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Using Borehole Sonic Logging to Infer Ice Microstructure and Climate History

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The physical properties of ice from glacial time periods appear to differ from those from interglacial time periods. Glacial ice typically has smaller crystals, higher impurity content, and stronger fabric (preferred orientation of crystal c-axes). Because ice deformation is sensitive to the orientation of crystals, the fabric affects patterns of ice flow, which in turn affects estimates of annual-layer thinning rates and the depth-age scale for ice-core records. Furthermore, a positive feedback exists between development of crystal fabric and ice deformation such that under certain stress conditions, a climate-induced variation of fabric near the surface may be enhanced through time and depth in an ice sheet.

We use borehole sonic logging to measure both compressional-wave (p-wave) speed which we use to infer a continuous profile of the fabric (after corrections for temperature and porosity). The speed for p-waves propagating along the c-axes is higher than the speed for waves propagating across the c-axes. Near ice-sheet centers, where the ice typically develops a vertical single maximum fabric, the p-wave speed in the vertical direction (along the axis of the borehole) provides a measure of the strength of the fabric for a volume of ice 3m along the length of the borehole and approximately 1m radius deep into the ice.

We review and compare borehole sonic-logging data from boreholes in the Greenland and Antarctic ice sheets. The Antarctic profiles show a stronger gradient in fabric during major climate transitions than the Greenland borehole profiles. Both ice sheets, however, eventually reach similar fabric strength at depth. We find that the strength of fabric derived from p-wave speed matches thin-section data for single maxima fabrics and is highly correlated with oxygen isotope ratios, suggesting a direct link to climate history. The p-wave speed is high (strong fabric) during periods of extremely negative oxygen isotope ratios (glacial periods). Furthermore, the magnitude of the variability of the p-wave speed and its correlation with oxygen isotopes increases with depth; this provides evidence in support of the positive feedback mechanism between fabric development, deformation, and climate.