Measurement and interpretation of bubble number-density evolution through the upper 1200 meters of the SPC14 South Pole Ice Core

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Abstract

Using samples from the South Pole Ice Core (SPC14), we present new bubble number-density (BND) measurements and a modeled temperature history reconstruction for the South Pole site back through ~18.5 ka. Additionally, we show that 3D micro-CT sample imagery can accurately quantify BND, enabling more rapid and efficient future analyses. Using sampling and imaging techniques previously established for analyses of the WAIS Divide ice core (Spencer et al., 2006; Fegyveresi et al., 2016), we measured BND as well as other bubble characteristics from just below pore close-off depth starting at ~160 m, down to ~1200 m, at 20-meter intervals (53 total samples), with typical values ranging between 800 and 900 bubbles cm^{-3} over this interval. These values are higher than any previously recorded for ice-core BND, indicative of both colder average temperatures, and higher average accumulation rates at South Pole. Below ~1100 m, we noted significant bubble loss owing to the onset of clathrate-hydrate formation. Using micro-CT technology, we also tested the use of 3D imagery to accurately measure and evaluate BND as a supplement and future alternative to painstaking thin-section measurements. We imaged a secondary set of ice-core samples at 100-meter intervals starting at 200 m, and across the sample total depth range. Once corrected for cut- and micro-bubbles, our results show comparable values and thus similar trends to the thin-section data. For our temperature model, we determined an accumulation record using both measured annual layer thicknesses as well as estimated $d^{15}N$-derived firn-column thicknesses estimates. Our temperature reconstruction was calculated using the model developed by Spencer et al. (2006), and using a South Pole site-specific bubble-to-grain ratio (G) of 1.6. the reconstruction reveals a warming across the glacial-interglacial transition of ~7°C, with a relatively stable trend through the Holocene (< 0.4°C warming). These results are in close agreement with those reported by other independent paleothermometers (i.e. isotope- and firn-derived reconstructions). Results of our temperature reconstruction also reveal that using 3D micro-CT imagery in place of traditional thin-section techniques produces comparable results, but with even greater accuracy, and lower measures of uncertainty.

Measurement and interpretation of bubble number-density evolution through the upper 1200 meters of the South Pole Ice Core (SPICECore)

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Abstract

Using samples from the South Pole Ice Core (SPC14), we present results of bubble number-density (BND) analyses and a temperature history reconstruction for the South Pole site back through ~18ka. The reconstruction reveals a warming across the glacial-interglacial transition of ~7.5°C. New ice-core samples were cut and prepared during the summers of 2016-2018 at the National Science Foundation Ice Core Facility. Using imaging techniques previously established for analyses of the WAIS Divide ice core (Spencer and others, 2006; Fegyveresi and others, 2016), as well as new techniques developed using micro-CT technology, we measured bubble number-density as well as other bubble characteristics from just below the pore close-of depth at ~160 m, down to ~1200 m, at 20-meter intervals (53 total samples). The most recent dating of the SPC14 core based on volcanic ECM sulfate matching to the WAIS Divide core, together with annually-resolved chemistry and visual stratigraphy (Winski et al., 2019), reveals an age at 1200 meters of approximately 26,000 BP (yrs bf 1950). Our results are in close agreement with those reported by other independent paleothermometers (i.e. isotope- and firn-derived reconstructions). Results of our temperature reconstruction also reveal that using 3D micro-CT imagery in place of traditional thin-section techniques produces comparable results, but with even greater accuracy, and lower measures of uncertainty. Below ~1100 m, we noted significant bubble loss owing to the onset of clathrate-hydrate formation.

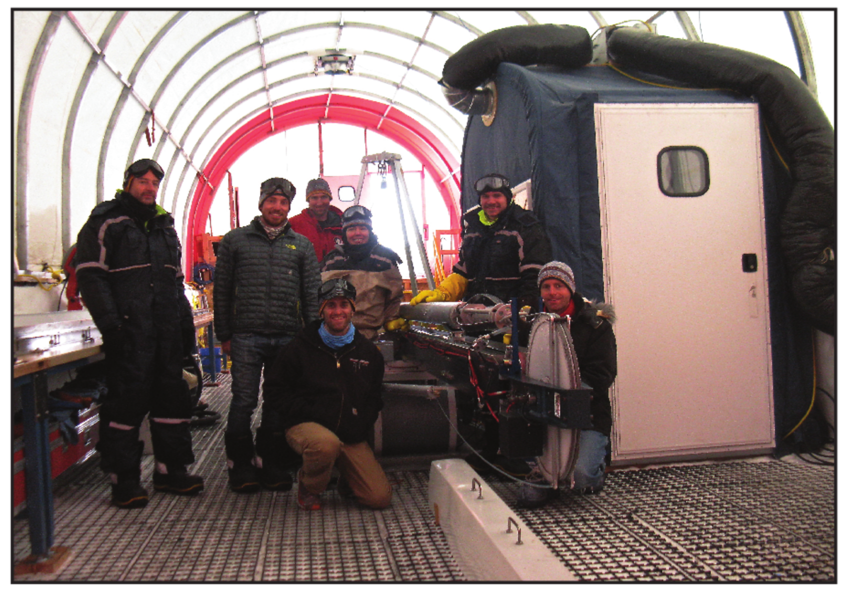
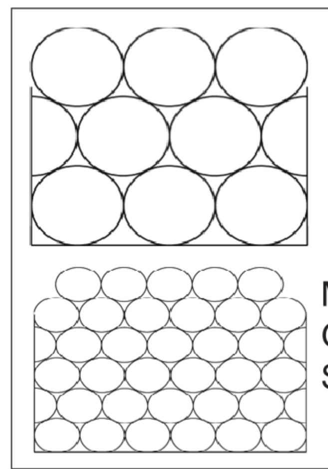


Fig 1a: SPICECore ice drilling and processing team inside the ice-core arch facility at South Pole.

The SPICEcore site has a total ice thickness of ~ 2700 m, and experiences an average modern accumulation rate of ~7.4 cm^{-yr} (w.e.).

Fig 1b: Site temperature and accumulation rate control grain size in glacier ice, which in turn controls bubble number-density.

Temp	↑	Grain Size	↑	Bubble Size	↑	Bubble Num-ber-Density	↓
Accum (Time)	↑	Grain Size	↓	Bubble Size	↓	Bubble Num-ber-Density	↑



Few Large Grains = Few Large Bubbles

Many Small Grains = Many Small Bubbles

Methods and Preparation

To obtain both the ice-core bubble thick-sections, and micro-CT sections, samples were first cut from the appropriate core depth sections at the National Science Foundation Ice Core Facility in Denver, Colorado. We used a band saw to first cut bubble thick-sections ~10 cm long by ~6 cm wide by 5 mm thick, at 20-meter depth intervals ranging from 160-1200 m depth in the core. One face of this sample was smoothed with a sledge-type microtome and then affixed to a glass slide using a combination of silicone oil and tinkered water-ice. Following Fegyveresi et al. (2016), the sample was microtomed to ~1.5 mm overall thickness and imaged to produce a high-resolution bubble thick-section. Micro-CT samples were cut at equivalent 20-meter intervals, and measured 2.5 cm square, by 8 cm long. Micro-CT measurements were made on site at the Cold Regions Research and Engineering Lab.

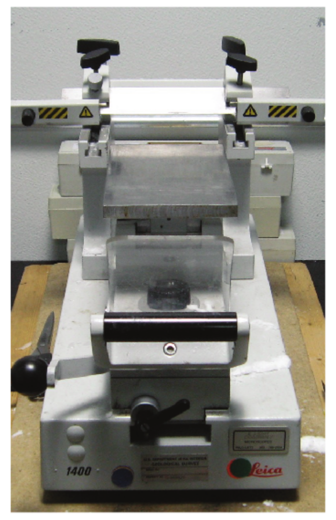


Fig 2a: While typically used to cut biological specimens into transparent thin sections, a medical microtome was used to shave down the ice core sample for image analyses.

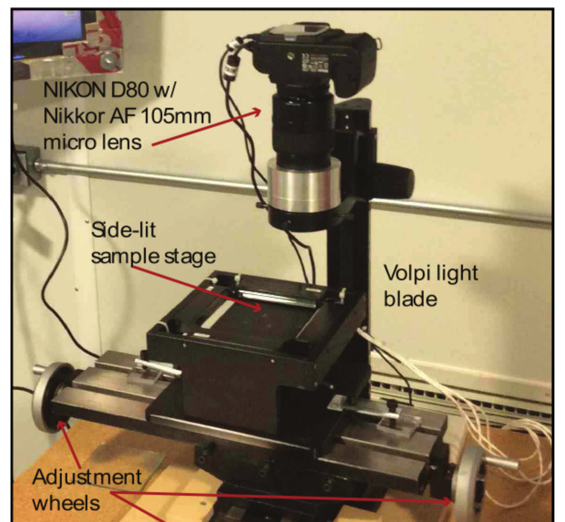


Fig 2b: Nikon D-80 bubble stage used for sample photography. The stage assembly is operated automatically via a direct computer interface.

Steps taken to prepare an ice core bubble thick section:

1. Sample is cut from the end of a meter long core and mounted on a glass plate using a bead of water.
2. This section is thinned down to ~1.5 mm using a microtome.
3. The thinned bubble section is then illuminated and photographed.

Steps taken to prepare an ice core bubble micro-CT section:

1. Sample "stick" is cut from the end of a meter long core, measuring 2.5 x 2.5 x 8 cm.
2. This section is cut in half in to create replicates for each sampling depth.
3. Samples are placed into small plastic housing and scanned in the micro-CT analyzer.

Fig 2c: We used a Bruker SkyScan 1173 for all micro-computed tomography. We set the X-ray emitter to operate at 40kV and 200 μA. Samples were rotated 180° in 0.3° steps, with 4-frame averaged attenuation images captured at each step using a camera exposure of 310 – 360 msec. We used a 2x2 binning protocol to create x-ray radiographs of 1120x1120 pixels. Reconstruction and analyses of the radiographs were done using Bruker NRECON and CTAn software. Scanner shown with mounted sample.

Data

Reducing bubble thick-section photographs into usable data involved several time-consuming steps, as shown in the following figures.

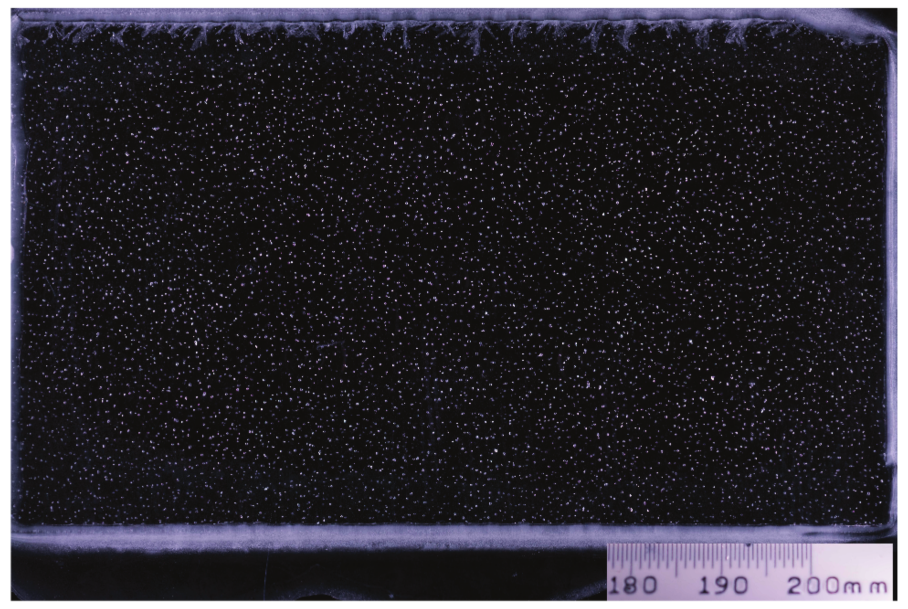


Fig 3: Fig 3: An unedited image, representing the 480 m vertically oriented bubble section that was photographed at NSF-ICF alongside a small ruler for scaling. By looking over the entire image for an area most free of smudges, cracks, or other marks, a smaller standard size 100 mm x 100 m square was selected for clean-up.

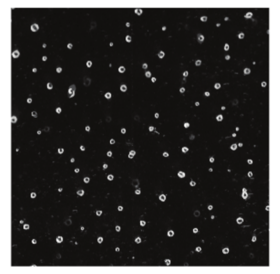


Fig 4a: The first step was to select the smaller 100 mm x 100 mm section.

Fig 4b: The second step involved editing shaded areas as well as removing non-bubbles.

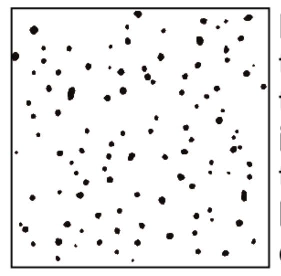


Fig 4c: The third step was to convert the image to binary to highlight bubbles and edit bad pixels.

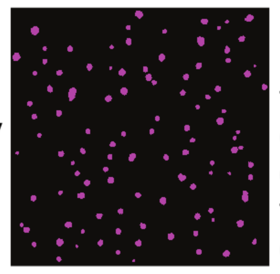


Fig 4d: The last step was to overlay a color binary onto original to check for errors.

Using micro-CT technology at the Cold Regions Research Lab, we measured a secondary set of 22 ice-core samples (11 in duplicate) at 100-meter intervals starting at 200 m, and across the sample total depth range. These samples were then corrected for cut- and micro-bubbles to determine final bubble counts.

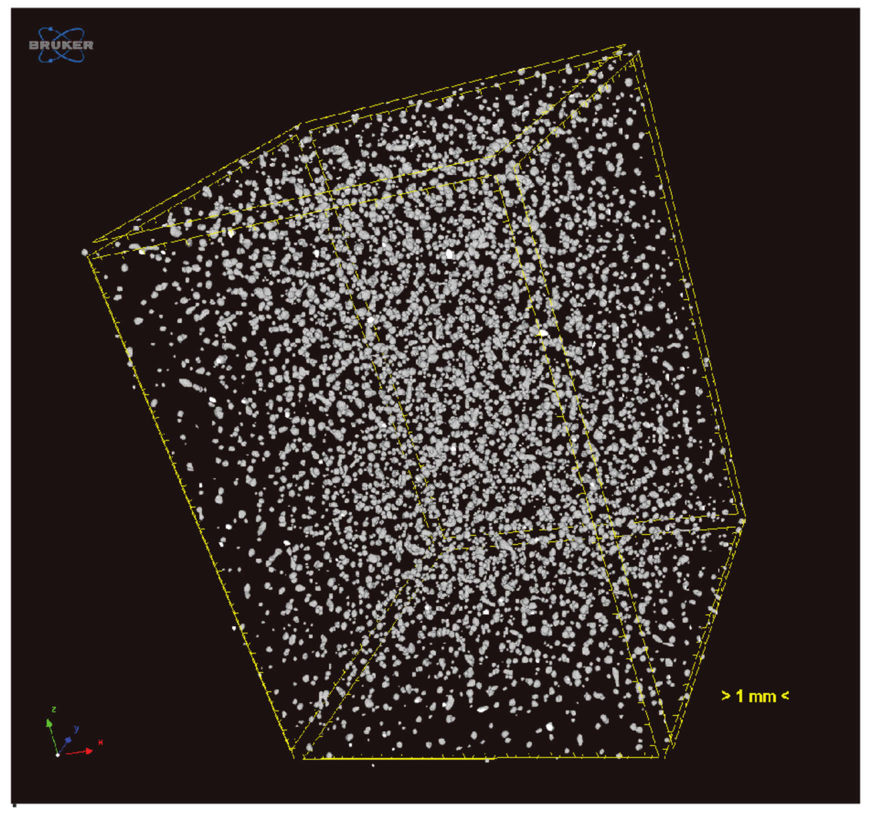


Fig 5: A volumetric 3D rendering of micro-CT analyses completed for the sample taken from 220 meters depth. Each small object represents a single bubble measured within the sample. The Bruker CTAn software returns values for total bubble counts (BND) and shape characteristics.

Results

We determined our accumulation record using measured annual layer thicknesses and estimated $\partial^{15}N$-derived firn-column thickness estimates. We measured BND from 160m, down to 1200 meters (or ~1,000-26,000 yrs bf 1950) using both thick section samples, and micro-CT samples. We measured typical values ranging between 800 and 900 bubbles cm^{-3} over this interval, with a maximum value of 938 bubbles cm^{-3} measured at 500 m depth, This observation is higher than any previously recorded values for ice-core BND, indicative of both the colder average temperatures, and higher average accumulation rates at South Pole. Temperature reconstructions were carried out using the model developed by Spencer et al. (2006), and using a South Pole site specific bubble-to-grain ratio (G) of 1.51. The reconstruction reveals a warming across the glacial-interglacial transition of ~7.5°C, which is in close agreement with other independent reconstructions. Results of our temperature reconstruction reveal that using 3D micro-CT imagery in place of traditional thick-section techniques produces comparable results, and with lower measures of uncertainty.

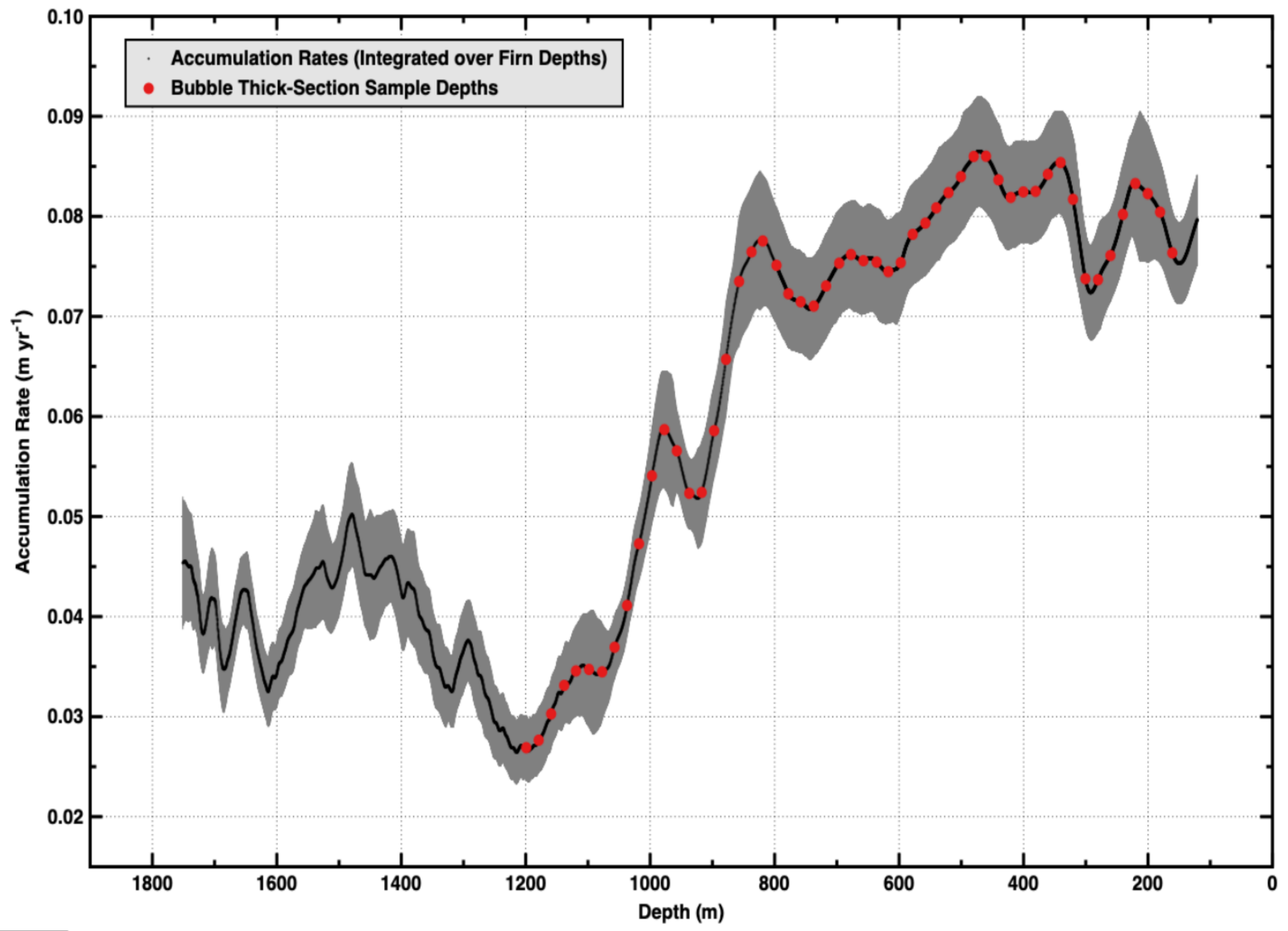
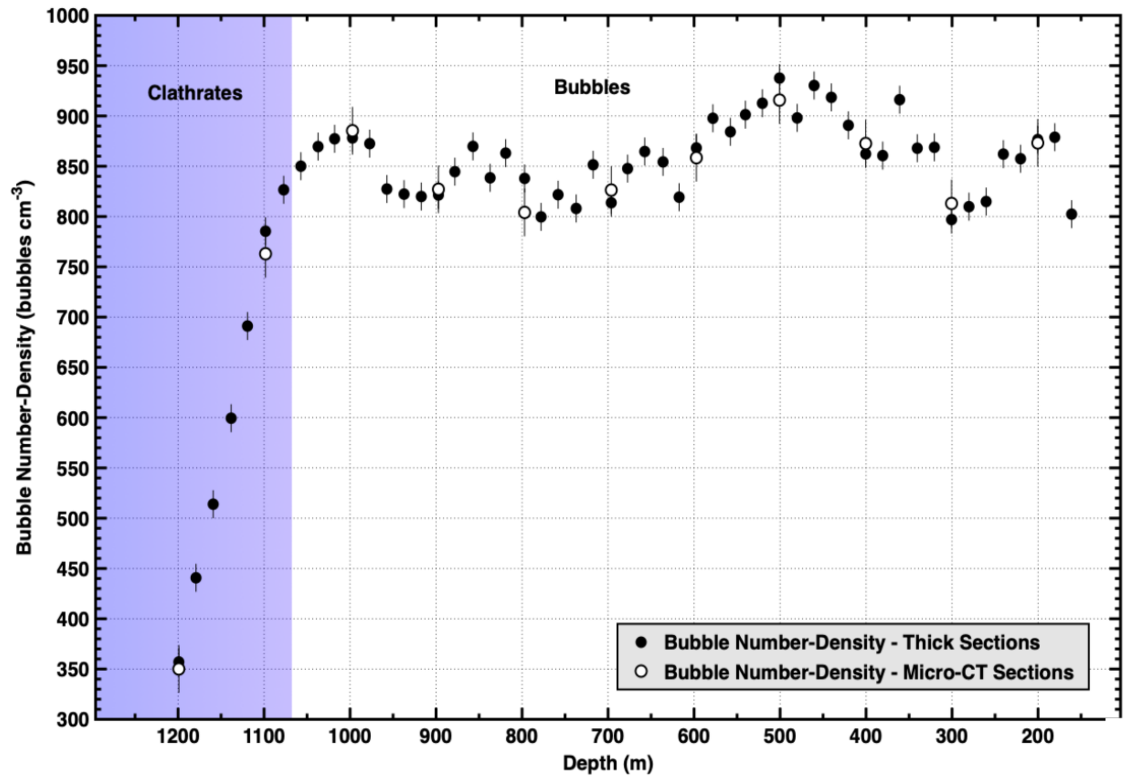
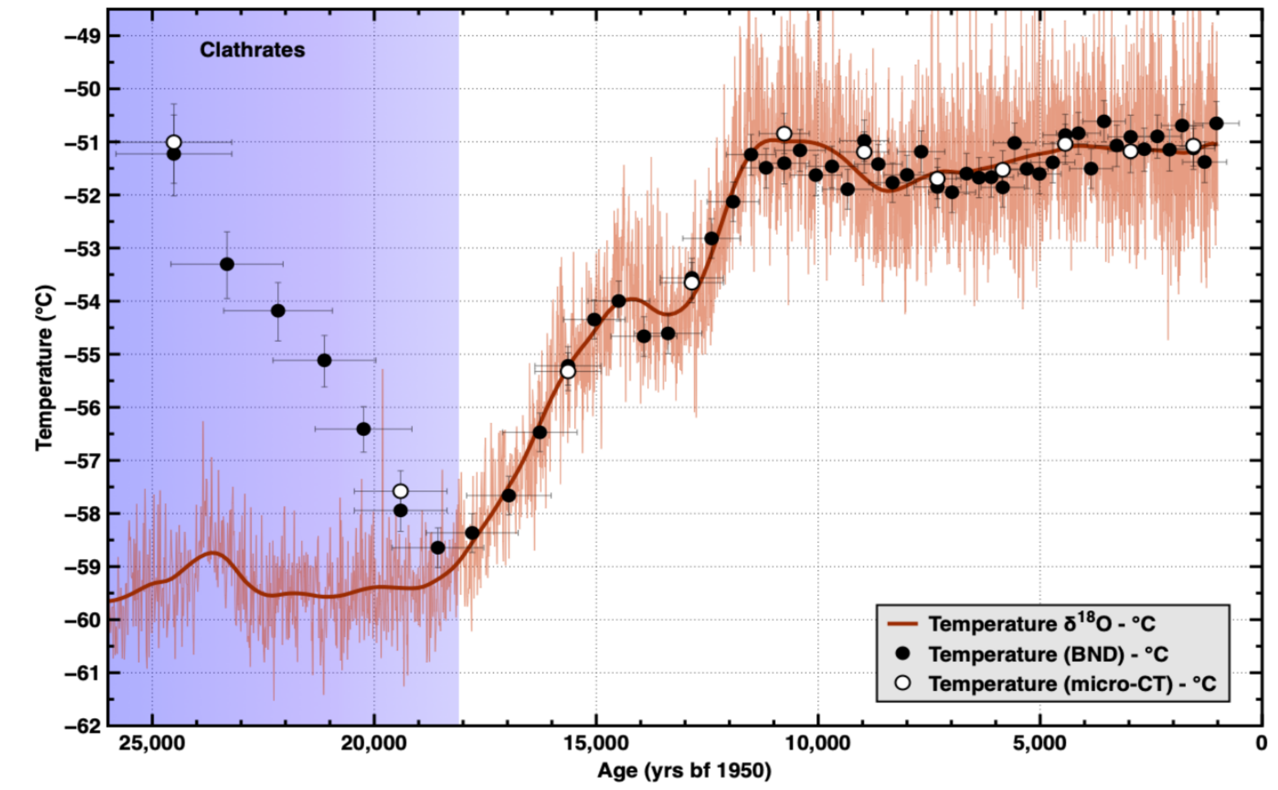


Fig 6a: Full accumulation record for the SPICEcoredown to 1750 meters depth or ~54.3kyrs bf 1950. Accumulation rates represent averages over the lifetime of the firn column above each respective depth. Lock-in depths were calculated using $\partial^{15}N$ measurements. Red dots represent bubble number-density sample depths used in this study.



<-- Fig 6b: Measured bubble number-density values plotted against depth. Error bars represent 1-sigma uncertainty of reproducibility across samples. A small correction was made to account for micro-bubbles (Fegyveresi et al., 2016). Values as high as 935 bubbles cm^{-3} were noted. Data are shown for both thick-section and micro-CT section measurements. An estimated clathrate is shown for reference.

Fig 6c: Reconstructed temperatures plotted against age (yrs bf 1950) from Winski et al. (2019). The results shows a warming of ~7.5°C across the glacial-interglacial transition. Data are shown for both traditional thick-section (2D) imagery (black dots), and novel micro-CT (3D) imagery (white dots). The trends do agree with preliminary results of $\partial^{18}O$ oxygen isotope analyses which have been corrected for deuterium excess (shown in brown). Horizontal error bars for age represent the firn-averaging time for each sample, and vertical bars represent 1-sigma uncertainty across duplicate measurements at each depth. Modeled temperatures prior to ~18ka become unreliable due to bubble loss from clathrate formation. An estimated clathrate zone is shown for reference.



Conclusions and Future Work

*** Measured bubble number-densities in the upper 1200 meters of the South Pole Ice Core reveal a ~7.5°C warming across the glacial-interglacial transition. This agrees with other independent estimates including a $\partial^{18}O$ reconstruction for the site.**

*** 3D micro-CT measurements have been shown to be a highly effective, accurate, and less time-consuming method for measuring bubble number-density.**

*** No significant brittle ice behavior or characteristics were encountered, although a small correction was still made to account for micro-bubbles.**

*** All bubble size, shape, and orientation analyses will be completed by May 2022.**

Acknowledgements

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References:

Spencer, M.K. and others, 2006. Developing a bubble number-density paleoclimatic indicator for glacier ice. J. of Glaciol., 52(178), 358-364.

Fegyveresi, J.M. and others, 2016. Five millennia of surface temperatures and ice core bubble characteristics from the WAIS Divide deep core, West Antarctica. Paleoceanography, 31(3), 416-433.

Winski D.A and others, 2019. The SP19 Chronology for the South Pole Ice Core – Part 1: Volcanic matching and annual-layer counting, Clim. Past Discuss., https://doi.org/10.5194/cp-2019-61, in review, 2019.