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Evidence that seismic anisotropy captures upstream palaeo ice fabric, with implications on present day deformation at Whillans Ice Stream, Antarctica

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Evidence that seismic anisotropy captures upstream palaeo ice fabric, with implications on present day deformation at Whillans Ice Stream, Antarctica

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ABSTRACT. Understanding deformation and slip at ice streams, which are responsible for 90% of Antarctic ice loss, is vital for accurately modelling large-scale ice flow. Ice preferred crystal orientation fabric (COF) has a first-order effect on ice stream deformation. For the first time, we use shear-wave splitting (SWS) measurements of basal icequakes at Whillans Ice Stream (WIS), Antarctica, to determine a shear-wave anisotropy with an average delay time of 7 ms and fast S-wave polarisation (φ) of 29.3°. φ is expected to align perpendicular to ice flow, whereas our observation is oblique to the current ice flow direction (~280°). Our results suggest that ice at WIS preserves upstream fabric caused by palaeo-deformation developed over at least the past 450 years, implying that changes in the shape of WIS occurs on timescales shorter than COF re-equilibration. The "palaeo-fabric" can somewhat control present-day ice flow, which we suggest may somewhat counteract the long-term slowdown at WIS. Our findings suggest that seismic anisotropy can provide information on past ice sheet dynamics, and how past ice dynamics can play a role in controlling current deformation.

INTRODUCTION

Despite ice streams spanning only 10% of Antarctica's surface area, they are responsible for 90% of Antarctic ice loss (Morgan and others, 1982). Therefore, studying ice stream rheology is important for understanding Antarctica's contribution to sea-level rise. One source of uncertainty in ice stream dynamics is the effect of ice fabrics on rheology, where ice with a crystal oriented fabric (COF) can be ten times weaker in shear in a particular direction relative to isotropic ice (Lutz and others, 2020). Glacial ice is commonly formed of anisotropic hexagonal ice crystals, such that the viscosity along the basal plane of ice (normal to c-axis) is sixty times less than that perpendicular to it (Duval and others, 1983). Under stress, the c-axes in a bulk polycrystalline ice mass can rotate to form an ice COF over timescales of hundreds of years, which can change in response to the stress it encounters (Azuma, 1994). Hence, understanding ice COF provides insight on past deformation history and how it might influence future ice flow.

Most ice COF measurements are taken from microstructural analyses of ice core samples. However, these are usually measured from stable or slow-moving regions of ice sheets, and cannot provide much information of the physical processes in fast-deforming regions (Fan and others, 2021; Llorens and others, 2021). In contrast, seismic anisotropy measurements can be used to deduce ice COF properties over large areas in different ice settings, including ice streams (Smith and others, 2017). Therefore, seismic anisotropy can provide insight in these key fast-flowing regions, which can inform models of ice-sheet dynamics.

Whillans Ice Stream (WIS) is a major ice stream in West Antarctica that flows into the Ross Sea embayment (see Figure 1; Picotti and others, 2015). The downstream portion of WIS is known as Whillans Ice Plain (WIP), and it flows at a speed of over 300 metres per year, with stable sliding of the ice stream punctuated 1-2 times daily by sudden unstable sliding motion during 30-minute slip events that also produce high frequency icequakes and tremor (Barcheck and others, 2018; Bindschadler and others, 2003; Winberry and others, 2013). Long-term slowdown of the ice stream can be seen, with longer periods of quiescence between slip events over time, suggesting possibility of future stagnation (Winberry and others, 2014). WIS is an excellent area to study basal seismicity given that seismic and GNSS data have been collected over last decade at numerous sites to study its stick-slip cycle (e.g. Barcheck and others, 2020; Pratt and others, 2014; Walter and others, 2011, 2015; Winberry and others, 2009, 2011) and basal hydrologic cycle (e.g. Fricker and Scambos, 2009; Siegfried and others, 2016).

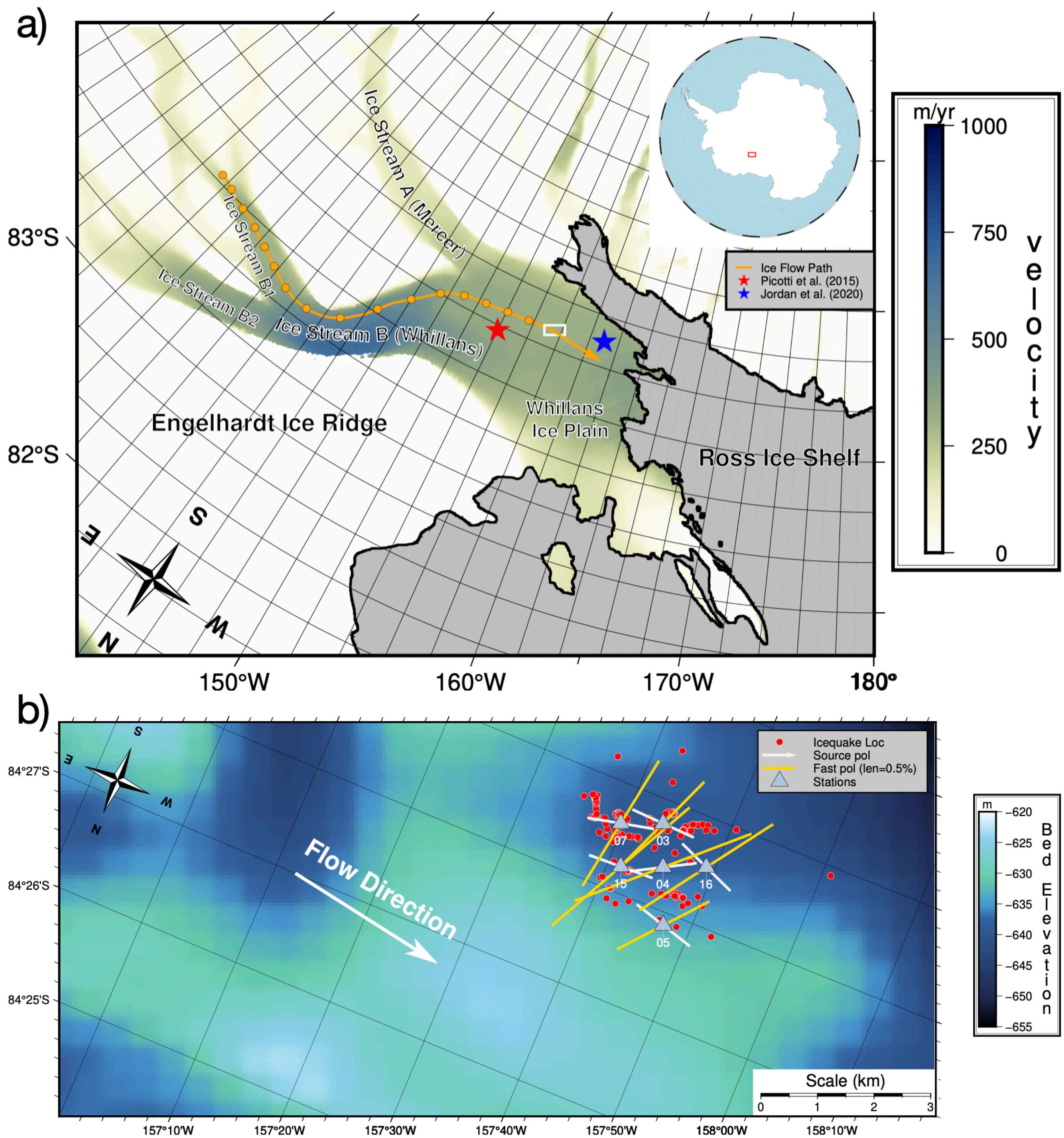
a)
Ice Stream A (Mercer)
Ice Stream B1
Ice Stream B2
Ice Stream B (Whillans)
Engelhardt Ice Ridge
Whillans Ice Plain
Ross Ice Shelf
83°S
82°S
150°W
160°W
170°W
180°
S
E
W
N
Ice Flow Path
Picotti et al. (2015)
Jordan et al. (2020)
m/yr
1000
750
500
250
0
velocity
b)
Icequake Loc
Source pol
Fast pol (len=0.5%)
Stations
Flow Direction
07
03
15
04
16
05
84°27'S
84°26'S
84°25'S
157°10'W
157°20'W
157°30'W
157°40'W
157°50'W
158°00'W
158°10'W
Scale (km)
0
1
2
3
m
−620
−625
−630
−635
−640
−645
−650
−655
Bed Elevation

Fig. 1. Stereographic maps showing Whillans Ice Stream (WIS) and study location. (a) Regional map of the WIS. The grounding line is marked in the thick black line, and the grey shaded areas mark regions of floating ice. The blue and red star show the study site locations of Jordan and others (2020) and Picotti and others (2015) respectively. The orange line outlines the upstream flow path of the ice at our study site location, assuming current flow velocities, with orange points marking the locations at intervals of 50 years (see supplementary information for flow path calculation). The background colour map shows the ice flow velocity obtained from MEaSUREs InSAR-Based Antarctica Ice Velocity Map, Version 2 (Rignot and others, 2017) The study area in (b) is outlined by the white box. (b) Detailed map of the study region. Stations are marked as blue triangles, and icequake locations are shown by red scatter points. Gold lines show the fast S-wave polarisation direction, with the length of the line representing the strength of anisotropy. White lines show the source polarisations for each event, as estimated from recorded shear waves. Dominant ice flow direction (280°) is indicated by the large white arrow. The background colour map shows the bed elevation Morlighem (2022).

There is currently an absence of ice COF observations for the entire ice column at WIS. Picotti and others (2015) used active seismic sources to suggest an azimuth-independent vertically transverse isotropic fabric (VTI) for the top 300 metres of WIS. Conversely, Jordan and others (2020) used electromagnetic methods to argue that the c-axes orient parallel to flow at WIS by polarimetric radar sounding that measured the top 400 metres of WIS (see Figure 1 for locations). Here, we provide the first seismic anisotropy measurements of the entire ice column at Whillans Ice Stream from shear-wave splitting of basal icequakes.

METHODOLOGY

This study uses 319 icequakes recorded between January 20th and February 27th, 2014 recorded by six seismometers at Whillans Ice Plain, Antarctica, part of a network active between 2012 to 2018 (Barcheck and others, 2020; Schwartz, 2012). The ice at the study site is between 690 and 710 m thick (Barcheck and others, 2020) and moving at $\sim$370 m/a (Morlighem, 2022). Since horizontal orientation of the instruments is important for studying seismic anisotropy, we verified the orientation of these instruments using a teleseismic event. We performed a manual search for icequakes focused within the duration of bidaily slip events at WIS, which were initially detected by QuakeMigrate (Hudson and others, 2019) and described in Barcheck and others (2021). Icequake arrival times are picked manually and are located using NonLinLoc, a probabilistic non-linear earthquake location algorithm (Lomax and others, 2000). Only icequakes originating at the bed of the ice stream are of interest for measuring total anisotropy in the ice column,

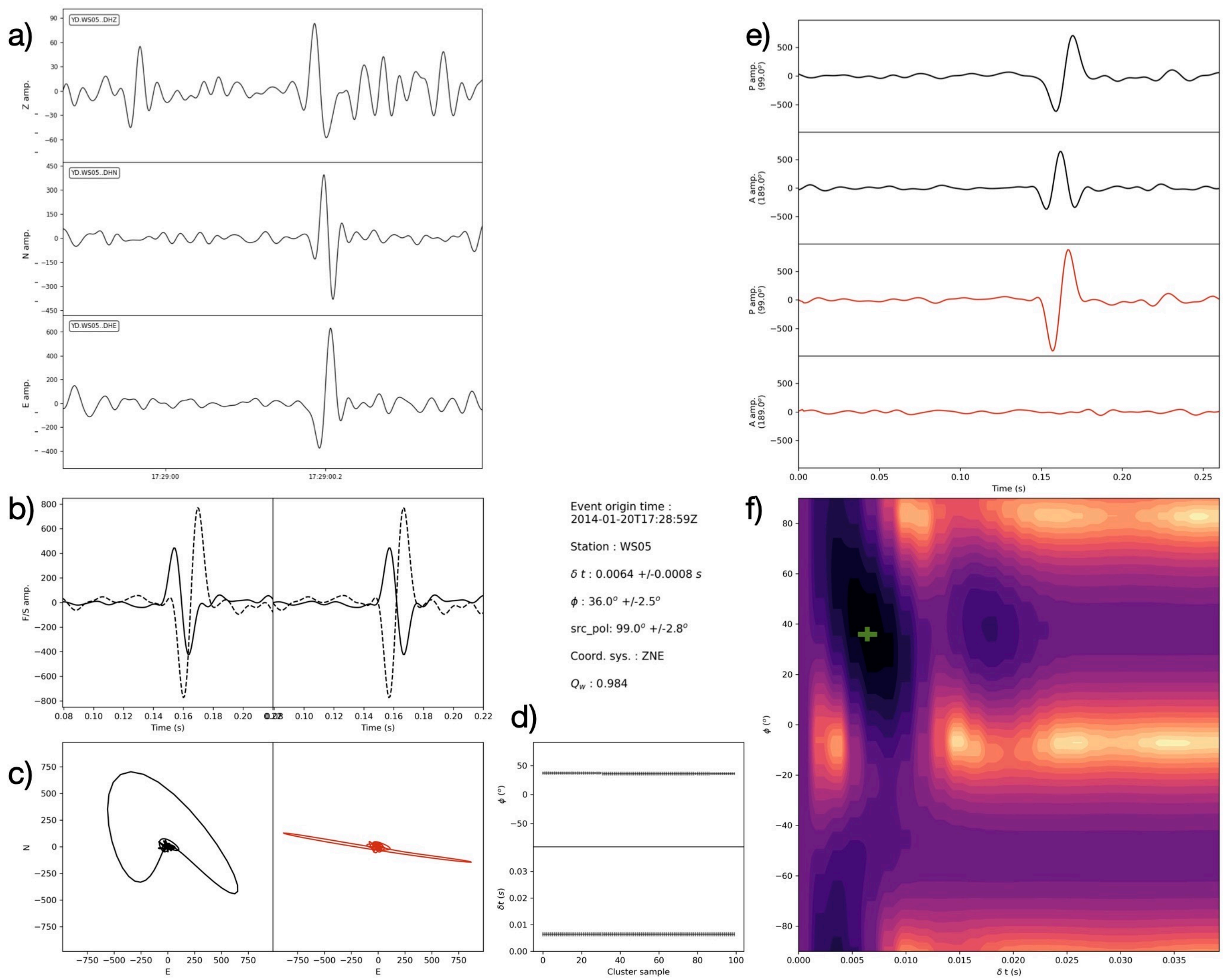

Fig. 2. An example of a well-constrained shear-wave splitting event. (a) Icequake signal before correction in the vertical, north and east component. (b) The waveforms before (left) and after (right) SWS correction, plotted in the fast (black line) and slow (dotted) directions. (c) Horizontal (north and east) particle motion before (left) and after (right) SWS correction (d) Optimal φ and δt for different cluster sizes. A good splitting measurement should have constant φ and δt values independent of cluster size. (e) Particle motion of icequakes in the source polarisation (P) and the perpendicular azimuth (A) before (top two) and after (bottom two) correction. (f) Error surface plotted on φ vs δt. Larger errors are represented with brighter colours, and smaller errors with darker colours. The optimal φ and δt and its uncertainties are shown with the green symbol.

therefore icequakes with a source depth shallower than 400 metres are removed. Each icequake is filtered by a 10-100 Hz bandpass filter, based on the dominant source spectra of the icequakes (see Figure S1). Seismic anisotropy is analysed on the horizontal (north and east) components because a ∼100 m thick firn layer refracts the ray path of icequakes to near-vertical incidence at the surface (Picotti and others, 2015).

Shear-wave splitting (SWS) analysis is conducted using the python package SWSPy (Hudson and others, 2023a), based on the approach of Wuestefeld and others (2010). It can be summarised as follows: First, a range of analysis time windows are defined because SWS measurements are sensitive to window lengths (Teanby and others, 2004). Second, a grid search is performed over fast shear-wave polarisation of -90°< $\varphi \leqslant 90°$ and delay times between fast and slow S-waves of $0 \leqslant \delta t \leqslant 0.1$ for each window. The splitting parameters, φ and δt, associated with the minimum second eigenvalue of the S-wave covariance matrix that best linearize particle motion, describe the anisotropy observed along a given source-receiver ray path. Third, density-based cluster analysis is performed on all optimal φ and δt values, such that the optimal φ and δt values are obtained from the most stable cluster with minimum variance in φ and δt (Ester and others, 1996; Teanby and others, 2004). The source polarisation is then calculated by taking the azimuth of the largest eigenvalue of the covariance matrix of the linearised waveforms (Walsh and others, 2013).

A well-constrained result after SWS correction is defined as satisfying the following four requirements: (1) the particle motion (see Figure 2c) becomes approximately linear after removing splitting using the optimal SWS parameters, (2) the error surface (see Figure 2f) has a unique, well-constrained solution, (3) splitting parameters (φ and δt) are stable (see Figure 2d) throughout different clusters, and (4) the quality factor Q_w is larger than 0.7. Q_w measures the robustness of the splitting measurement, and it is calculated by comparing the results from the eigenvalue method of Silver and Chan (1991) to the cross-correlation method of Menke and Levin (2003). A value of $Q_w = 1$ signifies a perfect match between the two methods, $Q_w =$ -1 a good null result, and $Q_w = 0$ a poor result (Wuestefeld and others, 2010).

The strength of anisotropy (δV), or the difference between fast and slow S-wave velocities, can be quantified by the change in velocity, derived from the delay time (δt):

$$\delta V = (V \times \delta t \times 100)/r \tag{1}$$

where $V = 1944$ m/s is the average isotropic shear-wave speed (Smith and others, 2017) and r the source-receiver distance.

RESULTS

80 results from 70 events fulfil the aforementioned four criteria, and therefore are chosen for further analysis. The fast S-wave polarisation φ and source polarisation of these events are plotted as polar histograms in Figure 3. For a double-couple icequake source associated with ice slip at the bed, S-wave source polarisation is aligned with the direction of slip (Hudson and others, 2020). One might typically expect the average S-wave source polarisation to align approximately with ice flow direction. Most source polarisation measurements lie approximately in the east-west direction with an average of 264°N ± 22º, which is in agreement with the Whillans Ice Stream's flow direction of 280°N ± 2° (Rignot and others, 2017).

The average delay time for these results is 7.1 ms and ranges from 1.6 ms to 19.2 ms. The average strength of anisotropy, δV, is ∼1.5%, with a maximum of 2.8%. This is below the maximum directional variation in S-wave velocities of single ice crystals of 12% (Lutz and others, 2020).

The shear-wave splitting measurements have an overall mean fast S-wave direction (φ) of 29.3°N ± 18° (see Figure 3a). The uncertainty in this result is defined as one standard deviation, likely representing an upper estimate of uncertainty in the result that could be caused by temporal variations in φ (see Figure S2). Individual receivers generally have mean φ that fall within a range of 22.4°N to 47.0°N (see Figure 1b), with the exception of station WS07, which has a mean φ of 9.1°N (see label 07, Figure 1b). Ice core studies (Alley, 1988; Llorens and others, 2021) and seismic anisotropy studies (Kufner and others, 2023; Smith and others, 2017) have found that regions of longitudinal extension, such as ice divides and ice streams, have a vertical girdle fabric. In such fabrics, φ is found to be perpendicular to the ice flow direction (Harland and others, 2013). Based on ice flow direction derived from InSAR (Rignot and others, 2017) and the source polarisation data in Figure 3b, one would expect φ ∼10°N at the Whillans study site (golden arrow, Figure 3). However, the mean φ we observe of 29.3°N ± 18º is oblique to this expected fast S-wave direction of ∼10°N, even after accounting for uncertainty. A t-test shows that the 95% confidence interval of the fast S-wave directions lies in between 25.3°N and 33.3°N (assuming that the distribution of fast S-wave directions in the data is Gaussian), confirming our confidence in this obliquity.

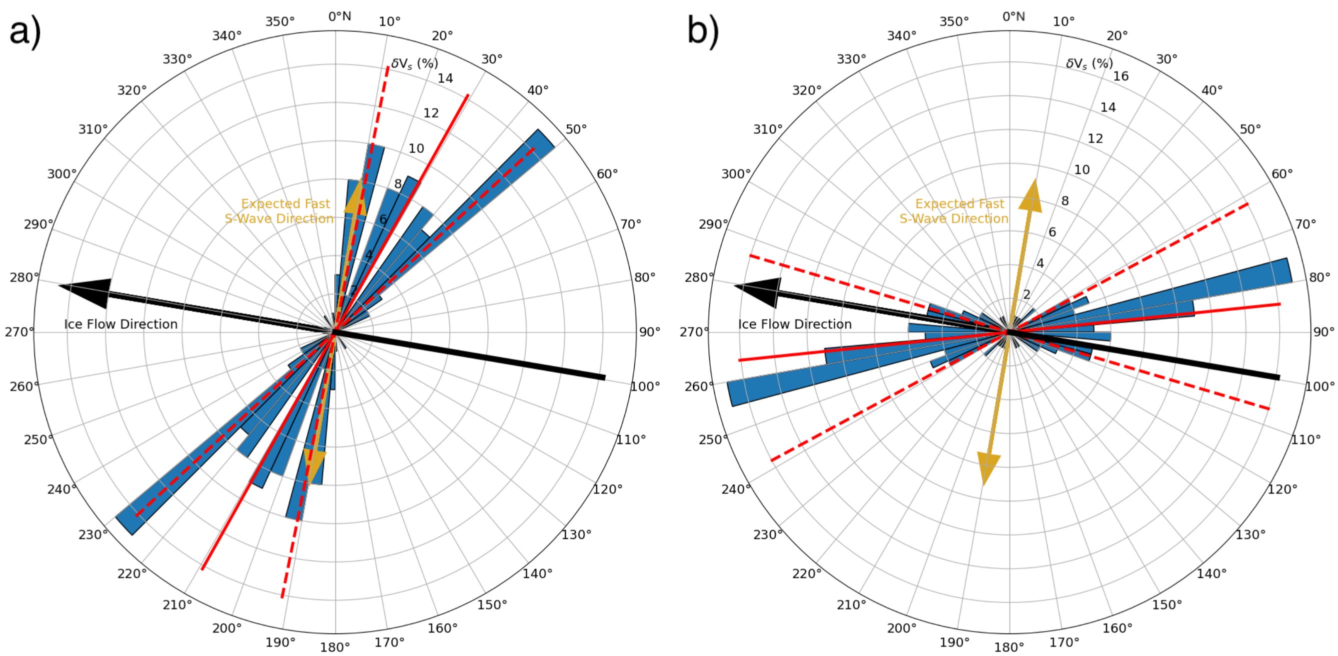

Fig. 3. Rose diagrams of (a) fast S-wave directions and (b) source polarisations for all the 80 SWS measurements. The solid and dotted red lines indicate the averages and uncertainties respectively. The gold arrows on both diagrams indicate the expected fast S-wave direction based on ice flow direction, which are shown as black arrows (see main text for further details). Method for estimating uncertainty is included in the supplementary information.

DISCUSSION

Possible origins of an ice COF with an oblique fast S-wave direction

Our results suggest that the ice COF at Whillans Ice Stream (WIS) is oriented oblique, rather than perpendicular, to the ice flow direction. This obliqueness suggests one of two hypotheses: either that the local strain at our study site acts oblique to ice flow; or that the ice COF at WIS is the result of preservation of historic deformation upstream of the study site.

Regarding the first hypothesis, a possible reason for extension oblique to ice flow is the differential ice flux between the two tributaries of Whillans Ice Plain (WIP) across a suture zone. The study site is located downstream of the confluence between the upper WIS and Mercer Ice Stream (MIS), where the faster flow of WIS relative to MIS leads to shear strain across the suture zone, which can reorientate ice crystals (see Figure 4; Beem and others, 2014). However, Bindschadler and others (1987) argue that shear is minimal between WIS and MIS. Additionally, we postulate that this suture zone has a negligible effect on the ice COF because the ice at our study site is in a laminar flow regime. Otherwise, we expect significant mixing to occur between the two ice streams, which would perturb the ice fabric on length scales of the order of hundreds of metres. This mixing would likely yield significant differences in the fast-polarisation S-wave azimuth (φ) between the different stations, yet the fast-polarisation S-wave azimuths remain constant within uncertainty across the network.

We instead favour the second hypothesis: that WIS has a "palaeo-COF" that preserves a record of WIS' upstream palaeo-deformation. Ice core studies suggest that such preservation of a COF upstream is possible (Alley, 1988; Llorens and others, 2021). Additionally, most of the ice deformation at WIP occurs along the shear margins (Truffer and Echelmeyer, 2003), so internal deformation at Whillans is minimal. This minimal internal deformation would allow an upstream ice COF to be preserved at our study site, and it implies that the main factor in ice fabric evolution at WIS is lattice rotation.

The ice COF always rotates towards the direction of most compression, which in ice streams is the direction perpendicular to the flow direction (Smith and others, 2017; Thorsteinsson and others, 2003). The meandering nature of WIS alters the direction of compression, and therefore the ice COF represents an integrated history of upstream strain induced from this changing stress. As such, it is difficult to pinpoint the origin of the fabric formation. However, for the ice COF to have developed the observed oblique φ, the ice at our study site must have preserved some of its deformation history from when the flow direction was

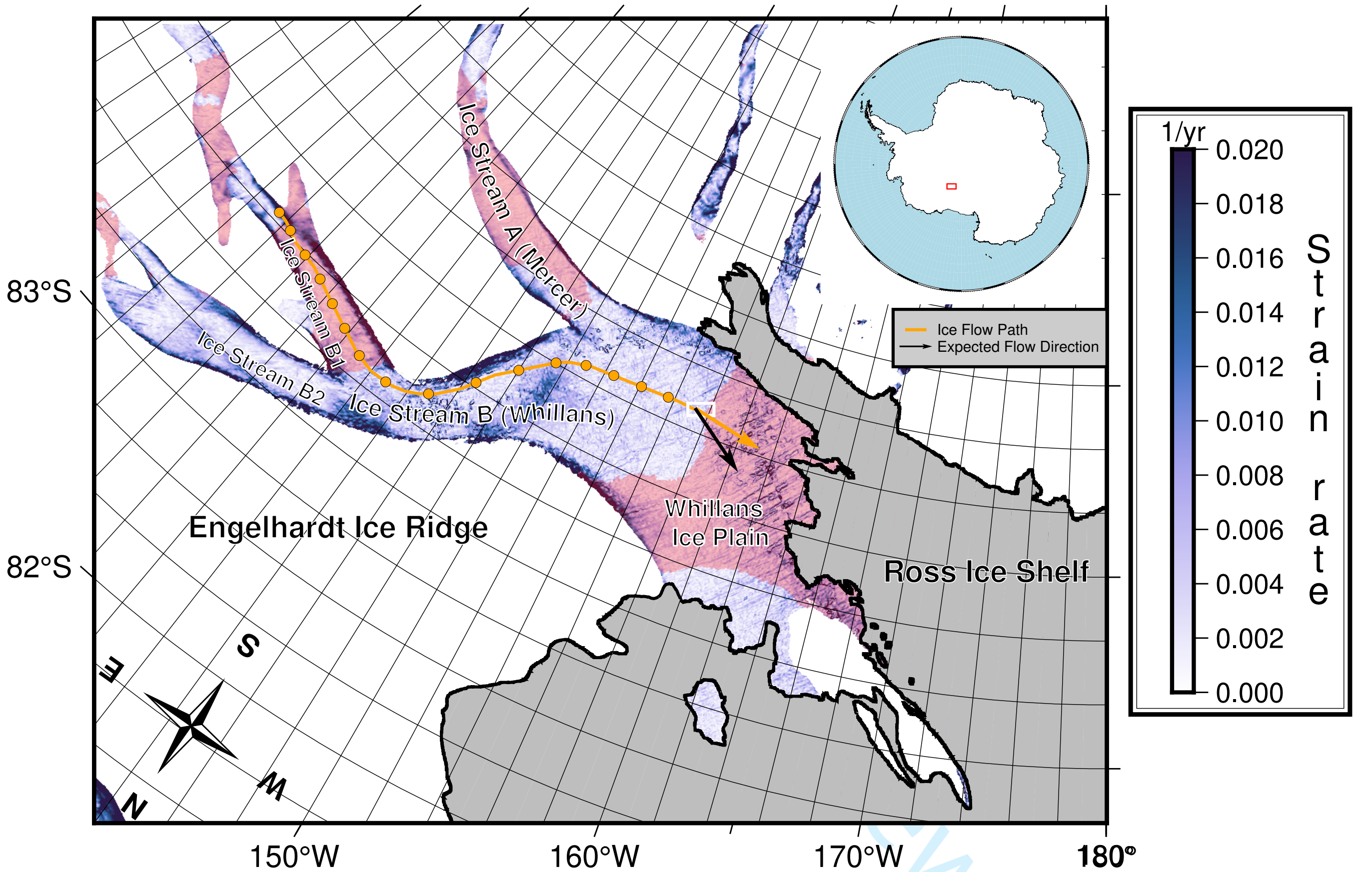

Fig. 4. A summary of the study findings. Regions with a flow direction between 281°N to 317°N, are shaded in red. The orange arrow shows the present-day flow direction, and the black arrow indicates the flow direction inferred from the fast S-wave polarisation direction. The background colour map is the strain rate calculated using Rignot and others (2017)'s velocity map (see supplementary information for calculation). Other features shown in this map are as in Figure 1a. The azimuth of the strain rate is shown in Figure S3.

perpendicular to φ. Considering the present-day westward flow direction only and fast S-wave polarisation uncertainties of 18°, these regions have a flow direction approximately in the west-northwest direction of 281°N to 317°N (see shaded red regions in Figure 4). The nearest region with such a flow direction along the ice flow path is in the southern tributary of WIS, indicating that the ice COF could not have been purely derived from the integrated strain alone over the past 450 years. Consequently, this implies that the flow direction of WIS changes on timescales shorter than ice COF re-equilibration. With this observation, we assume constant flow directions with time because ice-flow chronological studies do not suggest major changes in flow direction at WIS over the past 500 years (Catania and others, 2012). Furthermore, the validity of this assumption does not affect our conclusion of a palaeo-COF at WIS because present-day ice velocities are insufficient to explain the observed φ.

Larger strain rates can accelerate the rotation of lattices, and hence reduce the re-equilibration timescales of ice fabrics. From present-day velocities, the largest strain rates are located on the main trunk of WIS (see Figure 4). However, these strain rates could have been different in the past because of the dynamic nature of ice streams. Some studies show that ice streams in the Ross Sea sector have variable mass fluxes over the past centuries, in particular the Kamb Ice Stream (Bougamont and others, 2015; Catania and others, 2012; Conway and others, 2002). Further studies of ice anisotropy, in combination with more detailed past ice conditions and flow calculations, would further evidence any dynamic changes in ice anisotropy along WIS.

Given that the expected φ based on current ice flow is only just outside the uncertainty of our results, we cannot ignore the possibility of an ice COF derived from the present-day study site. However, there is only a negligible part of the study area that has a flow direction between 281°N and 317°N, with the remainder of this region located downstream of the study site (see red shaded regions in Figure 4). Hence, it is unlikely that enough time elapses for the ice COF to re-equilibrate with the present-day flow direction. We therefore suggest that the ice fabric is most likely derived from upstream palaeo-deformation.

Comparison to other COF studies at WIS

Our results of an oblique fast S-wave direction (φ) differ from both Picotti and others (2015)'s result of an azimuth-independent fabric and Jordan and others (2020)'s findings of φ parallel to flow. We attribute these differences to variations in sampling location and depth (see Figure 1a), with our study being the first to sample the effective anisotropy over the entire depth of WIS.

Jordan and others (2020) find a horizontal girdle fabric with φ parallel to flow, suggesting a longitudinally compressive instead of longitudinally extensional stress regime. However, their study was conducted near the grounding line (see Figure 1a), where stresses become longitudinally compressive due to stronger interactions between the ice and the bed topography (Bindschadler and others, 1987; Picotti and others, 2015). Other studies suggest that the stress regime at WIP is longitudinally compressive (Bindschadler and others, 1987). However, this likely does not apply to our study site. Firstly, the strain rates at WIS vary massively as little as 20 kilometres (see Figure 9 of Bindschadler and others, 1987). Secondly, the ice flow path inferred from present-day velocities indicates that the ice at our study site has travelled along the outer part of the curve at WIP, where we expect the stress regime to be longitudinally extensional (see Figure 4). Thirdly, longitudinal deviatoric stresses are also expected to be less prevalent farther away from the grounding line (Picotti and others, 2015).

Picotti and others (2015) observe an azimuth-independent fabric, and suggest that ice streams with low basal shear stress and highly-water-saturated sediments have COF profiles similar to ice divides due to the increasing influence of vertical compression relative to transverse compression. Their study site is located above Subglacial Lake Whillans, which is further inwards of the curve at WIP, where the stress regime is less longitudinally extensional (see Figure 1a). Additionally, their ice COF is likely to have undergone more equilibration caused by higher strain rates and lower flow velocities on the northern side of WIS (see Figure 4; Bindschadler and others, 1987). Given this variance in ice COF in WIS, future studies of ice deformation and anisotropy can furthermore reveal the spatial and temporal variability of ice COF at WIS.

Comparison to other ice streams

Shear-wave splitting studies from another Antarctic ice stream, Rutford Ice Stream (RIS), find that the COF at RIS is approximately perpendicular (~85º) to ice flow (Harland and others, 2013; Smith and others, 2017). Unlike the deviatoric nature of WIS stream flow, the flow direction at RIS is approximately linear over COF re-equilibration timescales. As such, it is not possible to discriminate to what extent the COF at RIS represents the current deformation or a preserved upstream deformation state. Kufner and others (2023) suggest that the RIS COF signal is dominated by the latter.

The strength of anisotropy at RIS is 3-5%, while that at WIS is 1.5%. This difference can be attributed to the driving stress, with the driving stess at RIS (40 kPa; Doake and others, 2001) at least twice that at WIS (<20 kPa; Bentley, 1987). The two ice streams have similar flowing speeds, with RIS moving at an average velocity of 377 m/a and WIS flowing at 370 m/a (Morlighem, 2022; Smith and others, 2017). Hence, the difference in driving stress is accommodated by the difference in basal friction. This can be explained by the relatively larger normal stress at RIS of 10 – 500 kPa, compared to that at WIS of 20 – 30 kPa (Hudson and others, 2023b; Lipovsky and Dunham, 2016). Lower friction at WIS results in less internal deformation of the ice column, leading to lower strengths of anisotropy.

A recent seismic anisotropy study at RIS by Kufner and others (2023) suggested that multi-layer anisotropy can be present in ice streams, where the deepest third of the ice stream is thought to comprise an azimuthally isotropic cluster fabric caused by basal-shearing-induced dynamic recrystallisation (Azuma, 1994). However, the apparent absence of double arrival times combined with the minimal basal shear stress at WIS (Bindschadler and others, 1987; Blankenship and others, 1986) suggest that any multi-layer anisotropic effects at WIS are negligible.

Implications of an oblique ice fabric on ice flow

Ice with a COF with the c-axis of a girdle fabric oriented perpendicular to flow can flow up to ten times faster than isotropic ice, because the viscosity of ice is sixty times lower parallel to the a-axis (the plane of weakest viscosity in the anisotropic crystal structure) than the c-axis (Harland and others, 2013). However, our results at WIS show a c-axis orientation that is not perpendicular, but oblique to ice flow. This implies that WIS is not deforming internally at its fastest possible rate, slowed by the misalignment of the a-axis with flow direction. This misalignment likely also contributes to the observation of little to no internal deformation of Whillans Ice Plain (Truffer and Echelmeyer, 2003).

Our observations suggest that palaeo ice COF can somewhat control present-day ice flow. If the shape of an ice stream deviates on length scales less than the distance ice travels within the COF re-equilibration time, then the COF may not be aligned with ice flow, limiting the rate of deformation of the ice column with respect to ice flow direction. If an ice stream flows linearly for a duration greater than the re-equilibration time, then the COF should re-equilibrate with the bulk stress, such that the a-axis direction will rotate parallel to the ice flow direction and increase the rate of deformation downstream. The degree of re-equilibration of an ice COF with the surrounding stresses is not only dependent on ice stream shape, but also on flow speed. Slower-flowing ice will have more time to re-equilibrate with the surrounding stress-field. The long-term slowdown at WIS can therefore provide more time for its ice COF re-equilibration, which in turn reduces the misalignment of the a-axis with flow direction and allows for faster flow. This counteraction to the slowdown has consequences on future predictions of ice flow at WIS.

Most icesheet-scale ice dynamics models assume either that ice is isotropic, or parameterise anisotropy effects via an enhancement factor to account for ice weakening due to COF orientation relative to ice flow. However, recent studies such as Smith and others (2017) and Kufner and others (2023), suggest that enhancement factors should no longer be used to parameterise ice viscosity in fast deforming regions such as ice streams. Our findings at WIS further support the importance of characterising directionally-dependent ice viscosity in ice flow models, and emphasise that understanding ice COF in both space and time is important for producing more realistic deformation in ice dynamics models.

CONCLUSION

This study provides shear-wave splitting (SWS) observations from basal icequakes at Whillans Ice Stream (WIS). From these observations, we infer the ice crystal orientation fabric (COF) anisotropy over the entire ice column. The observations provide insight into past and present deformation at WIS. The results from 80 discrete icequakes SWS observations show that WIS has an average fast S-wave direction (φ) of 29.3º, which is oblique to the expected direction of ∼10º based on ice flow direction at the study site of around 280º. We suggest that the ice COF records an integrated strain history along its flow path for at least the past 450 years to have preserved deformation in the direction of φ. The non-perpendicularity of φ to ice flow implies that the shape of an ice stream can affect its flow, such that spatially deviatoric ice streams including WIS are not flowing at their fastest potential. Given the long-term slowdown of WIS, the a-axis will have more time to re-equilibrate with the surrounding stress-field, which can counteract the long-term slowdown. Our results have implications for ice sheet models, suggesting that historic ice flow can preserve ice fabric and hence directionally-dependent ice viscosity that might play an important role in such models.

SUPPLEMENTARY MATERIAL

The supplementary material for this article can be found in suppl_mat_WIS_anisotropy.pdf, as attached with the submission of this manuscript.

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