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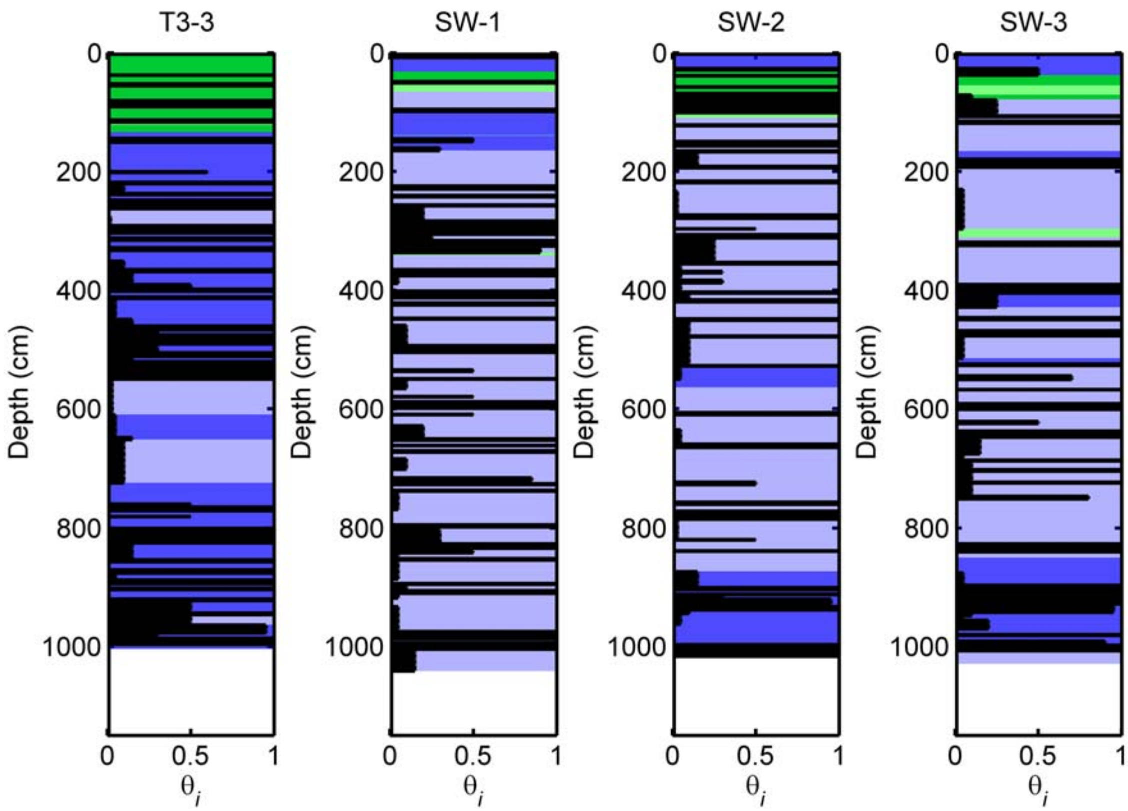

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Firn Stratigraphy and Temperature to 10 m Depth in the Percolation Zone of Western Greenland, 2007–2009

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PROJECT ABSTRACT

We present data from a field campaign focused on meltwater infiltration and horizontal water transport processes in firn of western Greenland. Data were collected during 2007–2009 along a 90 km transect extending from 2000 to 1300 m elevation. Fifteen intensive study sites were spaced 5–10 km along the transect. Near-surface heat flow was measured at each site with 33 channel thermistor strings extending to 10 m depth and logging year-round on a 30 min time base. Firn stratigraphy and density were measured in 10-m-deep ice cores, with 2 or more cores at each study site for a total of 34 cores.

Analysis and interpretation these data are made in other publications. Those analyses show that from 2000 to 1625 m elevation surface melt is minimal and meltwater infiltrates vertically to form thin ice layers. Between ~1625 and 1475 m elevation strong surface melt infiltrates to fill about half of the available pore space of the upper 10 m. Infiltration shows a high degree of spatial variability in this elevation zone, with some water moving vertically and some water moving horizontally on top of decimeter- to meter-thick ice layers of irregular extent. In places, meltwater infiltrates to more than 10 m depth, and through multi-decade-old firn (i.e., well below the previous year's accumulation). Below ~1475 m elevation, nearly all pore space is filled by infiltrated meltwater and excess water runs off. Both our thermal and density measurements indicate that the runoff limit is above the equilibrium line by on the order of 300 m in elevation and a distance of 30 km. Our results have implications for understanding the mass balance and surface elevation changes of the Greenland Ice Sheet.

1. INTRODUCTION

This paper presents temperature and shallow ice core stratigraphy and firn temperatures collected in the percolation zone of western Greenland (Fig. 1, Table 1). Ice cores were drilled at 15 different sites along a transect of the lower EGIG line (Fischer et al., 1995), with at least two cores drilled at each site. At one site, Crawford Point, nine cores were collected in a grid pattern (Fig. 2). Cores were collected over three field campaigns during the summers of 2007–2009 (Table 2). Firn temperatures were measured in at least one 10 m hole at each of the sites, and multi-year time series of temperature were collected at all but one site. The data and their collection methods are described in detail below.

The data presented here were collected as part of a study of meltwater runoff processes and firn densification in Greenland's percolation zone. Other observations, including radar imaging and dye tracing experiments, were also collected and are presented elsewhere (e.g., Brown et al., in press; Sturgis, 2009). The purpose of this paper is to simply archive temperature and stratigraphy data in a format and location accessible to future workers. Other papers either already published, or in preparation at the time of this publication, present detailed analysis and interpretation of these data.

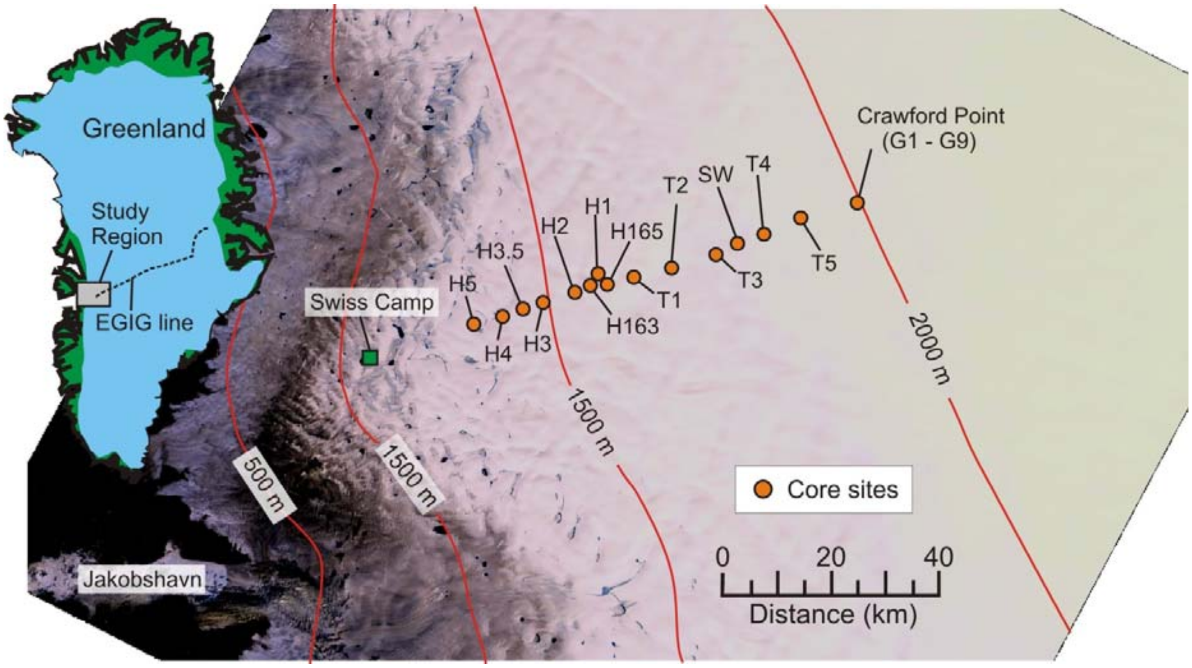

FIGURE 1. Map showing location of coring sites. Nine cores were collected at Crawford Point, four cores at SW, and one core at H5. Two cores were collected at all other sites. Temperature strings were installed at all sites but SW.

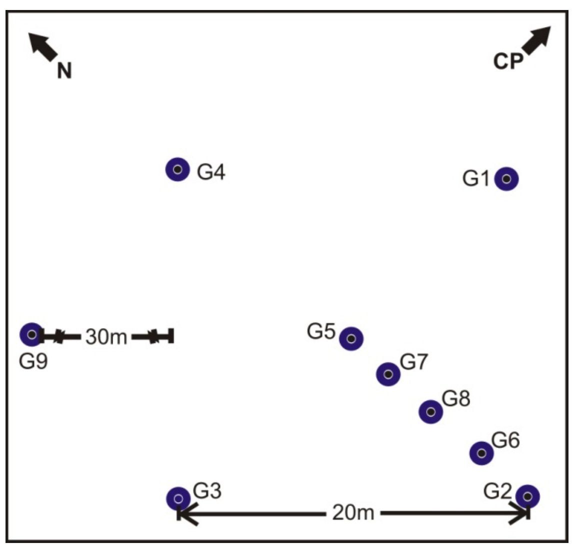

FIGURE 2. Map showing arrangement of coring sites in the 'grid' area at Crawford Point. See Figure 1 for location. Note that G9 is 30 m northeast of the G4/G3 border of the grid.

TABLE 1. Location of coring and temperature measurement sites shown in Figure 1.

Site	Latitude (°N)	Longitude (°W)	Elevation (m a.s.l.)
G1-G9	69.8765	47.0102	1997
T5	69.848017	47.273583	1932
T4	69.819983	47.4505	1877
SW 1	69.800944	47.567889	1845
SW 2	69.800944	47.567889	1845
SW 3	69.805861	47.542417	1856
SW 4	69.793222	47.607806	1835
T3	69.7836	47.670183	1819
T2	69.756933	47.880283	1750
T1	69.738017	48.060967	1710
GGU163	69.72505	48.1902	1660
H1	69.739083	48.2403	1680
GGU165	69.719783	48.2674	1644
H2	69.706167	48.344967	1555
H3	69.687433	48.499667	1540
H3.5	69.673933	48.591117	1497
H4	69.660183	48.68945	1401
H5	69.64372	48.81594	1333

TABLE 2. Year and date in which firn cores were drilled and logged. Core site names referenced to map show in Figure 1.

Year	Date	Coring Site
2007	6/25	T3-1
2007	6/28	T1-1
2007	6/28	T2-1
2007	7/1	G1
2007	7/1	G2
2007	7/1	G3
2007	7/1	G4
2007	7/1	G5
2007	7/8	T4
2007	7/5	SW-1
2007	7/5	SW-2
2007	7/5	SW-3
2007	7/5	SW-4
2007	7/6	G6
2007	7/6	G7
2007	7/7	T5
2007	7/9	T3-2
2007	7/9	T3-3
2007	7/10	G8
2007	7/10	G9
2008	5/16	H1
2008	5/18	H3
2008	5/21	GGU165
2008	5/21	H2
2008	5/22	GGU163
2008	5/23	H4-1
2008	5/24	T1-2
2008	5/27	H1-15
2008	5/27	H1-30
2008	5/28	H4-2
2008	5/28	H3.5

2. ICE CORE DRILLING

The cores were drilled using a Kovacs core drill with a 9-cm-diameter core barrel. A gasoline power-head was used to turn the drill (Fig. 3). Core segments of 10–50 cm were typically retrieved in each drilling/raising sequence. Plastic spacers (water bottles) were placed on the Kovacs drill extensions in order to prevent strings with multiple extensions from scraping the hole walls and filling the hole with shavings. A 10 m core could usually be drilled in about 1 hr with a crew of 2–3 experienced drillers. The core logging procedure, however, was usually rate limiting, especially where the stratigraphy was complex. Cores were therefore typically drilled over a time interval closer to 2 hrs.

FIGURE 3. Photograph showing drilling with Kovacs 9 cm coring drill and power-head. Note spacers on drill extensions.

3. CORE LOGGING

Cores were logged for stratigraphy and density in the field. The cores were subsequently discarded. Logging was done on a cleared and packed area of the snow surface and behind a wind shelter constructed adjacent to the drill hole (Fig. 4). Two people recorded the stratigraphy, a core-logger and a note-taker. As core segments were retrieved from the core barrel, the stratigraphy and other properties were immediately recorded for that segment. All stratigraphic units and boundaries were categorized by visual inspection, sometimes using a hand lens and a cutting saw. The volumetric percentage of ice was visually estimated.

The topmost ~1 m of the cores was typically disaggregated and thus was either poorly logged, or not logged at all. When the surface was melting, as was often the case in 2007, we started the hole at the base of a shallow snow pit dug through the surface slush. During 2008 and 2009 the surface conditions were always cold, but the surface snow was poorly consolidated. Attempts were made to collect and log this surface snow, but the cores sometimes disintegrated as they were removed from the core barrel.

After logging the stratigraphy, the cores were weighed in order to compute density based on mass and volume. In most cases, the core sections were cut to about 15 cm lengths for weighing if they were retrieved in longer sections. The section weights were measured using a battery powered digital scale with 1 g resolution and 4000 g capacity. Irregular breaks in the ends of the cores led to the biggest source of inaccuracy to the density calculations as the volume of the core is less certain. Attempts were made to minimize this inaccuracy by visually estimating the core length so that irregular breaks were averaged out. In addition, longer cores with irregular ends were not cut to shorter sections for weighing so that the irregular end would have smaller percentage-wise impact on the density calculation. As with the stratigraphy, the density of the upper 1 m was often difficult to measure. In some cases, surface densities were measured in an adjacent snowpit using a rip cutter snow sampler.

FIGURE 4. Photograph of core logging station. Cores were logged on a cleared area of the snow surface located behind a wind screen.

4. STRATIGRAPHIC UNITS

The data presented in this paper delineate the stratigraphy into seven different units.

Dry snow – Recent snowfall or snow from the previous winter season. Often consists of wind-blown angular crystal fragments. No signs of melt/freeze or grain rounding by dry or wet metamorphic processes.

Wet snow – Recent snowfall or snow from the previous winter season containing detectable pore water. Often consisting of wind-blown angular crystal fragments. Snow wetness ranges from damp (i.e., ~1% by volume free water) to saturated slush.

Faceted crystals – Coarse-grained crystals with angular corners and planar sides. Usually poorly bonded to one another. Commonly called "depth hoar". Interpreted to have formed under a temperature/vapor pressure gradient.

Wetted facets – Faceted crystals as described above, but with signs of subsequent wetting by liquid water. A fraction of the pore space filled with refrozen meltwater.

Unwetted firn – Fine-grained, well sintered firn showing no signs of infiltration by melt water.

Wetted firn – Fine-grained, well sintered firn with refrozen meltwater in pore spaces. Often accompanied by ice layers or ice pipes.

Percent ice – Fraction of the core occupied by refrozen meltwater in the form of discrete ice layers or ice pipes. Defined in the legend as θ and ranging from 0 to 1, where 1 indicates the core is entirely occupied by a layer or pipe of refrozen meltwater.

5. CORE PROFILES

The stratigraphy of 32 cores is displayed in Figures 5–12.

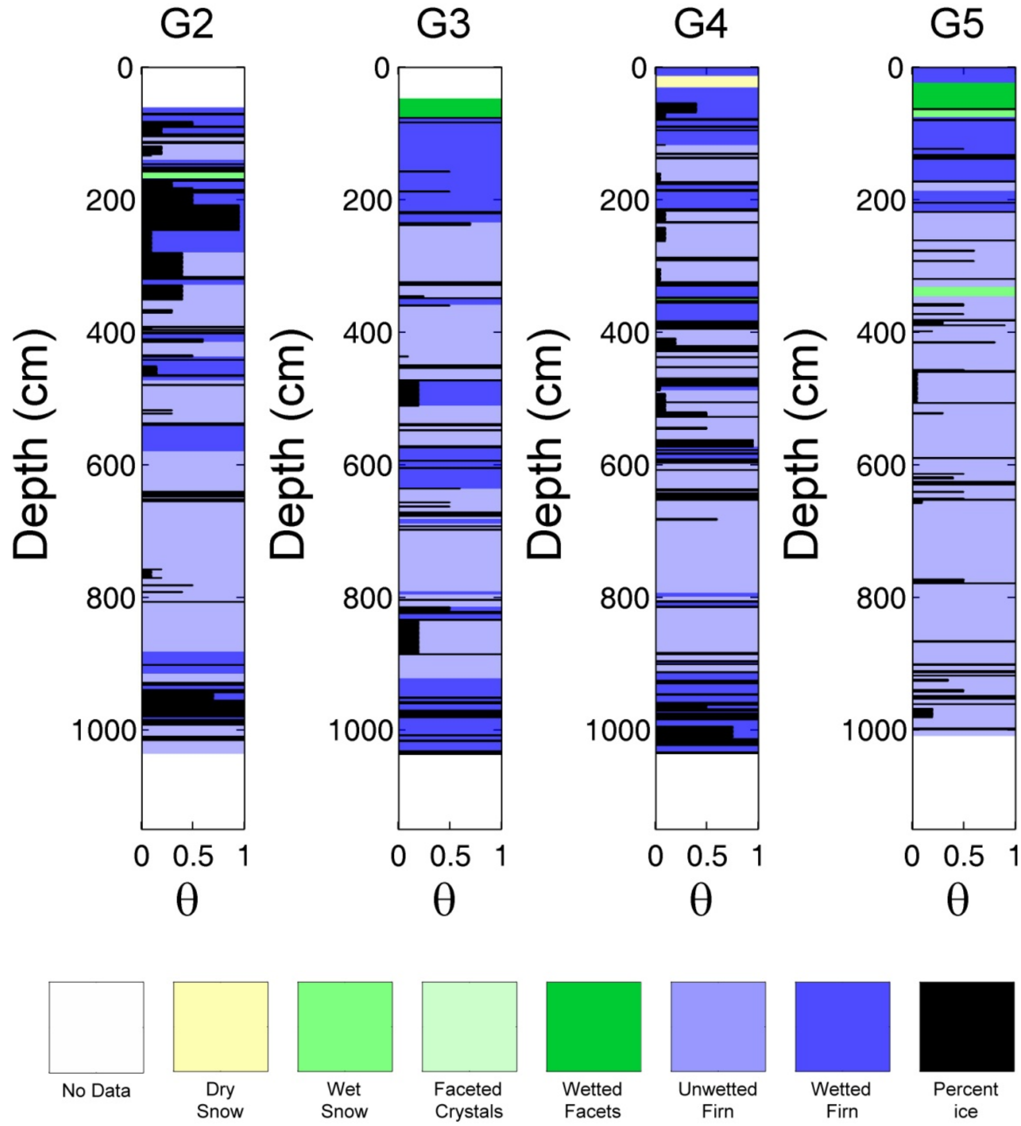

FIGURE 5. Plot showing stratigraphy and concentration of infiltration ice (θ, percent ice) of four ~10 m ice cores. Core locations are labeled at top of stratigraphic columns.

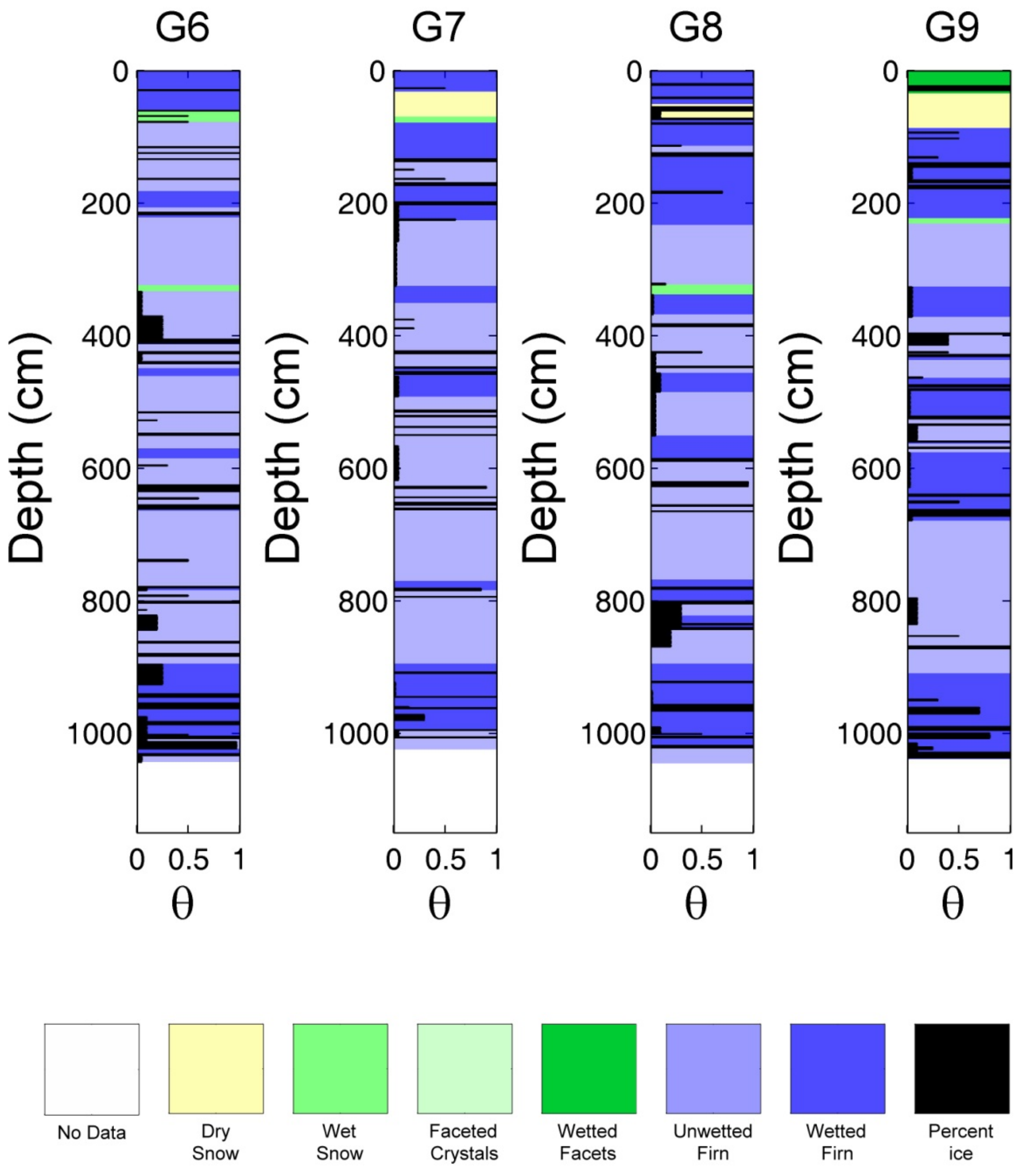

FIGURE 6. Plot showing stratigraphy and concentration of infiltration ice (θ, percent ice) of four ~10 m ice cores. Core locations are labeled at top of stratigraphic columns.

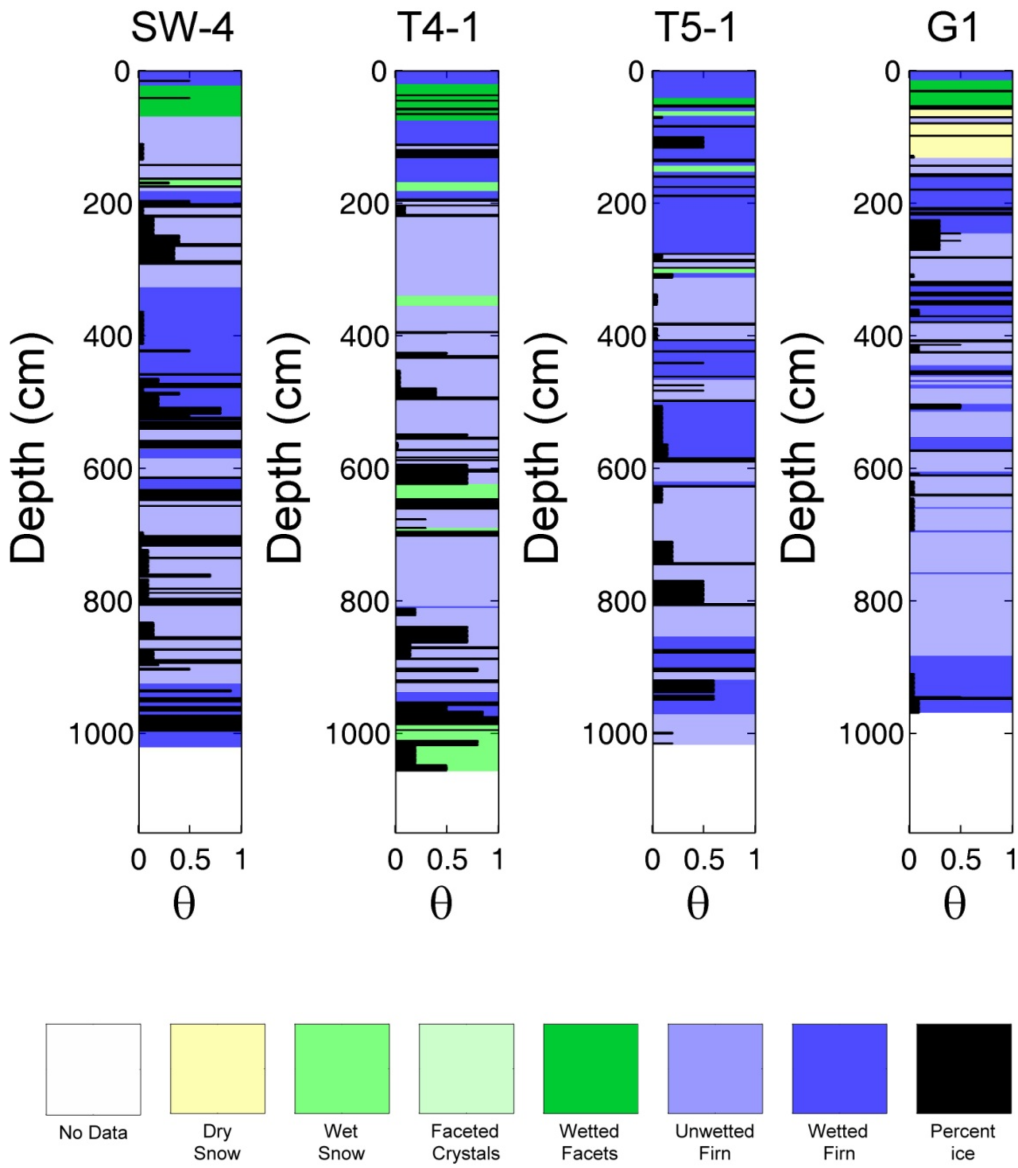

FIGURE 7. Plot showing stratigraphy and concentration of infiltration ice (θ, percent ice) of four ~10 m ice cores. Core locations are labeled at top of stratigraphic columns.

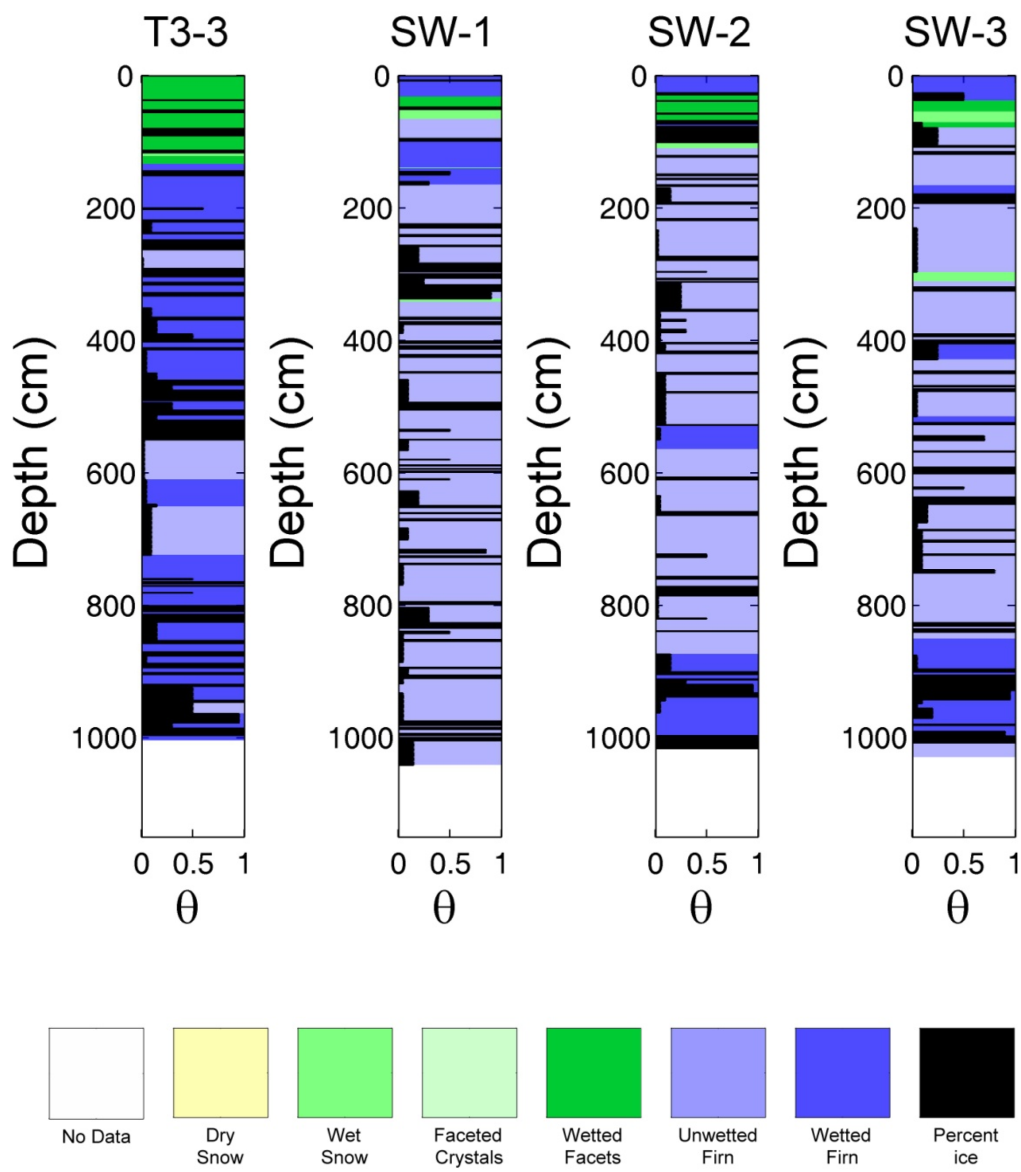

FIGURE 8. Plot showing stratigraphy and concentration of infiltration ice (θ, percent ice) of four ~10 m ice cores. Core locations are labeled at top of stratigraphic columns.

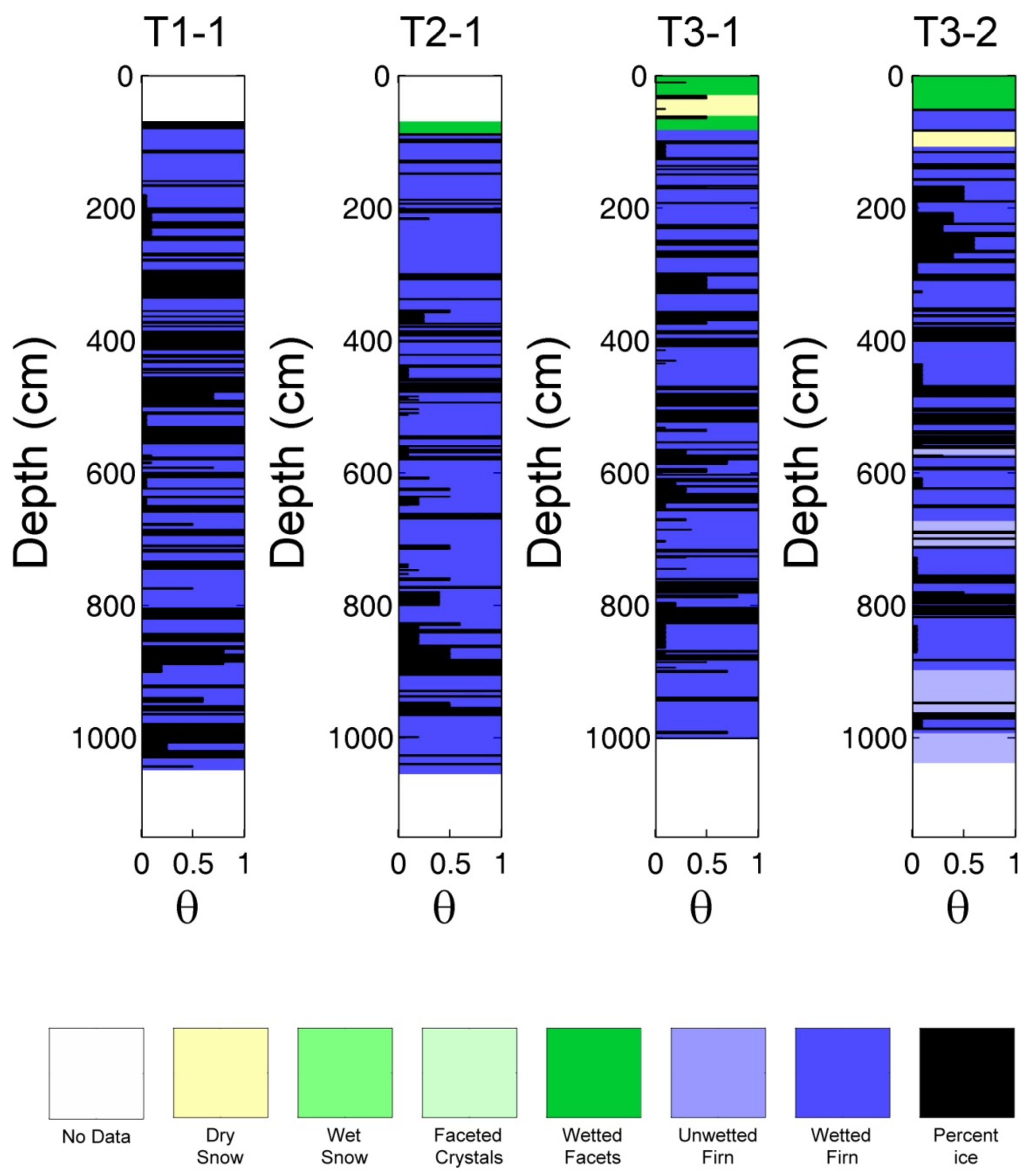

FIGURE 9. Plot showing stratigraphy and concentration of infiltration ice (θ, percent ice) of four ~10 m ice cores. Core locations are labeled at top of stratigraphic columns.

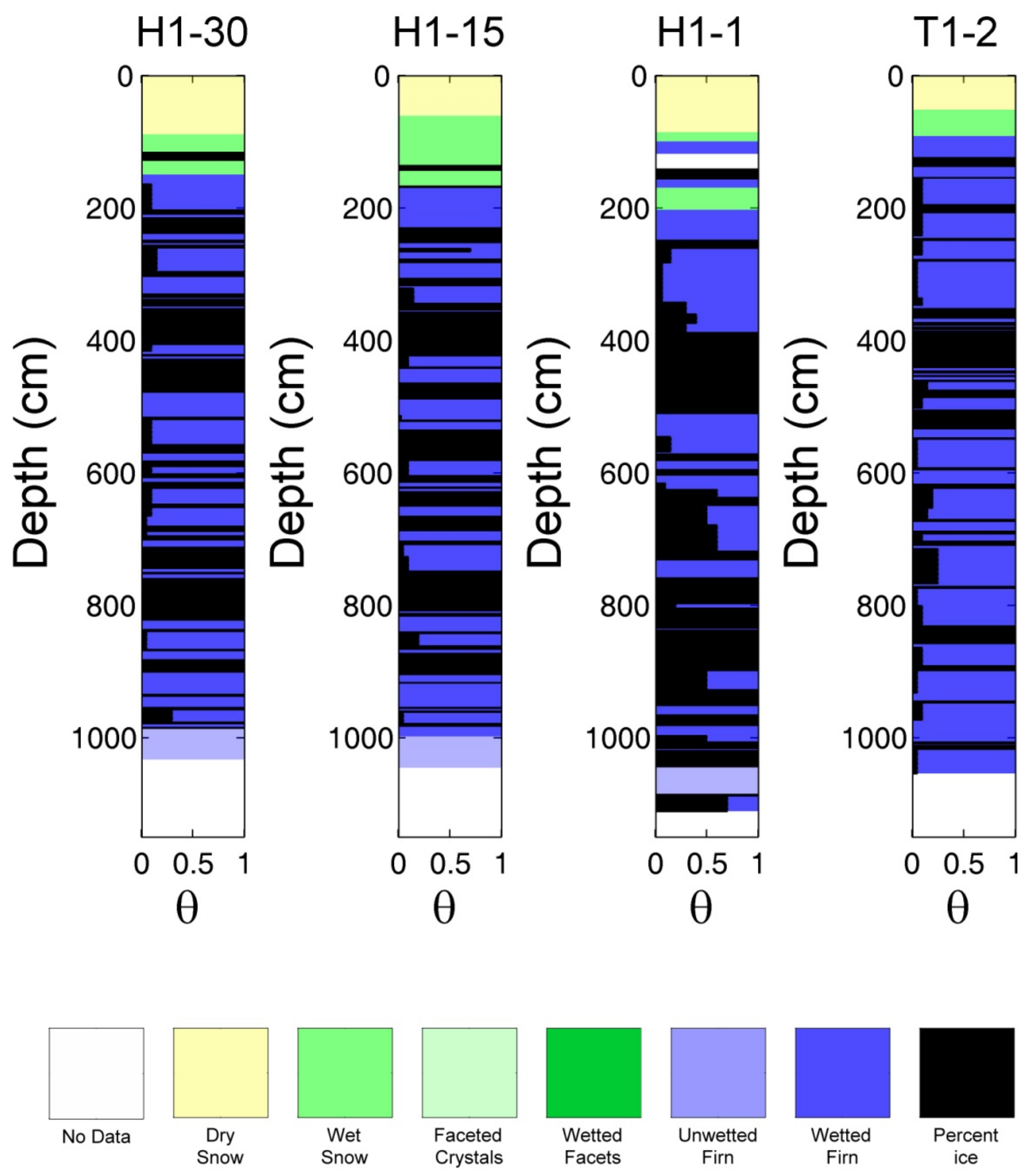

FIGURE 10. Plot showing stratigraphy and concentration of infiltration ice (θ, percent ice) of four ~10 m ice cores. Core locations are labeled at top of stratigraphic columns.

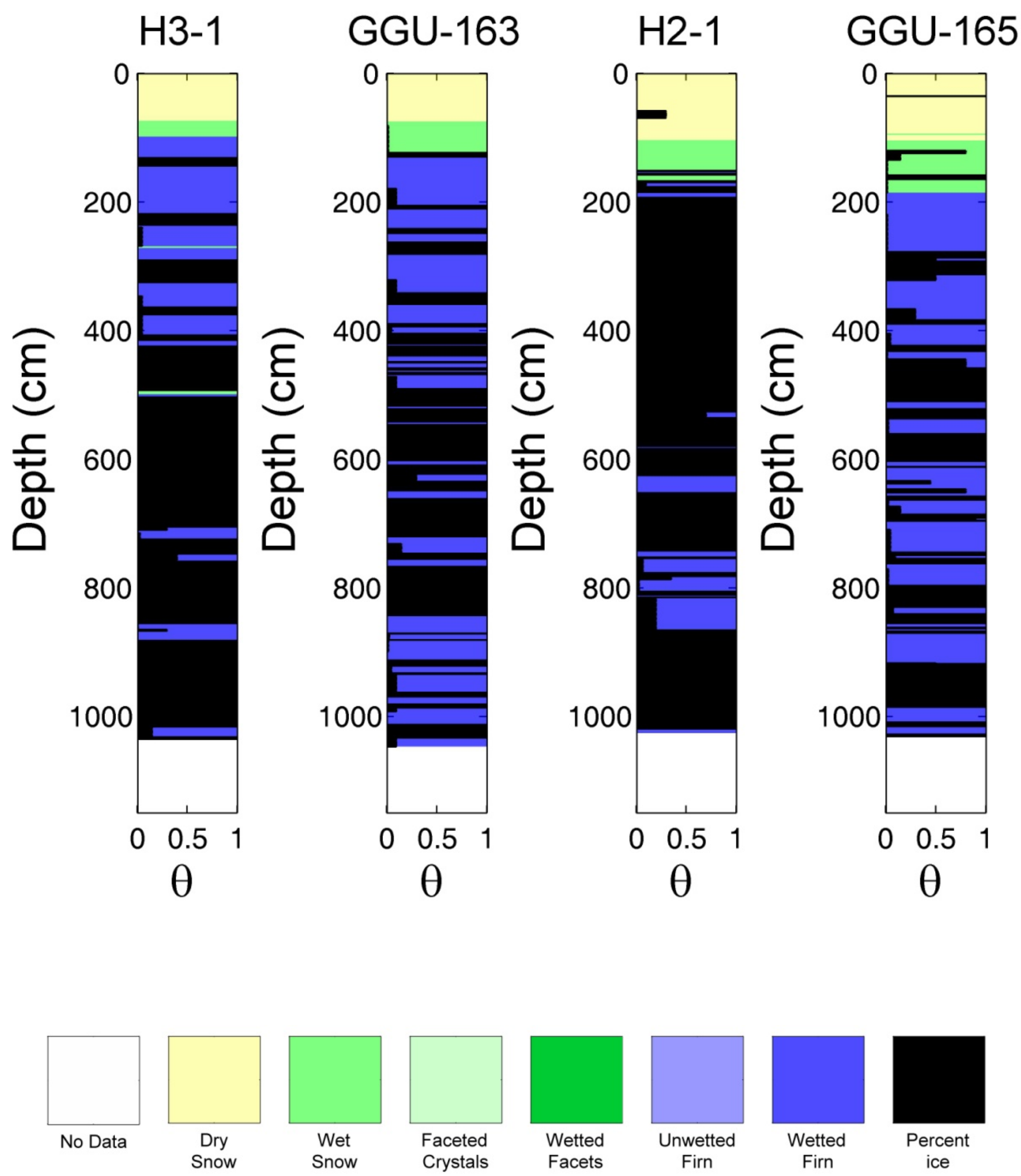

FIGURE 11. Plot showing stratigraphy and concentration of infiltration ice (θ, percent ice) of four ~10 m ice cores. Core locations are labeled at top of stratigraphic columns.

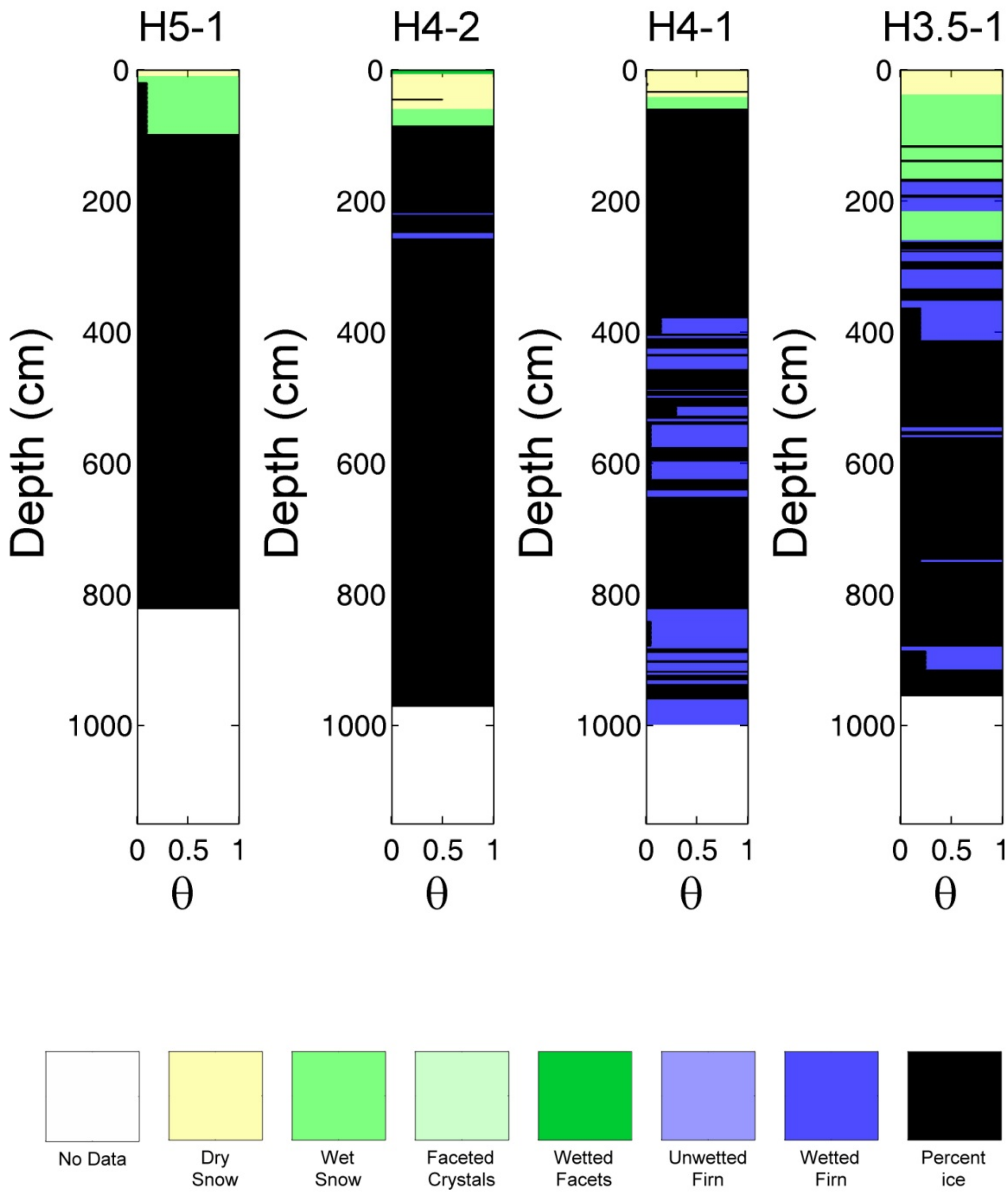

FIGURE 12. Plot showing stratigraphy and concentration of infiltration ice (θ, percent ice) of four ~10 m ice cores. Core locations are labeled at top of stratigraphic columns.

6. FIRN TEMPERATURE

At each of the study sites (Fig. 1) at least one borehole was instrumented for temperature using thermistor strings with 32 sensors. The lowest thermistor was installed at 10 m depth below the current snow surface. Other sensors were installed at 0.25 m to 0.50 m intervals between the surface and the bottom of the borehole (Table 3). The boreholes were backfilled with cold snow. We found that the 10 m temperature of the boreholes stabilized within a fraction of a degree in under a day after emplacement.

Sealed 50K ohm thermistors were used to reduce self heating. The thermistors have a nominal 1% accuracy, and performance of a sampled subset was checked from +5 °C to –15 °C compared to manufacturer supplied thermistor calibration curves. All thermistors were given a one-point calibration both in a cold room, and a final field calibration in a snow/water bath, before emplacement. As a result of these calibrations we believe that the temperatures recorded are accurate to better than ¼ °C. The temperature data were recorded to a precision of 1/50 °C. Thermistor aging caused some of the thermistors to vary with time on the order of ¼ °C.

Data were continuously recorded on specially constructed, 32 channel, 12 bit data loggers (Fig. 13). These ruggedized loggers operate on approximately 2 microamps of power, and can operate for over a year on small AA-sized lithium-ion batteries. The loggers use a 32 channel multiplexer of advanced design with less than 2 ohms differential between channels. The errors introduced by the logger did not exceed our test equipment, and therefore could not be measured. Data were stored in flash, nonvolatile, memory. The loggers operated for the duration of the project, recording data every 15 minutes in summer and every hour during winter. Water condensation within the logger cases in 2007 caused considerable lost data during the winter of 2007–2008. We cured the problem in 2008 and subsequently had complete data recovery.

As a result of the staggered installation and download dates, data along the line are not all from the same time period. For sites CP, T4, and T3 we have a year of data from approximately June 2007 to May 2008. For sites T2 and T1, we have data spanning two years from June 2007 to May 2009. For sites G165, G163, H1, to H4, we have data from May 2008 to May 2009. Finally we have a 2 day record from site H5 in May 2009. There are two temperature strings located 10 m apart at site T1, one installed in 2007 and one in 2008, which allowed us to compare the data obtained with slightly different thermistor strings and loggers used in the two years.

TABLE 3. Positions of thermistors on temperature strings.

Thermistor positions, nominally below surface (m)
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
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6.00
6.50
7.00
7.50
8.00
8.50
9.00
9.50
10.0

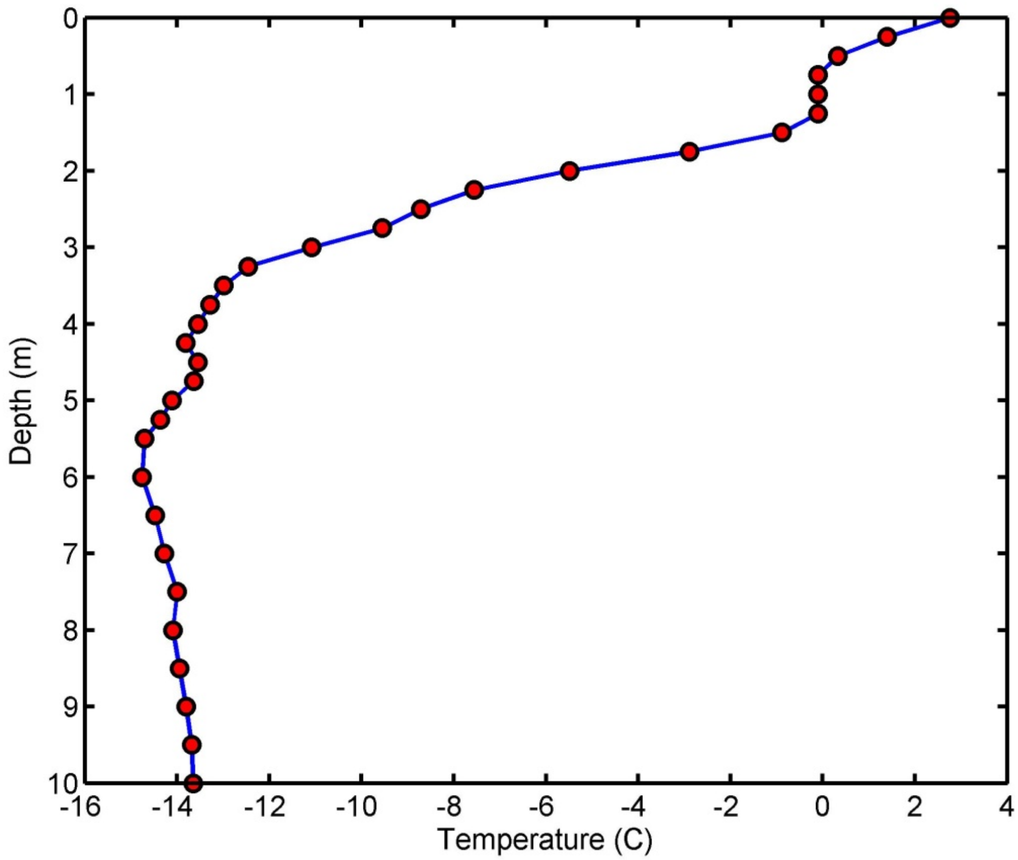

FIGURE 13. Plot showing example of temperature data from thermistor string at site T3. Red dots show 32 temperatures measured in 10 m borehole. A time slice on decimal day 176.3958 is shown in plot. Note that thermistors at positions 0 m, 0.25 m, and 0.50 m all show positive air temperatures. This indicates they have melted out by the time these data were collected and they now sit above the snow surface. Thermistors at 0.75 m, 1.0 m, and 1.25 m indicate melting snow conditions with temperatures at 0 °C.

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DIGITAL APPENDICES

Appendix 1. Core Data (“`CoreData.zip`” zipped directory, PC Windows).

List and description of files:

`readme.txt` – ASCII text file with general information about the data set.

`SiteLocations.txt` – ASCII text file with latitude, longitude, and elevation of coring sites as shown in Figure 1 of this paper. Column headings are given at top of file.

AllCores_Lithology.txt – ASCII text file with stratigraphic unit delineations for each core. Column headings are given at top of file. Stratigraphic delineations appear in column 4 and are keyed to the units described in Section 4 above, such that:
0 = no data; 1 = dry snow; 2 = wet snow; 3 = Faceted crystals; 4 = Wetted facets; 5 = Unwetted firn; 6 = Wetted firn; 7 = Ice layer.

AllCores_Mass.txt – ASCII text file with mass and density measurements. Column headings are given at top of file. Mass of core section and average density are displayed in last two columns.

Appendix 2/Firn Temperature Data ("TempData.zip" zipped directory, PC Windows).

List and description of files:

readme.txt – ASCII text file with general information.

CP.txt, G163.txt, G165.txt, H1.txt, H2.txt, H3.txt, H4.txt, H5.txt, T1new.txt, T1old.txt, T2_08.txt, T2_09.txt, T3.txt, T4.txt – ASCII text files with temperature data. The data files consist of ASCII text in lines with 33 columns of numbers. The first column is a time stamp and is the decimal days after the first second of January 1, 2007. For example, January 1, 2007, is a fractional day (not day 1 as it would be with day-of-year). The time interval between measurements is typically 5 to 15 minutes, although it is as long as 30 minutes at some of the lower stations during the coldest months of winter (the loggers were programmed to take fewer measurements during the depths of winter). The subsequent 32 columns in the data are the temperatures in Celsius of the thermistor locations, starting at the top of the temperature string. The thermistors are placed with a 25 cm spacing in the top 5.5 m and a 50 cm spacing in the lower 4.5 m. The bottom of the string is nominally at 10 m below the surface, with the top at the surface. However, as a result of the ablation and accumulation that occur during year or multi-year emplacements, these locations are nominal. The traverse line occupies the lower accumulation zone, so that most strings experienced between 25 cm and 1 m of accumulation, although at times during the peak of the melt season, 1 or more of the top thermistors were exposed to the atmosphere.

Note – T1new.txt and T1old.txt are two different thermistor strings installed at location T1. T1old was installed in 2007, and T1new was installed in 2008.

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