

Seeing directionally: radar polarimetry in ice

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Ice flow depends on properties within and beneath the ice that are *anisotropic*—properties that vary in different directions. For example, at the base of the ice, roughness in some directions can do more to prevent ice sliding than roughness in other directions, like how a properly oriented corrugated metal roof allows snow to slide off. Several forms of anisotropy also arise within the ice that enhance or restrict how it flows from land to ocean (**Error! Reference source not found.**).

Measuring these anisotropic properties is one key to better understanding how quickly the Greenland and Antarctic ice sheets will discharge ice to the ocean and contribute to sea-level rise. Advances in ice-penetrating radar technologies are revolutionizing our ability to observe directionally varying properties of the ice sheets, as summarized in a new article in *Reviews of Geophysics* (Hills et al., 2025). These new measurements are paving the way for projections of ice-sheet mass loss to include processes that have previously been neglected.

Crystal fabric: Memory and modulator of ice flow

Fabric, the orientation of the individual grains composing glacier ice, is the best-studied and arguably most important directionally varying property of ice. Fabric results from ice flow but also influences it. As ice deforms, for example by compacting vertically with depth in the interior of the ice sheets or stretching

horizontally as ice accelerates to the coast, the millimeter-scale grains composing ice are reoriented. Fabric thus contains a memory of past flow. Ice grains are about three orders of magnitude easier to shear in some directions than others, like a deck of cards sliding easily in some directions but resisting deformation in others. Alignment of these individual grains into preferred directions, or “strong fabrics,” then causes ice to flow differently at the large scale. While the potential importance of fabric for large-scale ice flow has long been recognized, there has not been sufficient data on fabric in the ice sheets to identify its implications for flow. Until recently, fabric could only be measured directly in ice cores,

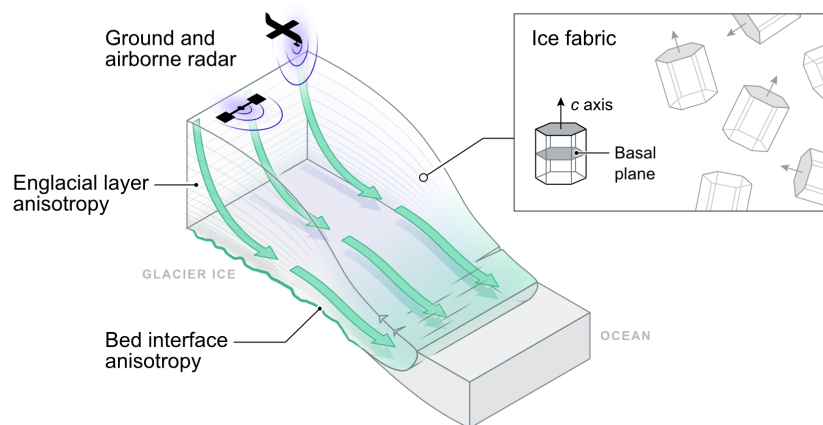


Figure 1: Anisotropy in glaciers and ice sheets. Besides intrinsic anisotropy resulting from fabric, other properties of the ice or the ice bed interface can be anisotropic. Many of these forms of

providing highly detailed information about how fabric develops at a handful of points in each ice sheet, but without preserving information about horizontal orientation that influences its effect on flow. This has changed over the last 20 years with the proliferation of radar polarimetry, which offers an alternative means for inferring fabric. These new methods are being used to observe fabric at the ice-sheet scale, leading to new understanding of its importance for ice-sheet flow.

Radar offers a new lens

An ice-penetrating radar transmits electromagnetic energy which travels through ice, reflecting off interfaces within and beneath the ice. The reflected energy is then measured as it returns to the radar. Early ice-penetrating radars were valuable tools for determining the thickness of the ice, but could only provide qualitative information on the internal properties of the ice. In recent decades, two key advances have greatly expanded applications of ice-penetrating radar for directionally varying properties. First, radars have gained the ability to measure the phase of the returned energy in addition to its amplitude. These *phase sensitive* radars permit very precise measurements of changes in range (vertical distance) and open the door to measuring vertical strain and basal melt with radar. Second, modern radar antennas typically transmit energy in a single, known polarization. Some *polarimetric* radar systems make it simple to vary this direction of transmission, sometimes even doing so thousands of times per second, and can also measure the reflected energy in different directions. Polarimetric, phase-sensitive radars now allow us to measure ice properties in different directions, at multiple depths, with enough precision to identify how key physical properties vary in the ice.

Polarimetric radar has been widely applied in recent years largely due to the advent of low-cost, ground-deployable systems that are phase coherent. For example, the popular Autonomous phase-sensitive Radio Echo Sounder (ApRES) from the British Antarctic Survey (BAS), can measure phase with ~1.5 mm precision. Its range resolution is ~42 cm, so the phase sensitivity gives the additional precision needed to identify anisotropic effects. Over the past decade, the use of ApRES to provide not only accurate but also high-resolution measurements of crystal fabric anisotropy was applied and validated at multiple ice core drilling sites across the Greenland and Antarctic ice sheets. A high match between these radar-derived and ice core measurements has built confidence in these techniques, enabling glaciologists to understand how the fabric of ice sheets becomes increasingly anisotropic as it moves away from these sites towards areas of faster flow.

OR

Over the past decade, the application of polarimetric ApRES has revealed insights into the flow history of glaciers and ice sheets over the past thousands to tens of thousands of years, capturing evidence of both gradual and abrupt changes in the directions of ice flow

corresponding to key events and trends in past climate. Because the overall fabric of ice sheets preserves the accumulated flow history of its recent past, these measurements offer a crucial window into its past ice dynamics, enabling improved understanding of how ice sheets have responded to previous cycles of advance and retreat.

The next generation of polarimetric radars are going beyond stationary soundings at one point at a time, now with full polarimetry capabilities on moving ground-based or even airborne platforms for radar profiling, and soon mapping directional ice properties at the scale of the entire ice sheet.

How radar waves reveal ice-crystal direction

Just as ice flow properties depend on grain alignment, the electrical properties of ice are anisotropic as well. The speed of radar waves through ice is approximately one percent faster if the wave is polarized across the crystal axis as opposed to in line with it, a difference referred to as *intrinsic anisotropy*. Though small compared to the flow properties which vary by orders of magnitude, this is enough to cause changes to radar returns. Typical radar survey geometries are most sensitive to the horizontal anisotropy, so they are best suited to identify how fabric varies in different horizontal orientations.

Waves with different polarizations relative to the preferred horizontal crystal orientation propagate at slightly different speeds (**Error! Reference source not found.**). When fabric is strong and the vertical resolution of the radar is high, reflections can be shifted in time between polarizations, an effect measurable even without phase-sensitive systems. When the shift is smaller, phase-sensitivity is required. Many ice-penetrating radars have wavelengths around 0.1 – 10 meters, and they propagate through 100 - 4000 of meters of ice. Because the propagation distance is so much further than a wavelength, even small speed differences between polarizations accumulate into measurable phase shifts, which can be related to the strength and orientation of horizontal anisotropy. Fabric also influences reflection strength, because small fabric changes can reflect more energy in some orientations. This amplitude anisotropy offers an independent way to identify fabric orientation and its depth variation without the cumulative effects through the full ice column which control travel-time and phase differences.

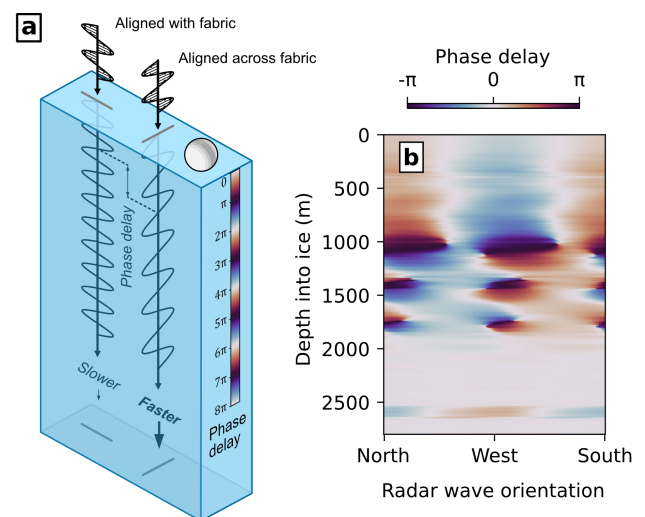


Figure 2: a) Polarized wave propagation through anisotropic ice. b) Example radar polarimetry data from Hercules Dome, Antarctica.

Insights from fabric

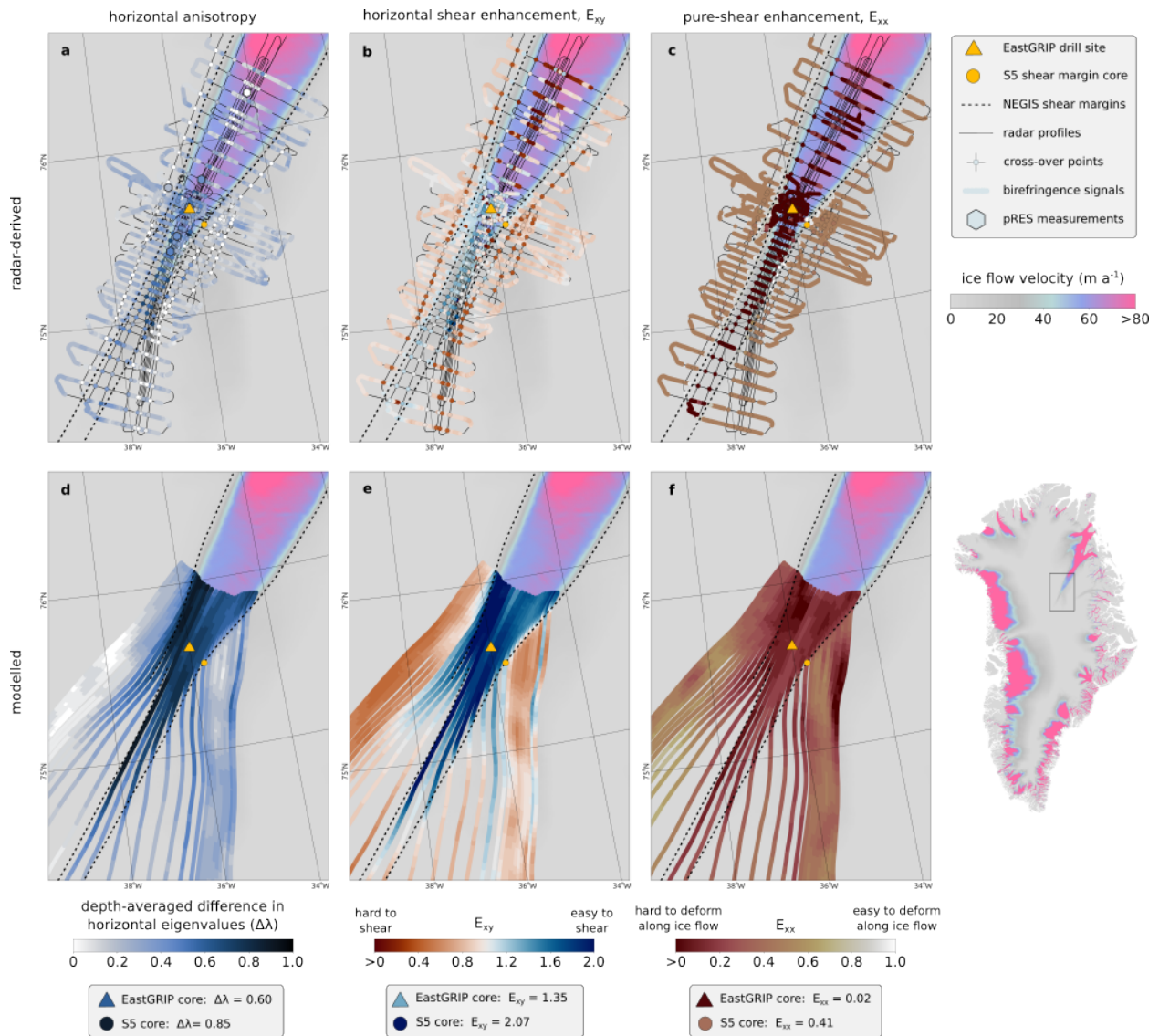
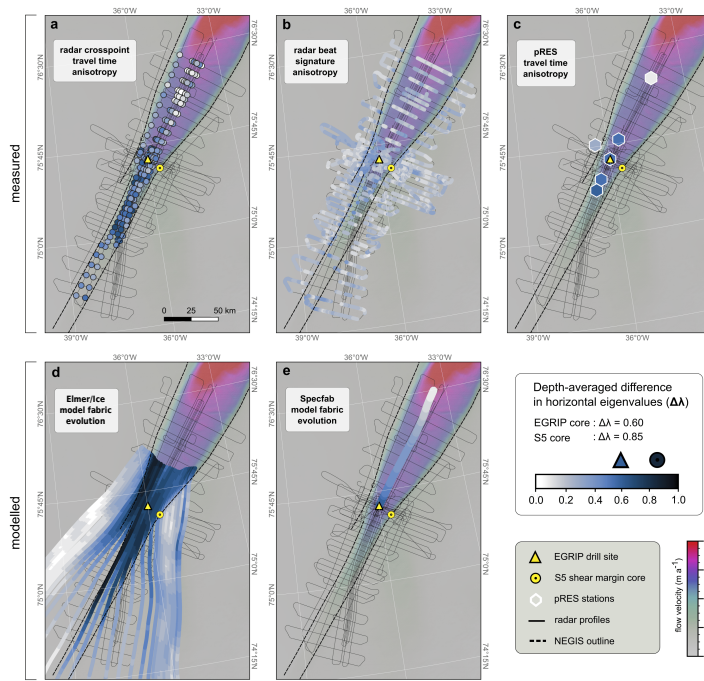


Figure 1: Fabric and its effect on flow in Northeast Greenland.

A growing number of studies near ice-core sites have bolstered confidence that fabric can be inferred from its effects on radar. With this validation, fabric is now being inferred from



radar in more dynamic areas, such as Thwaites Glacier, Rutford Ice Stream, and the Northeast Greenland Ice Stream (NEGIS). In general, strong fabrics have been observed in fast-flowing areas, suggesting that fabric is likely to be an important control on viscosity in these areas. The implications for ice flow are just beginning to be explored. For example, at Rutford Ice Stream in Antarctica, fabric causes sharp changes in viscosity in different directions with depth, a complexity that no ice-flow models consider. In Northeast Greenland, radar in combination with modeling suggests that fabric eases horizontal shear, allowing the ice to flow more quickly inside NEGIS, while fabric hardens the ice for along-flow stretching with potential consequences for how quickly coastal changes propagate inland (Figure 1).

Recent progress in modeling fabric also suggests that it softens ice by up to a factor of 10 in dynamic areas, particularly ice-stream shear margins. This agreement between radar observations and process-scale modeling suggests that fabric is an important control on the large-scale flow of the ice sheets, though it is not widely considered by ice-sheet scale models which are used for sea-level projections.

Beyond fabric

To date, most polarimetric radar studies have focused on fabric, but other ice properties can vary directionally, too. For instance, the air spaces within the ice sheet have dramatically different properties than the ice itself and can be brought into alignment by deformation of the ice. That could be either large-scale open crevasses, sub-millimeter-scale bubbles, or even continuous open space in the snow and firn above where bubbles have been isolated. Crevasses are generally too large to use the polarimetric methods discussed here, since they redirect the radar wave, but bubbles and airspace in the firn have been shown to be directional in terms of radar-wave propagation. Likewise, ice at the melting point can contain liquid water along the boundaries between grains, and if that water is aligned in one direction, it may affect electrical properties. Each of these properties has importance for ice flow, but the implications are yet to be explored.

The bottom boundary of the ice sheet can be rougher in one direction than another, with the roughness typically aligned with the ice flow or preferential melt orientation. Polarimetric radar can be used to measure these directional properties, especially for fine-scale directional differences in this bed roughness. New insights on bed properties are leading to discoveries in glacier geomorphology, ice-ocean interactions for the sub-ice-shelf basal boundary, and basal slip at the bed interface as it contributes to ice flow. Sub-shelf melt and the rate of basal slip are widely recognized as key controls on the future of the ice sheets.

Expanding horizons: Ice, planets, and particles

Radar polarimetry has already transformed our understanding of ice fabric, revealing how crystal alignment modulates the flow of Earth's ice sheets and filling critical gaps between the handful of ice-core sites where fabric had previously been measured directly. As these

geophysical techniques mature, their applications are expanding. Airborne radar platforms now collect continuous polarimetric data along flight lines, and systems mounted on autonomous rovers can survey remote areas without field teams. These advances will soon enable fabric mapping across entire ice sheet drainage basins, providing the spatial coverage needed to incorporate fabric into ice-flow models. Such models are essential for projecting how quickly ice sheets will contribute to sea-level rise, and fabric's potential to soften ice in dynamic regions highlight the limitations in projecting future ice loss.

While those applications will continue to drive forward the science of terrestrial glaciology, there are additional applications in tangential fields which could be just as impactful. For example, the techniques being developed to infer fabric with radars on Earth might lay the groundwork for similar application to Mars or icy Jovian moons like Europa, both of which have (or will have) orbital radar sounders which can see through icy masses on those planetary bodies. If Europa's ice shell flows—a key question for understanding the subsurface ocean that might harbor life—polarimetric measurements could reveal that motion through crystal alignment, just as they do for Earth's ice sheets. Additionally, astrophysical laboratories placed within the ice sheets on Earth sense neutrinos (from high-energy supernovae in our galaxy) for which the signals are also sensitive to the directionality of the ice, perhaps to be used synergistically with glaciological radar experiments to constrain ice fabric in more dimensions. As polarimetric radar systems become routine tools for glaciologists, and as similar instruments begin operating on spacecraft exploring icy worlds, a technique once limited to a few ice-core sites is poised to transform our understanding of ice across the solar system.

References

Hills, B. H., Young, T. J., Lilien, D. A., Babcock, E., Bienert, N., Blankenship, D., et al. (2025). Radar Polarimetry in Glaciology: Theory, Measurement Techniques, and Scientific Applications for Investigating the Anisotropy of Ice Masses. *Reviews of Geophysics*, 63(4), e2024RG000842. <https://doi.org/10.1029/2024RG000842>

Too little space—add in if possible?

Other signatures of anisotropy can also appear in single-polarized radar data. These methods are particularly promising since single-polarization radars have been flown and driven extensively over the ice sheets for decades. *Beat patterns* occur when the radar wave splits into components that travel with a phase shift through the anisotropic ice; when these components recombine at the receiver, they interfere with each other, producing a characteristic oscillating pattern in the reflected signal depending on fabric. Double reflections arise from birefringence, where a single reflector produces two closely

spaced echoes because the wave is refracted along two different polarization axes, like the double refraction seen in calcite crystals. Unlike the travel-time shift, these effects are strongest when the radar polarization is not aligned with the fabric's principal axes, providing complementary information on the orientation and strength of ice crystal anisotropy.