



**US Army Corps
of Engineers®**
Engineer Research and
Development Center

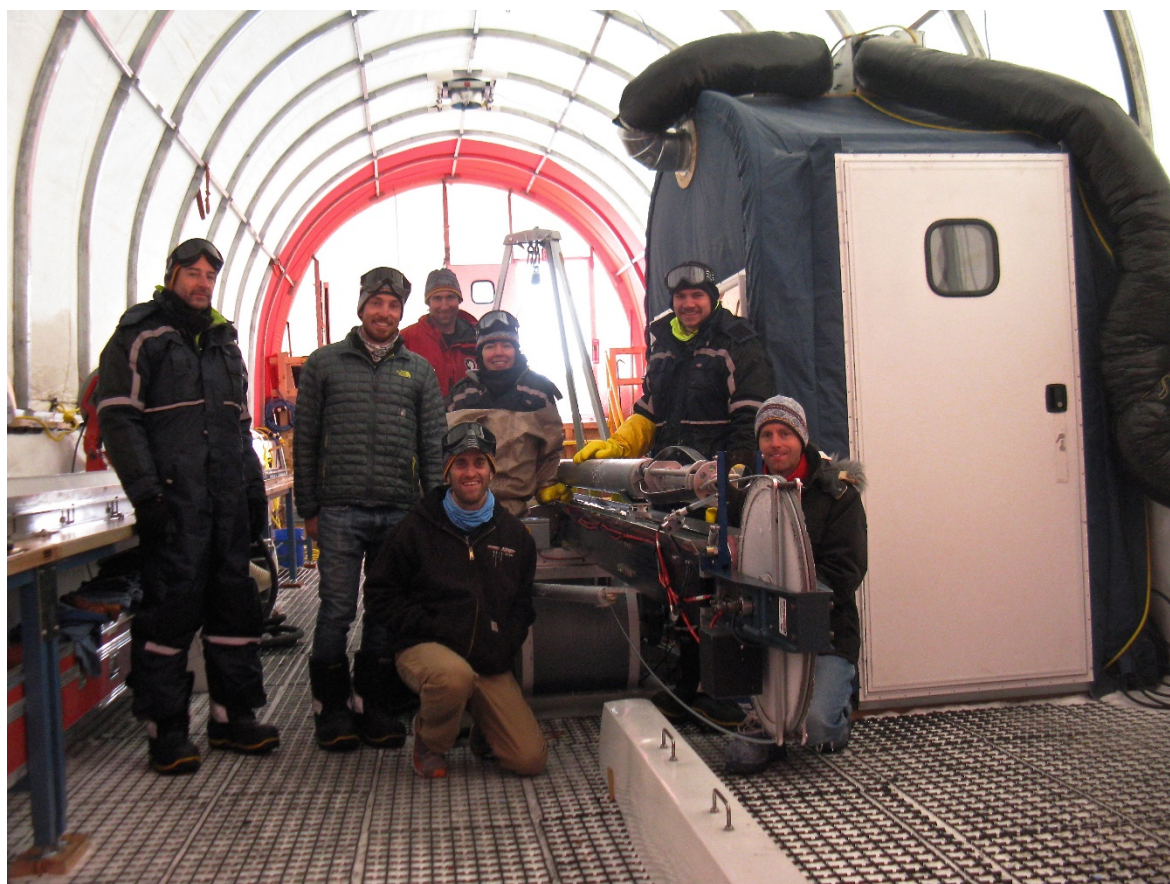


Visual Observations and Stratigraphy of the South Pole Ice Core (SPICEcore)

A Preliminary Holocene (~10.2 ka) Accumulation Record and Depth-Age Chronology

John M. Fegyveresi, Tyler J. Fudge, David G. Ferris,
Dominic A. Winski, and Richard B. Alley

July 2019



South Pole Ice Core Drilling and Science Team (2015–2016)

The U.S. Army Engineer Research and Development Center (ERDC) solves the nation's toughest engineering and environmental challenges. ERDC develops innovative solutions in civil and military engineering, geospatial sciences, water resources, and environmental sciences for the Army, the Department of Defense, civilian agencies, and our nation's public good. Find out more at www.erdcl.usace.army.mil.

To search for other technical reports published by ERDC, visit the ERDC online library at <http://acwc.sdp.sirsi.net/client/default>.

Visual Observations and Stratigraphy of the South Pole Ice Core (SPICEcore)

A Preliminary Holocene (~10.2 ka) Accumulation Record and Depth-Age Chronology

John M. Fegyveresi

*U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290*

Tyler J. Fudge

*University of Washington
Department of Earth and Space Sciences
Johnson Hall 070, Box 351310
4000 15th Avenue NE
Seattle, WA 98195-1310*

David G. Ferris

*Dartmouth College
Department of Earth Sciences
6105 Fairchild Hall
Hanover, NH 03755-3529*

Dominic A. Winski

*University of Maine
School of Earth and Climate Sciences & Climate Change Institute
5790 Bryand Global Sciences Center
Orono, ME 04469-5790*

Richard B. Alley

*Pennsylvania State University
Department of Geosciences
517B Deike Building
University Park, PA 16802*

Final Report

Approved for public release; distribution is unlimited.

Prepared for National Science Foundation (NSF)
 2415 Eisenhower Avenue
 Alexandria, VA 22314

Under NSF Award Number 1542778, "Climate History and Flow Processes from
 Physical Analyses of the SPICECORE South Pole Ice Core"

Abstract

We present an initial chronology for the newly drilled South Pole Ice Core (SPICEcore). Annual layers observed in the visual stratigraphy of the upper 735 m indicate a total ice age chronology of $10,235 \pm 51$ BP (years before 1950), with a total average accumulation rate of approximately $7.4 \text{ cm a}^{-1}_{\text{we}}$. Comparing electrical conductivity measurement peaks in the core with known volcanic events observed in other Antarctic ice cores corroborates these estimates.

This history shows accumulation trends, which could indicate past climatological or glaciological changes at the site. Specifically, one 1600-year interval between 6700 and 5100 years BP experienced a higher-than-average accumulation rate ($\sim 8.1 \text{ cm a}^{-1}_{\text{we}}$) while one 700-year interval from 3100 to 2400 years BP experienced a lower-than-average accumulation rate ($\sim 6.4 \text{ cm a}^{-1}_{\text{we}}$). We used seasonal equivalent coarse-grained and depth-hoar layers to identify the annual “picks” (noted as summers); and the stratigraphy in the core was generally uniform and well-preserved. We observed and documented over 1900 individual wind or iced crusts. We noted one visible tephra layer at a depth of 306.6 m in the core (~ 3560 years BP), which is likely tied to an eruption of Candlemas Island in the South Sandwich Islands.

DISCLAIMER: The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products. All product names and trademarks cited are the property of their respective owners. The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

DESTROY THIS REPORT WHEN NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.

Contents

Abstract	ii
Figures and Tables.....	iv
Preface	vi
Acronyms and Abbreviations	vii
1 Introduction.....	1
1.1 Background	1
1.2 Objectives.....	3
1.3 Approach	3
2 Methods, Assumptions, and Errors	5
2.1 Methods	5
2.2 Errors	8
2.3 Assumptions.....	10
3 Results and Data	12
4 Discussion	19
4.1 Depth-age-scale uncertainty	19
4.2 Accumulation history	24
5 Conclusions.....	27
References	29
Report Documentation Page	

Figures and Tables

Figures

1	Map of the SPICEcore drill-site location (<i>blue dot</i>) at South Pole relative to various research sectors, existing firn- and ice-core studies, ice-flow velocity, and prevailing wind direction.....	2
2	Dark booth used during all visual stratigraphy and physical properties observations (shown here with a raised curtain). The visible metal tray stand held the individual 1 m cores and illuminated them from below.....	6
3	We observed the physical properties of the illuminated cores within the dark booth as shown and recorded their respective depth offsets in paper log books	7
4	An ice-core log book with noted features and inferred annual picks shown	7
5	Annual picks for two separate cores from SPICEcore. At 70 m, the firn core had a much more distinct annual signal while the ice core from just below close-off at 132 m had a few vague areas where a layer had to be inferred or interpolated	9
6	Best-fit density profile for the South Pole ice-coring site assuming an ice density of 0.925 g cm^{-3} . Data are from Kuivinen et al. (1982). An approximate bubble pore close-off depth of 120 m (0.845 g cm^{-3}) is shown for reference.....	13
7	Depth-age scale determined from inspection of visual stratigraphy for the upper 735 m of SPICEcore	14
8	Full accumulation record for the upper 735 m of SPICEcore, shown with 300-year LOESS (locally estimated scatterplot smoothing) fit. The <i>red dashed line</i> indicates average accumulation over the entire record ($\sim 7.4 \text{ cm a}^{-1}_{\text{we}}$)	15
9	Frequency distribution of annual accumulation for the upper 735 m of SPICEcore (histogram bin width = 0.5 cm). <i>Vertical lines</i> indicate average annual accumulation values determined in this study ($\sim 7.4 \text{ cm a}^{-1}_{\text{we}}$) and in four additional studies for South Pole.....	16
10	Visible tephra/ash layer observed at 306.6 m in SPICEcore and preliminarily dated to approximately 3561 years BP. This 0.5 cm wide tephra layer is likely tied to the Candlemas Island eruption on the South Sandwich Islands identified within the WAIS Divide ice-core record. Stratigraphic up-core is to the right as indicated (<i>red arrow</i>)	17
11	Vertical representation of all approximately 1900 recorded crusts for the upper 735 m of SPICEcore. Inset shows frequency over a selected 10 m interval (avg. ~ 3 crusts per meter)	17
12	A bubble-free crust (<i>a</i>) observed at a depth of 74 m within SPICEcore shown with a pencil for scale. Inset (<i>b</i>) shows the crust as viewed through a $10\times$ hand lens.....	18
13	Final reconciled depth-age scale of the upper 735 m of SPICEcore, showing matches to known ECM peaks in the WAIS Divide core (see also Fig. 6 and Table 3)	22

14	Calculated age offsets (years) for all 65 identified ECM peaks in SPICEcore, based on known WAIS Divide (WD2014) ages (see also Table 3). <i>Red lines</i> indicate offsets of ± 6 years.....	22
15	Comparison of the upper approximately 210 m of SPICEcore and the SPRESSO core (2014 depth equivalent). Inset shows offset residuals between the two depth-age scales. Average absolute residual offset over the entire comparison is about 13 years (0.6%)	23
16	Full accumulation record for the upper 735 m of SPICEcore, shown with 300-year LOESS fit (see also Fig. 8). Bracketed estimates for average accumulation over time intervals between volcanic events of known ages are shown in <i>blue</i> . The <i>red dashed line</i> indicates average accumulation over the entire record ($\sim 7.4 \text{ cm a}^{-1}_{\text{we}}$).....	25

Tables

1	Timeline of SPICEcore recovery, shipment, and processing. Asterisk indicates the brittle ice zone	5
2	The 200 m density-depth data for South Pole (Kuivinen et al. 1982)	13
3	ECM-identified volcanic peaks within the upper 735 m of SPICEcore.....	20

Preface

This study was conducted for the National Science Foundation (NSF) under the Antarctic Glaciology Program, Award Number 1542778, “Climate History and Flow Processes from Physical Analyses of the SPICECORE South Pole Ice Core.” The program manager was Paul Cutler, NSF Office of Polar Programs.

The work was performed by the Terrestrial and Cryospheric Sciences Branch (CEERD-RRG) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL); the University of Washington, Department of Earth and Space Sciences; the University of Maine, School of Earth and Climate Sciences and Climate Change Institute; and Dartmouth College, Department of Earth Sciences. At the time of publication, Dr. John Weatherly was Chief, CEERD-RRG, and Mr. Jared Oren was Acting Chief, CEERD-RR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

COL Ivan P. Beckman was Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

BP	Years before 1950
cm a ⁻¹ _{we}	Centimeters per Year in Water Equivalent
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
ECM	Electrical Conductivity Measurements
ERDC	Engineer Research and Development Center
ITASE	International Trans-Antarctic Scientific Expedition
ICF	Ice Core Facility
ITASE	International Trans-Antarctic Scientific Expedition
LOESS	Locally Estimated Scatterplot Smoothing
Micro-CT	Micro-Computed Tomography
NSF	National Science Foundation
SPICE	South Pole Ice Coring Project
SPICEcore	South Pole Ice Core
SPRESSO	South Pole Remote Earth Science and Seismological Observatory
WAIS	West Antarctic Ice Sheet
WD2014	The Published WAIS Divide Deep-Ice-Core Chronology

1 Introduction

1.1 Background

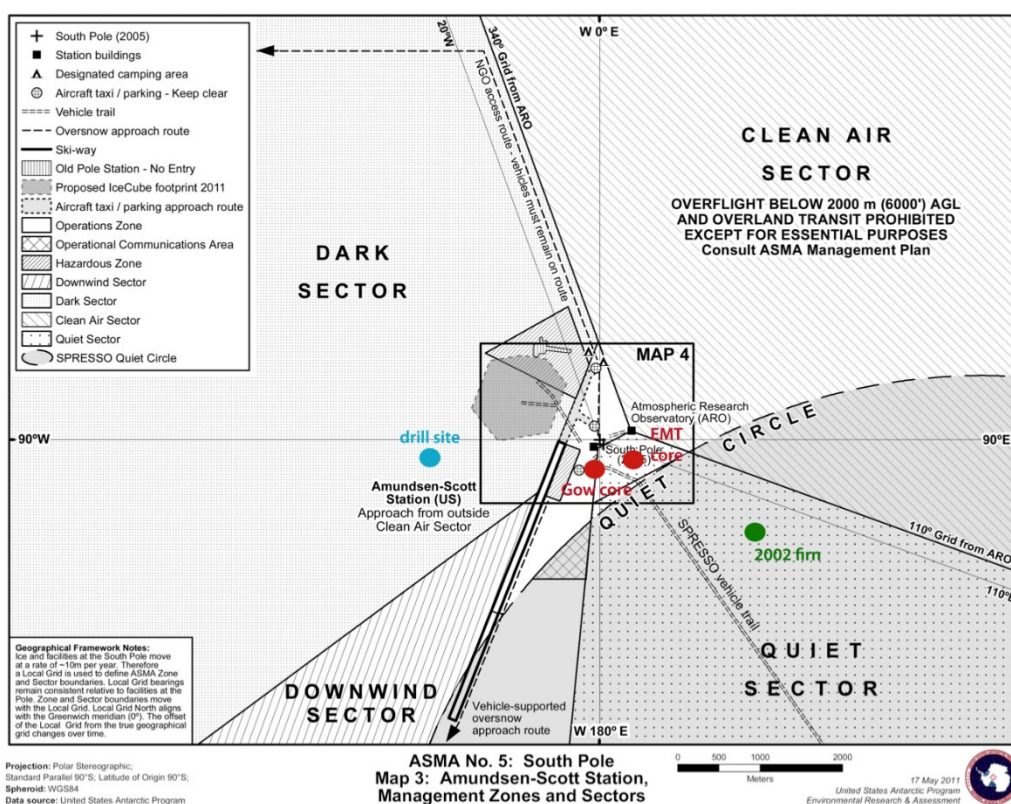
The South Pole Ice Coring Project (SPICE) began during the 2014–2015 austral summer Antarctic field season near the U.S. Amundsen-Scott South Pole Station. The South Pole site is unique in that the average annual site temperature at the drilling location (-49°C) is more typical of East Antarctic sites, while the average accumulation rate ($\sim 7\text{--}8\text{ cm a}^{-1}\text{we}^*$) is more typical of West Antarctic sites (Casey et al. 2014; Lazarra et al. 2012). The drilling site, located at 89.99°S , 98.16°W , and approximately 2 km from the primary South Pole Station (Figure 1), has an estimated ice thickness of 2700 m, an ice velocity of 10 m a^{-1} along 40°W , is situated at approximately 2835 m above sea level, and has an estimated depth to firn pore close-off of about 120 m (Casey et al. 2014; Sneed et al. 2011). Once the primary ice core (the South Pole Ice Core, SPICEcore) is fully analyzed and dated, the 3-year intermediate-depth drilling campaign will yield 1750 total meters of new ice and will reveal approximately 55,000 years of total atmospheric, isotopic, and glaciological history at the drilling site (Casey et al. 2014).

Over 20 years, beginning in 1965, several shallow firn and ice cores were drilled near South Pole Station (e.g., Gow 1965; Giovinetto and Schwerdtfeger 1965; Kuivinen 1983; Mosley-Thompson et al. 1985), each resulting in slightly different average accumulation-rate estimates, ranging between 5.0 and $8.0\text{ cm a}^{-1}\text{we}$ (see also van der Veen et al. 1999; Casey et al. 2014). More recently, the International Trans-Antarctic Scientific Expedition (ITASE) ice-core array project drilled a 207 m core during the 2002–2003 field season approximately 8 km from the South Pole Station. This core was specifically part of the South Pole Remote Earth Science and Seismological Observatory data set and was subsequently dubbed the SPRESSO core (Sneed et al. 2011). Field scientists measured the visual stratigraphy on this core in the field and determined an accumulation rate of approximately $7.6\text{ cm a}^{-1}\text{we}$ when averaged over all 207 m (A. Gow, pers. comm., 2015; Sneed et al. 2011).

* Centimeters per year in water equivalent.

In addition to firn and ice cores measured from the South Pole, countless surface stake studies have quantified regional trends in accumulation (Kuhns et al. 1997; Mosley-Thompson et al. 1999; McConnell et al. 1997). As a result of these stake studies, the average accumulation rates for South Pole were estimated as high as approximately $10 \text{ cm a}^{-1}\text{we}$. However, because the South Pole site is generally described as a flank site (not on an ice divide) with large surface-velocity uncertainties, the origin of the measured accumulation can be somewhat complicated (Casey et al. 2014). Measured ice and snow at the site may come from hundreds of kilometers away and from a very large total catchment area as the estimated regional ice-flow velocities for South Pole range between 9.6 m a^{-1} and about 10.1 m a^{-1} (Hamilton 2004; Bamber et al. 2000 Rignot et al. 2011; Casey et al. 2014). Accumulation has even been noted to be as high as about $16 \text{ cm a}^{-1}\text{we}$ ($\sim 53 \text{ cm}$ of snowfall) in a single year (Gow 1965).

Figure 1. Map of the SPICEcore drill-site location (*blue dot*) at South Pole relative to various research sectors, existing firn- and ice-core studies, ice-flow velocity, and prevailing wind direction (see also Mosley-Thompson and Thompson 1982; Kuivinen 1983; Aydin et al. 2008). (Modified and reprinted by permission from Casey et al. 2014.)



1.2 Objectives

The primary objective of this study was to document and analyze visual observations and physical properties of the recently drilled SPICEcore. Then, using the recorded visual stratigraphy, combined with noted electrochemical seasonal markers (e.g., WAIS [West Antarctic Ice Sheet] Divide Project Members 2013), we aimed to develop a preliminary depth-age chronology and accumulation history for the site. The derived chronology and accumulation record will be correlated with future studies to better identify and quantify climatic and ice-flow history and accumulation provenance for the site. A secondary objective for this study was to record any unique visual features observed in the core, such as density variations, crusts, hoar layers, and volcanic tephra. Future physical properties and grain-scale analyses of SPICEcore will also include discrete thin- and bubble-section sampling and three-dimensional micro-CT (micro-computed tomography) imagery and c-axis fabric measurements.

1.3 Approach

Numerous studies have examined the visual stratigraphy of ice cores within a dark booth, with generally high levels of success (e.g., Alley et al. 1997). The techniques for these examinations were first pioneered by Benson (1962, 1971) and Gow (1965) and were later expanded and improved (e.g., Alley et al. 1997; Mosley-Thompson et al. 1985; Hogan and Gow 1997; Kuivinen et al. 1982; van der Veen et al. 1999). Features observed in the ice cores during these examinations, such as density variations, crusts, hoar layers, and volcanic tephra, are used to reconstruct paleoconditions at the drilling site (such as past accumulation, temperature, and timing of volcanic eruptions). Physical seasonal differences in summer and winter accumulation are preserved independently within the firn and are generally observable at depth in ice cores (e.g., Gow 1965; Alley et al. 1997). Using this principle, we identified an annual accumulation signal in SPICEcore and determined a viable depth-age relationship.

We analyzed the visual stratigraphy of all sections of SPICEcore within a lit tray inside a dark booth and documented all of the physical observations. We made all age and accumulation calculations by measuring the annual layers in the visual-stratigraphy record, validating those measurements against known electrochemical volcanic markers, and then correcting layer thicknesses for density and the effects of thinning. Annual layers were not visually resolvable below 735 m in the core due to diffusion of the

accumulation signal. We therefore present results of our analyses for only the upper 735 m of ice, with a focus on the development of a preliminary depth-age scale and an estimated accumulation history for the Holocene (~10,235 years BP [years before 1950]).

2 Methods, Assumptions, and Errors

2.1 Methods

During the SPICEcore ice-core processing line that took place at the National Science Foundation Ice Core Facility (NSF-ICF) in Denver, Colorado, we documented the physical properties and visual stratigraphy of 734 separate cores (each approximately 1 m long) of SPICEcore. This included five (~1 m) hand-augered cores that were drilled at the surface and 729 cores drilled with the newly developed U.S. intermediate-depth drill (Johnson et al. 2014). Due to the nature of the ice recovered from the brittle-ice-zone depth interval (Neff 2014), much of the ice recovered from SPICEcore was processed out of order and over multiple years. This was complicated further by the limited cargo space available for the shipment of the ice following each drilling season. Table 1 shows when specific ice depth intervals of SPICEcore were recovered, shipped, and processed between 2015 and 2017.

Table 1. Timeline of SPICEcore recovery, shipment, and processing. Asterisk indicates the brittle ice zone.

Drilling and Processing Seasons	Core Depths Drilled (SPICEcore)	Core Depths Shipped to NSF-ICF	Core Depths Processed at NSF-ICF	Total Core Processed at NSF-ICF
12/14-01/15	0–735 m	0–585 m		
06/15			0–556 m	556 m
12/15-01/16	735–1751 m	586–735 m 1078–1477 m		
06/16			556–735 m 1078–1462 m	563 m
12/16-01/17		735–1078* m 1477–1751 m		
06/17			735–1078* m 1462–1751 m	632 m
TOTAL	1751 m	1751 m		1751 m

Each individual core was cut and planed horizontally during core processing to produce a smooth, flat surface for viewing (e.g., Souney et al. 2014). Using clear trays, the cores were slid into a dark booth for analysis (Figure 2). In the booth, each core was illuminated from below to reveal internal features and stratigraphy. For some cores, particularly from depths greater than approximately 250 m, side-directed tray lighting from

a scatter-diffuser was often more effective at revealing features. We recorded in paper log books all noteworthy physical properties and seasonal indicators observed during the core inspections within the dark booth (Figure 3).

Documentation primarily included density contrast in the cores (e.g., coarse- vs. fine-grained layering and obvious depth hoar layers). We also recorded in detail features such as crusts (and specifically hoar/crust couplets) and prominent variability, such as tilted layers, folded layers, cross-bedding, preserved sastrugi, double crusts, ash or tephra layers, and significant changes in bubble characteristics (shape or size). Following Gow (1965), we recorded more-detailed grain-size and coarseness specifics (especially within the firn) whenever possible. Lastly, we also documented any breaks, spalls, chips, or fractures in the cores. We recorded all data in meter-long log books (Figure 4).

Figure 2. Dark booth used during all visual stratigraphy and physical properties observations (shown here with a raised curtain). The visible metal tray stand held the individual 1 m cores and illuminated them from below.

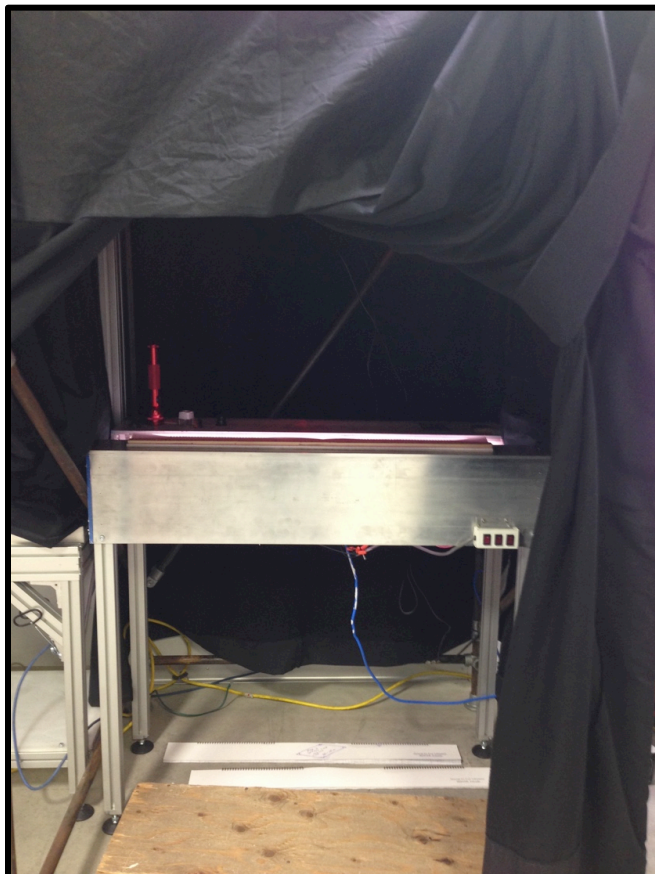
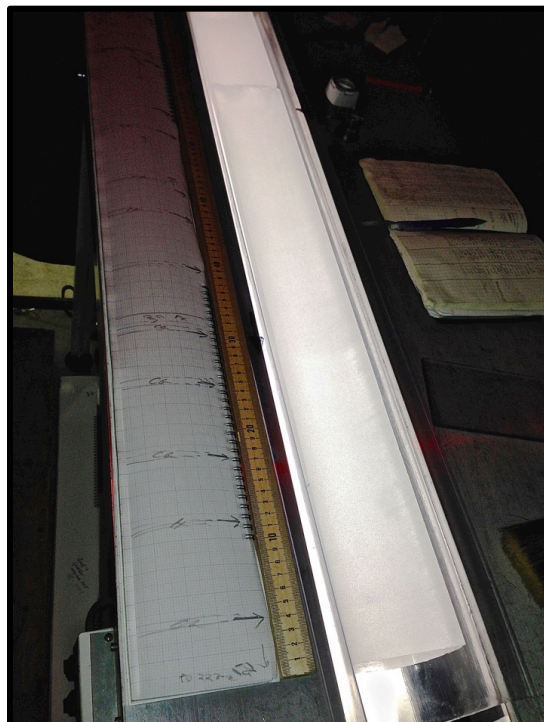


Figure 3. We observed the physical properties of the illuminated cores within the dark booth as shown and recorded their respective depth offsets in paper log books.



Figure 4. An ice-core log book with noted features and inferred annual picks shown (*arrows*).



We inferred annual stratigraphy using the method described by Gow (1965). Depth-hoar or equivalent coarse layers were used as markers for seasonal late-summer surfaces, with most hoar layers being overlain by an ice crust (forming a distinct couplet). We recorded the depths of all noted features to the nearest millimeter. For purposes of counting the annual layers, we make some assumptions here that are detailed in sections 2.2 and 2.3 (along with the associated error estimates).

2.2 Errors

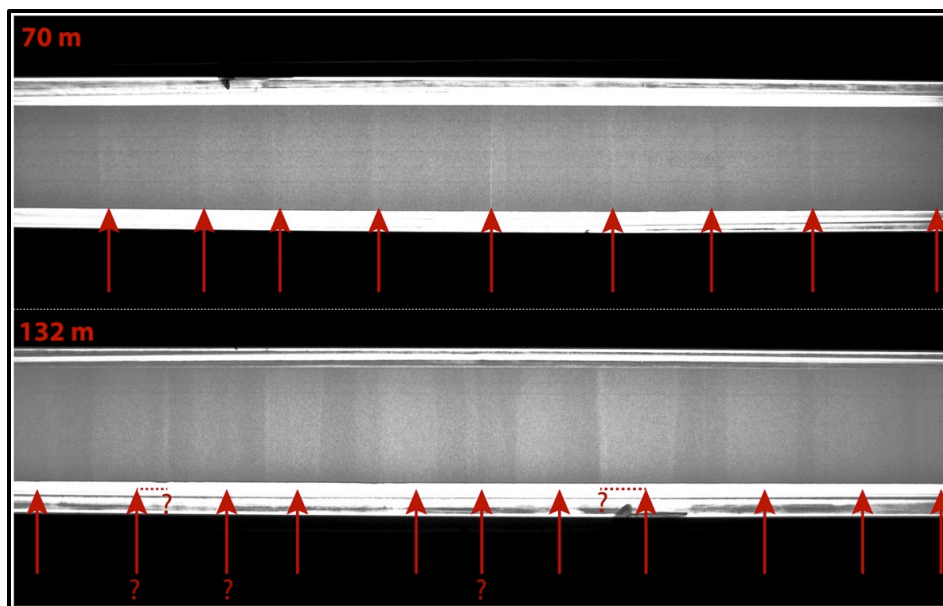
Many sources of error exist with both the recording and interpretation of the visual stratigraphy of ice cores, particularly when estimating a depth-age scale. Previous studies of visual stratigraphy and other depth-age-scale techniques estimate errors from as low as 0.1%–0.2% (Sigl et al. 2016; Buizert et al. 2015; WAIS Divide Project Members 2013) to as high as 5%–10% (Ferris et al. 2011; Hogan and Gow 1997; Kuivinen et al. 1982; van der Veen et al. 1999). While some degree of “underpicking” or “overpicking” of annual layers is expected from interpretation and from variations or hiatuses in accumulation (Kuivinen et al. 1982; Hogan and Gow 1997; Moseley-Thompson and Thompson 1982; van der Veen et al. 1999), it can be difficult to accurately estimate a true measure of annual-layer counting based on all of the possible sources of error.

Some layers may be physically absent either due to breaks in the ice or from drilling-related ice loss. We minimized this error with redundant secondary checks of all core length measurements during core processing. Additionally, each core was manually aligned and adjoined with the previous core before any cuts or analyses were made to ensure a proper and snug fit, reducing the possibility of undocumented lost ice.

Errors can also exist based on the placement of the observer’s annual “picks,” such as a distinct hoar layer simply being overlooked during counting. Documented annual layers could also be added or lost based on where marks are made at the top or bottom of each log book. For example, it would be possible to “double pick” (and therefore overcount) the same annual layer if one layer was chosen at the bottom of one core, and then again at the top of the very next core. We attempted to minimize this error by doing secondary independent layer picks for each core to establish reproducibility.

Finally, the largest likely source of error in identifying annual layers in the core was simply from the interpretation of variations in the observed layering. Van der Veen et al. (1999) showed that two separate cores, both drilled at South Pole, had very different layer thickness frequency distributions over similar depths because of different assumptions and criteria used by the two interpreters. It was possible that within SPICEcore the formation of two distinctive layers of depth hoar in a single accumulation year could be confused for two separate years of accumulation (thereby overcounting one year). Conversely, it was possible that two layers of depth hoar that formed approximately a year apart could appear to an observer to be one large single layer and be counted as only one year of accumulation (thereby undercounting one year). This scenario was particularly plausible in deeper ice where thinning may make adjacent layers appear even closer. Figure 5 shows annual picks for two cores from SPICEcore, one above and one below bubble close-off depth (70 m and 132 m), along with some of the interpretation difficulties faced during dark-booth observations. The 70 m core had a more clearly delineated annual signal while the 132 m core had notably more questionable areas. We expect that some annual layers (and therefore years) are simply missing from the record due to wind erosion or lack of accumulation (van der Veen et al. 1999) and therefore are not counted. Additionally, other very large and unreasonable accumulation years likely represented two separate years and thus required us to assume an interpolated layer in between.

Figure 5. Annual picks for two separate cores from SPICEcore. At 70 m, the firn core had a much more distinct annual signal while the ice core from just below close-off at 132 m had a few vague areas where a layer had to be inferred or interpolated.



Based on these known errors and how we made our observations, there was a higher tendency to overpick intra-annual layers as separate years. However, more of the low-accumulation and eroded layers were also missed altogether. Therefore, averaged over the full 735 m of the core, we believe that these two errors had a natural tendency to negate each other. Later comparisons with other local depth-age estimates (electrical conductivity measurements, or ECM, discussed in sections 3 and 4) further corroborate this observation. We note that there were some discrete depths (e.g., 200–230 m depth) within the core that appeared much more homogeneous during viewing, and therefore annual layers were picked with a higher level of uncertainty.

We considered several approaches for representing an accurate measure of uncertainty in annual-layer counting. First, we performed multiple counts per core to establish an approximate reproducibility error. We marked vague or questionable annual layers to include in overall uncertainty estimates; however, it was ultimately very difficult to quantify this error over the entire depth range. Different error percentages were even considered for specific depth ranges; but this approach became too complicated, and it proved difficult to find proper bounds for these ranges. Eventually, by comparing the final depth-age scale with existing independent depth-age estimates and volcanic ties (discussed in section 4) and factoring in an average of identified vague layer reads and reproducibility, a flat 0.5% error was applied to the results (approximately ± 51 years at 735 m). We believe, that this overall 0.5% estimate may be high (specifically at certain depth intervals) and that the resultant annual picks and depth-age scale are much more precise. However, until another independent scale can be used for corroboration (i.e., chemically or isotopically derived depth-age scales), this estimate will safely represent any possible measurement or interpretation error. Final uncertainty estimates will also likely not be static over the entire interval but vary by depth and physical ice properties.

2.3 Assumptions

To maintain consistency throughout the visual-stratigraphy examination and annual-layer identification, we made several assumptions related to the nature and formation mechanisms behind various seasonal surface features at South Pole. Following Gow (1965), we assumed that a single layer of depth hoar is formed each year and that the greatest opportunity

for the formation of that layer is in late summer or fall. These layers become the identifying features used to determine annual picks in the estimated depth-age scale.

Based on stake studies originally carried out by Gow (1965), we also assumed that the largest practical accumulation at the site for a single year is approximately 53 cm of snow ($\sim 16 \text{ cm}_{\text{we}}$). Therefore, we considered any measured annual accumulation that was larger than about $16 \text{ cm}_{\text{we}}$ an exception to the yearly depth hoar assumption. We thus treated these anomalous layers as two separate years by linearly interpolating at evenly spaced intervals over the measured accumulation. As previously noted, this potentially contributed to an overcounting error. Conversely, measured annual accumulation within the core was only treated as an independent year of accumulation if its total thickness was greater than 2 cm_{we} . Therefore, two depth hoar layers that were measured under 2 cm apart were also considered an exception to the yearly depth hoar assumption. In these rare cases, the two hoar layers were simply included as part of the same year (thus potentially contributed to undercounting error). Cumulative counts were kept of both interpolated and ignored annual picks to accurately estimate overall errors (see section 2.2). If we determined that stratigraphic hiatuses may have occurred within the core, we assumed them to be accumulation hiatuses and not due to surface scouring of preexisting layers.

3 Results and Data

We determined an initial SPICEcore chronology using annual picks that we identified in the dark booth. Regular, equivalent, coarse-grained, and depth-hoar layers were used to identify the annual “picks” (noted as late summers). These initial raw counts revealed an approximate age at 735 m of about 10,185 years BP $\pm$ 102 years ($\sim$ 1%). We determined a more-detailed chronology later by comparing observed ECM peaks in the core with known volcanic events observed in the WAIS Divide deep ice core (see section 4) (Sigl et al. 2016). To best estimate trends in accumulation thicknesses and timing, we corrected raw annual-layer thicknesses for plastic deformation (ice thinning) and density. Although the site is characterized as a flank-flow site, a simple correction with an ice-flow model that uses a uniform strain rate (Nye 1963; Fegyveresi et al. 2011, 2016) offers a sufficient approximation due to the shallow depths of ice measured (<735 m). A depth to bed (H) of 2700 m was used (Casey et al. 2014), which equates to only about 25% layer thinning in the deepest cores measured in this study (Nye 1963; van der Veen et al. 1999). Therefore, when compared to other uncertainties, the effects of vertical strain introduced little error. We assumed a bubble pore close-off depth of approximately 120 m for the site based on our physical observations and previous observations by Kuivinen et al. (1982).

Kuivinen et al. (1982) originally compiled density-depth data for South Pole (Table 2) (see also van der Veen et al. 1999). The relationship between the ice-density ρ_i (g cm^{-3}) and depth (m) fits well to

$$\rho_i = a + b \cdot (1 - \exp(c \cdot x)), \quad (1)$$

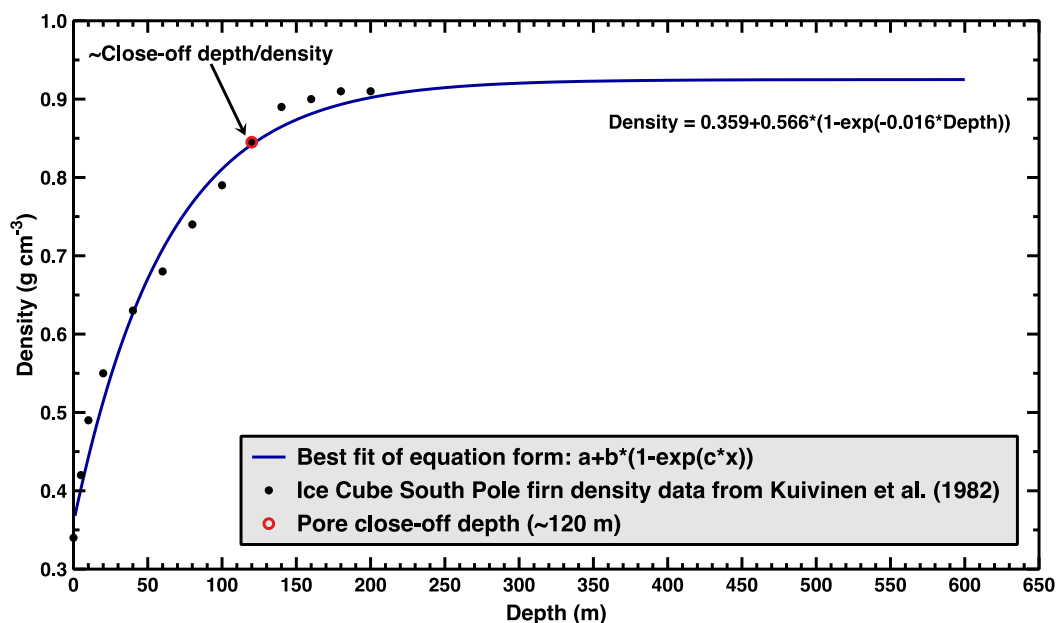
where a , b , and c are constants and x is the measured depth in the ice (m). The best-fit equation to these published data that guarantees a smooth approach to an asymptotic density of 0.925 g cm^{-3} , is shown in Figure 6 and given by

$$\rho_i = 0.359 + 0.566 \cdot (1 - \exp(-0.016 \cdot x)). \quad (2)$$

Table 2. The 200 m density-depth data for South Pole (Kuivinen et al. 1982).

Depth (m)	Density (g cm ⁻³)
0	0.340
5	0.420
10	0.490
20	0.550
40	0.630
60	0.680
80	0.740
100	0.790
120	0.845
140	0.890
160	0.900
180	0.910
200	0.910

Figure 6. Best-fit density profile for the South Pole ice-coring site assuming an ice density of 0.925 g cm⁻³. Data are from Kuivinen et al. (1982). An approximate bubble pore close-off depth of 120 m (0.845 g cm⁻³) is shown for reference.



Thus, to determine water equivalent thicknesses of each measured layer (and therefore accumulation history), we first applied a simple Nye thinning correction using the equation

$$T_N = \frac{T_m \cdot H}{Z}, \quad (3)$$

where

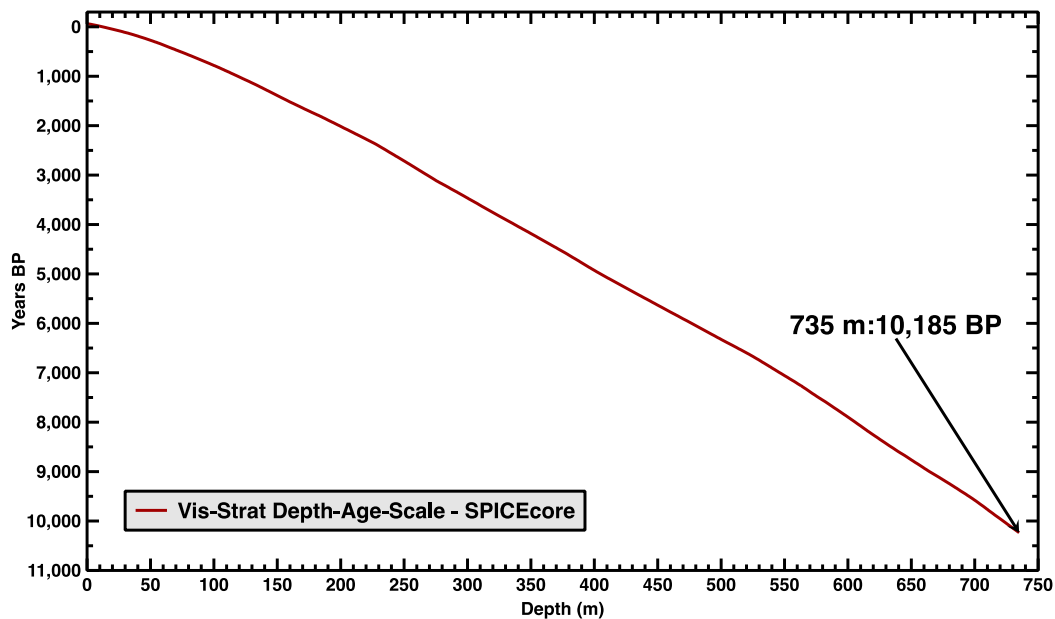
- T_m = the measured in situ layer thickness (cm),
- H = the total ice-sheet thickness at South Pole (2700 m),
- Z = the height of the given layer from the bed of the ice sheet (m),
and
- T_N = the ice-flow corrected layer thickness (cm).

We applied density corrections to determine water equivalent thicknesses (T_{we}) by using the equation

$$T_{w.e.} = \frac{T_N \cdot \rho_i}{\rho_w}, \quad (4)$$

where ρ_w represents a simple and constant water density of 1 g cm^{-3} and ρ_i represents the ice density calculated at depth Z using equation (2) above. The resultant depth-age scale, shown in Figure 7, is based on the visual stratigraphy for the 735 m of analyzed ice and the calculation above.

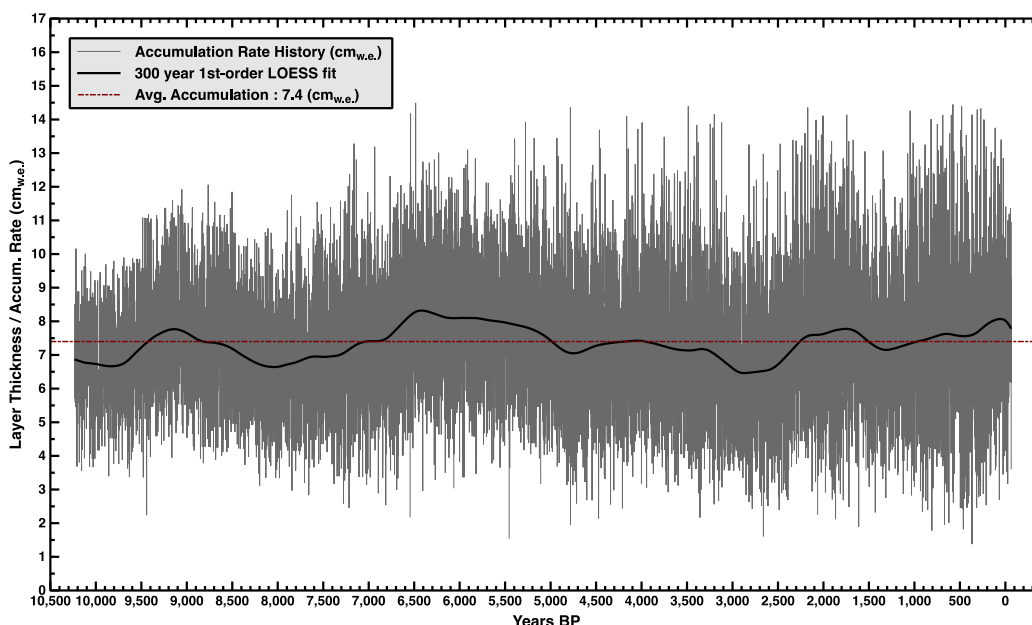
Figure 7. Depth-age scale determined from inspection of visual stratigraphy for the upper 735 m of SPICEcore.



The average annual accumulation determined over the 735 m interval of ice analyzed was approximately $7.4 \text{ cm a}^{-1}_{we}$, with a few internal variations noted (Figure 8). This history shows several subtrends of increases and decreases in accumulation, which could be indicative of past climatological

or glaciological changes at the site. Specifically, we observed two noteworthy trends in accumulation in the record. One 1600-year interval between 6700 and 5100 years BP experienced an accumulation rate higher than the average rate ($\sim 8.1 \text{ cm a}^{-1}_{\text{we}}$) for the measured 735 m interval while one 700-year interval from 3100 to 2400 years BP, experienced an accumulation rate lower than the average rate ($\sim 6.4 \text{ cm a}^{-1}_{\text{we}}$) for the measured 735 m interval. Two additional extended areas of possible interest are also visible within the record between 8400 and 7300 years BP and before 9600 years BP.

Figure 8. Full accumulation record for the upper 735 m of SPICEcore, shown with 300-year LOESS (locally estimated scatterplot smoothing) fit. The *red dashed line* indicates average accumulation over the entire record ($\sim 7.4 \text{ cm a}^{-1}_{\text{we}}$).



A frequency distribution of the accumulation record (Figure 9) indicates a generally uniform distribution with only a slight (0.33) right-skewness (median value of $\sim 7.2 \text{ cm a}^{-1}_{\text{we}}$). This result is consistent with previous investigations for the site ranging from 7.0 to 7.6 $\text{cm a}^{-1}_{\text{we}}$, as well as with the recent estimates published for the SPICEcore site of about 8.0 $\text{cm a}^{-1}_{\text{we}}$ (Mosley-Thompson et al. 1985; Hogan and Gow 1997; van der Veen et al. 1999; Sneed et al. 2011; Casey et al. 2014).

The visual investigation of SPICEcore revealed uniform stratigraphy without any significant dip ($>5^\circ$) or deformation to the internal layering. One visible tephra layer 0.5 cm thick was noted at a depth of 306.6 m in the

core and preliminarily dated to approximately 3561 ± 5 years BP (Figure 10). This layer was matched to a layer recently identified in the WAIS Divide ice core that was dated at about 3560 years BP (Sigl et al. 2016). This estimate also agrees with a layer previously identified from a shallow (361 m) ice core that was drilled at South Pole during the 1983–1984 field season (Palais et al. 1987; Parker et al. 1982). Based on the depth and estimated age of this layer within the core, it is very likely tied to the eruption of Candlemas Island in the South Sandwich Islands (Palais et al. 1987). This age and assessment is consistent with the preliminary depth-age scale determined here.

In addition to the many depth-hoar layers identified through the visual-stratigraphy observations, we also noted hundreds of wind or iced crusts. We observed and documented over 1900 individual crusts, equating to approximately 3 crusts per meter of core measured (Figure 11). We also observed several variations both with the frequency and appearance of these crusts, including 100 double crusts (defined as two crusts located <1 mm apart), 4 triple crusts (defined as three crusts each located <1 mm apart), and 58 bubble-free crusts (defined as clear crusts appearing to lack any internal bubbles, as in Figure 12).

Figure 9. Frequency distribution of annual accumulation for the upper 735 m of SPICEcore (histogram bin width = 0.5 cm). *Vertical lines* indicate average annual accumulation values determined in this study ($\sim 7.4 \text{ cm a}^{-1}_{\text{w.e.}}$) and in four additional studies for South Pole.

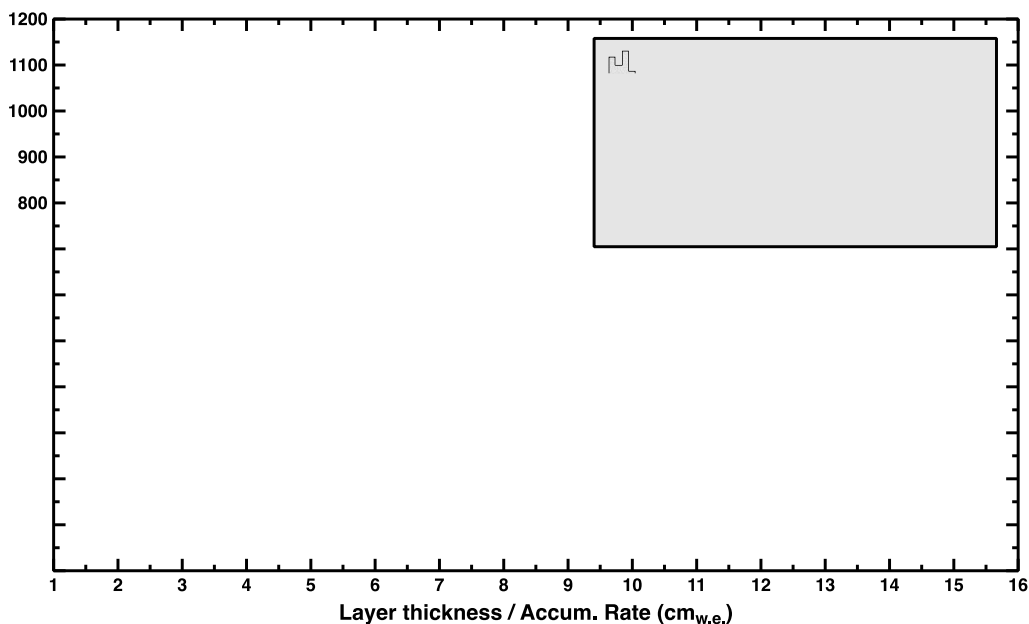


Figure 10. Visible tephra/ash layer observed at 306.6 m in SPICEcore and preliminarily dated to approximately 3561 years BP. This 0.5 cm wide tephra layer is likely tied to the Candlemas Island eruption on the South Sandwich Islands identified within the WAIS Divide ice-core record. Stratigraphic up-core is to the right as indicated (*red arrow*).



Figure 11. Vertical representation of all approximately 1900 recorded crusts for the upper 735 m of SPICEcore. Inset shows frequency over a selected 10 m interval (avg. ~3 crusts per meter).

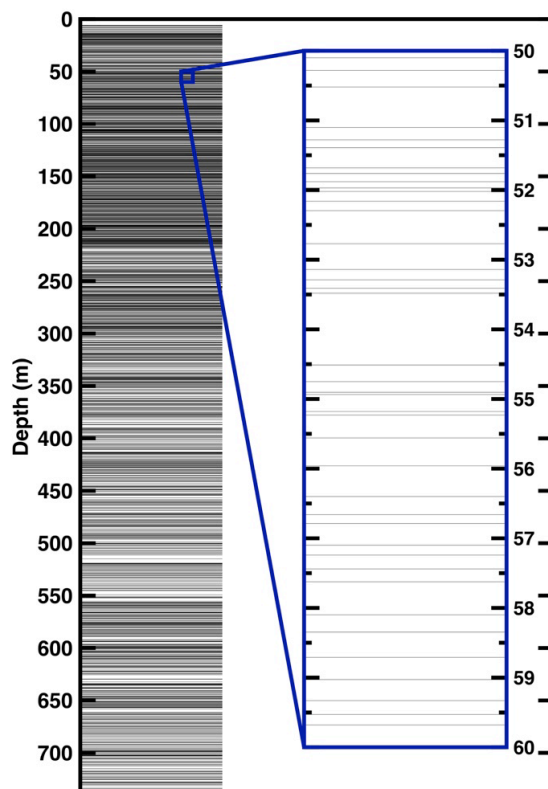
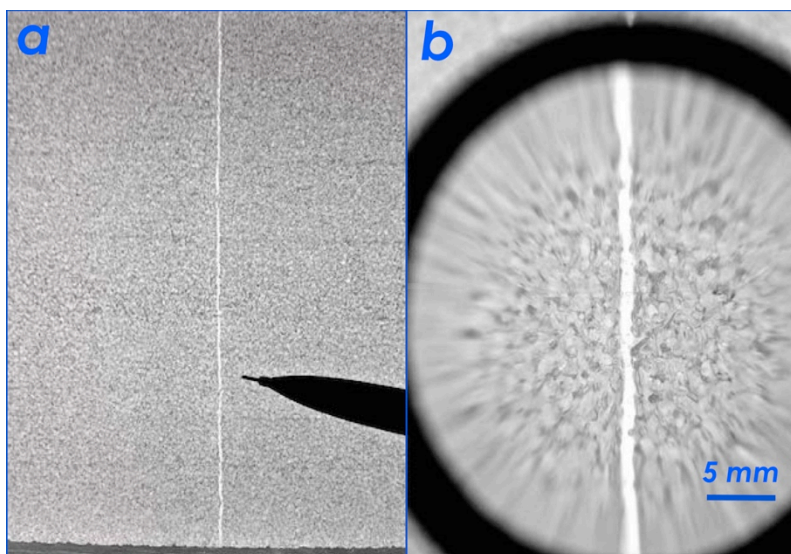


Figure 12. A bubble-free crust (*a*) observed at a depth of 74 m within SPICEcore shown with a pencil for scale. Inset (*b*) shows the crust as viewed through a 10× hand lens.



We noted a slightly higher number of crusts per core within the firm and shallow ice above 300 m, although below these depths it became more difficult to discern individual features due to the onset of significant layer diffusion. As seen in previous studies for South Pole (Gow 1965), we most often observed crusts as couplets, overlaying a low-density or hoar layer.

We have not conducted a detailed analysis of the crust seasonality in this study; however, preliminary estimates do indicate a slightly higher incidence of crust formation during late-summer periods based on the preliminary depth-age scale and identification of peak summers. This may indicate that crust formation at South Pole is at least partially driven by diurnal or meteorological forcings that create temperature inversions in the near surface of the snow (upper 40 cm), leading to upward vapor transport and deposition on the surface. This is consistent with findings by Fegyveresi et al. (2018) for other sites in Antarctica; however, a more-detailed investigation into the timing of the crusts would be necessary to confirm this hypothesis. Whitlow et al. (1992) noted that the South Pole site is characterized by low-level temperature inversions that can persist for much of the year due to a negative net-radiative surface energy balance, further bolstering this hypothesis. Near-surface temperature strings were recently (2016) deployed near the site at South Pole to measure for these temperature variations; however, these data have not yet been analyzed.

4 Discussion

4.1 Depth-age-scale uncertainty

To better constrain the SPICEcore depth-age-scale estimates and uncertainties, it was necessary to compare those estimates with other existing independent age estimates for the site. We made continuous ECM of each meter-long section of SPICEcore by using the scanning apparatus previously built and designed by Taylor et al. (1993). These measurements were taken during core processing just before each core was sent through the visual inspection booth. The purpose of these scans was not only to determine seasonal indicators such as acidity but also to ascertain specific volcanic markers using known eruptions dated in the WAIS Divide ice core (Sigl et al. 2013; Ferris et al. 2011). Volcanic events register as a distinct and recognizable return peak in their electrical output due the increased sulfate concentration (Taylor and Alley 2004).

In total, we documented 65 ECM peaks in SPICEcore that were confidently tied to known volcanic events observed in the WAIS Divide ice core (Table 3). We made these ties by comparing determined ages based on the published WAIS Divide timescale (WD2014) (Sigl et al. 2016; Buizert et al. 2015) and the preliminary SPICEcore depth-age scale determined here using visual stratigraphy. The maximum offset in ages between the preliminary SPICEcore timescale and the ECM tie-point dates at these 65 peaks (as dated using the WD2014 timescale) was 9 years; the average difference in the number of years between events was less than 2%.

After comparing the preliminary timescale with the determined ECM tie points, we produced a final reconciled SPICEcore timescale by adjusting the visual-stratigraphy interpretation within its uncertainty to better match the ages at ECM peaks (Figure 13). The offsets in the ECM matches at the 65 identified peaks between the SPICEcore visual stratigraphy timescale and the WD2014 timescale were thus reduced to less than 6 years and within the uncertainty of the WD2014 scale itself (see also Figure 14). The two oldest identified ECM matches were in the very bottom core at 734.8 and 734.9 m depths and dated to approximately 10,232 years BP and 10,234 years BP, respectively, making the overall total age at the very bottom (735 m) 10,235 years BP. The 65 discrete ECM tie points allowed for overall reduction in error estimates in the final SPICEcore depth-age scale, and therefore the aforementioned flat 1.0% error was reduced to a

0.5% error and was subsequently applied to the overall final depth-age-scale results (giving an approximately ± 51 years at 735 m).

Thus, the final bottom-depth age estimate (at 735 m) for SPICEcore is **10,235 $\pm$ 51** years BP. As previously noted in section 2.2, the overall 0.5% error is a high estimate (specifically at certain depth intervals), and our resultant annual picks and depth-age scale are likely much more precise. This estimate does, however, allow for the average of identified vague layer uncertainty, count reproducibility, and the various assumptions and other uncertainties previously discussed. Until a chemically or isotopically derived depth-age scale is determined for SPICEcore, this estimate safely represents any possible measurement or interpretation error.

Table 3. ECM-identified volcanic peaks within the upper 735 m of SPICEcore.

Depth (m)	SPICEcore Age (BP)	WDC14 Age (BP)	Offset (years)	Likely Source
33.2	134.5	134.6	-0.10	Tambora
33.9	140.2	140.6	-0.40	
72.5	491.0	491.6	-0.60	Kuwae
83.6	605.1	605.5	-0.40	
89.3	664.4	664.4	0.00	
90.2	673.6	673.5	0.10	Quilotoa
90.9	680.2	680.5	-0.30	
91.9	692.1	692.0	0.10	Samalas
94.6	720.2	720.4	-0.20	
99.7	778.4	778.5	-0.10	
140.7	1270.2	1268.0	2.20	
148.9	1375.3	1375.1	0.20	
151.6	1410.1	1409.7	0.40	
159.3	1511.4	1515.5	-4.10	
174.0	1689.1	1684.0	5.10	
176.6	1718.5	1713.6	4.90	Taupo
228.2	2380.5	2376.0	4.50	
275.7	3118.3	3122.0	-3.70	
289.6	3314.5	3311.0	3.50	
292.7	3359.6	3357.0	2.60	
293.4	3367.9	3365.0	2.90	
302.6	3502.0	3501.0	1.00	
306.6	3561.0	3560.0	1.00	Tephra—South Sandwich Islands
307.8	3577.1	3578.0	-0.90	
309.6	3604.6	3606.0	-1.40	
313.8	3667.9	3668.0	-0.10	
324.4	3818.0	3817.0	1.00	

Table 3 (cont.). ECM-identified volcanic peaks within the upper 735 m of SPICEcore.

Depth (m)	SPICEcore Age (BP)	WDC14 Age (BP)	Offset (years)	Likely Source
325.2	3830.6	3829.0	1.60	
328.3	3874.6	3874.0	0.60	
332.1	3928.0	3925.0	3.00	
336.6	3993.5	3989.0	4.50	
353.1	4226.3	4223.0	3.30	
395.6	4860.4	4861.0	-0.60	
430.7	5364.7	5361.0	3.70	
438.2	5468.6	5468.0	0.60	
447.6	5597.5	5599.0	-1.50	
448.7	5614.3	5616.0	-1.70	
497.1	6285.4	6283.0	2.40	
500.3	6328.2	6326.0	2.20	
511.7	6481.8	6480.0	1.80	
516.3	6545.4	6543.0	2.40	
517.0	6554.7	6552.0	2.70	
524.2	6655.7	6653.0	2.70	
524.9	6665.1	6662.0	3.10	
557.5	7173.0	7177.0	-4.00	
581.4	7573.0	7572.0	1.00	
598.7	7874.0	7871.0	3.00	
615.3	8175.0	8178.0	-3.00	
618.3	8227.0	8229.0	-2.00	
619.4	8246.0	8250.0	-4.00	
620.4	8262.0	8267.0	-5.00	
623.6	8320.0	8321.0	-1.00	
625.9	8359.0	8362.0	-3.00	
630.6	8443.0	8440.0	3.00	
651.5	8786.0	8781.0	5.00	
692.6	9451.0	9448.0	3.00	
701.6	9608.0	9606.0	2.00	
705.6	9683.0	9681.0	2.00	
707.9	9724.0	9725.0	-1.00	
711.4	9793.0	9790.0	3.00	
713.7	9837.0	9838.0	-1.00	
726.6	10079.0	10080.0	-1.00	
728.2	10110.0	10115.0	-5.00	
734.8	10232.0	10234.0	-2.00	
734.9	10234.0	10236.0	-2.00	

Figure 13. Final reconciled depth-age scale of the upper 735 m of SPICEcore, showing matches to known ECM peaks in the WAIS Divide core (see also Fig. 6 and Table 3).

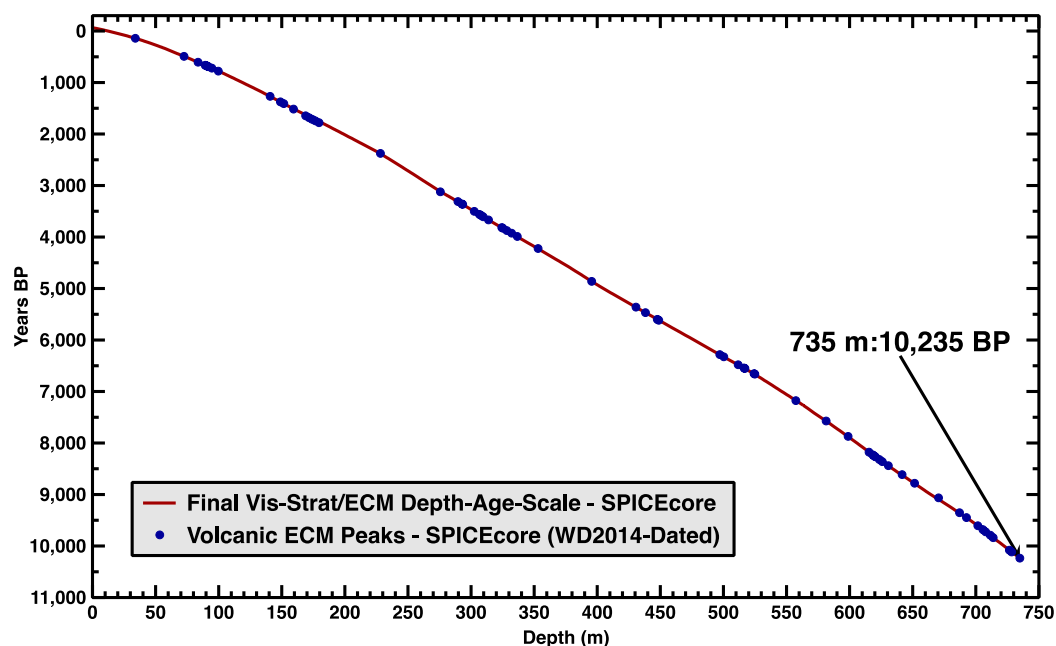
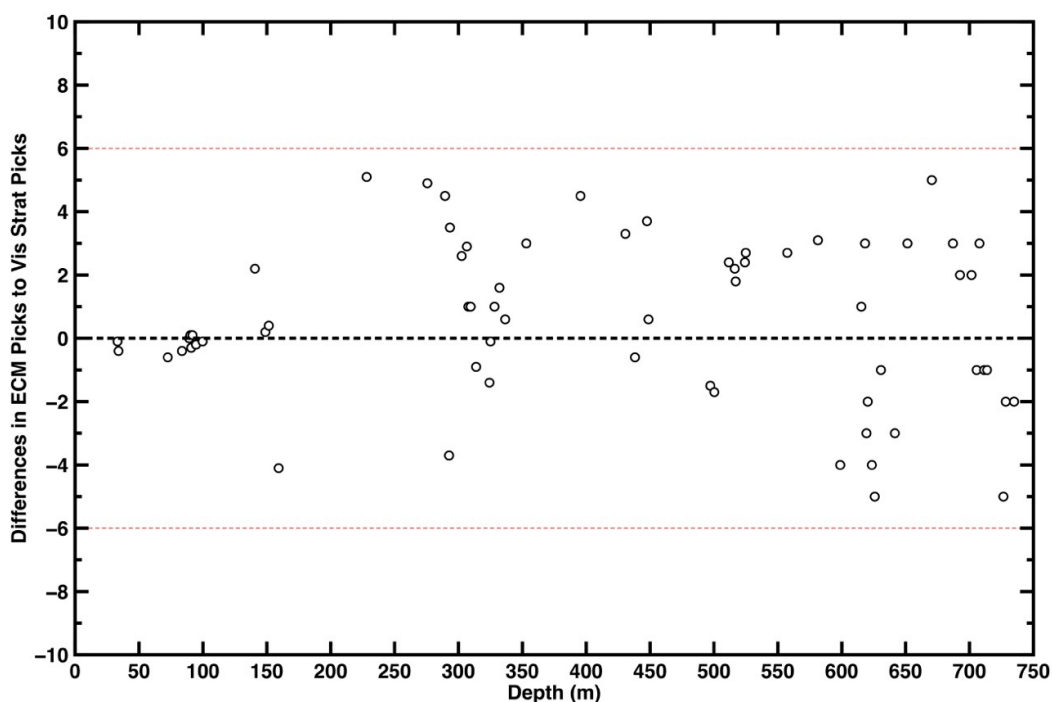


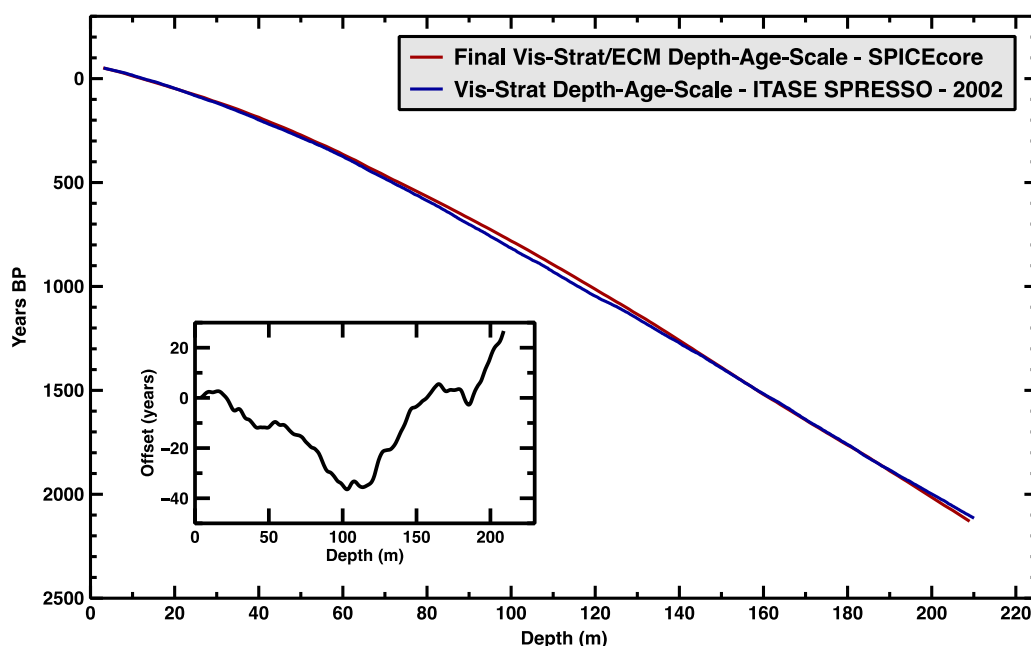
Figure 14. Calculated age offsets (years) for all 65 identified ECM peaks in SPICEcore, based on known WAIS Divide (WD2014) ages (see also Table 3). *Red lines* indicate offsets of ± 6 years.



As a means to further corroborate the accuracy of the final reconciled depth-age scale for SPICEcore, we compared it with the 207 m SPRESSO

core that was drilled as a part of the ITASE ice-core array project during the 2002–2003 field season (A. Gow, pers. comm., 2015; Sneed et al. 2011). This comparison (Figure 15) reveals a close agreement over the upper roughly 207 m of ice at the South Pole site. Because of the 12-year offset in core retrieval dates between SPICEcore and the SPRESSO core, (2002 vs. 2014) and the slight effects of snow compaction and thinning, it was necessary to offset the depth-age scale of the SPRESSO core by about 3 m to normalize both scales with the same depth registrations. This simple correction based on the SPICEcore depth for 12 years was sufficient for comparison purposes here and also agrees with an average year accumulation rate of about 7.5 cm_{we}. The bottom depth of 207 m in the SPRESSO core was therefore adjusted to a 2014-equivalent depth of 210 m in SPICEcore.

Figure 15. Comparison of the upper approximately 210 m of SPICEcore and the SPRESSO core (2014 depth equivalent). Inset shows offset residuals between the two depth-age scales. Average absolute residual offset over the entire comparison is about 13 years (0.6%).



At equivalent bottom depths (210 m), SPICEcore and the SPRESSO core give ages of approximately 2142 years BP and 2115 years BP, respectively. While this 27-year offset does equate to an approximate error of 1.3% for those ages, the average absolute residual error over the entire 210 m interval is about 13 years, or roughly 0.6% (see Figure 15 inset). This number is consistent with the established 0.5% average error discussed above. Most notably with the comparison, a maximum offset of 37 years occurs be-

tween these two timescales at 100 m depth. Though this equates to an almost 2% total error, it is important to note that the SPRESSO core timescale was compiled entirely using observations of visual stratigraphy (resulting in higher errors). As discussed in sections 2.2 and 2.3 above and similarly noted by van der Veen et al. (1999) in their analysis of previous South Pole accumulation studies, there are many errors and assumptions made when compiling measurements of visual stratigraphy that likely result in instances of either over- or undercounting of annual signals.

Also note that while this comparison between SPICEcore and the SPRESSO core only elucidates relative ages for the upper 210 m at the site, it still presents a useful result and an independent assessment of the reproducibility of ice-core dating through observations of visual stratigraphy.

As shown in section 3 (Figure 8), we determined a simple accumulation record for SPICEcore, which corrected for the effects of ice thinning and densification. While this reconstruction offers a sufficient approximation for the site due to the shallow depths of the ice measured, it does make several assumptions about the ice dynamics both at and upstream of the SPICEcore drill site. Most notably, this reconstruction assumes a uniform vertical strain rate (Nye thinning) for a site specifically characterized as a steep flank-flow site (Casey et al. 2014).

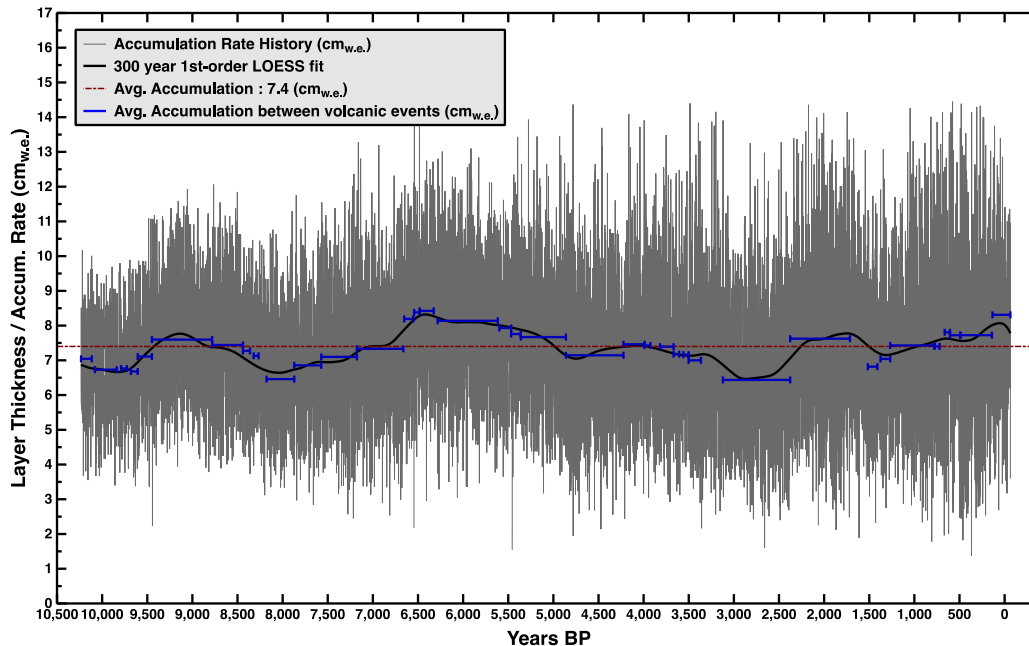
4.2 Accumulation history

Hamilton (2004) showed that for sites like South Pole, snow-accumulation rates are sensitive to local changes in ice-sheet surface slope and that topographic effects near a flank-flow site can be preserved in ice-core records. Thus, reconstructed accumulation rates derived from ice-core records like SPICEcore may be directly affected by the specific topographic trajectories of the source snow. On a relatively steep flank like South Pole, mean annual accumulation can be up to roughly 18% smaller than on a nearby topographic depression (Hamilton 2004). Combined with possible historical shifts in ice provenance and flow direction at South Pole, it is conceivable that observed trends in the accumulation history are not climatic signals but rather a result of ice-dynamics effects.

We inspected the SPICEcore accumulation record closer to further assess the observed extended trends in the reconstructed accumulation record, like those at 6700–5100 BP and 3100–2400 BP. Using the known ECM volcanic events within SPICEcore as tie points for well-defined depths and

ages (Table 3), average accumulation rates were determined over higher-resolution bracketed time intervals between volcanic events. These accumulation rates were therefore calculated independently by using only known depths and ages of identified volcanic events and not by reconstructing individual measured ice-layer thicknesses within the core itself. In this case, accumulation rates were averaged only over bracketed time intervals of at least 50 years to ensure adequate time to represent possible climatic signals. Figure 16 shows the resultant accumulation record with the bracketed estimates for average accumulation over time intervals between volcanic events of known ages. These higher-resolution accumulation estimates match well to the initial accumulation reconstruction and do corroborate the observed extended trends in the record, specifically those between 6700 and 5100 BP and 3100 and 2400 BP. This technique also appears to validate the two additional extended areas of possible interest between 8400 and 7300 BP and before 9600 BP.

Figure 16. Full accumulation record for the upper 735 m of SPICEcore, shown with 300-year LOESS fit (see also Fig. 8). Bracketed estimates for average accumulation over time intervals between volcanic events of known ages are shown in *blue*. The *red dashed line* indicates average accumulation over the entire record ($\sim 7.4 \text{ cm a}^{-1}_{\text{we}}$).



Truly authenticating the source of these extended accumulation trends requires additional analyses and site surveys. Specifically, an analysis of the stable isotopic record ($\delta^{18}\text{O}$) of SPICEcore will better elucidate true climatic signals. A secondary project is also planned for the SPICEcore

site at South Pole, including a several-hundred-kilometer upstream survey, to conduct ancillary ice-dynamics measurements. This project will better constrain the historical ice provenance for the SPICEcore site and help to deconvolve topographic effects from potential climate signals within the core.

5 Conclusions

We developed an initial chronology to 735 m and $10,235 \pm 51$ years BP for ice ages of SPICEcore. The ice-age timescale is based on two independent data sets: (1) visual identification of annual layers and (2) matches of ECM peaks to the WD2014 timescale for the WAIS Divide ice core via volcanic sulfate concentration peaks. The visual identification of annual layers was based on coarse-grained and depth-hoar layers (which were often overlain by a wind or iced crust). In total, we documented 65 ECM peaks in SPICEcore that we confidently tied to known volcanic events observed in the WAIS Divide ice core. By adjusting the visual-stratigraphy interpretation of SPICEcore within its uncertainty to match the ages at the 65 known ECM peaks, we determined a final reconciled timescale. The annual interpretation included an estimate of uncertainty of about 0.5%, which is in part corroborated through a comparison with the SPRESSO core. The offsets in ages between the final SPICEcore timescale (with the ECM matches) and the WD2014 timescale at the 65 peaks was reduced to less than 6 years and are all within the uncertainty of the WD2014 scale itself. The two oldest identified ECM matches were in the very bottom core at 734.8 and 734.9 m depths and dated to about 10,232 years BP and 10,234 years BP, respectively, making the overall total age at the bottom (735 m) $10,235 \pm 51$ years BP.

The timescale also allows an assessment of the accumulation history for SPICEcore. The thinning of layers due to ice flow is estimated based on a linear vertical strain rate (Nye model). The average accumulation rate is $7.4 \text{ cm a}^{-1}_{\text{we}}$ over the upper 735 m, approximately equal to the modern value (Casey et al. 2014). The accumulation history shows variability at centennial to millennial timescales, specifically with one 1600 year interval between 6700 and 5100 years BP that experienced higher-than average accumulation rates of $8.1 \text{ cm a}^{-1}_{\text{we}}$ and one 700 year interval from 3100 to 2400 years BP that experienced a lower-than average accumulation rate of $6.4 \text{ cm a}^{-1}_{\text{we}}$. These variations may be climatological in origin or they may be the result of either ice flow over undulating topography upstream or historical changes in ice provenance. Current and future funded investigations will allow the causes of these variations to be further assessed.

Through the physical properties investigation, we also observed and documented over 1900 individual crusts in SPICEcore. We documented several other variations that we observed in the core, including double crusts, triple

crusts, and bubble-free layers. One visible tephra layer was noted at a depth of 306.6 m in the core (~3560 BP), which is likely tied to an eruption of Candlemas Island in the South Sandwich Islands (Palais et al. 1987).

The preliminary chronology and accumulation record derived as a result of this study will ultimately be correlated with more-detailed future studies to better quantify a finalized depth-age scale, as well as climatic and ice-flow history and accumulation provenance for the South Pole site.

References

- Alley, R. B., C. A. Shuman, D. A. Meese, A. J. Gow, K. C. Taylor, K. M. Cuffey, J. J. Fitzpatrick, P. M. Grootes, G. A. Zielinski, M. Ram, and G. Spinelli. 1997. "Visual-Stratigraphic Dating of the GISP2 Ice Core: Basis, Reproducibility, and Application." *Journal of Geophysical Research: Oceans* 102 (C12): 26367–26381.
- Aydin, M., M. B. Williams, C. Tatum, and E. S. Saltzman. 2008. "Carbonyl Sulfide in Air Extracted from a South Pole Ice Core: A 2000 Year Record." *Atmospheric Chemistry and Physics* 8 (24): 7533–7542.
- Bamber, J. L., D. G. Vaughan, and I. Joughin. 2000. "Widespread Complex Flow in the Interior of the Antarctic Ice Sheet." *Science* 287 (5456): 1248–1250.
- Benson, C. S. 1962. *Stratigraphic Studies in the Snow and Firn of the Greenland Ice Sheet*. Research Report 70. Hanover, NH: U.S. Army Snow, Ice, and Permafrost Research Establishment.
- . 1971. "Stratigraphic Studies in the Snow at Byrd Station, Antarctica, Compared with Similar Studies in Greenland." In *Antarctic Snow and Ice Studies II*, ed. A. P. Crary, 333–353. Washington, DC: American Geophysical Union.
- Buizert, C., K. M. Cuffey, J. P. Severinghaus, D. Baggenstos, T. J. Fudge, E. J. Steig, B. R. Markle, M. Winstrup, R. H. Rhodes, E. J. Brook, T. A. Sowers, G. D. Clow, H. Cheng, R. L. Edwards, M. Sigl, J. R. McConnell, and K. C. Taylor. 2015. "The WAIS Divide Deep Ice Core WD2014 Chronology—Part 1: Methane Synchronization (68–31 ka BP) and the Gas Age–Ice Age Difference." *Climate of the Past* 11 (2): 153–173.
- Casey, K. A., T. J. Fudge, T. A. Neumann, E. J. Steig, M. G. P. Cavitte, and D. D. Blankenship. 2014. "The 1500 m South Pole Ice Core: Recovering a 40 ka Environmental Record." *Annals of Glaciology* 55 (68): 137–146.
- Fegyveresi, J. M., R. B. Alley, M. K. Spencer, J. J. Fitzpatrick, E. J. Steig, J. W. C. White, J. R. McConnell, and K. C. Taylor. 2011. "Late-Holocene Climate Evolution at the WAIS Divide Site, West Antarctica: Bubble Number-Density Estimates." *Journal of Glaciology* 57 (204): 629–638.
- Fegyveresi, J. M., R. B. Alley, J. J. Fitzpatrick, K. M. Cuffey, J. R. McConnell, D. E. Voigt, M. K. Spencer, and N. T. Stevens. 2016. "Five Millennia of Surface Temperatures and Ice Core Bubble Characteristics from the WAIS Divide Deep Core, West Antarctica." *Paleoceanography* 31 (3): 416–433.
- Fegyveresi, J. M., R. B. Alley, A. Muto, A. J. Orsi, and M. K. Spencer. 2018. "Surface Formation, Preservation, and History of Low-Porosity Crusts at the WAIS Divide site, West Antarctica." *The Cryosphere* 12 (1): 325–341.
- Ferris, D. G., J. Cole-Dai, A. R. Reyes, and D. M. Budner. 2011. "South Pole Ice Core Record of Explosive Volcanic Eruptions in the First and Second Millennia AD and Evidence of a Large Eruption in the Tropics around 535 AD." *Journal of Geophysical Research: Atmospheres* 116 (D17).

- Giovinetto, M. B., and W. Schwerdtfeger. 1965. "Analysis of a 200 Year Snow Accumulation Series from the South Pole." *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie A*, 15 (2): 227–250.
- Gow, A. J. 1965. "On the Accumulation and Seasonal Stratification of Snow at the South Pole." *Journal of Glaciology* 5 (40): 467–477.
- Hamilton, G. S. 2004. "Topographic Control of Regional Accumulation Rate Variability at South Pole and Implications for Ice-Core Interpretation." *Annals of Glaciology* 39 (1): 214–218.
- Hogan, A. W., and A. J. Gow. 1997. "Occurrence Frequency of Thickness of Annual Snow Accumulation Layers at South Pole." *Journal of Geophysical Research: Atmospheres* 102 (D12): 14021–14027.
- Johnson, J. A., A. J. Shturmakov, T. W. Kuhl, N. B. Mortensen, and C. J. Gibson. 2014. "Next Generation of an Intermediate Depth Drill." *Annals of Glaciology* 55 (68): 27–33.
- Kuhns, H., C. Davidson, J. Dibb, C. Stearns, M. Bergin, and J. L. Jaffrezo. 1997. "Temporal and Spatial Variability of Snow Accumulation in Central Greenland." *Journal of Geophysical Research: Atmospheres* 102 (D25): 30059–30068.
- Kuivinen, K. C. 1983. "A 237-Meter Ice Core from South Pole Station." *Antarctic Journal of the United States* 18 (5): 113–114.
- Kuivinen, K. C., B. R. Koci, G. W. Holdsworth, and A. J. Gow. 1982. "South Pole Ice Core Drilling, 1981–1982." *Antarctic Journal of the United States* 17 (5): 89–91.
- Lazzara, M. A., G. A. Weidner, L. M. Keller, J. E. Thom, and J. J. Cassano. 2012. "Antarctic Automatic Weather Station Program 30 Years of Polar Observations." *Bulletin of the American Meteorological Society* 93 (10): 1519–1537.
- McConnell, J. R., R. C. Bales, and D. R. Davis. 1997. "Recent Intra-Annual Snow Accumulation at South Pole: Implications for Ice Core Interpretation." *Journal of Geophysical Research: Atmospheres* 102 (D18): 21947–21954.
- Mosley-Thompson, E., and L. G. Thompson. 1982. "Nine Centuries of Microparticle Deposition at the South Pole." *Quaternary Research* 17 (1): 1–13.
- Mosley-Thompson, E., P. D. Kruss, L. G. Thompson, M. Pourchet, and P. Grootes. 1985. "Snow Stratigraphic Record at South Pole: Potential for Paleoclimatic Reconstruction." *Annals of Glaciology* 7:26–33.
- Mosley-Thompson, E., J. F. Paskievitch, A. J. Gow, and L. G. Thompson. 1999. "Late 20th Century Increase in South Pole Snow Accumulation." *Journal of Geophysical Research: Atmospheres* 104 (D4): 3877–3886.
- Neff, P. D. 2014. "A Review of the Brittle Ice Zone in Polar Ice Cores." *Annals of Glaciology* 55 (68): 72–82.
- Nye, J. F. 1963. "Correction Factor for Accumulation Measured by the Thickness of the Annual Layers in an Ice Sheet." *Journal of Glaciology* 4 (36): 785–788.

- Palais, J. M., P. R. Kyle, E. Mosley-Thompson, and E. Thomas. 1987. "Correlation of a 3,200-Year-Old Tephra in Ice Cores from Vostok and South Pole Stations, Antarctica." *Geophysical Research Letters* 14 (8): 804–807.
- Parker, B. C., E. J. Zeller, and A. J. Gow. 1982. "Nitrate Fluctuations in Antarctic Snow and Firn: Potential Sources and Mechanisms of Formation." *Annals of Glaciology* 3 (1): 243–248.
- Rignot, E., J. Mouginot, and B. Scheuchl. 2011. "Ice Flow of the Antarctic Ice Sheet." *Science* 333 (6048): 1427–1430.
- Sigl, M., J. R. McConnell, L. Layman, O. Maselli, K. McGwire, D. Pasteris, D. Dahl-Jensen, J. P. Steffensen, B. Vinther, R. Edwards, and R. Mulvaney. 2013. "A New Bipolar Ice Core Record of Volcanism from WAIS Divide and NEEM and Implications for Climate Forcing of the Last 2000 Years." *Journal of Geophysical Research: Atmospheres* 118 (3): 1151–1169.
- Sigl, M., T. J. Fudge, M. Winstrup, J. Cole-Dai, D. Ferris, J. R. McConnell, K. C. Taylor, K. C. Welten, T. E. Woodruff, F. Adolphi, and M. Bisiaux. 2016. "The WAIS Divide Deep Ice Core WD2014 Chronology—Part 2: Annual-Layer Counting (0–31 ka BP)." *Climate of the Past* 12 (3): 769–786.
- Sneed, S. B., P. A. Mayewski, and D. A. Dixon. 2011. "An Emerging Technique: Multi-Ice-Core Multi-Parameter Correlations with Antarctic Sea-Ice Extent." *Annals of Glaciology* 52 (57): 347–354.
- Souney, J. M., M. S. Twickler, G. M. Hargreaves, B. M. Bencivengo, M. J. Kippenhan, J. A. Johnson, E. D. Cravens, P. D. Neff, R. M. Nunn, A. J. Orsi, and T. J. Popp. 2014. "Core Handling and Processing for the WAIS Divide Ice-Core Project." *Annals of Glaciology* 55 (68): 15–26.
- Taylor, K. C., and R. B. Alley. 2004. "Two-dimensional Electrical Stratigraphy of the Siple Dome (Antarctica) Ice Core." *Journal of Glaciology* 50 (169): 231–235.
- Taylor, K. C., C. U. Hammer, R. B. Alley, H. B. Clausen, D. Dahl-Jensen, A. J. Gow, N. S. Gundestrup, J. Kipfstuhl, J. C. Moore, and E. D. Waddington. 1993. "Electrical Conductivity Measurements from the GISP 2 and GRIP Greenland Ice Cores." *Nature* 366 (6455): 549–552.
- Van der Veen, C. J., E. Mosley-Thompson, A. J. Gow, and B. G. Mark. 1999. "Accumulation at South Pole: Comparison of Two 900-Year Records." *Journal of Geophysical Research: Atmospheres* 104 (D24): 31067–31076.
- WAIS Divide Project Members. 2013. "Onset of Deglacial Warming in West Antarctica Driven by Local Orbital Forcing." *Nature* 500 (7463): 440–444.
- Whitlow, S., P. A. Mayewski, and J. E. Dibb. 1992. "A Comparison of Major Chemical Species Seasonal Concentration and Accumulation at the South Pole and Summit, Greenland." *Atmospheric Environment. Part A. General Topics* 26 (11): 2045–2054.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) July 2019		2. REPORT TYPE Technical Report/Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Visual Observations and Stratigraphy of the South Pole Ice Core (SPICEcore): A Preliminary Holocene (~10.2 ka) Accumulation Record and Depth-Age Chronology				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) John M. Fegyveresi, Tyler J. Fudge, David G. Ferris, Dominic A. Winski, and Richard B. Alley				5d. PROJECT NUMBER 1542778	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) See reverse.				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CRREL TR-19-10	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Science Foundation 2415 Eisenhower Avenue Alexandria, VA 22314				10. SPONSOR/MONITOR'S ACRONYM(S) NSF	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT We present an initial chronology for the newly drilled South Pole Ice Core (SPICEcore). Annual layers observed in the visual stratigraphy of the upper 735 m indicate a total ice age chronology of $10,235 \pm 51$ BP (years before 1950), with a total average accumulation rate of approximately $7.4 \text{ cm a}^{-1}_{\text{we}}$. Comparing electrical conductivity measurement peaks in the core with known volcanic events observed in other Antarctic ice cores corroborates these estimates. This history shows accumulation trends, which could indicate past climatological or glaciological changes at the site. Specifically, one 1600-year interval between 6700 and 5100 years BP experienced a higher-than-average accumulation rate ($\sim 8.1 \text{ cm a}^{-1}_{\text{we}}$) while one 700-year interval from 3100 to 2400 years BP experienced a lower-than-average accumulation rate ($\sim 6.4 \text{ cm a}^{-1}_{\text{we}}$). We used seasonal equivalent coarse-grained and depth-hoar layers to identify the annual "picks" (noted as summers); and the stratigraphy in the core was generally uniform and well-preserved. We observed and documented over 1900 individual wind or iced crusts. We noted one visible tephra layer at a depth of 306.6 m in the core (~ 3560 years BP), which is likely tied to an eruption of Candlemas Island in the South Sandwich Islands.					
15. SUBJECT TERMS Antarctic history, Climatic changes, Cyrospheric science, Glaciology, Ice core chronology, Ice core dating, Ice cores, Ice--Antarctica, Ice-sheet History, Polar science, Polar volcanic records, Snow accumulation, South Pole history, SPICEcore					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) (cont.)

U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

University of Washington
Department of Earth and Space Sciences
Johnson Hall 070, Box 351310
4000 15th Avenue NE
Seattle, WA 98195-1310

Dartmouth College
Department of Earth Sciences
6105 Fairchild Hall
Hanover, NH 03755-3529

University of Maine
School of Earth and Climate Sciences & Climate Change Institute
5790 Bryand Global Sciences Center
Orono, ME 04469-5790

Pennsylvania State University
Department of Geosciences
517B Deike Building
University Park, PA 16802