Old ice preservation explained by 3D ice flow model in the Allan Hills Blue Ice Area, Antarctica.

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Background

Allan Hills, Antarctica contains the oldest ice found on Earth to date (Shackleton et al., 2025). Antarctic ice cores contain bubbles of ancient atmosphere preserved from the time of snow deposition and firn compaction that can be sampled directly. The climate information recovered from these ice cores will extend the ice core climate record back into the early Pleistocene where glacial cycles were weaker in amplitude and more frequent. To contextualize climate records derived from ice core proxies, it is important to understand the current climate and how the ice might have been modified in the recent past. Blue ice areas (BIAs) have been the target for old ice drilling since the discovery of a collection of meteorites at the surface of BIAs (Whillans and Cassidy, 1983). **Figure 1** shows hypothesized ice flow at the Allan Hills to account for old ice and the collection of meteorites. Here, we use finite element modeling to better understand ice flow in 3D and to explain the preservation of ancient ice in Allan Hills (see **Figure 2**).

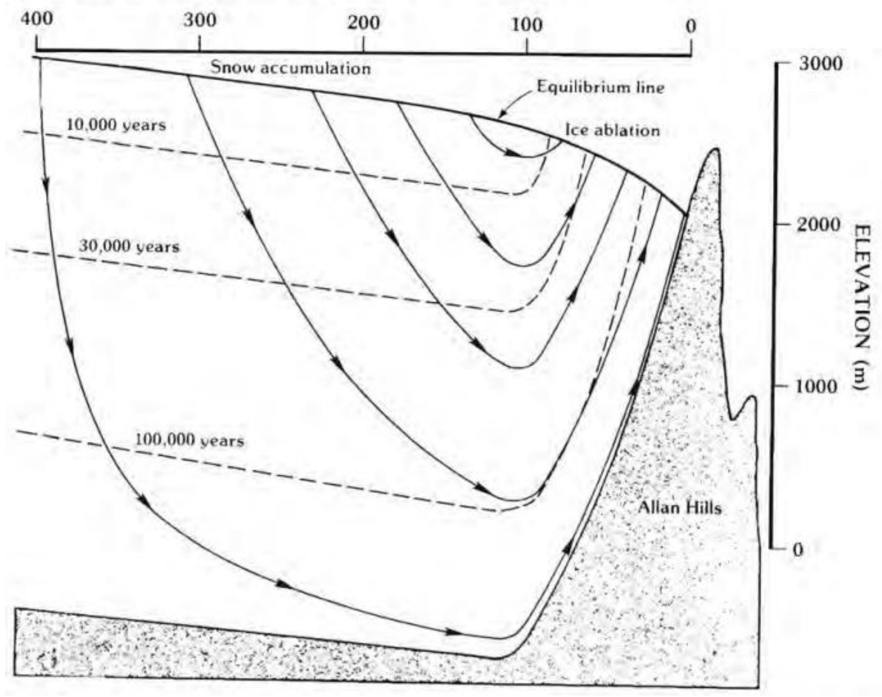

Figure 1 (Top). From Whillans and Cassidy, 1983. Modeled ice flow in a 2D flowline causing meteorite concentration and the exposure of old ice at the surface.

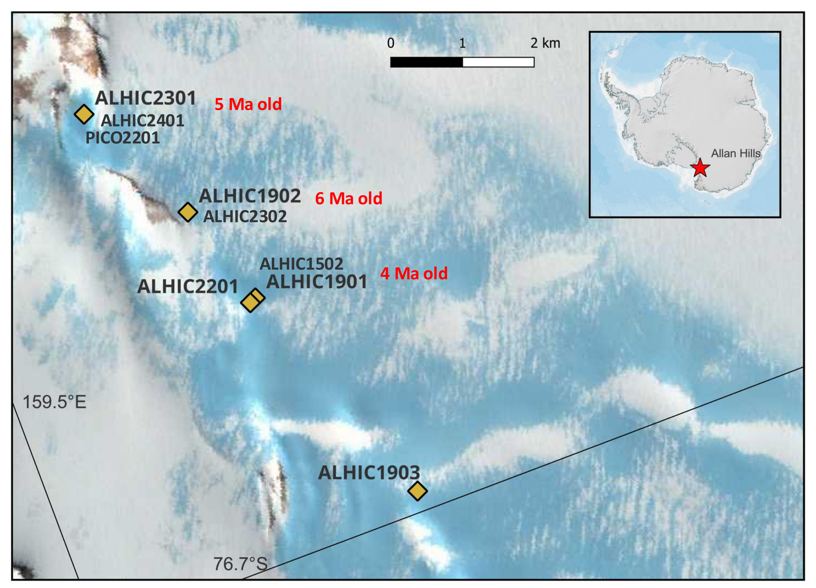

Figure 2 (Left). Map showing the location of drilled ice cores in the Allan Hills and ice core ages. Borehole naming convention follows as: location, year drilled, and number of that year.

Methods

Distributed Temperature Sensing (DTS) – a robust platform for high resolution temperature measurements (Fig. 3).

- Fiber optic cables have low thermal mass – the fiber optic cable is capable of equilibrating to ambient temperature within tens of minutes of deployment.
- One calibration for the fiber – unlike typical thermistor string measurements in boreholes where each thermistor needs to be calibrated individually, a DTS enabled fiber only needs a single calibration performed and the measurement error is well defined.
- High spatial and temporal resolution – DTS interrogators are capable of recording temperature to a precision of ~0.01 C and can measure a new temperature profile every 10 seconds when necessary. Measurements do not require constant supervision or manipulation of the fiber once deployed.

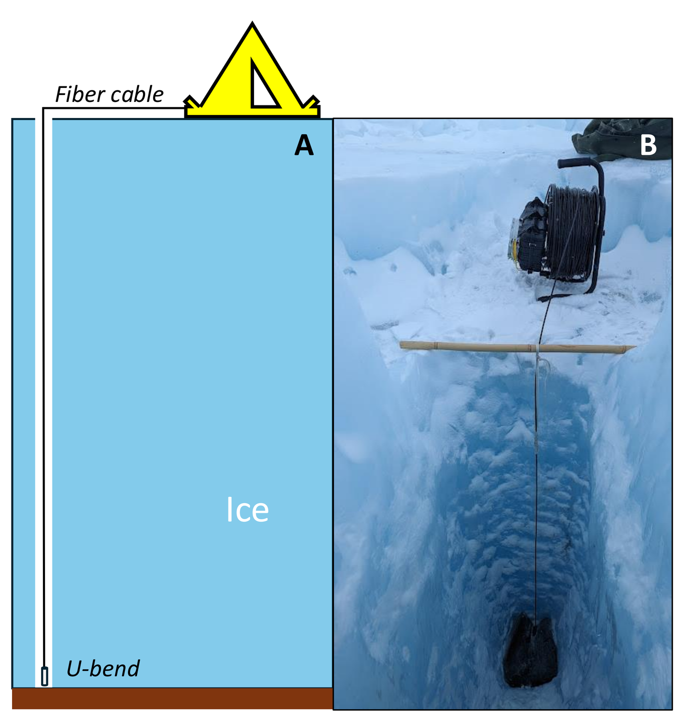

Figure 3 (Top). [A] Schematic of fiber optic cable deployed in a glacier borehole. **[B]** Image of fiber optic cable deployed in ALHIC2301 borehole Allan Hills, Antarctica.

We develop a 3D full Stokes thermo-mechanically coupled ice flow model that uses hi-res bed (Nesbitt et al., 2023) and surface digital elevation models as input.

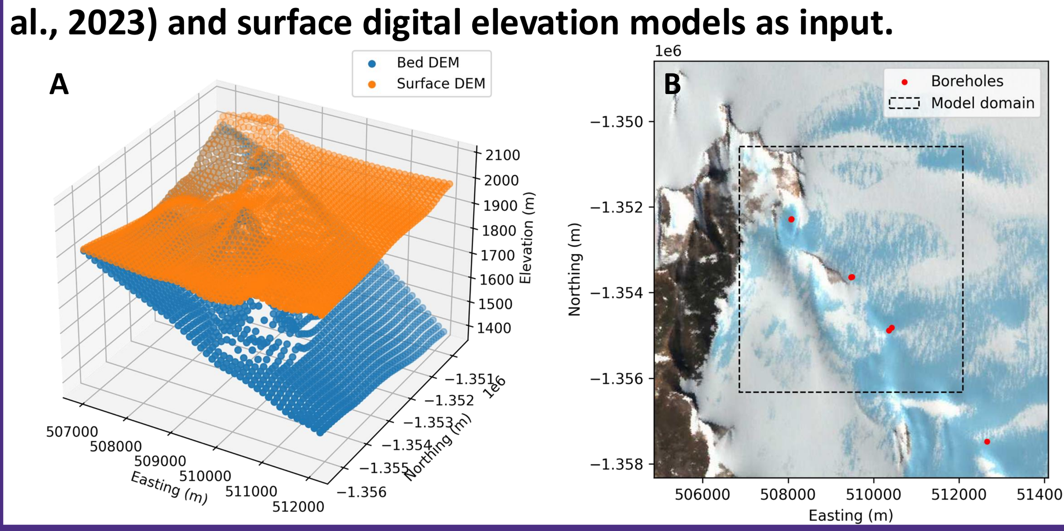

Figure 4 (Left). [A] Finite element nodes of the mesh surface (REMA) and mesh bed topography. **[B]** High resolution model domain. This model uses ice flow results of a larger coarse mesh on the boundary of the smaller domain mesh shown.

Results

Basal ice flow on the windward side of the ALHIC1902/2302 ice core site nunatak is slow or stagnant caused by the interaction between predominant ice flow and bed topography.

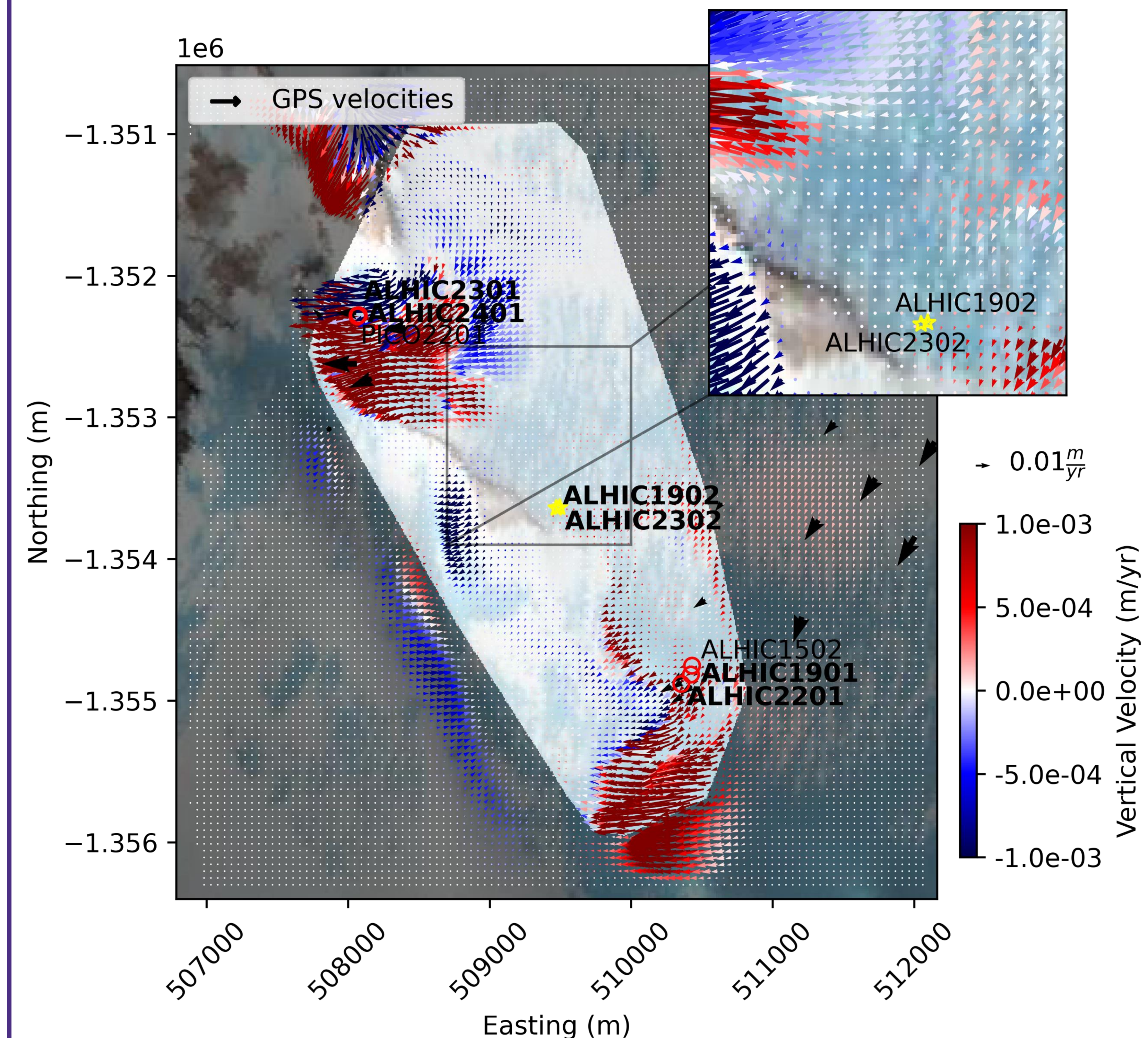

Figure 5 (Top). Modeled ice flow 10 meters above the bed. On the windward side (north-northeast) of the nunatak near the ALHIC1902/ALHIC2302 core site, the basal ice is nearly stagnant. Highlighted area indicates the region where we have high-resolution ground-penetrating radar data (Nesbitt et al., 2023). Shadow area uses BedMachine. The yellow stars indicate the ice cores with the oldest ice.

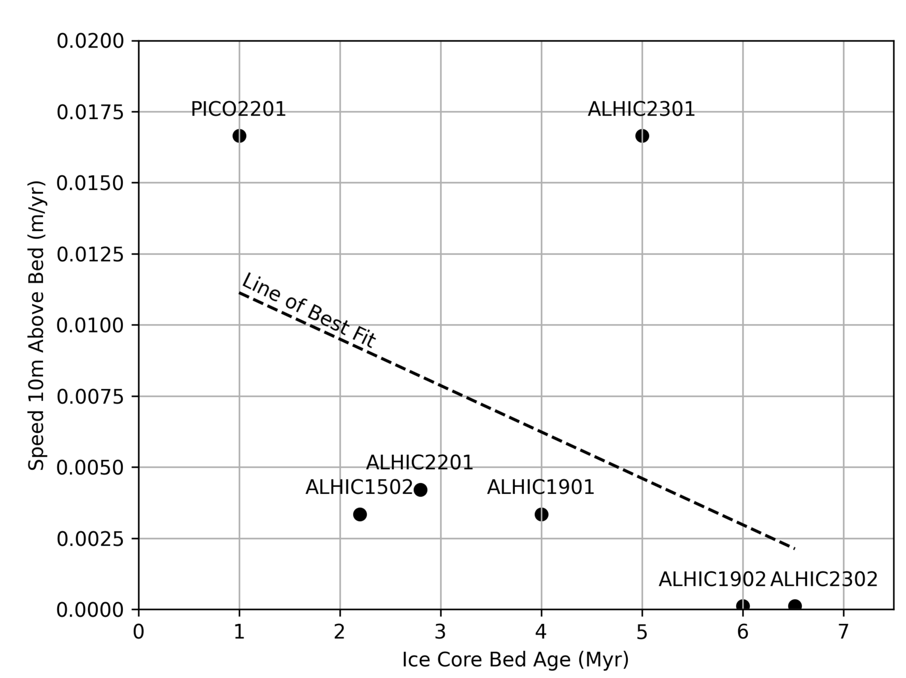

Figure 6 (Left). Modeled ice speed 10 m above bed and maximum ice core age at each core site.

Slower flowing basal ice is associated with older maximum ice core age (Fig. 6).

- PICO2201 was not drilled to bedrock and would likely plot near ALHIC2301.
- PICO2201 and ALHIC2301 are both drilled in the "Cul-de-sac". This area is a large surface depression relative to the other core sites and likely has a different geophysical and climatological characterization.

Acknowledgements

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Results

Borehole temperatures indicate a 2C warming in Allan Hills over the last 150 years.

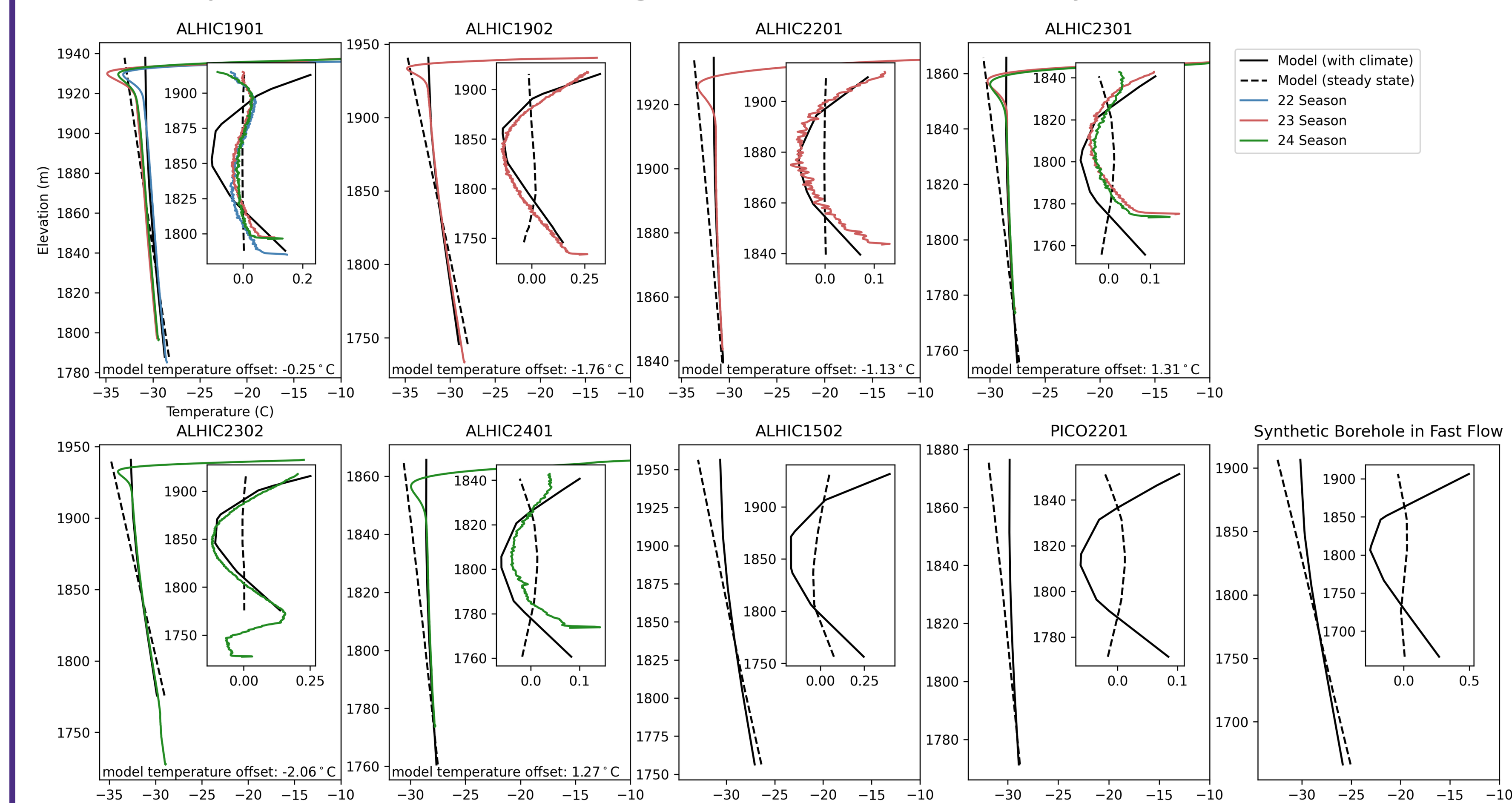
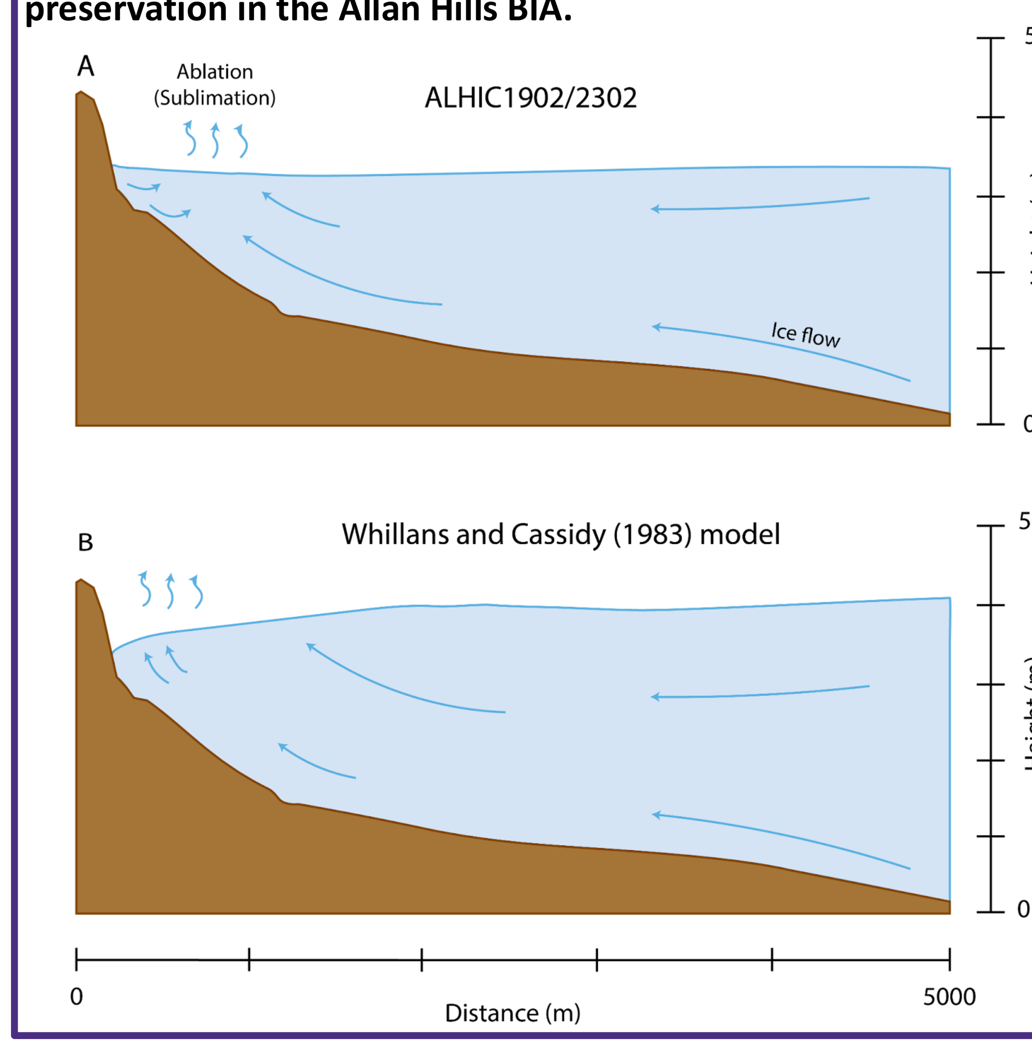


Figure 7 (Top). Modeled ice temperature profiles at each ice core site compared to borehole temperature measurements from DTS. Solid colored lines are DTS measurements during each field season. Solid black line is the modeled ice profile temperature given a linear increase of 2C at the surface over the last 150 years. Dashed black line shows the modeled ice profile temperature if the climate remained a constant temperature.

Proposed ice flow model indicates flow off the windward side of the nunatak is important for old ice preservation in the Allan Hills BIA.



- We add a new description of ice flow in Antarctic BIAs that describes the preservation of old ice.
- Additionally, we can use this model to test different surface elevation scenarios.

Figure 8 (Left). Schematic of new model of ice flow in Antarctic BIAs interacting with steep basal topography. In the ALHIC1902/ALHIC2302 model, some ice remains on the nunatak causing it to flow downwards against the predominant ice sheet flow direction. This causes younger ice to divert around the nunatak and preserves an area of stagnated old ice near the bed.

Conclusions

We present the first comprehensive ice flow in 3D for an Antarctic BIA where old ice has been recovered and provide a mechanism for the preservation of old ice.

- Old ice is preserved in areas of slow basal ice flow.
- Ice is diverted around nunataks and steep basal rises. Ice flowing off nunatak converges with predominant ice flow and leads to an area of stagnant ice flow.
- This study provides a framework to test glacier geometries possible during the last glacial .

A linear warming trend of 2C over the last 150 explains observed ice temperature profiles.

- A location dependent temperature offset applied to improve fit might be indicative of local meteorological variability.