Surface Elevation and Velocity Changes on the South Central Greenland Ice Sheet: 1980-2011 - Data Summary

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Cover photo (courtesy of Dr. K.C. Jezek): A Twin Otter aircraft supports re-occupation of an OSU cluster site marked here with an aluminum pole and red flag. The sites were first occupied in 1980 and measurements have continued through 2011. Future measurements are anticipated in support of NASA's ICESat-2.

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Table of Contents

Abstract

Glaciological observations were made from 1980 to 2011 at a network of measurement sites on the south central Greenland Ice Sheet. Measurements include in situ observations begun by I. Whillans, Wallops Flight Facility airborne lidar measurements, in situ measurement made as part of PARCA, ICESat measurements, and in situ measurement made by the author. Data are summarized here in tabular form. A digital spread sheet of the results is also available. Graphical depictions and a discussion of the results can be found in Jezek (2012).

1. Introduction

Three measurement networks were established on the south-central Greenland ice sheet by The Ohio State University (OSU) in 1980 and again in 1981. At each site, in situ surface elevation, ice thickness, surface velocity, surface gravity, and firn physical property measurements were first carried out by a team led by Ian Whillans (Whillans and others, 1984; Whillans and others, 1987; Kostecka and Whillans, 1988). Whillans designated the sites as Dye-3, Central and Western Cluster (Figure 1). Whillans' original data are summarized in van der Veen and others (2000).

Subsequent to Whillans' study, in-situ GPS surface measurements were repeated at several OSU sites as part of the PARCA surface traverse program (Thomas and others, 2000): three Central Cluster sites in 1993 and again in 1995. Several of the Central and Western sites were reoccupied during June 2003, 2004 and 2005, and surface gravity, position and elevation were re-measured by the author using Global Positioning System instruments and gravimeters. All of the original cluster sites have been over-flown on an opportunity basis by the Wallops Flight Facility Airborne Topography Mapper (ATM) (Krabill and others, 1995; Thomas and others, 1999). The last overflight occurred in 2011 as part of NASA's Operation IceBridge, which is tasked with assuring continuity of the ice sheet elevation change record during the period between ICESat and ICESat-2. In fact, ICESat data acquired within the vicinity of one benchmark in each cluster allow for an estimate of elevation change during the ICESat period of observations.

This brief report summarizes observations at the clusters from 1980 to 2011. Included are measurements not previously presented in tabular form in the literature and also measurement summaries which conflate several data sets individually available elsewhere. Amongst these data are: in situ GPS geodetic measurements carried out at the Western and Central sites from 2003-2005; combined surface elevation measurements at all three OSU sites; gravity measurements at Central Cluster; surface velocity at several sites in Central and Western clusters; accumulation rate measurements at Central Cluster; shallow pit and core data at Central Cluster. Jezek (2012) discusses the scientific interpretation of the data set.

2. The OSU Clusters

Whillans and others (1984) made geodetic and other geophysical measurements at the Cluster sites in 1980 and 1981 using Doppler satellite tracking receivers tied to Doppler receiver base stations at fixed sites in Sondrestrom and Nuuk on the west coast of Greenland. Receivers were positioned at the node points shown in Figure 1. Sites were marked with accumulation rate poles, usually visible for one to two years after initial emplacement. Barometric measurements of relative ice elevation were used to interpolate elevations between the nodes.

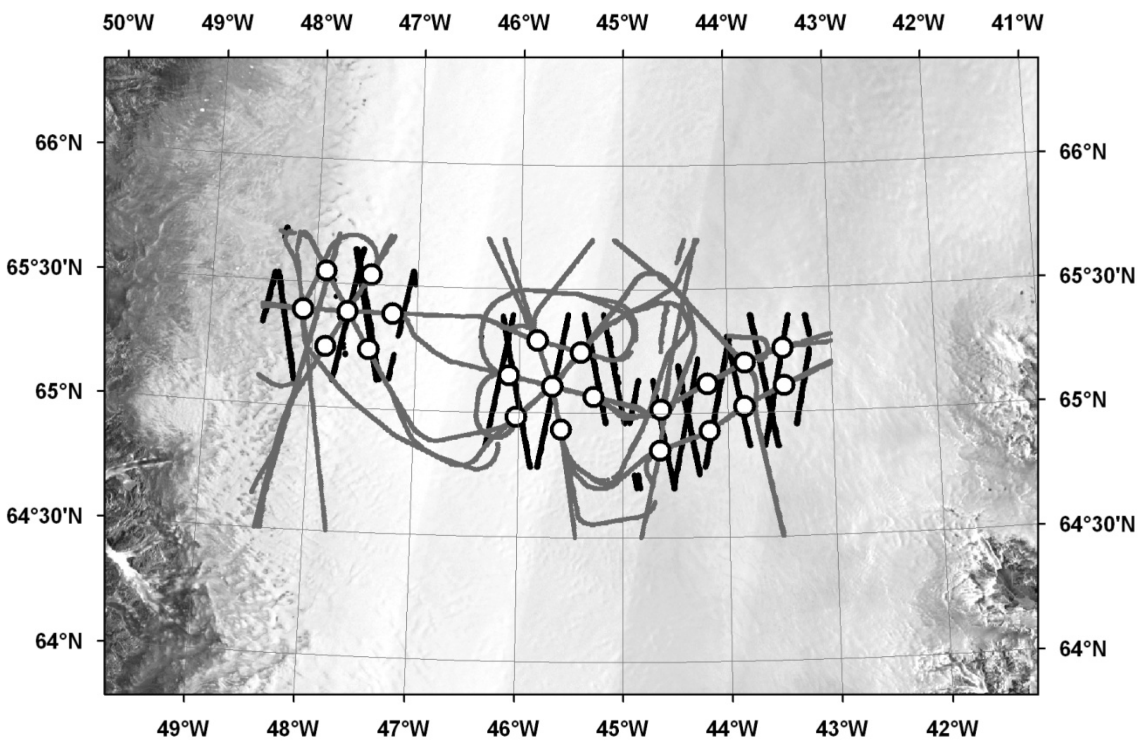

Figure 1. Locations of original OSU cluster nodes (circles), ATM overflights (grey) and ICESat observations (black). Western cluster (about 47.5^{o} W long) and Central Cluster (45.6 ^{o} W long) are located on the western side of the ice divide which in turn is located at the western extent of Dye-3 cluster. The central node for the two hexagonal clusters is labeled 01. The due east node becomes 02 with the labels increasing in a clockwise direction. At Dye-3 the most northeasterly site is labeled 01 progressing up and down till station 08 in the south west corner. A two digit prefix is appended to each node to identify the cluster (e.g. 1001 is the central node at the

western cluster; 2001 is the central node at the central cluster; 3001 is the most northeasterly node at the Dye-3 cluster). Background is a Radarsat-1 synthetic aperture radar (SAR) image mosaic.

Sites were subsequently resurveyed using Whillans' geographic coordinates as benchmarks. GPS receivers, operated on the surface and tied to a base station in Sondrestrom, were used to relocate the sites and this was successfully done to within about 20 m based on the post processing results. Receivers were deployed usually in early June and for several hours to several days to determine the precise locations where a new aluminum pole was deployed. GPS data reduction was carried out by the Wallops Flight Facility team (J. Sonntag, personal communications, 2003-06). Repeated measurements were used for estimating surface displacement and accumulation. Aircraft laser altimeter flights were also designed to resurvey the sites (Krabill and others, 1995a; Thomas and others 1999). The most recent of these missions was part of the Arctic 2011 Operation IceBridge Campaign. Because the cross track scan of the ATM is about 200 m when the aircraft if flown 500 m above the ice sheet surface, elevation data were typically collected within a few meters of the designated measurement site.

Gravity measurements were made at all the sites in 1981 (Jezek and others, 1985) and at the Central site in 2003 using a Lacoste Romberg meter. Data were referenced to the International Gravity Station Network by occupying several stations in and around Sondrestrom and are estimated to be accurate to about 0.02 mgal. The meter was transported to the sites via surface vehicle in 1981 and via a Twin Otter aircraft in 2003. The gravity measurements were made within about 1 m of the GPS antenna in the field.

A 10-m core was collected at Central Cluster in 1993. Density and stratigraphy were recorded. Shallow pit data were also collected at Central Cluster in 2003.

ICESat data are distributed across the cluster sites. However, only three sites were located close enough to ICESat tracks so as to enable a reasonably accurate slope correction. The near coincident sites were Western Cluster 1001, which is the center node of the rosette; Central Cluster 2001, which is also the central node; and 3001 which is the farthest north-east point in the Dye-3 cluster)

3. Tabular Data

The following tables include data collected during the 2003-2005 deployments to the OSU cluster sites as well as data summaries that span the period from 1980-1981. Original measurements reported or otherwise available elsewhere are not duplicated here (for example Whillans 1980-81 data are all available in van der Veen and others (2000, 2001) and ICESat data are available from NSIDC). However references to the location of basic measurements are included.

3.1. GPS Data: Years 2003-2005

Original surface elevation data from in situ GPS measurements for the years 2003-2005 are presented in Table 1. Coordinates are referenced to ITRF 2000 and the WGS-84 ellipsoid. Snow surface heights are in meters. The data were processed from the raw GPS files by J. Sonntag. These data show the actual antenna coordinates and surface elevations as determined in 2003-2005 and so do not include slope corrections to translate the observations back to the original OSU coordinate.

Table 1. Surface Elevation and Position from In Situ GPS Observations: 2003-2005

Year: 2003							
Station	2001	2002	2003	2004	2005	2006	
Lat	65 06 30.74771	65 04 02.49242	64 55 58.04774	64 58 53.86262	65 08 56.81268	65 17 35.10058	
Long	45 41 12.70018	45 17 14.58329	45 35 46.24260	46 01 35.06830	46 06 13.32414	45 50 02.17894	
Surface Elevation	2526.907	2594.598	2575.4273	2493.988	2451.285	2465.695	
Year: 2004							
Station	1001		1003			1006	1007
Lat	65 23 16.27305		65 14 13.76876			65 32 49.48577	65 32 24.51312
Long	312 19 35.84841		312 32 21.95937			312 6 15.42224	312 32 12.95967
Surface Elevation	2031.39		2135.36			1913.44	2033.81
Station	2001	2002	2003	2004	2005	2006	
Lat	65 6 30.89714	65 4 2.64626	64 55 58.18229	64 58 54.01177	65 8 56.97243	65 17 35.28739	
Long	314 18 46.61795	314 42 44.93101	314 24 13.15826	313 58 24.11803	313 53 45.82488	314 9 57.06943	
Surface	2527.16	2594.83	2575.46	2494.29	2451.42	2465.9	

Elevation							
Year: 2005							
Station	1001		1003			1006	1007
Lat	65 23 16.64613		65 14 14.17703			65 32 49.84334	65 32 24.92086
Long	312 19 33.23243		312 32 19.29587			312 6 12.05403	312 32 13.25639
Surface Elevation	2031.66		2135.12			1913.24	2033.79
Station	2001				2005	2006	
Lat	65 6 31.04769				65 8 57.12736	65 17 35.47246	
Long	314 18 45.93146				313 53 44.97529	314 9 56.31762	
Surface Elevation	2527.37				2451.71	2465.96	
Coordinates referenced to ITRF 2000, WGS-84 ellipsoid							
Surface Heights in meters							
GPS data processed by J. Sonntag							
Note that local slope corrections were subsequently applied based on offset between GPS antenna							
position and original OSU coordinate. Data shown here are GPS antenna positions and do not include slope correction.							

3.2. Elevation Time Series

In situ and Airborne Topographic Mapper elevation data were compiled and conflated to create time series observations at the cluster stations. Data averaging was applied for years in which more than one measurement was made. The 1980 geographic coordinates in table 2 were provided by E. Fredericks and referenced to ITRF93. Because these coordinates were used to control ATM flights over the clusters and because a comparison of Central Cluster coordinates showed less than 1 meter difference between ITRF93 geographic coordinates and ITRF2000, the coordinates of the 1980 stations are taken equivalent in either frame for the purposes of this table. Sites re-occupied with GPS instruments were typically displaced from the intended site by several 10s of meters. Hence, in order to extrapolate the elevation and other measurements to the intended location, slope corrections were applied by computing the local, average slope vector and computing the scalar product of the slope and measurement-offset vectors. Average slopes can be deduced from the elevation contour maps constructed from the original OSU data.

Regional slope at lower cluster station 1001 is about (~.01). Slopes are slightly less at Central (~0.004) and Dye-3 (~0.007). These tend to mask small scale changes in slope that can be important in local corrections. Consequently slopes provided as part of the ATM ICESSN 1-km product were used to refine slope estimates (Figure 2) (Krabill, 2010a). The local correction is key to making a proper comparison between the ICESat and in situ data at this site.

Individual laser shot data acquired by the ATM instrument, termed q-fit by the ATM project (Krabill, 2010b), were incorporated into the elevation records for each OSU station. As noted above, shot locations did not always coincide exactly with the OSU stations. Consequently, several shots about the station were interpolated to the station position.

Table 2. Time series of combined ATM and in situ elevation (in meters) data for the OSU Cluster Sites. Data were averaged in cases where multiple observations were made in a particular year.

Lower Cluster

Station	Lat 1980	Long 1980	1980	1981	1993	1994	1995	1997	1998	2003	2004	2005	2011
1001	65.387647	312.327239	2029.103	2028.813	2030.736	2030.887			2031.03		2031.487	2031.899	2031.3247
1002	65.386762	312.762313	2170.423		2170.967	2171.031			0				2171.561
1003	65.23707	312.540178	2133.089	2133.169	2134.708	0			2135.31		2135.945	2136.304	2135.233
1004	65.242286	312.129507	1995.31		1997.047	1996.968			1997.451				1996.731
1005	65.390374	311.890526	1866.984		1869.062	1868.921			1869.427				1868.174
1006	65.546866	312.104823	1910.978	1912.698	1913.24	0			1913.813		1913.467	1913.312	1911.88
1007	65.539912	312.537651	2032.457	2032.639	2034.191	2034.349			2034.201		2034.534	2034.587	2033.153

Central Cluster

Station	Lat 1980	Long 80	1980	1981	1993	1994	1995	1997	1998	2003	2004	2005	2011
2001	65.108176	314.313638	2525.649	2525.259	2526.3735	2526.425	2526.502		2526.536	2527.031	2527.327	2527.579	2527.39
2002	65.067255	314.713182	2592.989	2592.769	2593.997	2593.932			2594.05	2594.633	2594.876	NaN	2594.85
2003	64.932856	314.403601	2572.934	2573.534	2574.539	2574.637		2574.766	2574.732	2575.334	2575.428	NaN	2575.54
2004	64.981484	313.973897	2491.794	2491.704	2493.315				2493.424	2494.033	2494.354	NaN	2494.42
2005	65.149097	313.896816	2448.78	2449.38	2450.2955	2450.444	2450.582		2450.756	2451.371	2451.542	2451.869	2451.57
2006	65.292962	314.166266	2463.456	2463.466	2464.691	2464.804	2464.882	2464.984	2465.049	2465.746	2465.992	2466.094	2465.98
2007	65.246832	314.591373	2536.415	2536.745	2537.682				2538.051				2538.9

Dye-3

Station	Lat 1980	Long 1980	1980	1981	1993	1994	1995	1997	1998	2003	2004	2005	2011
3001	65.258899	316.533129	2421.37			2420.088			2419.446				2418.49
3002	65.106181	316.534737	2481.756			2479.746		2478.874					2478.44
3003	65.201544	316.160011	2529.128		2528.507	2528.652			2528.17				2527.64
3004	65.025476	316.152189	2562.714			2562.625		2562.169					2561.65
3005	65.118702	315.802468	2598.036		2597.821	2597.713			2597.465				2597.22
3006	64.926553	315.820358	2654.971			2654.522		2654.166					2654.29
3007	65.014155	315.357009	2672.413		2672.354	2671.697			2672.195				2672.76
3008	64.849788	315.347001	2707.539		2708.316	2708.026		2708.336					2708.99

3.3. ICESat Data

A subset of the NSIDC ICESat data set was provided by Ben Smith. Averaged values were referenced to ITRF2000 and the WGS 84 ellipsoid. ICESat observations are displaced from the cluster nodes. Consequently a slope correction as discussed above was used to migrate the ICESat measurement back to the OSU coordinate. After all corrections, estimated accuracies for the elevation data sets are: 20 cm uncertainty in ICESat data largely due to slope correction uncertainties; 10-20 cm uncertainties in ATM data (Krabill and others, 1995b); 5 cm uncertainties for in situ, slope corrected GPS data (J. Sonntag, personal communication, 2011); 10-20 cm uncertainties in Doppler Satellite elevations (van der Veen and others, 2000; Bolzan, 1994).

Table 3. ICESat surface elevation in meters (relative to ITRF2000 and the WGS84 Ellipsoid) for three cluster sites. Data were slope corrected to migrate the elevation to the original OSU measurement site. Data in a particular year were averaged.

Station	Latitude	Longitude	Year:	2004	2005	2006	2007	2008	
1001	65.387647	312.327239		2031.308	2031.34	2031.895	2031.08	2031.085	
Station	Lat	Long		2004	2005	2006	2007	2008	2009
2001	65.10818488	314.3136512		2527.2	2527.3	2527.505	2527.363	2527.36	2527.58
Station	Lat	Long	2003	2004	2005				
3001	65.258899	316.533129	2419.125	2419.1	2419.228				

3.4. Velocity Data

Displacements between repeat in situ GPS measurements were computed along a spheroidal surface using the Vincenty formula. Measurements were generally straightforward at the Central site where aluminum poles used to mark the measurement location stayed in place between years. Western cluster data were adjusted for the fact that poles were tilted by melt. The western cluster sites are taken to have large velocity errors (1 m/yr and perhaps more).

1980/81 velocities are from Whillans (see van der Veen and others, 1999). 1993 velocity is from van der Veen and others (1999). Later velocity data were computed by using the GPS coordinates in Table 1 and applying the Vincenty formula to compute displacement and azimuth.

Table 4. Surface velocity from repeat GPS measurements

Lower Cluster Velocity

Year	2004/05		1980/81	
Station	Speed (m/yr)	Azimuth (degrees)	Speed (m/yr)	Azimuth (degrees)
1001	35.7	288	35.76	288
1003	36.83	290	36.07	290
1006	44.63	284	44.05	285

Note that errors at Lower Cluster are large (1 m/yr at least) because of pole tilt uncertainty between 2004 and 2005

Central Cluster Velocity

Year	1980/81		1993		2003/04		2004/05	
Station	Speed	Azimuth	Speed	Azimuth	Speed	Azimuth	Speed	Azimuth
2001	9.32	298			10.09	297	10.13	298
2002	7.55	309			7.989	307		
2003	8.58	298			8.96	298		
2004	11.38	293			11.69	293		
2005	11.56	295			12.21	294	12.10	293
2006	10.95	302	11.19	299	11.39	301	11.34	300

3.5. Accumulation data

Accumulation was estimated from remeasurement of aluminum pole height-above-surface and application of a snow density for converting to water equivalent. Table 5 provides detailed information for measurements between 2003 and 2004. Table 6 presents results which include an additional measurement year.

Table 5. Accumulation rate from repeat measurements of pole height above surface for years 2003 and 2004.

Station	2003 Pole Ht	2004 Pole Ht	Accum (cm)	Delta T (days)	A (cm/yr)	Water Eq (cm/yr)	Average, 1980 Accumulation rates from Whillans (cm/yr)
2001	292.10	190.00	102.10	364.00	102.38	39.93	38.30
2002	314.88	205.00	109.88	364.00	110.18	42.97	36.10
2003	308.88	204.00	104.88	364.00	105.17	41.02	40.70
2004	297.88	179.00	118.88	364.00	119.21	46.49	37.20
2005	281.94	180.00	101.94	364.00	102.22	39.87	36.90
2006	284.48	178.00	106.48	364.00	106.77	41.64	35.60

Table 6. Accumulation derived from 2003/2004 and 2004/2005 pole height re-measurements

	Accumulation cm/yr water equivalent	Accumulation cm/yr water equivalent	Accumulation cm/yr water equivalent
Station	Year - 1980	Year -2003	Year-2004
2001	38.3	39.9	42.2
2002	36.1	43.0	
2003	40.7	41.0	
2004	37.2	46.5	
2005	36.9	39.9	42.6
2006	35.6	41.6	33.4
ave	37.47	41.99	39.40

3.6. Gravity

Gravity was measured in 1981 and in 2003 using Lacoste and Romberg gravimeters. Relative gravity was converted to absolute gravity by using ties to the International Gravity Station Network in Sondrestrom, Greenland. Data were also collected in 2004 and 2005 using a

Scintrex meter but the data are considered unreliable. However, Scintrex did provide a correction table for the 2004 data and these could potentially be retrieved. Scintrex data in 2005 yielded consistent gravity differences between local IGSN stations but appeared to be offset from the Lacoste Romberg data for unexplained reasons.

Table 7. Absolute gravity measured at OSU cluster sites in different years. Relative gravity was measured with a LaCoste Romberg meter and later tied to local IGSN stations in Sondrestrom.

Year	Station	Abs g (mgal)
1981	2001	981604.287
1993	2001	981603.827
1995	2001	981604.26
2003	2001	981604.03
1981	2002	981581.464
1993	2002	
1995	2002	
2003	2002	981581.275
1981	2003	981580.775
1993	2003	
1995	2003	
2003	2003	981580.33
1981	2004	981605.03
1993	2004	
1995	2004	
2003	2004	981604.73
1981	2005	981617.24
1993	2005	
1995	2005	981616.67
2003	2005	981616.98
1981	2006	
1993	2006	981610.359
1995	2006	981610.35
2003	2006	981610.517

3.7. 1993 Shallow Pit Data

Typical measurements of temperature, density, firn characterization and grain size were made in a shallow pit at station 2006 in 1993.

Table 8. 1993 Shallow Pit data Station 2006.

Depth (cm)	Temperature (^oC)
0	-4
1	-2
10	-6.5
20	-6.5
30	-7
40	-7.5
50	-8.5
60	-9
70	-9.5
80	-10
90	-10.5
100	-11.5
110	-12.5
120	-13.5
130	-14.5

Depth (cm)	Wt (gm)	Wt-bag (gm)	Density (cm/cc)
5	189.5	179.5	0.351961
10	196.5	186.5	0.365686
20	199.5	189.5	0.371569
30	210	200	0.392157
40	202.5	192.5	0.377451
50	209.5	199.5	0.391176
60	215	205	0.401961
70	198	188	0.368627
80	202.5	192.5	0.377451
90	183.5	173.5	0.340196
100	199	189	0.370588
110	177.5	167.5	0.328431
120	225	215	0.421569

Thickness (cm)	Description	Depth (cm)
4	new snow	4
1	bonded coarse	5
1	ice	6
4	fine	10
1	ice	11
4	fine	15
0.5	ice	15.5
11.5	fine	27
1	ice	28
4	medium	32
4	massive fine	36
11	fine	47
0.2	wind crust	47.2
6.8	fine	54
0.2	wind crust	54.2
4.8	fine	59
0.2	wind crust	59.2
5.8	fine	65

Depth (cm)	Grain Size (mm)
0	0.2
4	0.2
4	1
5	1
5	0
6	0
6	0.4
10	0.4
10	0
11	0
11	0.5
15	0.5
15	0
15.2	0
15.2	0.5
27	0.5
27	0
28	0

3	massive fine	68
5	fine	73
7	coarse	80
10	massive fine	90
0.2	wind crust	90.2
2.8	fine	93
3	DH	96
0.2	wind crust	96.2
1.8	DH	98
4	fine	102
2	bonded medium	104
16	medium	120
5	massive fine	125

28	0.6
32	0.6
32	0.5
65	0.5
65	0.55
73	0.55
73	1
80	1
80	0.4
93	0.4
93	1
98	1
98	0.5
102	0.5
102	0.7
104	0.7
104	0.8
120	0.8
120	0.5

Definitions:

fine	0<grain size<=0.5 mm
massive fine	fine grains that are consolidated, need a shovel to chop out blocks
wet, fine	fine grains that can be molded into a snowball
dense, hard fine	qualitatively more consolidated than massive fine, need a saw
medium grain	0.5<grain size <1mm
bonded, medium	medium grains bonded into a brittle matrix
coarse	1 mm<=grain size <2mm
bonded coarse	coarse grains bonded together in a brittle matrix
very coarse	grain size >=2 mm
ice lense	horizontal lens
ice pipe	vertical
ice crust/DH	wind or melt crust underlain by depth hoar
laminar ice	fine filament or web of very thin (mm) ice layers
Loose, Granular	similar to dry sugar, finer grains than depth hoar
DH	Depth hoar
ice layers	thicker less frequent ice layers than laminar ice layers
massive laminar ice	solid matrix of layers interspersed with medium to coarse, bonded grains
wind crust	very thin crust/ice layer (1mm or less)
new snow	fresh layer of very fine (.2-.3 mm) grains

3.8. 1993 10 m core Station 2006

A 10-m core was collected and processed at station 2006 in 1993. Density data are tabulated in Table 9. Stratigraphic records were recorded in core-log books archived at the Byrd Polar Research Center. Samples were also collected for oxygen isotope data and these may be available from K. Kuivinen.

Table 9. 10-m core at Station 2006 collected in 1993 by Kuivinen, Jezek, and Thomas.

Depth to top of sample (cm)	Ave. Core Section Thickness (cm)	Weight (gm)	Bag	Bag Weigh (gm)	Length a (cm)	Length b (cm)	Diameter c (cm)	Corrected Weight (gm)	Volume (cc)	Density (gm/cc)
0	5	91.5	1	8.75	4.9	4.6	7.6	82.75	215.3726	0.384218
5	5	102.5	1	8.75	4.9	4.6	7.6	93.75	215.3726	0.435292
10	5	100.5	1	8.75	4.9	4.6	7.6	91.75	215.3726	0.426006
15	5	105	1	8.75	4.9	4.6	7.6	96.25	215.3726	0.4469
20	5	104	1	8.75	4.9	4.6	7.6	95.25	215.3726	0.442257
25	5	104	1	8.75	4.9	4.6	7.6	95.25	215.3726	0.442257
30	5	92	1	8.75	4.9	4.6	7.6	83.25	215.3726	0.386539
35	5	102	1	8.75	4.9	4.6	7.6	93.25	215.3726	0.432971
40	5	113	1	8.75	4.9	4.6	7.6	104.25	215.3726	0.484045
45	5	95.5	1	8.75	4.9	4.6	7.6	86.75	215.3726	0.40279
50	5	104	1	8.75	4.9	4.6	7.6	95.25	215.3726	0.442257
55	5	88.5	1	8.75	4.9	4.6	7.6	79.75	215.3726	0.370289
60	5	91	1	8.75	4.9	4.6	7.6	82.25	215.3726	0.381896
65	5	88	1	8.75	4.9	4.6	7.6	79.25	215.3726	0.367967
70	5	91.5	1	8.75	4.9	4.6	7.6	82.75	215.3726	0.384218
75	5	80	1	8.75	4.9	4.6	7.6	71.25	215.3726	0.330822

80	5	73	1	8.75	4.9	4.6	7.6	64.25	215.3726	0.29832
85	5	82.5	1	8.75	4.9	4.6	7.6	73.75	215.3726	0.34243
90	5	79.5	1	8.75	4.9	4.6	7.6	70.75	215.3726	0.3285
95	5	69	2	10.5	4.9	4.6	7.6	58.5	215.3726	0.271622
100	5	88	2	10.5	4.9	4.6	7.6	77.5	215.3726	0.359842
105	5	79	2	10.5	4.9	4.6	7.6	68.5	215.3726	0.318053
110	5	87	2	10.5	4.9	4.6	7.6	76.5	215.3726	0.355198
115	5	83	2	10.5	4.9	4.6	7.6	72.5	215.3726	0.336626
130	5	90.5	2	10.5	4.9	4.6	7.6	80	215.3726	0.371449
135	5	93.5	2	10.5	4.9	4.6	7.6	83	215.3726	0.385379
140	5	98.5	2	10.5	4.9	4.6	7.6	88	215.3726	0.408594
145	5	92.5	2	10.5	4.9	4.6	7.6	82	215.3726	0.380736
150	5	94.5	2	10.5	4.9	4.6	7.6	84	215.3726	0.390022
155	5	95.5	2	10.5	4.9	4.6	7.6	85	215.3726	0.394665
160	5	97.5	2	10.5	4.9	4.6	7.6	87	215.3726	0.403951
240	5	101.5	1	8.75	4.9	4.6	7.6	92.75	215.3726	0.430649
245	5	105	1	8.75	4.9	4.6	7.6	96.25	215.3726	0.4469
250	5	108.5	1	8.75	4.9	4.6	7.6	99.75	215.3726	0.463151
255	5	105.5	1	8.75	4.9	4.6	7.6	96.75	215.3726	0.449221
260	5	110	1	8.75	4.9	4.6	7.6	101.25	215.3726	0.470116
265	5	123.5	1	8.75	4.9	4.6	7.6	114.75	215.3726	0.532798

270	5	120.5	1	8.75	4.9	4.6	7.6	111.75	215.3726	0.518868
275	5	100.5	1	8.75	4.9	4.6	7.6	91.75	215.3726	0.426006
280	5	114	1	8.75	4.9	4.6	7.6	105.25	215.3726	0.488688
285	5	93	1	8.75	4.9	4.6	7.6	84.25	215.3726	0.391183
290	5	76	1	8.75	4.9	4.6	7.6	67.25	215.3726	0.31225
295	5	148.5	1	8.75	4.9	4.6	7.6	139.75	215.3726	0.648875
300	5	96	1	8.75	4.9	4.6	7.6	87.25	215.3726	0.405112
305	5	110.5	1	8.75	4.9	4.6	7.6	101.75	215.3726	0.472437
310	5	85	1	8.75	4.9	4.6	7.6	76.25	215.3726	0.354038
315	5	87.5	1	8.75	4.9	4.6	7.6	78.75	215.3726	0.365645
320	5	88.5	1	8.75	4.9	4.6	7.6	79.75	215.3726	0.370289
325	5	75	1	8.75	4.9	4.6	7.6	66.25	215.3726	0.307606
330	5	152	1	8.75	4.9	4.6	7.6	143.25	215.3726	0.665126
335	5	66	1	8.75	4.9	4.6	7.6	57.25	215.3726	0.265818
340	5	84.5	1	8.75	4.9	4.6	7.6	75.75	215.3726	0.351716
345	5	73	1	8.75	4.9	4.6	7.6	64.25	215.3726	0.29832
350	5	143.5	1	8.75	4.9	4.6	7.6	134.75	215.3726	0.62566
355	5	105.5	1	8.75	4.9	4.6	7.6	96.75	215.3726	0.449221
360	5	91.5	1	8.75	4.9	4.6	7.6	82.75	215.3726	0.384218
365	5	98.5	1	8.75	4.9	4.6	7.6	89.75	215.3726	0.41672
370	5	89	1	8.75	4.9	4.6	7.6	80.25	215.3726	0.37261
375	5	93.5	1	8.75	4.9	4.6	7.6	84.75	215.3726	0.393504
380	5	82	1	8.75	4.9	4.6	7.6	73.25	215.3726	0.340108
385	5	83	1	8.75	4.9	4.6	7.6	74.25	215.3726	0.344751
390	5	87	1	8.75	4.9	4.6	7.6	78.25	215.3726	0.363324
395	5	110	1	8.75	4.9	4.6	7.6	101.25	215.3726	0.470116
400	5	82.5	1	8.75	4.9	4.6	7.6	73.75	215.3726	0.34243

405	5	96	1	8.75	4.9	4.6	7.6	87.25	215.3726	0.405112
410	5	203	1	8.75	4.9	4.6	7.6	194.25	215.3726	0.901925
415	5	110	1	8.75	4.9	4.6	7.6	101.25	215.3726	0.470116
420	5	118.5	1	8.75	4.9	4.6	7.6	109.75	215.3726	0.509582
425	5	110.5	1	8.75	4.9	4.6	7.6	101.75	215.3726	0.472437
430	5	110.5	1	8.75	4.9	4.6	7.6	101.75	215.3726	0.472437
435	5	114	1	8.75	4.9	4.6	7.6	105.25	215.3726	0.488688
440	5	117	1	8.75	4.9	4.6	7.6	108.25	215.3726	0.502617
445	5	99.5	1	8.75	4.9	4.6	7.6	90.75	215.3726	0.421363
450	5	100.5	1	8.75	4.9	4.6	7.6	91.75	215.3726	0.426006
455	5	109.5	1	8.75	4.9	4.6	7.6	100.75	215.3726	0.467794
460	5	113	1	8.75	4.9	4.6	7.6	104.25	215.3726	0.484045
465	5	87	1	8.75	4.9	4.6	7.6	78.25	215.3726	0.363324
470	5	94	1	8.75	4.9	4.6	7.6	85.25	215.3726	0.395826
475	5	110.5	1	8.75	4.9	4.6	7.6	101.75	215.3726	0.472437
480	5	98	1	8.75	4.9	4.6	7.6	89.25	215.3726	0.414398
485	5	116.5	1	8.75	4.9	4.6	7.6	107.75	215.3726	0.500296
490	5	94	1	8.75	4.9	4.6	7.6	85.25	215.3726	0.395826
495	5	94.5	1	8.75	4.9	4.6	7.6	85.75	215.3726	0.398147
500	5	99	1	8.75	4.9	4.6	7.6	90.25	215.3726	0.419041
505	5	100	1	8.75	4.9	4.6	7.6	91.25	215.3726	0.423684
510	5	109	1	8.75	4.9	4.6	7.6	100.25	215.3726	0.465472
515	5	107	1	8.75	4.9	4.6	7.6	98.25	215.3726	0.456186
520	5	103.5	1	8.75	4.9	4.6	7.6	94.75	215.3726	0.439935
525	5	110	1	8.75	4.9	4.6	7.6	101.25	215.3726	0.470116
530	5	171	1	8.75	4.9	4.6	7.6	162.25	215.3726	0.753346
535	5	102	1	8.75	4.9	4.6	7.6	93.25	215.3726	0.432971
540	5	110.5	1	8.75	4.9	4.6	7.6	101.75	215.3726	0.472437
545	5	104	1	8.75	4.9	4.6	7.6	95.25	215.3726	0.442257
550	5	104	1	8.75	4.9	4.6	7.6	95.25	215.3726	0.442257
555	5	96	1	8.75	4.9	4.6	7.6	87.25	215.3726	0.405112
560	5	90	1	8.75	4.9	4.6	7.6	81.25	215.3726	0.377253

565	5	105.5	1	8.75	4.9	4.6	7.6	96.75	215.3726	0.449221
570	5	107.5	1	8.75	4.9	4.6	7.6	98.75	215.3726	0.458508
575	5	104.5	1	8.75	4.9	4.6	7.6	95.75	215.3726	0.444578
580	5	106	1	8.75	4.9	4.6	7.6	97.25	215.3726	0.451543
585	5	135	1	8.75	4.9	4.6	7.6	126.25	215.3726	0.586193
590	5	110.5	1	8.75	4.9	4.6	7.6	101.75	215.3726	0.472437
595	5	104	1	8.75	4.9	4.6	7.6	95.25	215.3726	0.442257
600	5	100	1	8.75	4.9	4.6	7.6	91.25	215.3726	0.423684
605	5	135.5	1	8.75	4.9	4.6	7.6	126.75	215.3726	0.588515
610	5	109	1	8.75	4.9	4.6	7.6	100.25	215.3726	0.465472
615	5	121	1	8.75	4.9	4.6	7.6	112.25	215.3726	0.52119
620	5	123	1	8.75	4.9	4.6	7.6	114.25	215.3726	0.530476
625	5	100	1	8.75	4.9	4.6	7.6	91.25	215.3726	0.423684
630	5	104	1	8.75	4.9	4.6	7.6	95.25	215.3726	0.442257
635	5	136.5	1	8.75	4.9	4.6	7.6	127.75	215.3726	0.593158
640	5	112	1	8.75	4.8	4.5	7.6	103.25	210.8384	0.489711
645	5	109	1	8.75	4.9	4.6	7.6	100.25	215.3726	0.465472
650	5	119	1	8.75	4.8	4.6	7.6	110.25	213.1055	0.517349
655	5	119	1	8.75	4.9	4.6	7.6	110.25	215.3726	0.511904
660	5	108	1	8.75	4.9	4.6	7.6	99.25	215.3726	0.460829
665	5	112.5	1	8.75	4.9	4.6	7.6	103.75	215.3726	0.481723
670	5	113	1	8.75	4.9	4.6	7.6	104.25	215.3726	0.484045
675	5	115	1	8.75	4.9	4.6	7.6	106.25	215.3726	0.493331
680	5	102	1	8.75	4.9	4.6	7.6	93.25	215.3726	0.432971
685	5	126	1	8.75	4.9	4.6	7.6	117.25	215.3726	0.544405
690	5	131	1	8.75	4.9	4.6	7.6	122.25	215.3726	0.567621
695	5	93	1	8.75	4.9	4.6	7.6	84.25	215.3726	0.391183
700	5	169	1	8.75	5.8	5.6	7.6	160.25	258.4471	0.620049
705	5	111.5	1	8.75	4.9	4.6	7.6	102.75	215.3726	0.47708
710	5	101	1	8.75	4.9	4.6	7.6	92.25	215.3726	0.428327
715	5	105.5	1	8.75	4.9	4.6	7.6	96.75	215.3726	0.449221
720	5	111	1	8.75	4.9	4.6	7.6	102.25	215.3726	0.474759
725	5	121	1	8.75	4.9	4.6	7.6	112.25	215.3726	0.52119
730	5	127	1	8.75	4.9	4.6	7.6	118.25	215.3726	0.549048

735	5	120	1	8.75	4.9	4.6	7.6	111.25	215.3726	0.516547
740	5	125	1	8.75	4.9	4.6	7.6	116.25	215.3726	0.539762
745	5	118	1	8.75	4.9	4.6	7.6	109.25	215.3726	0.50726
750	5	105	1	8.75	4.9	4.6	7.6	96.25	215.3726	0.4469
755	5	120.5	1	8.75	4.9	4.6	7.6	111.75	215.3726	0.518868
760	5	135	1	8.75	4.9	4.6	7.6	126.25	215.3726	0.586193
765	5	117.5	1	8.75	4.9	4.6	7.6	108.75	215.3726	0.504939
770	5	111.5	1	8.75	4.9	4.6	7.6	102.75	215.3726	0.47708
775	5	127	1	8.75	4.9	4.6	7.6	118.25	215.3726	0.549048
780	5	165.5	1	8.75	7.5	5.7	7.6	156.75	299.2546	0.523802
785	5	102	1	8.75	4.9	4.6	7.6	93.25	215.3726	0.432971
790	5	119	1	8.75	4.9	4.6	7.6	110.25	215.3726	0.511904
795	5	115	1	8.75	4.9	4.6	7.6	106.25	215.3726	0.493331
800	5	133	1	8.75	4.9	4.6	7.6	124.25	215.3726	0.576907
805	5	110	1	8.75	4.9	4.6	7.6	101.25	215.3726	0.470116
810	5	107.5	1	8.75	4.9	4.6	7.6	98.75	215.3726	0.458508
815	5	121	1	8.75	4.9	4.6	7.6	112.25	215.3726	0.52119
820	5	126.5	1	8.75	4.9	4.6	7.6	117.75	215.3726	0.546727
825	5	123	1	8.75	4.9	4.6	7.6	114.25	215.3726	0.530476
830	5	126	1	8.75	4.9	4.6	7.6	117.25	215.3726	0.544405
835	5	126.5	1	8.75	4.9	4.6	7.6	117.75	215.3726	0.546727
840	5	126.5	1	8.75	4.9	4.6	7.6	117.75	215.3726	0.546727
845	5	126.5	1	8.75	4.9	4.6	7.6	117.75	215.3726	0.546727
850	5	127.5	1	8.75	4.9	4.6	7.6	118.75	215.3726	0.55137
855	5	128	1	8.75	4.9	4.6	7.6	119.25	215.3726	0.553692
860	5	125	1	8.75	4.9	4.6	7.6	116.25	215.3726	0.539762
865	5	132	1	8.75	4.9	4.6	7.6	123.25	215.3726	0.572264
870	5	136.5	1	8.75	5.6	5.4	7.6	127.75	249.3788	0.512273
875	5	119	1	8.75	4.9	4.6	7.6	110.25	215.3726	0.511904
880	5	115	1	8.75	4.9	4.6	7.6	106.25	215.3726	0.493331
885	5	123	1	8.75	4.9	4.6	7.6	114.25	215.3726	0.530476
890	5	122.5	1	8.75	4.9	4.6	7.6	113.75	215.3726	0.528154
895	5	122.5	1	8.75	4.9	4.6	7.6	113.75	215.3726	0.528154
900	5	120	1	8.75	4.9	4.6	7.6	111.25	215.3726	0.516547
905	5	124	1	8.75	4.9	4.6	7.6	115.25	215.3726	0.535119

910	5	125	1	8.75	4.9	4.6	7.6	116.25	215.3726	0.539762
915	5	124	1	8.75	4.9	4.6	7.6	115.25	215.3726	0.535119
920	5	122	1	8.75	4.9	4.6	7.6	113.25	215.3726	0.525833
925	5	121.5	1	8.75	4.9	4.6	7.6	112.75	215.3726	0.523511
930	5	146	1	8.75	6	5.4	7.6	137.25	258.4471	0.531056
935	5	112.5	1	8.75	4.9	4.6	7.6	103.75	215.3726	0.481723
940	5	124	1	8.75	4.9	4.6	7.6	115.25	215.3726	0.535119
945	5	127.5	1	8.75	4.9	4.6	7.6	118.75	215.3726	0.55137
950	5	129.5	1	8.75	4.9	4.6	7.6	120.75	215.3726	0.560656
955	5	107.5	1	8.75	5.1	4	7.6	98.75	206.3043	0.478662
960	5	109	1	8.75	4.9	4.6	7.6	100.25	215.3726	0.465472
965	5	120	1	8.75	4.9	4.6	7.6	111.25	215.3726	0.516547
970	5	124.5	1	8.75	4.9	4.6	7.6	115.75	215.3726	0.537441
975	5	127.5	1	8.75	4.9	4.6	7.6	118.75	215.3726	0.55137
980	5	155.5	1	8.75	4.9	4.6	7.6	146.75	215.3726	0.681377
985	5	125.5	1	8.75	4.9	4.6	7.6	116.75	215.3726	0.542084
990	5	131	1	8.75	4.9	4.6	7.6	122.25	215.3726	0.567621
995	5	132.5	2	10.5	4.9	4.6	7.6	122	215.3726	0.56646
1000	5	119.5	2	10.5	4.9	4.6	7.6	109	215.3726	0.5061
1005	5	129.5	2	10.5	4.9	4.6	7.6	119	215.3726	0.552531
1010	5	107.5	2	10.5	4.9	4.6	7.6	97	215.3726	0.450382
1015	5	135	2	10.5	4.9	4.6	7.6	124.5	215.3726	0.578068
1020	5	131	2	10.5	4.9	4.6	7.6	120.5	215.3726	0.559495
1025	5	131.5	2	10.5	4.9	4.6	7.6	121	215.3726	0.561817
1030	5	131.5	2	10.5	4.9	4.6	7.6	121	215.3726	0.561817
1035	5	133	2	10.5	4.9	4.6	7.6	122.5	215.3726	0.568782
1040	5	130.5	2	10.5	4.9	4.6	7.6	120	215.3726	0.557174
1045	5	127.5	2	10.5	4.9	4.6	7.6	117	215.3726	0.543245
1050	5	118.5	2	10.5	4.9	4.6	7.6	108	215.3726	0.501457
1055	5	124	2	10.5	4.4	4.1	7.6	113.5	192.7018	0.588993
1060	5	125	2	10.5	4.9	4.6	7.6	114.5	215.3726	0.531637
1065	5	131	2	10.5	4.9	4.6	7.6	120.5	215.3726	0.559495
1070	5	131.5	2	10.5	4.9	4.6	7.6	121	215.3726	0.561817
1075	5	117	2	10.5	4.9	4.6	7.6	106.5	215.3726	0.494492
1080	5	130.5	2	10.5	4.9	4.6	7.6	120	215.3726	0.557174
1085	5	128	2	10.5	4.9	4.6	7.6	117.5	215.3726	0.545566

1090	5	132.5	2	10.5	4.9	4.6	7.6	122	215.3726	0.56646
1095	5	134.5	2	10.5	4.9	4.6	7.6	124	215.3726	0.575746
1100	5	135.5	2	10.5	4.9	4.6	7.6	125	215.3726	0.58039
1105	5	134.5	2	10.5	4.9	4.6	7.6	124	215.3726	0.575746
1110	5	139	2	10.5	4.9	4.6	7.6	128.5	215.3726	0.59664
1115	5	134.5	2	10.5	4.9	4.6	7.6	124	215.3726	0.575746
1120	5	138.5	2	10.5	4.9	4.6	7.6	128	215.3726	0.594319
1125	5	128	2	10.5	4.9	4.6	7.6	117.5	215.3726	0.545566
1130	5	134.5	2	10.5	4.9	4.6	7.6	124	215.3726	0.575746
1135	5	127.5	2	10.5	4.9	4.6	7.6	117	215.3726	0.543245
1140	5	148	2	10.5	5.7	4.9	7.6	137.5	240.3105	0.572176

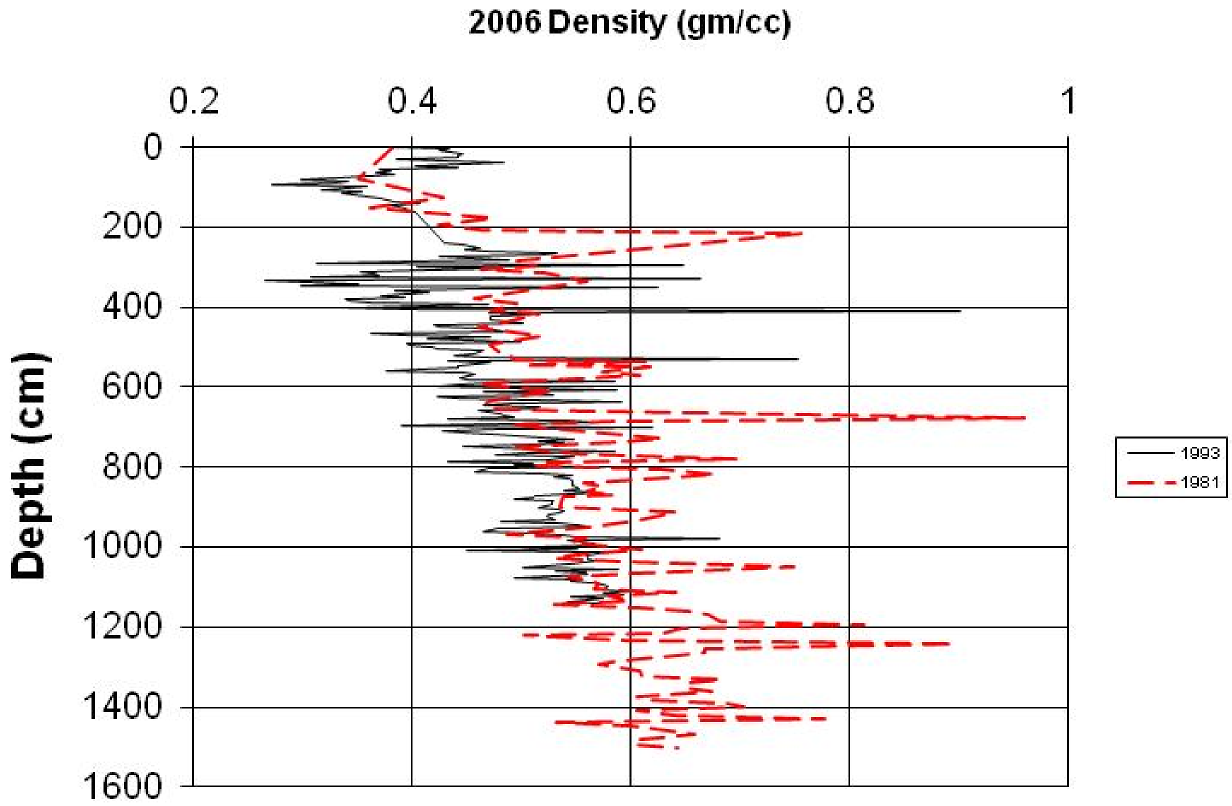

Figure 2. Comparison of 1981 and 1993 density data. Accumulation data from 1981 available in van der Veen and others (2001).

3.9. 2003 Shallow Pits

Rudimentary pit studies were collected at stations 2004 and 2001 in 2003.

Table 10. Shallow pit data collected in 2003 at station 2004

Station 2004
8-Jun-03

Stratigraphy		Temperature	
Layer Thickness (cm)	snow type	Depth (cm)	Temp (°C0
5	medium snow	0	-4
6	ice layers	1.6	-3.8
3	medium snow	5	-4.9
5.2	ice layers	25	-8.5
27.8	massive fine	50	-10
4	ice layers	76	-11
12	fine snow		
2	ice layers		
13	fine snow		
10	medium snow		

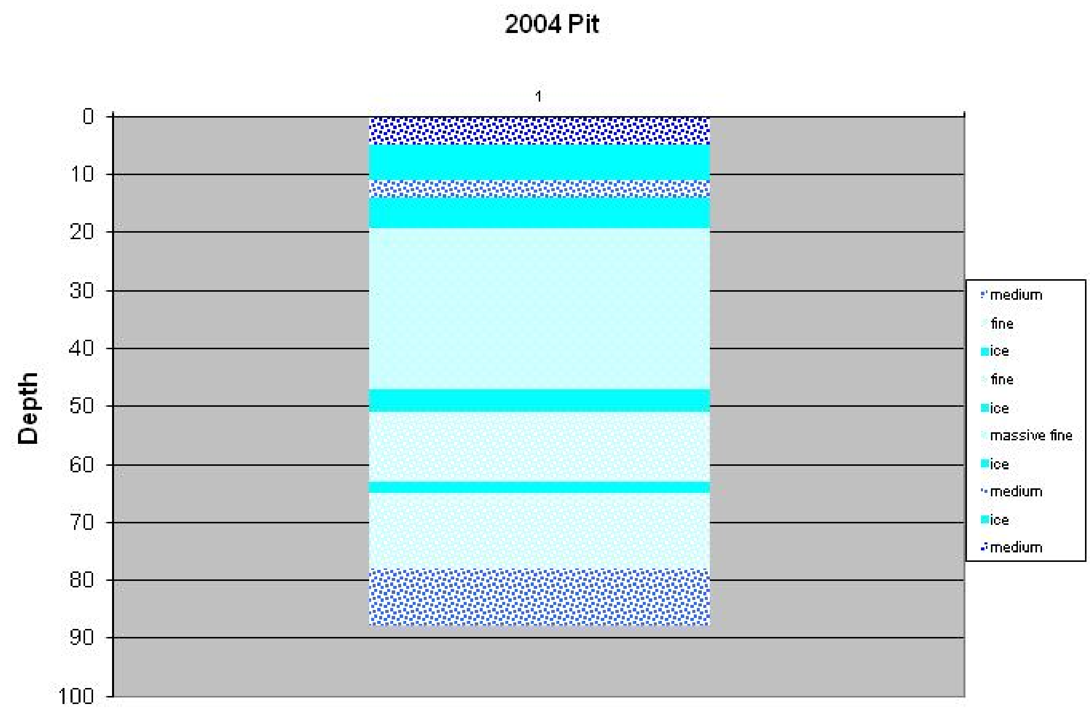

Figure 3. Diagrammatic firn stratigraphy at station 2004 illustrating roughly 75-80 cm of annual snow accumulation as suggested by the firn texture and layering.

Table 11. Rudimentary Pit Data Collected at Station 2001.

2001

Stratigraphy

Thickness (cm)	Type
5	snow
0.1	ice
0.9	snow
0.1	ice
2.9	snow
0.1	ice
3.9	snow
0.5	ice
19.5	snow

Temperature

Depth(cm)	Temp (^{o}C)
0	-1
5	-3
30	-8

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