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Abstract

We compare different ways the bulk flow nonlinearity of glacier ice can be captured in an orthotropic rheology. Specifically, we compare the unapproximated orthotropic rheology, derived from plastic potential theory, to existing approximations that assume either the nonlinear viscosity or fluidity is identical to that of Glen’s isotropic flow law. We find, overall, a reasonable agreement between the three orthotropic rheologies, and with existing Dye 3 ice-core deformation tests, although assuming Glen’s viscosity provides the best approximation to the unapproximated rheology. Our results therefore suggest that previous studies based on either approximation to the orthotropic rheology are on relatively safe ground in the sense that both approximations generally agree with the unapproximated rheology and experimental data. Finally, we provide the forward and inverse analytical forms of all three rheologies for use in future numerical ice-flow modelling.

Introduction

The crystal orientation fabric of glacier ice co-evolves with deformation and can locally enhance the rate of deformation by orders of magnitude (Shoji and Langway, 1985; Pimienta et al., 1987). How exactly fabric anisotropy evolves and affects the large-scale flow of ice masses has received a lot of attention in the literature, covering a broad range of topics. Questions examined include: How is the flow and age–depth relationship at ice divides affected by fabric anisotropy (Durand and others, 2007; Martin and others, 2009; Pettit and others, 2011; Martin and Gudmundsson, 2012)? How does fabric anisotropy affect the flow of grounded ice and ice shelves (Ma and others, 2010)? How does fabric anisotropy affect the dynamics of mountain glaciers and ice streams compared to temperature variations (Hruby and others, 2020)? Do near-surface variations in fabric contain climatic information (Kennedy and others, 2013; Kennedy and Pettit, 2015)? Can fabric be used as a proxy with memory of past flow conditions (Thorsteinsson and others, 2003; Wilson and Peternell, 2011) for discovering e.g. palaeo ice streams (Lilien and others, 2021; Llorens and others, 2021)? How might fabric affect inferred basal sliding and hence mass fluxes (Rathmann and Lilien, 2021)?

Addressing such questions requires being able to accurately model the large-scale flow of anisotropic ice. This demands, in turn, a bulk anisotropic rheology that can capture the relevant viscous effects of fabric anisotropy for a given application. Many anisotropic rheologies have been proposed (see e.g. Montagnat and others, 2014) and often fall into one of two categories:

1. The bulk rheology is taken to be the grain-averaged, anisotropic monocrystal rheology, for some appropriately defined average (e.g. Martin and others, 2009; Rathmann and others, 2021, and references therein).
2. The grain c-axis orientation distribution function (ODF) is assumed to possess certain symmetries, thereby allowing a bulk rheology to be derived from e.g. plastic potential theory (e.g. Gillet-Chaulet and others, 2005; Rathmann and Lilien, 2021, and references therein).

Both approaches have pros and cons; choosing one over the other is a trade off. The first approach places no constraints on what ODFs are permitted, whereas the second approach is, strictly speaking, only valid for a subset of possible ODF patterns (symmetries). Although this makes the first approach attractive, it depends on high-order fabric structure tensors (ODF moments) for flow exponents $n > 1$ – e.g. structure tensors through order eight for the popular flow exponent of $n = 3$ – which makes deriving the inverse rheology (needed for numerical modelling) too involved even for simple cases like assuming a homogeneous stress field over the polycrystal scale (Rathmann and others, 2021). While a linear-viscous monocrystal rheology ($n = 1$) or a nonlinear monocrystal fluidity that is independent of crystal orientation (Pettit and others, 2007) does not necessarily suffer from this problem, neglecting the observed directionally-dependent nonlinear fluidity of monocrystals (Duval and others, 1983) can lead to bulk strain-rate enhancements being underestimated by at least an order of magnitude (Rathmann and others, 2021).

The second approach is widely adopted in ice-flow modelling but requires specifying the directional viscosities (due to fabric) in the directions of the ODF symmetry axes (elaborated...
on below). The problem is therefore twofold in the sense that the directional viscosities must be calculated using a separate model that depends on the orientation fabric (a so-called ‘micro-macro’ (μ-M) model, that may or may not function as an average over the grains). For example, the bulk anisotropic ‘GOLF’ rheology in the model Elmer/Ice (Gillet-Chaulet and others, 2005) uses tabulated directional viscosities calculated from a separate viscoplastic self-consistent model.

The GOLF rheology in Elmer/Ice is currently the only operational anisotropic rheology of the second category above. The GOLF rheology assumes that the fabric is orthotropic; that is, the ODF has three planes of reflection symmetry with normals $\mathbf{m}_i$ ($i = 1, 2, 3$) (Fig. 1a). The initial version of the rheology (Gillet-Chaulet and others, 2005, 2006) considered a linear bulk viscosity, but has (e.g. Ma and others, 2010; Licciulli, 2018; Lilien and others, 2021) been extended following Martin and others (2009) (henceforth M09 approximation) and Petit and others (2007) (henceforth P07 approximation) to include a nonlinear viscosity or fluidity, respectively, taken to depend on the directional viscosities calculated from a separate viscoplastic self-consistent model.

The validity of assuming Glen’s viscosity or fluidity is, however, untested, and does not conform with plastic potential theory by demanding that the rheology be invariant under reflections with respect to $\mathbf{m}_i$. Objectivity implies that the forward rheology must depend on the six stress-tensor invariants of the symmetry (reflection) transformations, i.e. $\tau \cdot \mathbf{m}_i \mathbf{m}_i$ or equivalently (Naumenko and Altenbach, 2007)

\[
I_1(\sigma) = \tau \cdot \mathbf{m}_i \mathbf{m}_i, \quad I_2(\sigma) = \tau \cdot \mathbf{m}_i \mathbf{m}_i, \quad I_3(\sigma) = \tau \cdot \mathbf{m}_i \mathbf{m}_i
\]

Written compactly, the forward rheology is (see Naumenko and Altenbach (2007) for a derivation)

\[
\dot{\epsilon} = \eta^{-1} \sum_{i=1}^{3} \left[ \lambda_i I_{ij}^3 \mathbf{m}_i \mathbf{m}_j + \lambda_i I_{ij} \mathbf{m}_i + \mathbf{m}_j \right]
\]

where the nonlinear fluidity is

\[
\eta^{-1} = A \left( \sum_{i=1}^{3} \left[ \lambda_i I_{ij}^3 + \lambda_i I_{ij} \right] \right)^{(n-1)/2}.
\]

Here, $A$ is the flow-rate factor, $\lambda_i$ are six free material parameters, $I_i = I_i(\sigma)$ is assumed implicit, and the index tuples are defined as

\[
(j_1, j_2, j_3) = (2, 3, 1),
\]

\[
(k_1, k_2, k_3) = (3, 1, 2).
\]

Notice that a factor of $1/(n-1)/2$ has been absorbed into $A$ compared to the conventional definition of $A$ in the literature.

The rheology (1)–(2) may be posed in a form that is more relevant to glaciology by expressing $\lambda_i$ in terms of directional strain-rate enhancement factors (caused by the crystal orientation fabric), defined relative to Glen’s isotropic law $\dot{\epsilon}^{\text{Glen}} = A(\tau \cdot \tau)^{(n-1)/2}$. Specifically, we consider the shear and longitudinal strain-rate enhancements w.r.t. the three symmetry axes $\mathbf{m}_s$, $\mathbf{m}_b$, and $\mathbf{m}_h$ (Fig. 1b):

\[
E_{ij} = \frac{\dot{\epsilon}(\tilde{\tau}(\mathbf{m}_s), \mathbf{m}_j) \cdot \mathbf{m}_i}{\dot{\epsilon}^{\text{Glen}}(\tilde{\tau}(\mathbf{m}_s), \mathbf{m}_i) \cdot \mathbf{m}_j} \quad \text{for } i, j = 1, 2, 3,
\]

where $\tilde{\tau}(\mathbf{m}_s, \mathbf{m}_j)$ is an idealized compression ($i = j$) or shear ($i \neq j$) stress-tensor function aligned with the fabric symmetry directions:

\[
\tilde{\tau}(\mathbf{m}_s, \mathbf{m}_j) = \eta_0 \begin{cases} 1/3 - \mathbf{m}_i \mathbf{m}_j & \text{if } i = j \\ \mathbf{m}_i \mathbf{m}_j + \mathbf{m}_i & \text{if } i \neq j \end{cases}
\]

Calculating the six independent constraints from Eqn (5), gives

\[
\lambda_i = \frac{4}{3} \left( E_{i,j}^{(n+1)} + E_{i,k}^{(n+1)} - E_{j,k}^{(n+1)} \right), \quad \lambda_{i+3} = 2 E_{i,k}^{(n+1)},
\]

where $E_{ij}$ remain to be specified using a separate model that depends on the local orientation fabric (elaborated on below).

### Orthotropic bulk rheology

The orthotropic bulk rheology can be constructed from plastic potential theory by demanding that the rheology be invariant under reflections with respect to $\mathbf{m}_i$. Objectivity implies that the forward rheology must depend on the six stress-tensor invariants of the symmetry (reflection) transformations, i.e. $\tau \cdot \mathbf{m}_i \mathbf{m}_i$ or equivalently (Naumenko and Altenbach, 2007)

\[
I_1(\sigma) = \tau \cdot \mathbf{m}_i \mathbf{m}_i, \quad I_2(\sigma) = \tau \cdot \mathbf{m}_i \mathbf{m}_i, \quad I_3(\sigma) = \tau \cdot \mathbf{m}_i \mathbf{m}_i
\]

where the nonlinear fluidity is

\[
\eta^{-1} = A \left( \sum_{i=1}^{3} \left[ \lambda_i I_{ij}^3 + \lambda_i I_{ij} \right] \right)^{(n-1)/2}.
\]

This letter provides such a comparison between the M09 approximation and comparison of the three rheologies.

### Notation

Throughout, inner, double inner and outer products, are denoted by $A \cdot B = \sum_j A_i B_j$, $A \cdot B = \sum_j A_{ij} B_{jk}$ and $ab = a_ib_j$, respectively, where lower and upper case bold denote vectors and second-order tensors, respectively.
Inverse rheology

Posing Eqns (1)–(2) in its inverse form, \( \tau(\mathbf{e}) \), amounts to solving a nonlinear matrix equation. Unlike other anisotropic rheologies, such as the transversely isotropic rheology (e.g. Rathmann and others, 2021), the orthotropic rheology does not tensorially depend on \( \tau \) but on its projections \( \mathbf{m} \cdot \mathbf{m} \). Inverting the rheology is therefore possible by calculating the invariants \( I_i(\mathbf{e}) \) \( (i=1, 2, 3, 4, 5, 6) \) using Eqns (1)–(2) and solving for \( I_i(\tau) \), combined with the assumption that the inverse law should, too, depend tensorially only on \( \mathbf{m}_1 \mathbf{m}_2 \mathbf{m}_3 \) and \( \mathbf{m}_4 \mathbf{m}_5 + \mathbf{m}_6 \mathbf{m}_1 \). It follows from long but arithmetically straightforward calculations that

\[
\tau = \eta \sum_{i=1}^{3} \left[ \frac{\lambda_i}{\gamma} (I_{ij} - I_k) I - \frac{3m_i m_j}{2} \right] + \frac{4}{\lambda_{i+3}} \frac{m_i m_j + m_i m_j}{2}, \]

where \( I_j = I_j(\mathbf{e}) \) is assumed implicit, and the nonlinear viscosity is

\[
\eta = A^{-1/n} \left( \sum_{i=1}^{3} \left[ \frac{\lambda_i}{\gamma} (I_{ij} - I_k) I - \frac{3m_i m_j}{2} \right] + \frac{4}{\lambda_{i+3}} \frac{m_i m_j + m_i m_j}{2} \right)^{(1-n)/2n}. \quad (7)
\]

For convenience, the shorthand \( \gamma \) is defined as

\[
\gamma = \sum_{i=1}^{3} \left[ 2E_{ij}^2(1+1/n) E_{ij}^2(1+1/n) - E_{ij}^2(1+1/n) \right]. \quad (8)
\]

Indeed, we have numerically verified that the inverse satisfies \( \mathbf{e}(\tau(\mathbf{e})) = \mathbf{e} \) for various \( \mathbf{e} \). Note that the inverse rheology was simplified by applying the identity \( m_i m_j + m_i m_j + m_i m_j = I \), and that \( I_j - I_k = -3/2 \mathbf{e} \cdot \mathbf{m} \mathbf{m} \).

Pettit and others (2007) approximation

Pettit and others (2007) proposed capturing the bulk flow non-linearity in a linear-viscous anisotropic rheology by replacing the fluidity with that of Glen’s law:

\[
\eta^{-1} = A(\mathbf{r} \cdot \mathbf{r})^{(n-1)/2}. \quad (9)
\]

If Eqn (2) is replaced by (9), the bulk flow enhancements (5) imply that

\[
\lambda_i = \frac{4}{3} \left( E_{ij} + E_{jk} \right), \quad \lambda_{i+3} = 2E_{ijk}. \quad (10)
\]

The inverse rheology can be determined following the same procedure outlined above, yielding Eqn (6) but with the viscosity

\[
\eta = A^{-1/n} \left( \sum_{i=1}^{3} \left[ \frac{3 \lambda_i^2}{\gamma^2} (I_{ij} - I_k)^2 + \frac{8}{\lambda_{i+3}} I_{i+3}^2 \right] + \frac{3 \lambda_i \lambda_k}{2 \gamma^2} (I_j - I_k)(I_j - I_k) \right)^{(1-n)/2n}, \quad (11)
\]

where

\[
\gamma = \sum_{i=1}^{3} \left[ 2E_{ij} E_{ijk} - E_j^2 \right]. \quad (12)
\]

Martin and others (2009) approximation

Martin and others (2009) proposed capturing the bulk flow non-linearity in a linear-viscous anisotropic rheology by instead replacing the viscosity with that of Glen’s law:

\[
\eta = A^{-1/(n-1)}(\mathbf{r} \cdot \mathbf{r})^{(1-n)/2n}. \quad (13)
\]

In order to derive the forward and inverse orthotropic rheology consistent with the viscosity (13), consider replacing the fluidity of the forward rheology (2) with

\[
\eta^{-1} = A \left( \sum_{i=1}^{3} \left[ \frac{\lambda_i^2}{\gamma^2} + \lambda_i^2 + \lambda_i I_{i+3}^2 \right] \right)^{(n-1)/2}, \quad (14)
\]

where \( \lambda_i' \neq \lambda_i \). The corresponding inverse rheology, \( \tau(\mathbf{e}) \), is then given by Eqn (6) with Glen’s viscosity (13) if

\[
\lambda_i' = \frac{1}{2} \left( \frac{\lambda_i^2 + \lambda_i + \lambda_i}{2} - \frac{\lambda_i \lambda_i}{2} \right), \quad \lambda_{i+3}' = \frac{1}{2} \lambda_{i+3}^2, \quad (15)
\]

and

\[
\gamma = \frac{9}{16} \left( \lambda_1 \lambda_2 + \lambda_1 \lambda_3 + \lambda_2 \lambda_3 \right). \quad (16)
\]

Relating \( \lambda_i \) to the enhancements \( E_j \) using Eqn (5), yields

\[
\lambda_{i+3} = 2E_{ijk} \quad (17)
\]

and

\[
E_{ij} = \left( \frac{3}{16} \right)^{(n+1)/2} \left( \lambda_1 + \lambda_k \right) \left( \frac{\lambda_1^2 + \lambda_k^2}{2} + \lambda_1 \lambda_k \right)^{(n-1)/2}, \quad (18)
\]

where \( \lambda_1(E_{11}, E_{22}, E_{33}) \) can be inverted for numerically.

Comparison of rheologies

It is not immediately clear how the three orthotropic rheologies compare. Although the rheologies are constructed to reproduce the same directional enhancement factors when the principal stress and fabric directions are aligned by virtue of Eqn (5), the rheologies are not guaranteed to agree when the stress and fabric directions depart from these idealized ‘calibration states’ – except for \( n = 1 \) where the rheologies are identical by construction. To quantify the potential discrepancies, we consider two experiments: (1) numerically reproducing existing deformation tests made on Dye 3 ice-core samples, and (2) calculating strain-rates for synthetic ODFs that are modelled separately.

Dye 3 deformation tests

Shoji and Langway (1985) investigated how strain rates depend on the misalignment between the axis of uniaxial compression (stress direction) and the preferred direction of a strong single maximum fabric in Dye 3 ice-core samples. Specifically, they considered the longitudinal strain-rate parallel to the stress direction, divided by that predicted by Glen’s law for an isotropic fabric. In terms of the notation above, they calculated the strain-rate ratio

\[
\dot{e}_{\text{vy}} = \frac{\dot{e}(\mathbf{r} \cdot \mathbf{v})}{\dot{e}(\mathbf{r} \cdot \mathbf{v})} = \frac{\dot{e}(\mathbf{r} \cdot \mathbf{v})}{\dot{e}(\mathbf{r} \cdot \mathbf{v}) \cdot \mathbf{v} \cdot \mathbf{v}} \cdot \mathbf{v} \cdot \mathbf{v}, \quad (19)
\]

where \( \dot{e}_{\text{vy}} \) is the experimentally determined quantity, \( \mathbf{v} \) is the compressive axis, and \( \theta \) is the angle between

\[ \sin(\theta), 0, \cos(\theta) \]
the compressive axis and the single-maximum direction. Only when \( \theta = 0^\circ \) are the three rheologies guaranteed (constructed) to agree (by virtue of Eqn 5), and when \( \theta = 90^\circ \) by virtue of symmetry in the rheology. Considering intermediate angles allows, therefore, to make the differences between the rheologies clear, and to validate the rheologies against Dye 3 deformation tests.

Following Shoji and Langway (1985), we take \( n = 3 \) and note that both \( A \) and the stress tensor magnitude cancel by the division in (19) (the same applies, in principle, to other isotropic contributions, such as impurities or strain-hardening, insofar as their effect can be captured in \( A \)). We furthermore assume that the orientation fabric is effectively unidirectional (all \( c \)-axes aligned with \( \hat{z} \)) which is approximately true (Herron and others, 1985). The six bulk enhancement factors \( E_n \) (the remaining free parameters of the rheologies) are calculated using a grain-averaged, transversely isotropic monocrystal rheology that depends on the ODF, calibrated to reproduce directional enhancement factors observed from simple-shear deformation experiments (see Rathmann and Lilien 2021) for details). Notice that the visco-plastic self-consistent approach adopted by Elmer/Ice (Gillet-Chaulet and others, 2005) could equally well have been used to calculate \( E_n \) and that \( E_n \) are constants independent of \( \theta \) as far as the orthotropic rheologies are concerned.

Figure 2 shows the predicted relative strain-rates (lines) compared to those measured by Shoji and Langway (1985) (markers). We find that the M09 approximation provides the best approximation to the unapproximated orthotropic rheology, but that all three rheologies compare relatively well with observations. However, the symmetry around \( \theta = 45^\circ \), predicted by the orthotropic rheologies, is not supported by the deformation tests; that is, the deformation tests suggest that compression perpendicular to the single-maximum direction is slightly softer than compression parallel to it.

The fluidity always cancels in the division (19) for the P07 approximation, implying that the strain-rates predicted by the P07 approximation, relative to Glen’s flow law (i.e. Fig. 2 and results below), are identical for all \( n \). Hence, in the linear limit (\( n = 1 \)) all three rheologies produce relative strain-rates identical to those shown here for the P07 approximation (recall the three rheologies are constructed to conform in the linear limit).

We mention in passing that the community appears lately to have become more receptive to evidence that alternative flow exponents, \( n \approx 4 \), might be relevant in some circumstances (Bons and others, 2018; Qi and Goldsby, 2021; Müllein and others, 2022). The grey lines in Figure 2 show the corresponding behaviour for \( n = 4 \). Although the data provided by Shoji and Langway (1985) is calculated assuming \( n = 3 \), and therefore cannot be used to discriminate between different \( n \), we note that the difference between \( n = 3 \) and \( n = 4 \) is relatively small compared to \( n = 1 \) (dotted black line).

**Synthetic fabrics**

We also quantified the potential discrepancies between the three rheologies by calculating the strain rates predicted for a synthetic ice parcel with an evolving fabric. Specifically, we used our spectral fabric model (Rathmann and Lilien, 2021; Rathmann and others, 2021) to generate synthetic fabric (ODF) histories of an ice parcel subject to confined vertical compression or vertical simple shear, prescribed in terms of a constant strain-rate tensor. The two experiments consider exclusively the effect of lattice rotation (strain-induced rotation of \( c \)-axes) for \( \sim 3/4 \) of the total modelled parcel strains, whereas discontinuous dynamic recrystallization (DDRX) is assumed to dominate throughout the remaining deformation. We refer the reader to Rathmann and Lilien (2021) for details on the model, but note that the (normalized) stress tensor – which determines the orientation of nucleated grains during DDRX – is assumed to be coaxial with the strain-rate tensor, and in this way no ice-flow modelling is involved. Examples of the simulated ODFs for different parcel strains, \( \epsilon \), are shown in Figures 3b–e and 4b–e for the two deformation experiments (red dots denote the fabric principal directions).

Given the synthetic ODFs at each degree of parcel strain, we calculate \( E_{ij} \) in the same way as done above for the Dye 3 experiments.

Figures 3a and 4a show the longitudinal (\( \epsilon_{zz} \)) and shear (\( \epsilon_{xy} \)) strain rates predicted by the three rheologies, relative to Glen’s law, for a constant (shared) stress-tensor that is coaxial with the strain-rate tensor used to model the parcel deformation. Note again that both the rate factor, \( A \), and the stress-tensor magnitude cancel by considering strain rates relative to (divided by) Glen’s law. We find that the largest difference between the M09 approximation and the unapproximated rheology is 5% (across both experiments), whereas for the P07 approximation the largest difference is 30%.

We point out that orthotropy might be a poor approximation for fabrics (ODFs) strongly affected by DDRX, such as seen in Figure 3e where a tetragonal symmetry is found. In this case, the double maximum pattern (two maxima in each hemisphere) introduce two additional symmetry axes along which the directional viscosities cannot be specified in an orthotropic rheology.

**Discussion and conclusion**

Overall, we find that both M09 and P07 approximations provide a reasonable nonlinear extension to the linear orthotropic rheology when compared to the unapproximated rheology derived from plastic potential theory. We suggest, therefore, that previous studies relying on an orthotropic bulk rheology with either the M09 or P07 approximation (see Introduction) are on relatively safe grounds even though not rigorously justified. Of course, carefully constructed deformation tests are needed to determine which version of the orthotropic rheology best agrees with the behaviour of real polycrystalline ice. For this purpose, deformation tests like those conducted on Dye 3 ice-core samples (Shoji and Langway, 1985) might be useful (i.e. varying the misalignment between the compressive stress direction and the preferred fabric direction). However, existing experimental results (e.g. Shoji and...
Langway, 1985, considered here) seem too ambiguous for discriminating between the rheologies (Fig. 2). In this light, the fact that the rheologies are found to produce relatively similar responses is a comforting result.

We emphasize, however, that the P07 approximation to the unapproximated orthotropic rheology is less accurate than the M09 approximation. This is particularly true for ice under compression with a stress direction that is misaligned with the preferred fabric direction (Fig. 2), possibly relevant in warm, highly stressed areas of ice sheets where DDRX is active (Figs. 3 and 4) (Duval and Castelnau, 1995). As numerical ice-flow models develop support for DDRX in the future, our results provide an important caveat: the choice of a bulk flow nonlinearity in anisotropic rheologies (of the second kind described in the introduction) might affect modelled ice velocities for DDRX-induced fabrics. The two approximations might additionally lead to larger discrepancies in coupled ice-flow modelling as reported by Martin and Gudmundsson (2012); if small differences in viscosity lead to
different deformation and fabric, minor differences could, poten-
tially, be amplified to become significant.

We end by noting that both the forward and inverse analytical
forms of all three rheologies were newly provided here in
coordinate-independent form (i.e. not the fabric eigen basis) for
use easy in future numerical ice-flow modelling.

**Code availability.** The model code (rheologies, fabric evolution
and enhancement-factor calculations) is available at https://github.com/nicholasmr/specfab.

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**References**

**Bons PD, and 6 others (2018)** Greenland ice sheet: higher nonlinearity of ice
flow significantly reduces estimated basal motion. Geophysical Research

**Durand G, and 8 others (2007)** Change in ice rheology during climate varia-
tions – implications for ice flow modelling and dating of the EPICA Dome

**Duval P, Ashby MF and Anderman I (1983) Rate-controlling processes in
the creep of polycrystalline ice. The Journal of Physical Chemistry 87(21),
4066–4074. doi: 10.1021/j100244a014

**Duval P and Castelnau O (1995)** Dynamic recrystallization of ice in polar ice
sheets. Le Journal de Physique IV 5(C3), C3–197. doi: 10.1051/jpke:1995317

**Gillet-Chaulet F, Gagliardini O, Meyssonnier J, Montagnat M and Castelnau
of Glaciology 51(172), 3–14. doi: 10.1017/S0022143005005781

**Gillet-Chaulet F, Gagliardini O, Meyssonnier J, Zwinger T and Ruokolainen J
(2006)** Flow-induced anisotropy in polar ice and related ice-sheet flow mod-

**Herron SL, Langway Jr CC and Brugger KA (1985)** Ultrasonic Velocities and

**Hruby K, and 5 others (2020)** The impact of temperature and crystal ori-
tervation fabric on the dynamics of mountain glaciers and ice streams. Journal
of Glaciology 66(259), 755–765. doi: 10.1017/jog.2020.44

**Kennedy JH and Pettit EC (2015)** The response of fabric variations to
simple shear and migration recrystallization. Journal of Glaciology 61

**Kennedy JH, Pettit EC and Di Prinzio CL (2013)** The evolution of crystal
fabric in ice sheets and its link to climate history. Journal of Glaciology
59(214), 357–373. doi: 10.3189/2013JoG12J159

**Licciulli C (2018)** Full Stokes ice-flow modeling of the high-Alpine glacier saddle
Colle Gnifetti, Monte Rosa: flow field characterization for an improved inter-
pretation of the ice-core records. Ph.D. thesis, University of Heidelberg,
Heidelberg, Germany. doi: 10.11588/heidol.00023981.

**Lilien DA, Rathmann NM, Hvidberg CS and Dahl-Jensen D (2021)**
Modeling ice-crystal fabric as a proxy for ice-stream stability. Journal of
Geophysical Research: Earth Surface 126(9), e2021JF006306. doi: 10.1029/
2021JF006306.

**Llorens MG, and 9 others (2021)** Can changes in ice-sheet flow be inferred
from crystallographic preferred orientations!. The Cryosphere Discussions
2021, 1–24. doi: 10.5194/tc-2021-224

**Ma Y, and 5 others (2010)** Enhancement factors for grounded ice and ice
shelves inferred from an anisotropic ice-flow model. Journal of Glaciology
56(199), 805–812. doi: 10.3189/002214310794457209

**Martin C and Gudmundsson GH (2012)** Effects of nonlinear rheology, tem-
perature and anisotropy on the relationship between age and depth at ice
divides. The Cryosphere 6(5), 1221–1229. doi: 10.5194/tc-6-1221-2012

**Martin C, Gudmundsson GH, Pritchard HD and Gagliardini O (2009)** On
the effects of anisotropic rheology on ice flow, internal structure, and the
age–depth relationship at ice divides. Journal of Geophysical Research:
Earth Surface 114(F4), F04001. doi: 10.1029/2008JF001204

**Mills JD, Minchew BM and Pegler SS (2022)** Ice viscosity is more sensi-
tive to stress than commonly assumed. Communications Earth &
Environment 3(1), 1–7. doi: 10.1038/s43247-022-00385-x

**Montagnat M, and 11 others (2014)** Multiscale modeling of ice deformation

**Naumenko K and Altenbach H (2007)** Modelling of creep for structural ana-
lysis. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-540-70839-1

**Pettit EC, and 6 others (2011)** The crossover stress, anisotropy and the ice
flow law at Siple Dome, West Antarctica. Journal of Glaciology 57(201),
39–52. doi: 10.1017/S002214301179506619

**Pettit EC, Thorsteinsson T, Jacobson HP and Waddington ED (2007)** The
role of crystal fabric in flow near an ice divide. Journal of Glaciology
53(181), 277–288. doi: 10.3189/172756507782202766

**Pimienta P, Duval P and Lipenkov VY (1987)** Mechanical behaviour of
anisotropic polar ice. In *The Physical Basis of Ice Sheet Modelling*, IAHS

**Qi C and Goldsby DL (2021)** An experimental investigation of the effect of
grain size on ‘dislocation creep’ of ice. Journal of Geophysical Research:

**Rathmann NM, and 11 others (2021)** Can changes in ice-sheet flow be inferred
from crystallographic preferred orientations!. The Cryosphere Discussions
2021, 1–24. doi: 10.5194/tc-2021-224

**Rathmann NM, Hvidberg CS, Grinsted A, Lilien DA and Dahl-Jensen D
(2021)** Effect of an orientation-dependent non-linear grain fluidity on
bulk directional enhancement factors. Journal of Glaciology 67(263),
569–575. doi: 10.1017/jog.2020.117

**Rathmann NM and Lilien DA (2021)** Inferred basal friction and mass flux
affected by crystal-orientation fabrics. Journal of Glaciology 1, 1–7. doi:
10.1017/jog.2021.88

**Shoji H and Langway CC (1985)** Mechanical Properties of Fresh Ice Core from
3189/GM033p0039.

**Thorsteinsson T, Waddington ED and Fletcher RC (2003)** Spatial and tem-
poral scales of anisotropic effects in ice-sheet flow. Annals of Glaciology
37, 40–48. doi: 10.3189/172756503781815429

techniques in Sørsdal Glacier, East Antarctica. Journal of Glaciology
57 (205), 881–894. doi: 10.3189/002214311798043744