Supplemental Information

S1. Annual Layer Counting Methods

Layer counting was done in two phases. The first phase spans 5 to 540 m depth and the second phase includes 540 to 798 m depth. The specific annual-layer counting procedure is described for each phase.

S1.1 Layer Counting from 5-540 meters

Above 540 m, all five interpreters independently picked annual layers using the glaciochemical time series described above. These efforts resulted in five separate timescales. Over the top 540 m of SPICEcore, the different interpreters identified between 6529 and 6807 years, with sometimes inconsistent offsets between the interpreters. These five timescales are plotted in Figure S1 with respect to a timescale passing through each of the tie points developed in section 3.2, with positive values indicating that layer counts are missing in order to synchronize ages with WAIS Divide (blue lines). To combine the 5 sets of timescales into a single unified timescale, we first identified clusters of individual layer picks. For depths above 540 m, we calculated the sum of the number of individual layer picks within a moving window +/- 2 cm wide at 0.5 cm increments. In an ideal scenario, with all 5 researchers picking a layer in the same position, reconciliation among the sets of picks is simple (Fig. 6A). However, in some areas choosing between the 5 sets of picks is non-trivial (Fig. 6B). DW and DF individually and independently reviewed the five sets of picks using independently established criteria to decide whether each cluster of picks represented a year for inclusion within the timescale or not. These decisions generated two new sets of timescales containing 6791 and 6856 years within the top 540 m (Figure S1, black dashed). While eliminating most of the discrepancies among the five interpreters, there remained a difference of 65 years (1%) and 481 specific locations in the core where DW and DF made different choices about the presence of an annual demarcation. DW made one final round of choices after investigating the chemical stratigraphy surrounding each of these years to reconcile the remaining differences into a single timescale containing 6826 years above 540 m (Figure S1, red). For comparison, roughly 6932 years would be expected between 5 and 540 m based on volcanic synchronization, indicating that our layer counting missed at least 106 years out 6932 (1.5%).

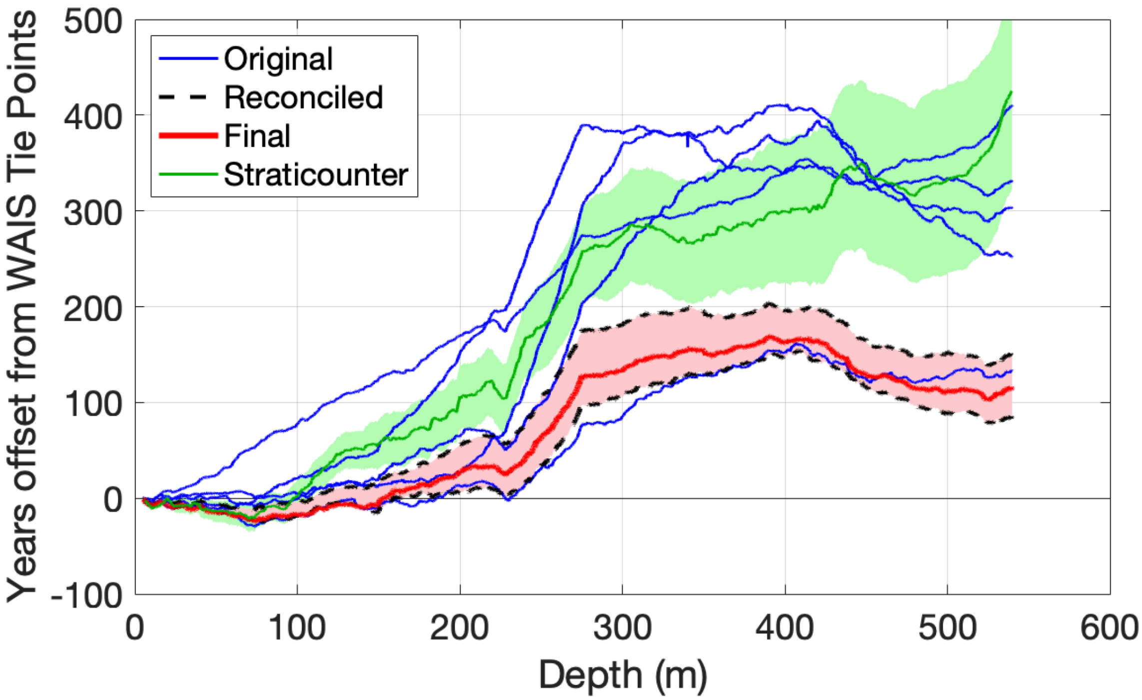

Figure S1: Offset between annual layer counting and SPICEcore-WAIS Divide tie points. Positive values on the y-axis indicate younger SPICEcore layer count ages relative to the synchronization with WAIS Divide (i.e. interpreters were missing years). Each blue line represents one of the 5 original independent sets of layer counts. The dashed black lines show the reconciled layer counted timescales after independent merging of the five original sets of picks by DW and DF. The red line indicates the final independent layer counted timescale. The green line shows the offset from SPICEcore-WAIS Divide tie points of automated layer counting using Straticounter (Winstrup et al. 2012) with the green shading inclusive of the 5th to 95th percentile ages. All of the layer counting efforts depicted were done independently of the stratigraphic tie points. All interpreters undercounted years, particularly during the interval from 228 to 275 m depth.

S1.2 540-798 meters

Between 540 and 798 m, sampling resolution permitted further annual layer counting. One interpreter (DW) continued the counting to 798 m, below which point annual layers were not consistently detectable. DW counted 4597 layers between 540 and 798 m, leading to an initial age of 11321 BP at the bottom of the annually dated section of the core.

S1.3 Sections with Missing Data

<u>*S1.3.1 Gaps and Damaged Core*</u> Within the top 798 m, where layer counting took place, there is a total of 2.74 m with missing data due to poor core quality or melter system errors. To fill these gaps in the timescale, we assigned an annual layer spacing equal to the average annual layer thickness of the 10 years above and below the gap. Layer thicknesses within the gap were rounded to make an integer number of equally spaced years. In total, 31 years were interpolated using this procedure.

<u>*S1.3.2 Dating the Top 5 meters*</u> The SPICEcore chemistry dataset begins at 5.15 m below the surface. We used chemistry from a hand-augered (HA) core drilled near the SPICEcore drill site to date the uppermost firn. The HA core was recovered from the surface to a depth of 9.86 m during the 2014/2015 field season; the same time as the beginning of SPICEcore drilling. The short length allows us to date the HA core with extra care using the following measurements: chloride, sulfate, sodium, magnesium, liquid conductivity, particle counts (small channel), Cl^-/Na^+ and SO_4^{2-}/Na^+. Layer counting of the HA core indicates a date at 5.15 m between 1992 and 1993 (5.03=1993, 5.29=1992). The nearest volcanic tie point to the top of SPICEcore is at 10.58 m depth with an age of -14 years before 1950 (1964 CE).

S1.4 Validation with Straticounter

We performed a semi-independent check on our manual layer counting ability using Straticounter, an automated layer counting software package described in (Winstrup et al. 2012). This software has been used to aid in the dating of previous ice cores in Greenland (Winstrup et al. 2012), Antarctica (Sigl et al. 2016), and Alaska (Winski et al. 2017). We used the Straticounter program to identify annual layers within the top 540 m of SPICEcore given sodium, magnesium, sulfate and microparticle data, as well as the reconciled version of our layer counts. Results produce ages ranging from 6408 to 6615 years between 5-540 m, agreeing closely with 4 of the 5 interpreters, but differing from the stratigraphically matched timescale by approximately 250-500 years (Figure S1, green). Because of the scrutiny applied to the manual layer counting efforts, and because the reconciled version of the hand-picked annual layer chronology is closer to the stratigraphically coordinated timescale, we use the manual layer counts to interpolate between tie points.

S2. Reconciling Layer Counts with Stratigraphic Ties

To a depth of 798 m, 86 volcanic tie points to WAIS Divide were identified, bracketing 85 depth intervals within which a known number of years must be present. To make the layer-counted timescale consistent with these tie points, years were added or subtracted, as necessary, within each interval such that the layer-counted timescale passes through each tie point within +/- 1 year of its age, linking SPICEcore with the WAIS Divide WD2014 chronology. In most intervals, very few years (1-5) needed to be added or subtracted, although in certain sections layer counting consistently differed from the WAIS-tied timescale. For instance, 105 years are missing between 228 and 275 m while 78 extra years were counted between 626 and 687 m. Because of the different counting methods, procedures for adding and subtracting years differ above and below 540 m and are described separately.

Above 540 m, years were preferentially added or subtracted where DF and DW disagreed in their final reconciliation (see Section S1.1). If an interval required the addition or subtraction of a number of years that exceeded the number of disagreements between DF and DW within the same interval, we first added years with 5 picks, then 4, then 3, then 2, then 1 until we met the required number of years within each interval (the opposite order applying to the subtraction of years). Between 540 and 798 m only one interpreter (DW) picked layers, so positions where years were added or subtracted were selected manually. After adding or subtracting the appropriate number of years within each interval, the layer-counted timescale passes within +/- 1 year of each stratigraphic tie point. The Holocene layer-counted timescale is then merged with the Pleistocene smoothest annual layer thickness interpolated timescale (Fudge et al. 2014) to form the final SP19 timescale.

S3. Layer Counting Performance

Using multiple interpreters to develop the timescale provides the ability to assess which areas contain better agreement among the different sets of picks. We assume that our layer count chronology is more robust in regions where all 5 sets of picks agree (e.g. Fig. 6A) than in regions with high discrepancy among picks (e.g. Fig. 6B). We create the following index of layer count quality using the following rules: For picks where all interpreters assigned a year within +/- 2 cm, we assign a value of 1. For picks where there was disagreement among the five interpreters, but agreement between DW and DF while reconciling, we assign a value of 0. For picks where there was disagreement between DW and DF while reconciling, we assign a value of -1. By calculating smoothed values of the layer count quality index over the top 540 m, patterns emerge showing areas of higher and lower layer counting confidence (Fig. S2). Most notable is the section between 412 and 456 m (5100 to 5700 BP) where analytical issues obscured robust annual signals. Fortunately, this section is well constrained by volcanic events. The very low accumulation values centered on 2400 BP are associated with another interval of slightly lower certainty in our layer counting ability. This is partly due to a lack of stratigraphic tie points, but the low accumulation here also caused all interpreters to consistently undercount years (between 228 and 275 m) leading to greater potential uncertainties.

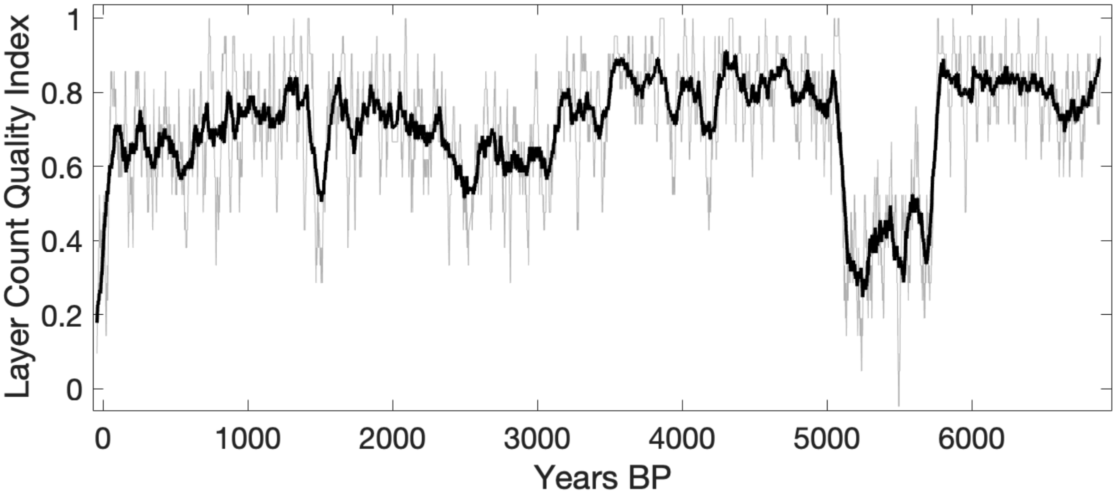

Figure S2: An index of layer counting quality over time. Higher values indicate greater confidence in layer counting ability. The index reflects the level of agreement among the five interpreters (see text). The 20-year (light gray) and 100-year (bold) running means are shown.

S4. Interval from 180 – 275 meters

We have identified only one tie point in the interval from 180m to 275m. Both interpreters (TJF, DF) have spent considerable time examining this interval but have not consistently identified the same events. The challenge of matching volcanic events in this period has two primary causes: 1) a sharp change in accumulation rate and 2) numerous small volcanic events. These two factors combine to make it difficult to distinguish sequences of volcanic eruptions because the depth between events may be varying due to the change in accumulation rather than a change in duration, and because there is no distinct pattern to relative amplitudes of the events. One interpreter revisited this interval to make another round of volcanic matches, which were made without any direct information from the annual interpolation. These matches indicate a similar timescale to the annual interpretation, which can be seen in Figure S3 of the average annual layer thickness. However, the second interpreter did not find the same matches when revisiting the interval and thus we exclude them from the underlying timescale.

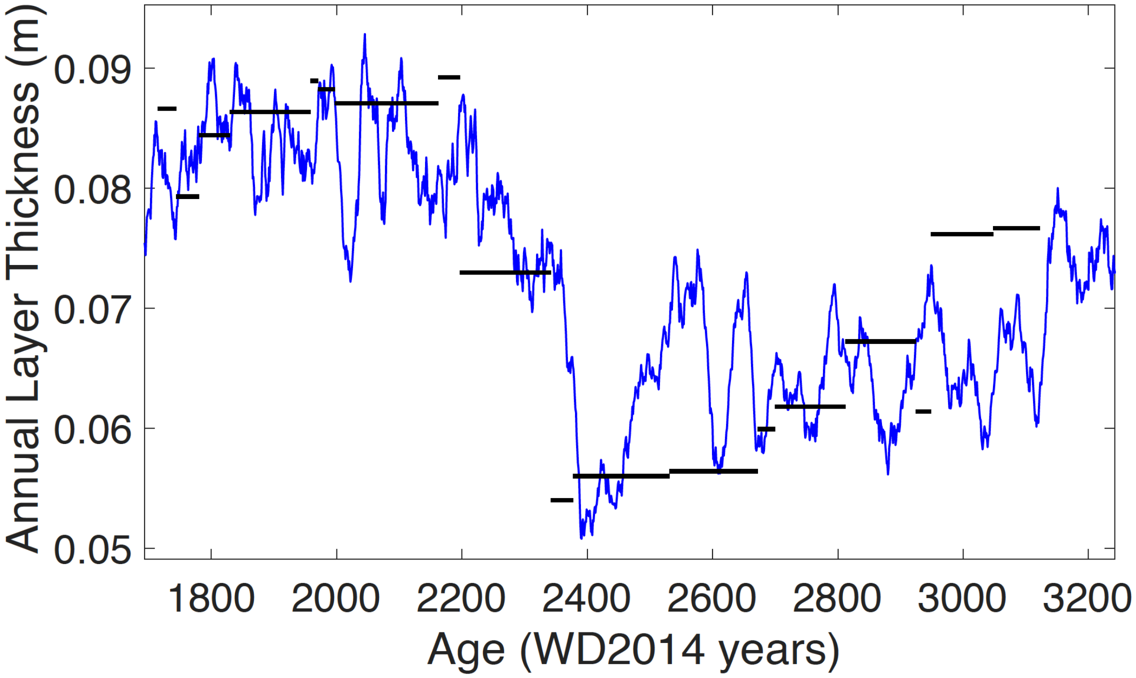

Figure S3: Annual layer thickness comparison between the SP19 timescale (blue – smoothed) and independent volcanic matches to WAIS-Divide (black). The volcanic matches were made without reference to the annual layer counts yet show a very similar pattern of annual layer thickness, further improving confidence in an accumulation anomaly at this time.