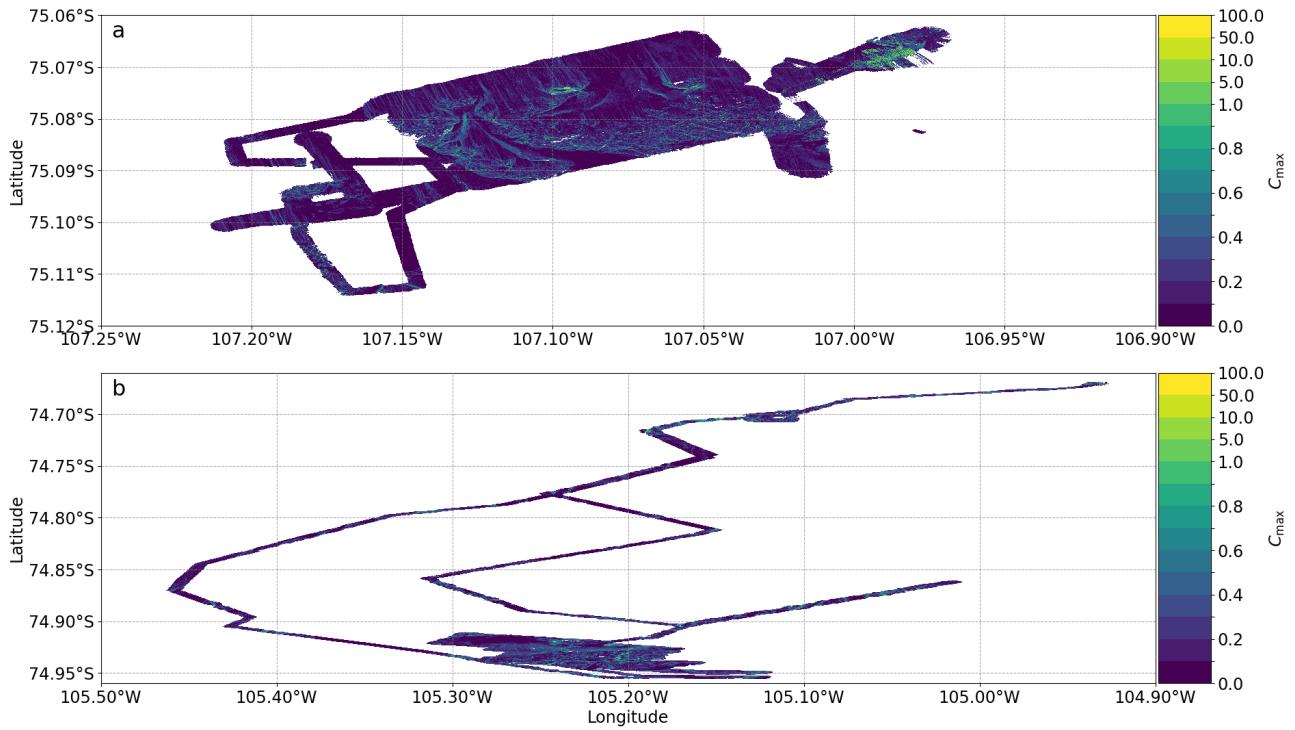
Figure S10. Spatial distribution of the autonomous underwater vehicle (AUV) data shown in Fig. S9. Note the change in colorbar step at $C_{\mathrm{max}} = 1.0$.

S7 Acoustic impedance data-model misfit under different sliding laws ~~(maximum 3D)~~

S7.1 ~~Weertman (~~Fixed effective pressure endmember scenarios $N = 0$ Pa and $N = p_\mathrm{i}$~~)~~
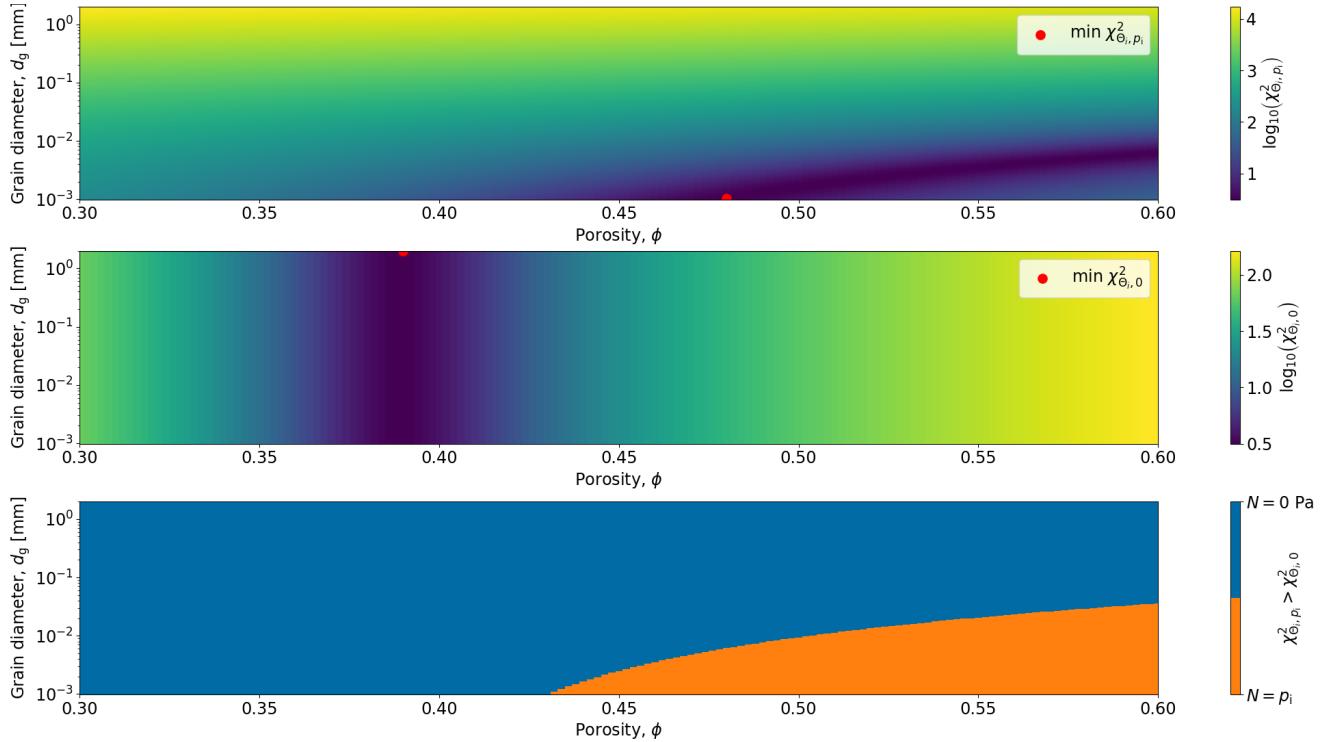
Figure S11. Variations of the misfit $\chi^2_{\Theta_i}$ with the two model parameters grain diameter (d_g) and porosity (ϕ) under the ~~Weertman-type~~ fixed effective pressure endmember scenarios $N = p_\mathrm{i}$ (top panel) and $N = 0$ Pa (center panel). The bottom panel shows the preferred ~~sliding law~~ endmember scenario within the parameter space. The red dots mark the minimum misfit.
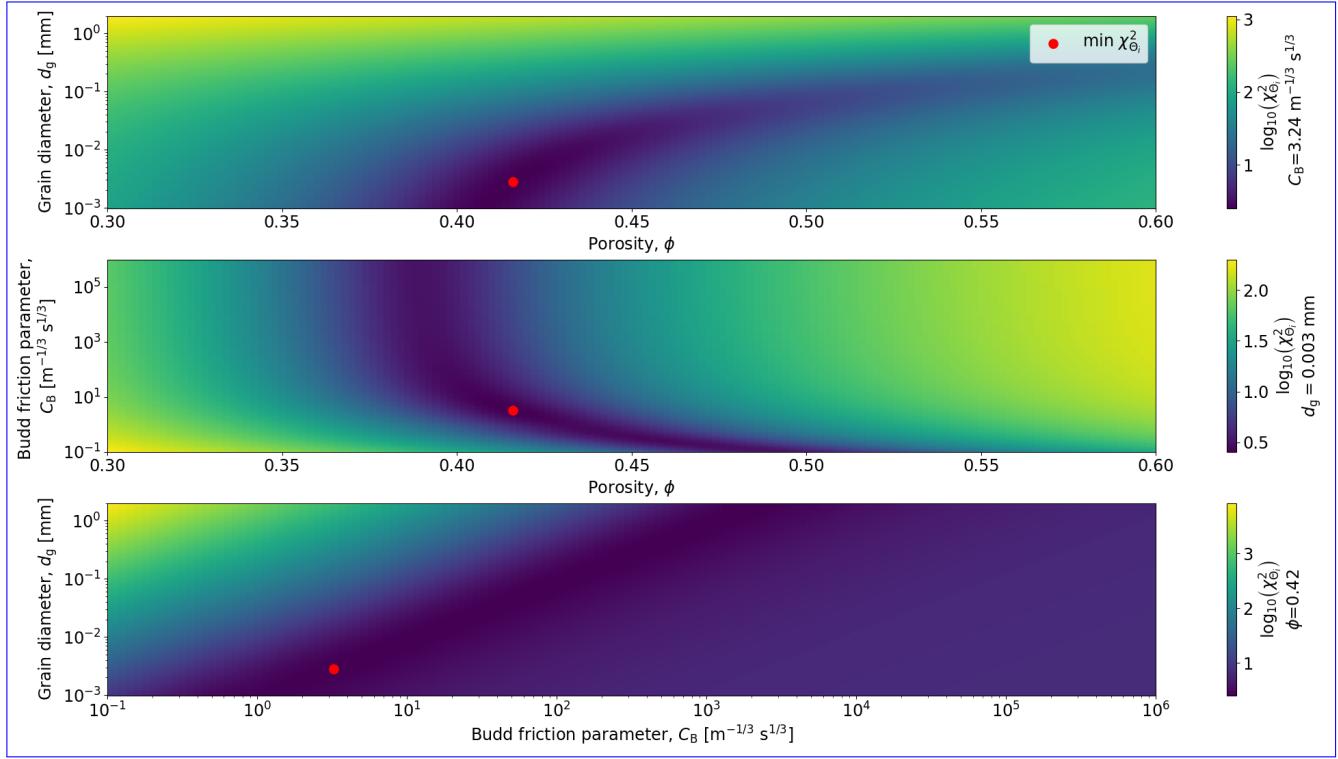
Figure S12. Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_{g}), porosity (ϕ), and Budd friction parameter (C_{B}) under a Budd sliding law. For the parameter not shown, the value yielding the minimum misfit is used and denoted next to the colorbar of the corresponding panel. The red dots mark the minimum misfit.

S7.3   ~~Coulomb (μ)~~

~~Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_{g}), porosity (ϕ), and Coulomb friction coefficient (μ) under a Coulomb sliding law. Otherwise as Fig. S12.~~

S7.3 Tsai-Budd (C_B)
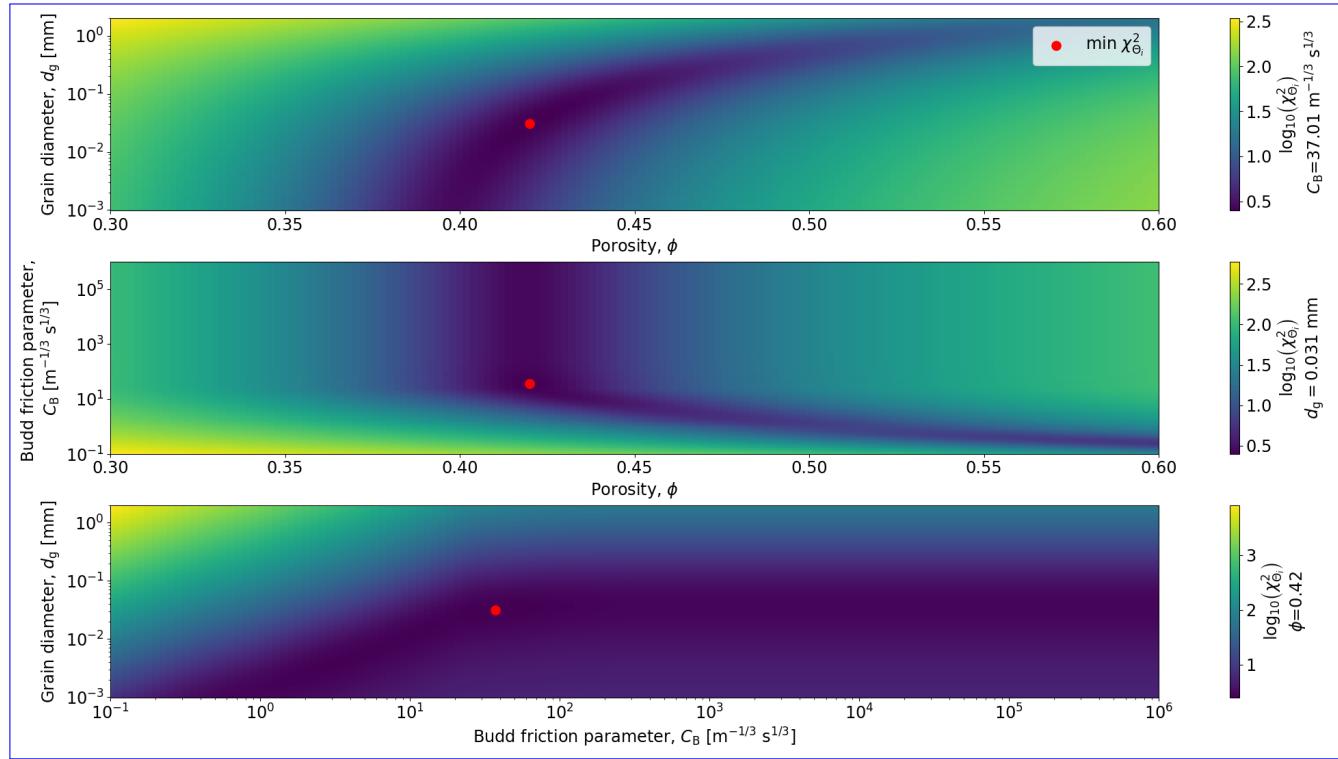
Figure S13. Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_g), porosity (ϕ), and Budd friction parameter (C_B) under a Tsai-Budd sliding law (μ fixed at 0.5). Otherwise as Fig. S12.

 S7.4 Tsai-Budd (μ)
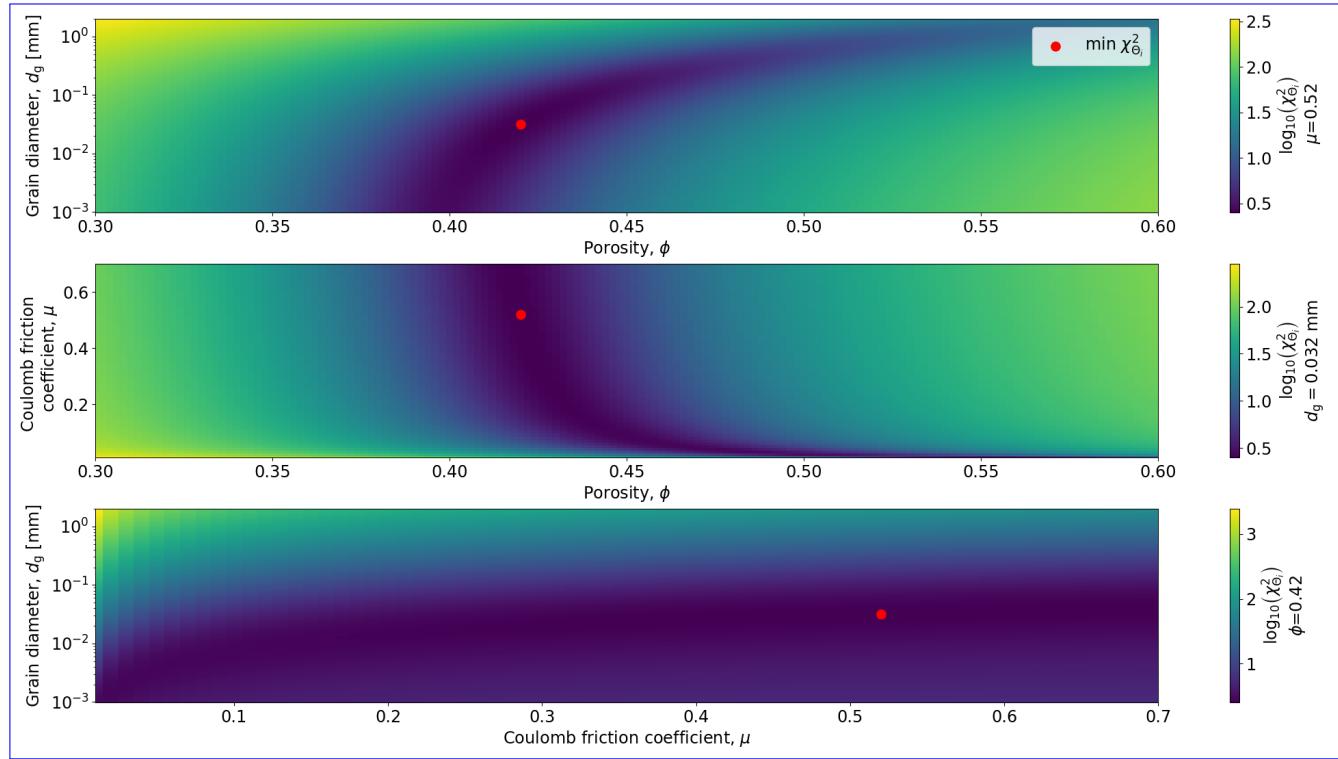
Figure S14. Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_g), porosity (ϕ), and Coulomb friction coefficient (μ) under a Tsai-Budd sliding law (C_B fixed at 37.01 m$^{-1/3}$ s$^{1/3}$). Otherwise as Fig. S12.

S7.5 Schoof (C_S)
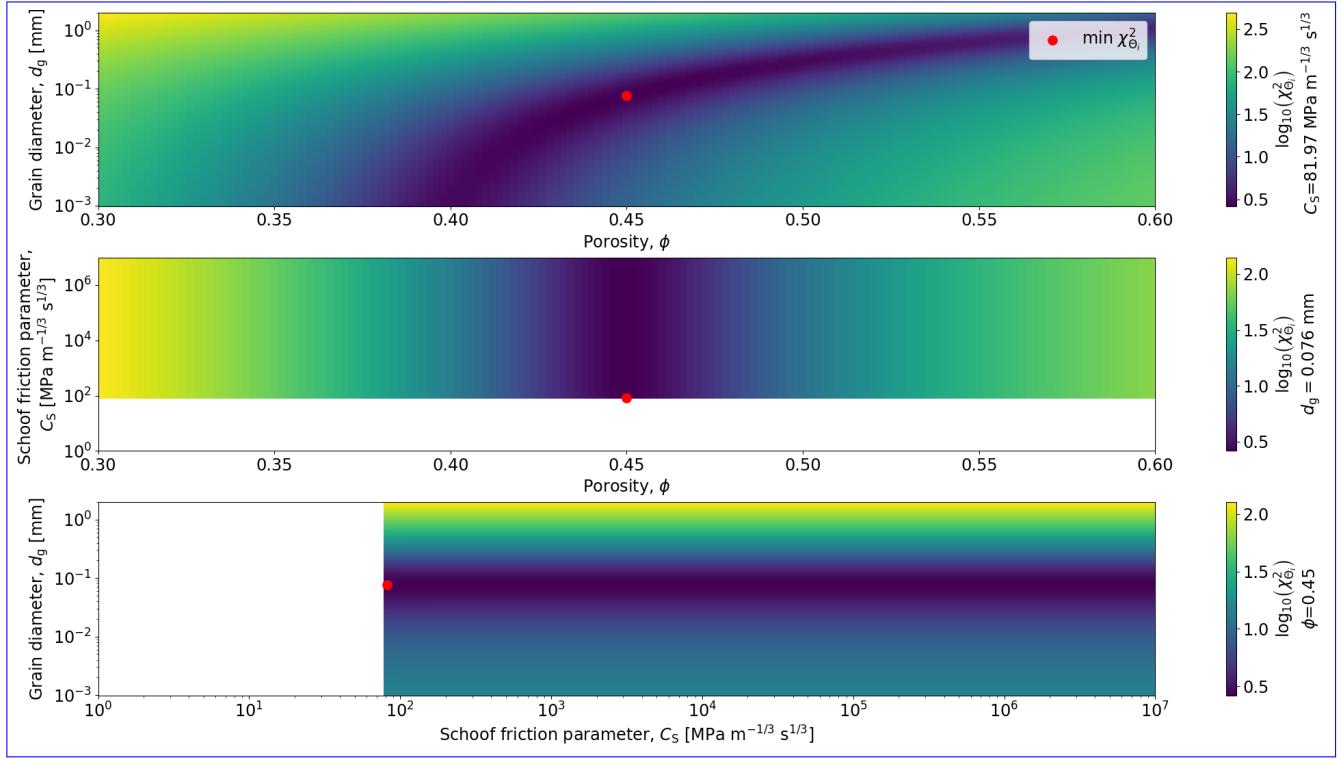
Figure S15. Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_g), porosity (ϕ), and Schoof friction parameter (C_S) under a Schoof sliding law ($C_{\max}$ fixed at ~~0.5~~0.2). The determination of $\chi^2_{\Theta_i}$ is only possible when the number of incompatible $u_b - \tau_b$ pairs is small (Fig. S16). Otherwise as Fig. S12.
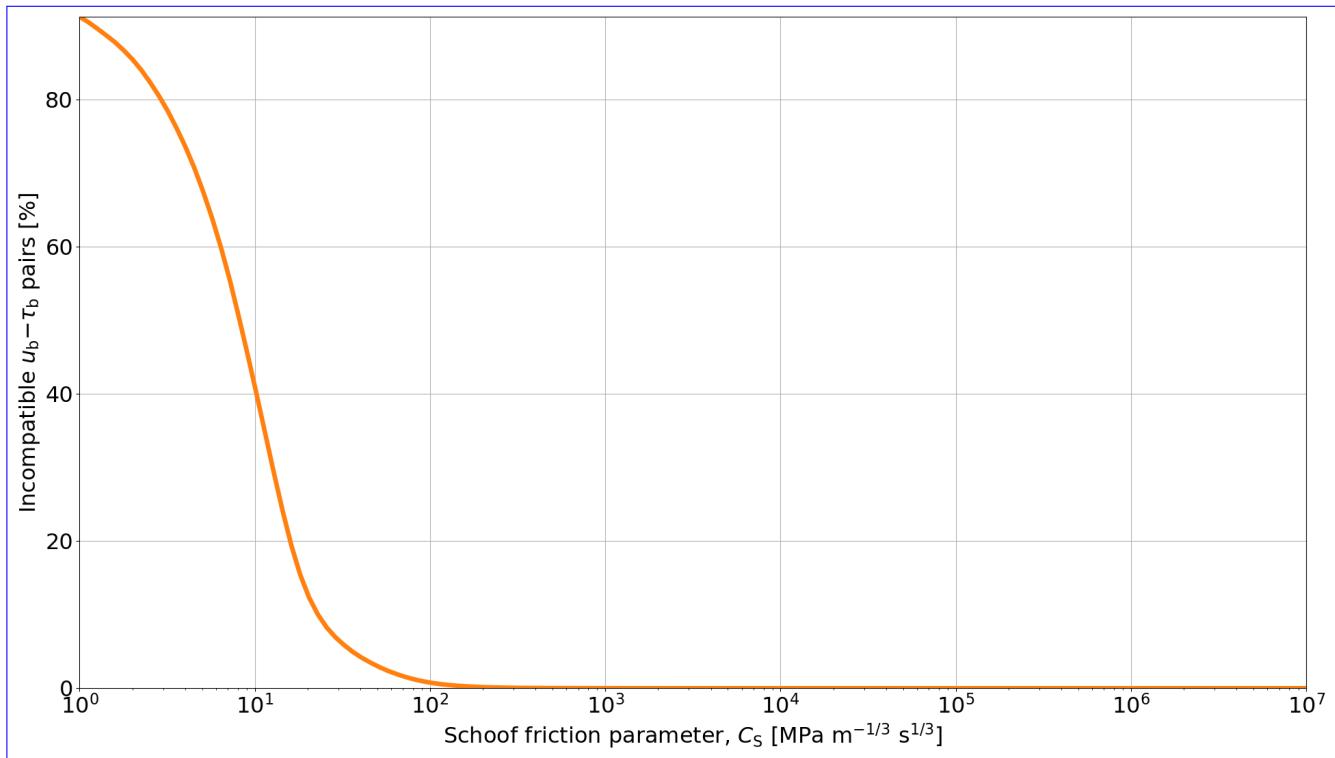
Figure S16. Percentage of incompatible $u_\mathrm{b}-\tau_\mathrm{b}$ pairs under a Schoof sliding law when varying the Schoof friction parameter (C_S; C_max fixed at ~~0.5~~0.2).

S7.6 Schoof (C_{max})
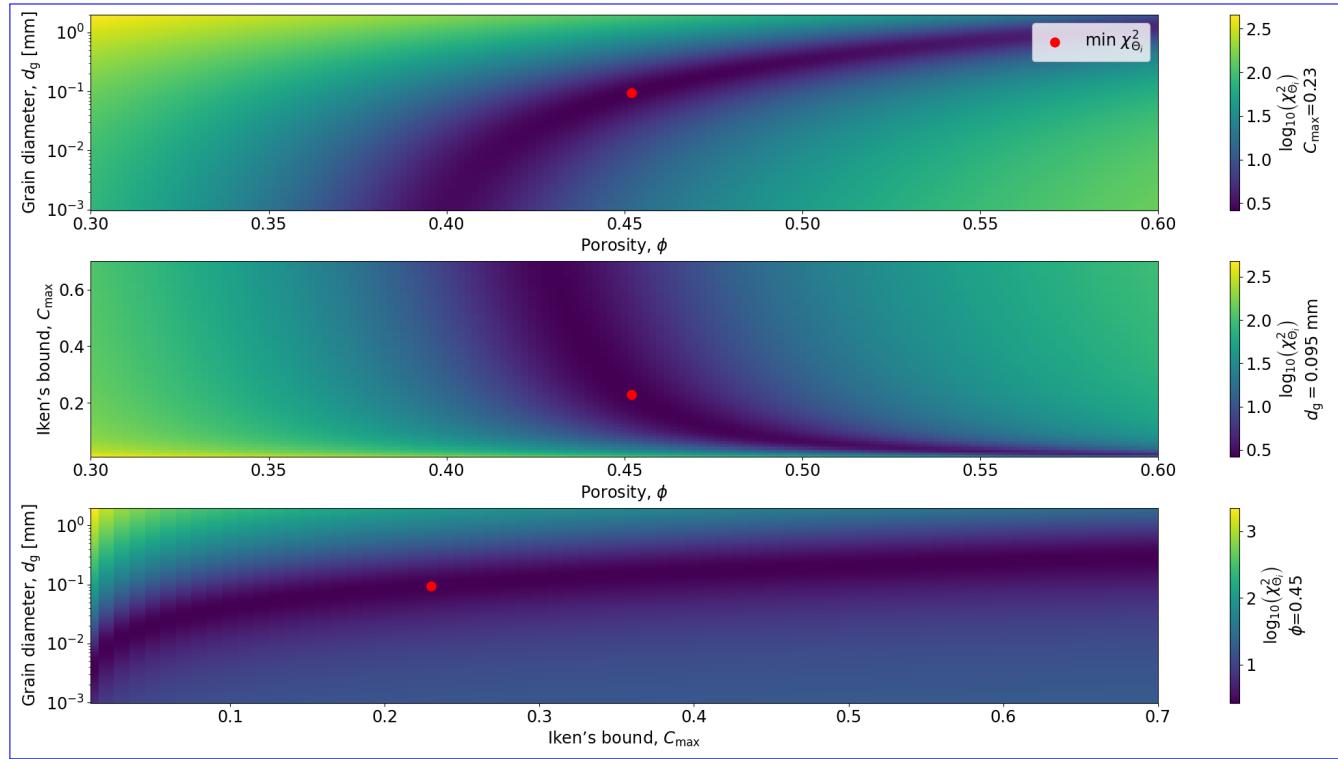
Figure S17. Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_{g}), porosity (ϕ), and Iken's bound (C_{max}) under a Schoof sliding law (C_{S} fixed at $1 \cdot 10^3$ MPa m$^{-1/3}$ s$^{1/3}$; Sec. S5). Otherwise as Fig. S12.
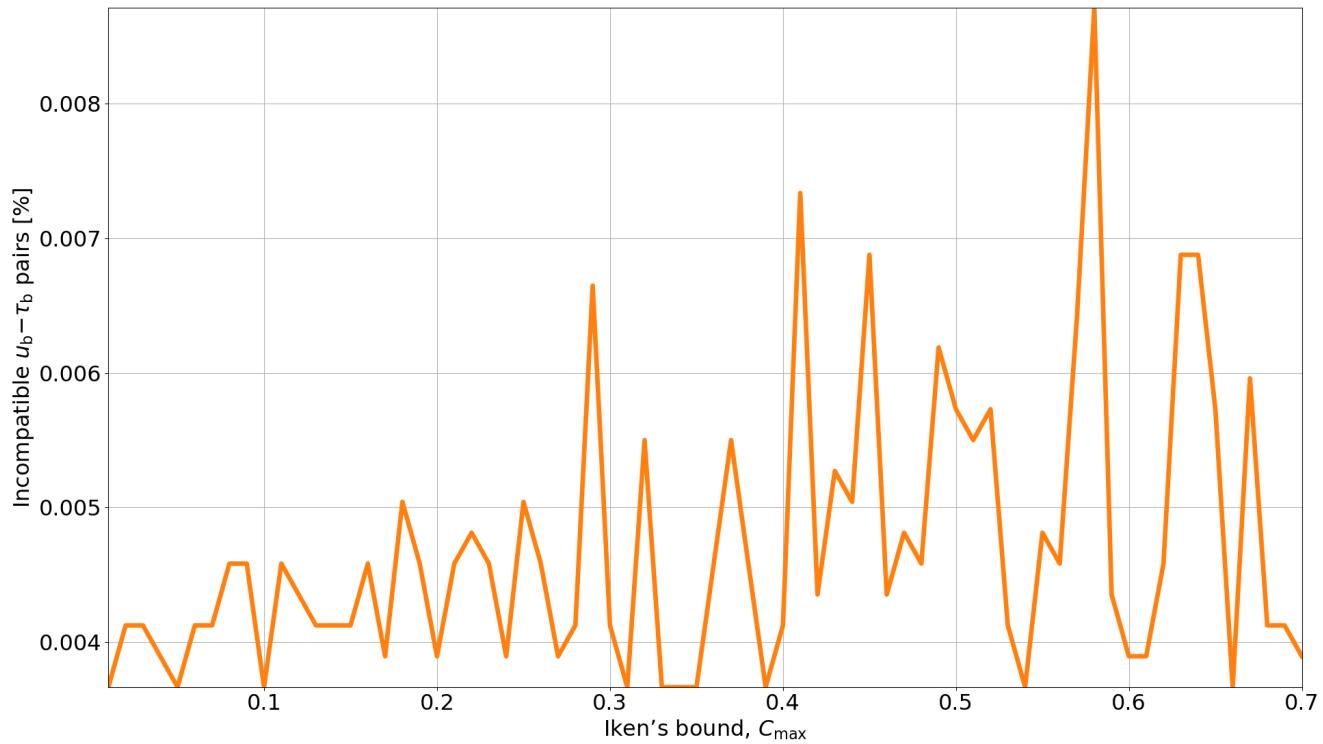
Figure S18. Percentage of incompatible $u_b - \tau_b$ pairs under a Schoof sliding law when varying Iken's bound (C_{max}; C_S fixed at $1 \cdot 10^3$ MPa m$^{-1/3}$ s$^{1/3}$; Sec. S5).

S7.7 Zoet-Iverson (μ)
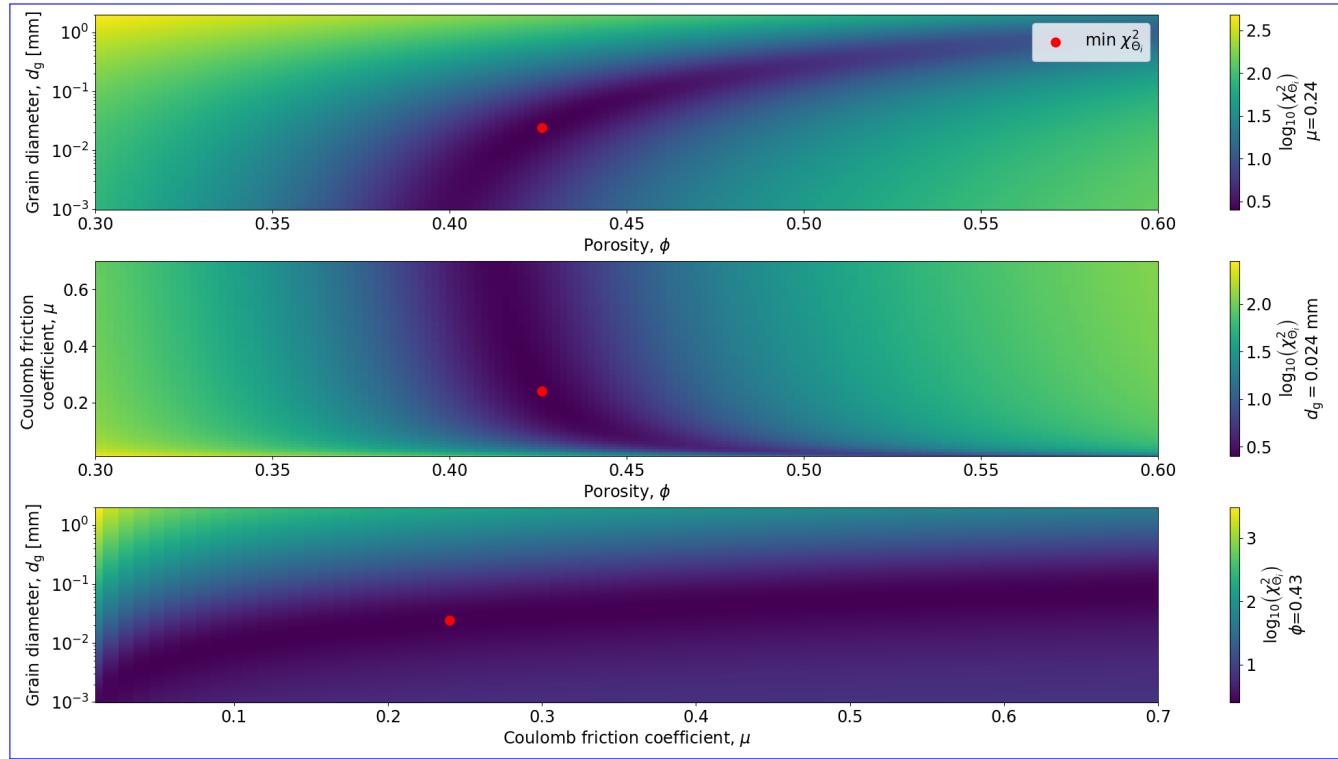
Figure S19. Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_{g}), porosity (ϕ), and Coulomb friction coefficient (μ) under a Zoet-Iverson sliding law ($\overline{u_{\mathrm{t,noN}}}~C_{\mathrm{ZI}}$ fixed at $\sim \overline{333~\mathrm{MPa}^{-1}~\mathrm{m~a}^{-1}}~\sim 340~\mathrm{MPa}^{-1}~\mathrm{m~a}^{-1}$). Otherwise as Fig. S12.
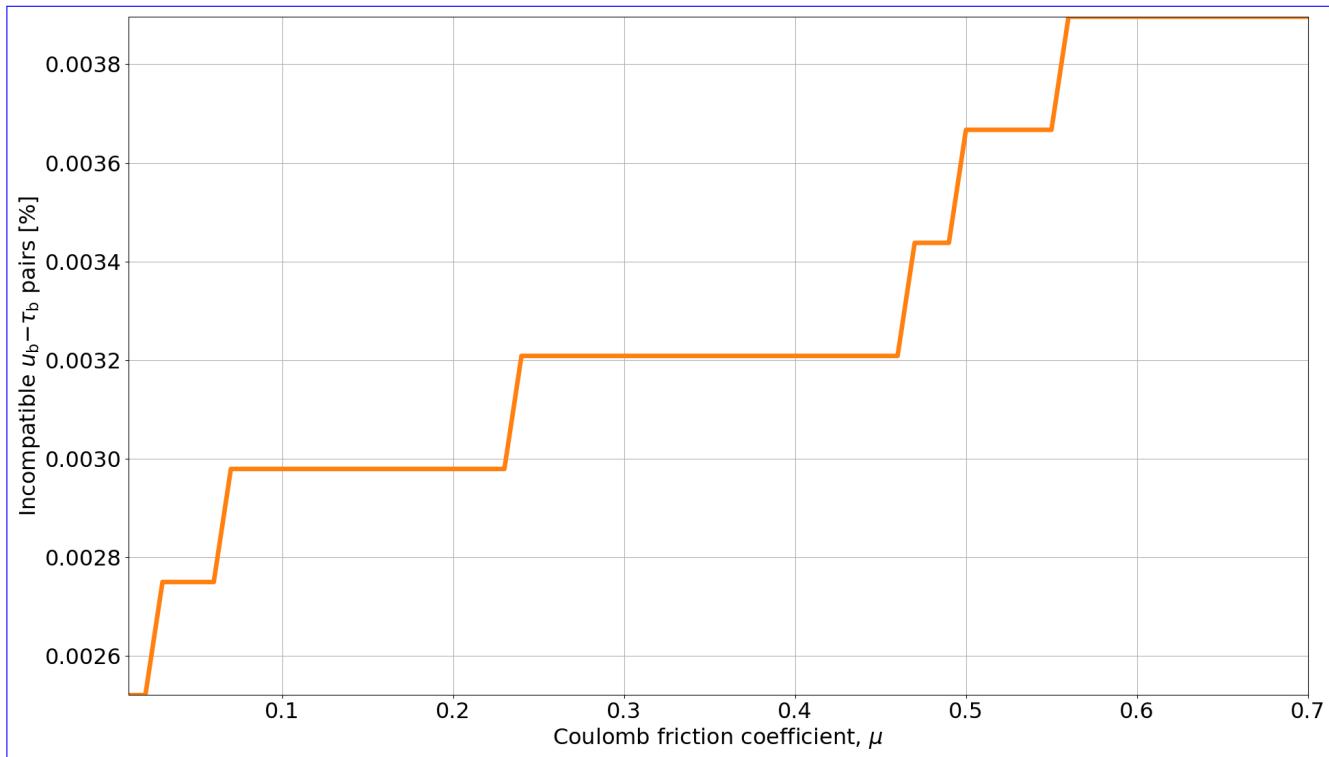
Figure S20. Percentage of incompatible $u_b-\tau_b$ pairs under a Zoet-Iverson sliding law when varying the Coulomb friction coefficient (μ; ~~$u_{t,noN}$~~ C_{ZI} fixed at ~~$\sim 333\ \text{MPa}^{-1}\,\text{m}\,\text{a}^{-1}$~~ $\sim 340\ \text{MPa}^{-1}\,\text{m}\,\text{a}^{-1}$).

S7.8 Zoet-Iverson $(u_{t,noN})(C_{ZI})$
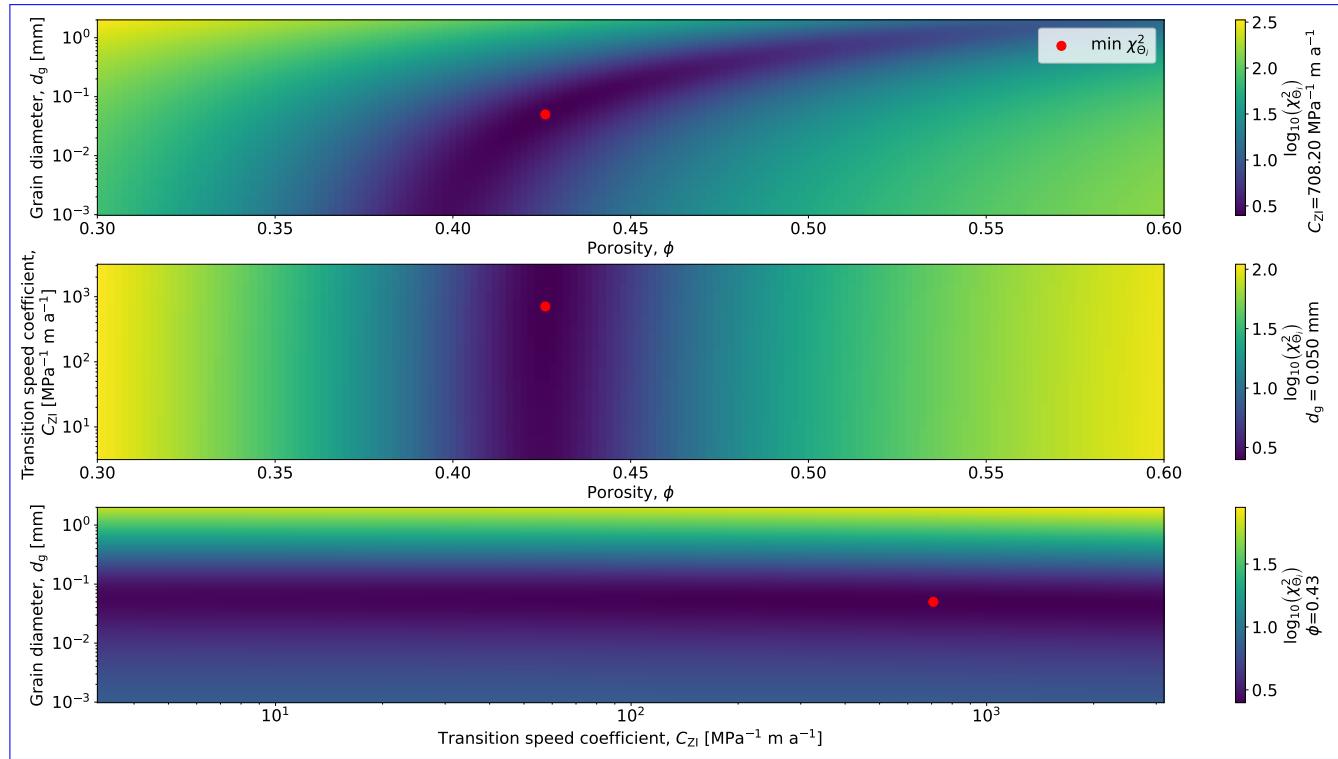
Figure S21. Variations of the misfit $\chi^2_{\Theta_i}$ with the three model parameters grain diameter (d_g), porosity (ϕ), and transition speed coefficient (C_{ZI}) under a Zoet-Iverson sliding law (Coulomb friction coefficient μ fixed at 0.5). Otherwise as Fig. S12.
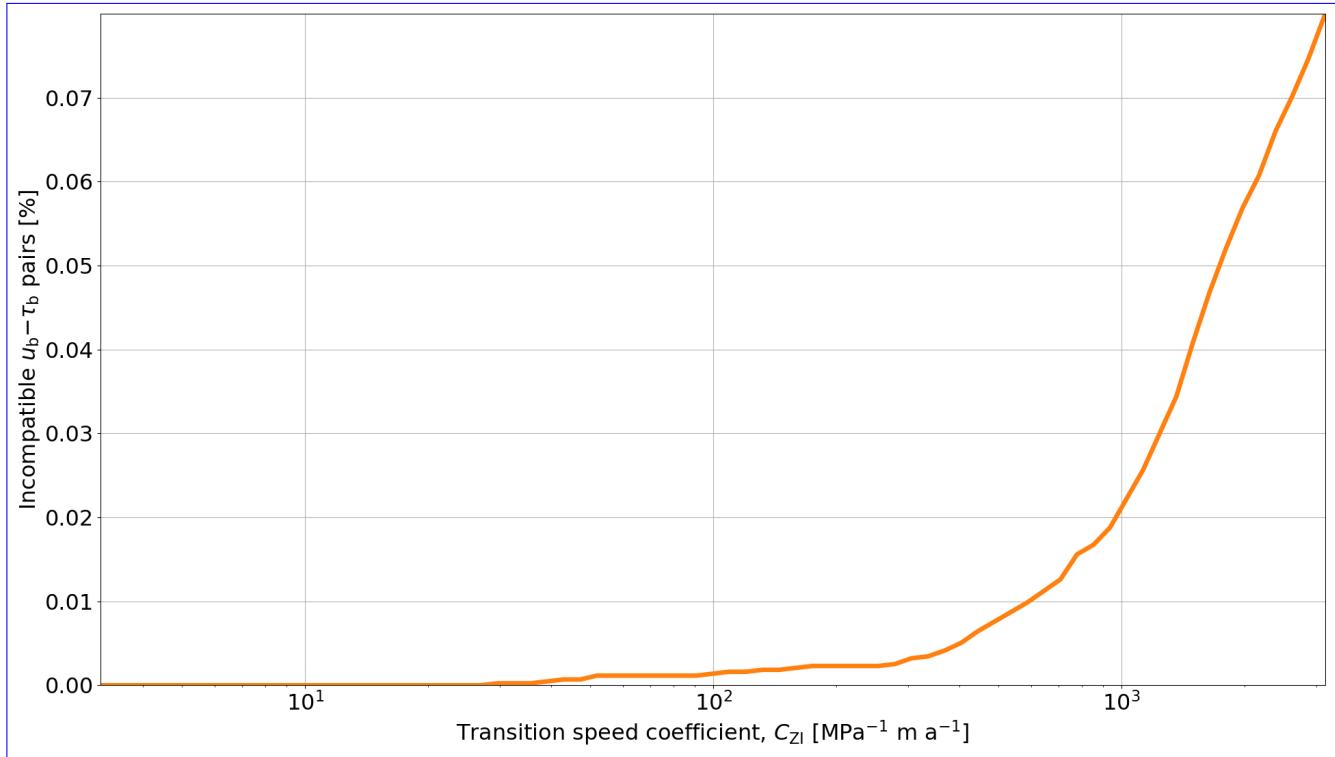
Figure S22. Percentage of incompatible $u_b-\tau_b$ pairs under a Zoet-Iverson sliding law when varying the transition speed ~~without the dependence on N~~ coefficient ($u_{t,noN}$ C_{ZI}; μ fixed at 0.5).
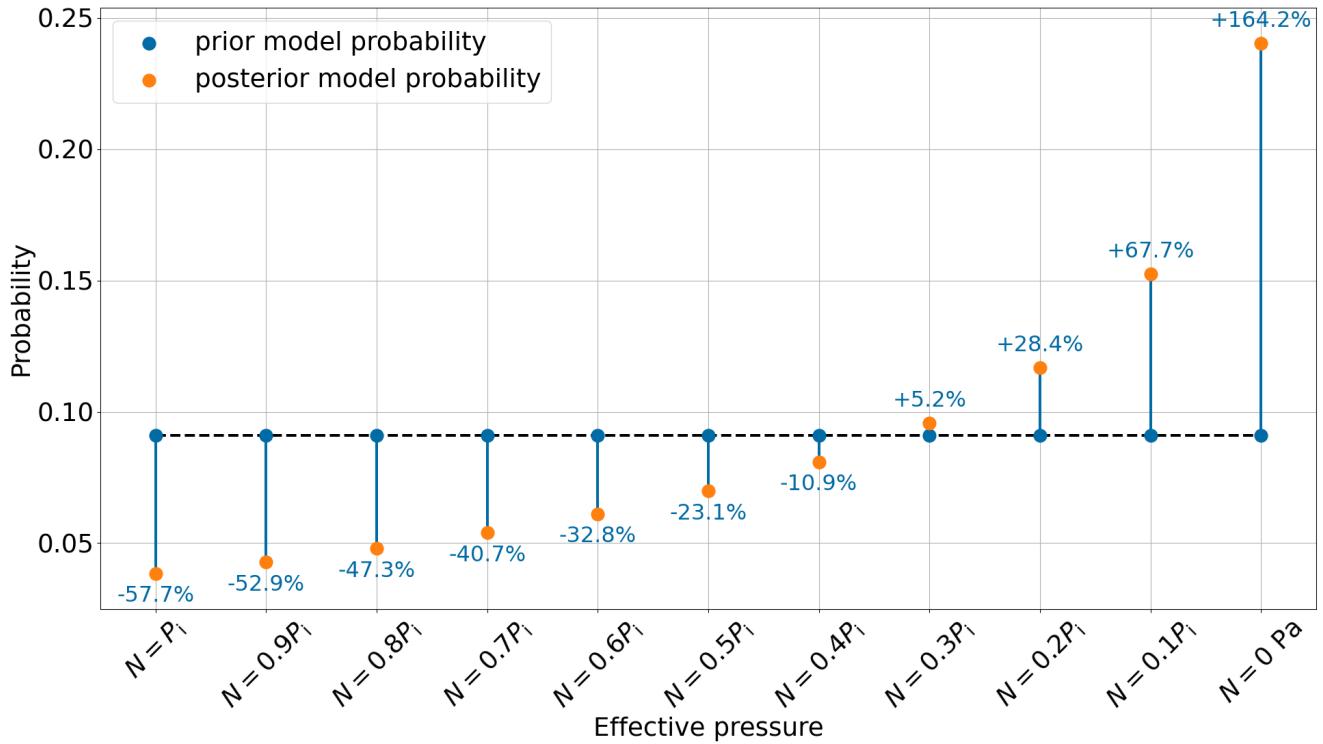
Figure S23. Normalized probabilities (Eq. 20) given the seismic observations collected on PIG when using different fractions of the over-burden pressure, including the two ~~Weertman-type~~ endmember scenarios ($N = 0$ Pa and $N = p_i$). Otherwise, as Fig. 6 in the main text.

S9 Acoustic impedance for most probable parameters
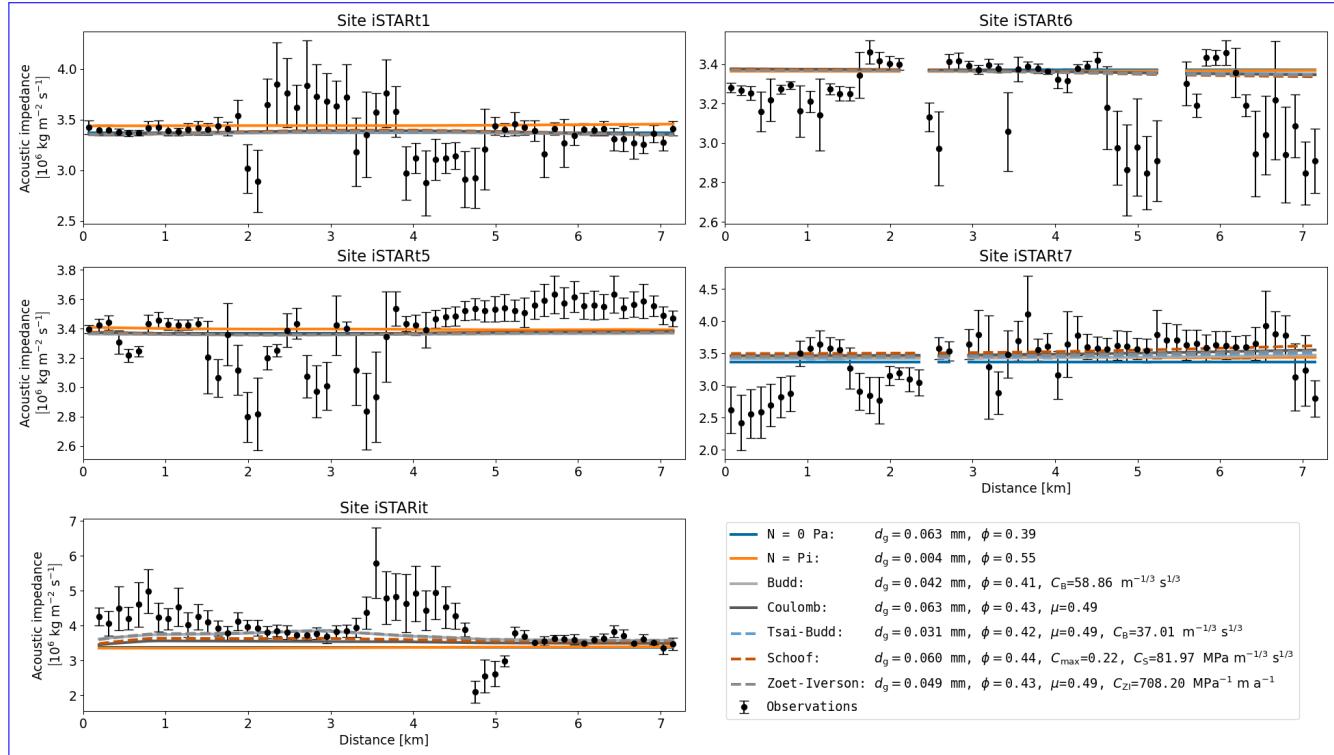
Figure S24. The different panels show the predicted acoustic impedance at the five data sites. For all sliding laws, the acoustic impedance curve is based on the MAP (highest posterior probability) model parameters shown in the legend.
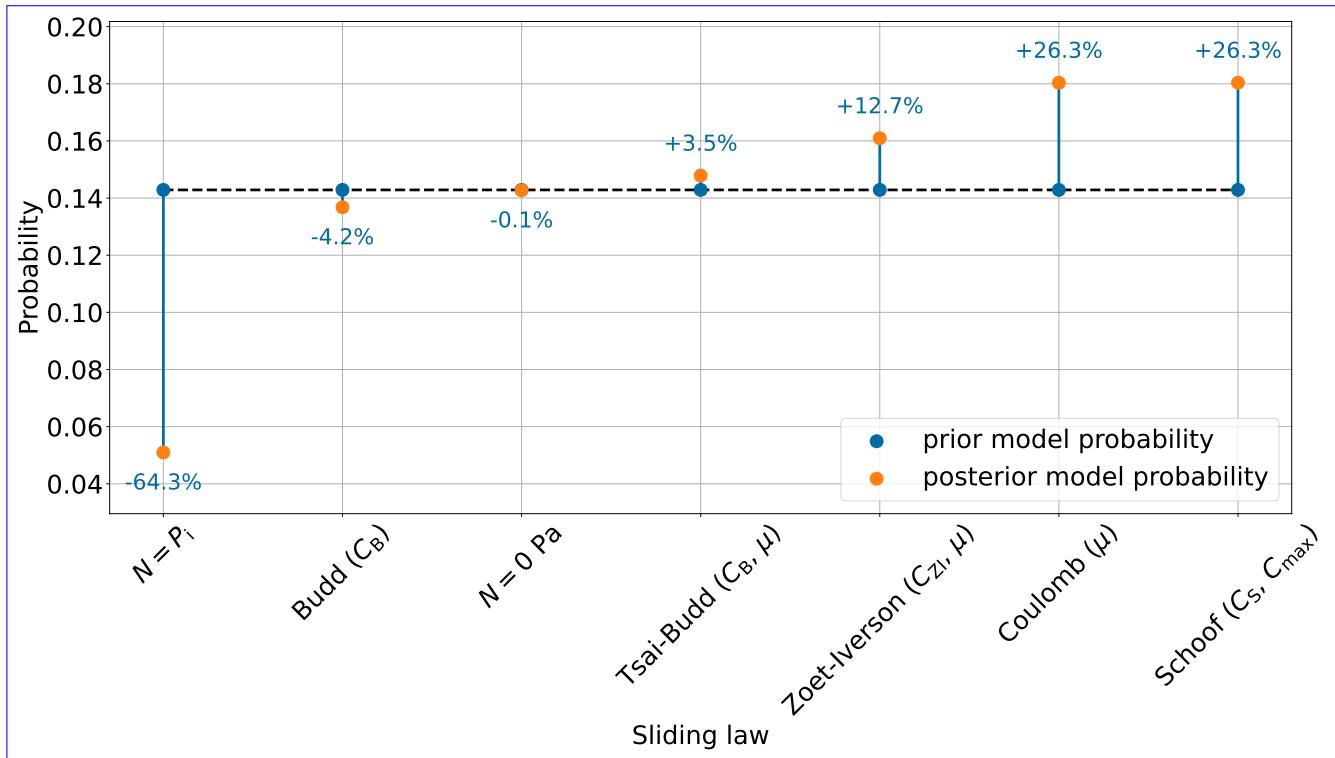
Figure S25. Normalized probabilities (Eq. 20) of all sliding laws examined in this study given the acoustic impedance observations collected on PIG, and log-uniform prior distributions for scaling coefficients and uniform priors for other parameters. Otherwise, as Fig. 6 in the main text.

S11 Effective pressure for most probable parameters
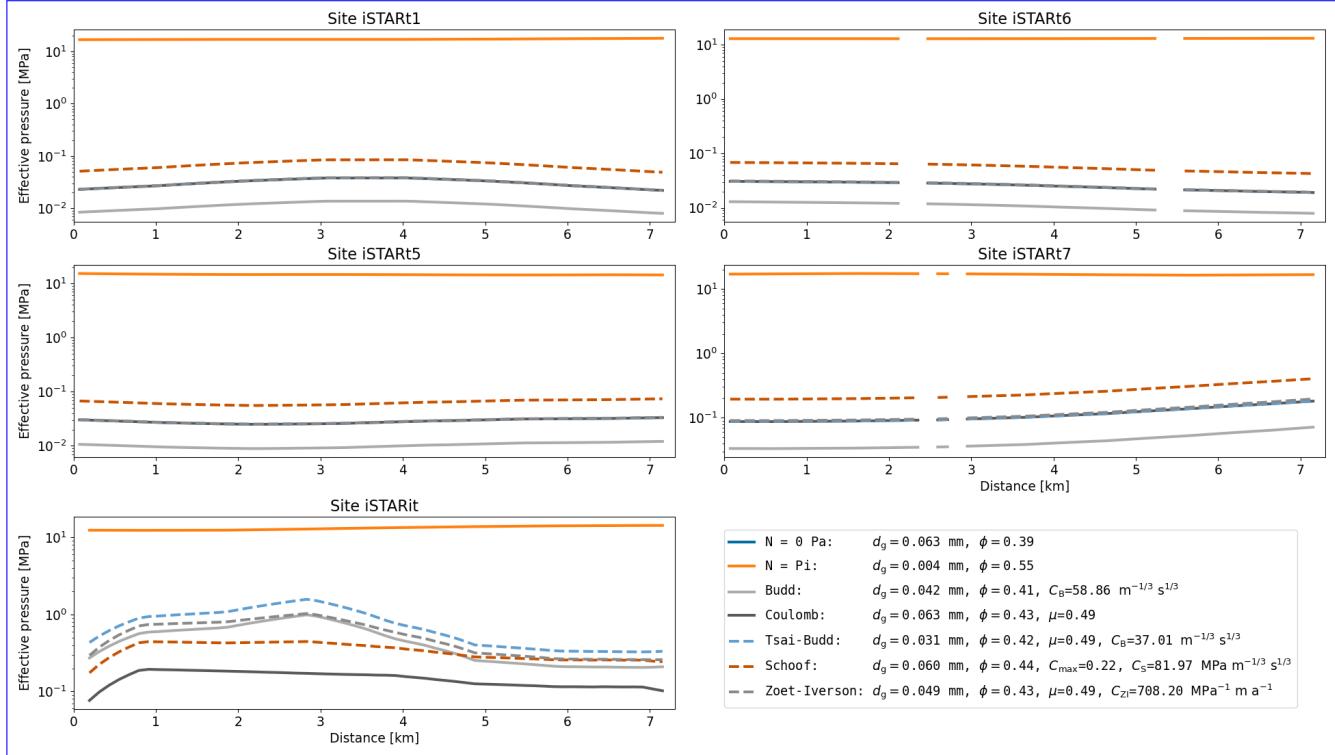
Figure S26. The different panels show the predicted effective pressure at the five data sites. For all sliding laws, the effective pressure curve is based on the MAP (highest posterior probability) model parameters. By definition, the low effective pressure ~~Weertman-type~~ endmember scenario has $N = 0$ Pa and only the MAP parameter values are shown here (not the curve itself). Note the logarithmic scale of the y-axes.

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