Sea Ice Mass Balance in the Antarctic
Geophysical Assessment

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INTRODUCTION

This project report contains information obtained during "Sea Ice Mass Balance in the Antarctic" (Project O-270-N) involving a variety of different geophysical measurements performed using electrical, physical, and remote sensing methods. The measurements commenced on the morning of September 8, 2007 following the ship's fire and during the departure from Palmer Station, and continued until reaching the approximate ice edge. On the second voyage to the ice, measurements commenced on September 25, 2007 when reaching the ice edge and continued through the transit out of the ice pack on October 26, 2007.

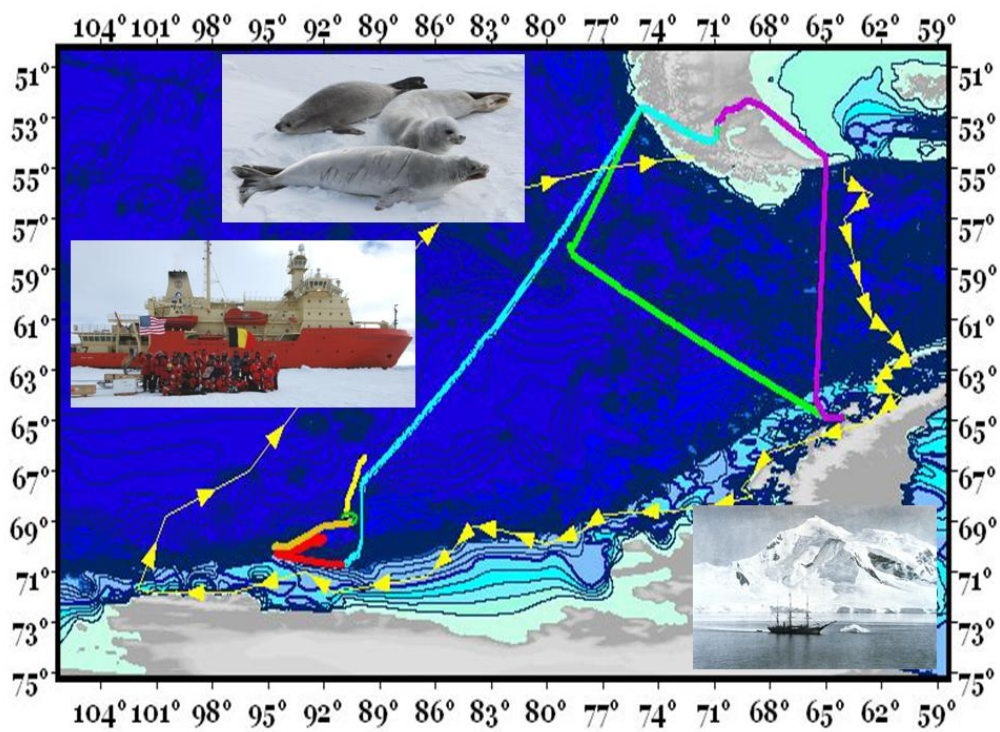


Figure 1 SIMBA cruise track and drift positions

IN TRANSIT ACTIVITIES

The In-Transit activities included geophysical and remote sensing measurements obtained aboard the RVIB Nathaniel B Palmer while underway and temporary stations established at stopping points along the way. These measurements included sea ice thickness by Electromagnetic Induction (EMI) and digital imagery obtained by surveillance cameras mounted to the ship. Three separate way stations were established where geophysical measurements and snow/ice characterization were performed during the transit. Drifter buoy deployment was planned for the way stations while in-transit, however, technical difficulties prevented the completion of this activity.

Ice Thickness by Ship-borne Electromagnetic Induction (EMI)

EMI Open Water Calibration

Calibration of EMI conductance for instrument height was conducted using the open water method. Twenty two (22) conductance measurements were acquired over open water (an ice lead at Palmer Station) at heights ranging from 4.2 to 0.6 meters, as acquired from an on-board distance ranger. All conductance values at heights over 1.4 meters (corresponding to the right flank of the theoretical curve) were fit to an exponential model (Eqn 1).

$$y = 840.85e^{-0.4947x} \qquad \text{Eqn 1}$$

where y is conductance in millisiemens/meter, and x is instrument height (or distance to sea water). This equation was subsequently inverted to generate distance from seawater from conductivity measurements acquired in underway operations. A plot of calibration values and the fitted calibration curve can be seen in Figure 2.

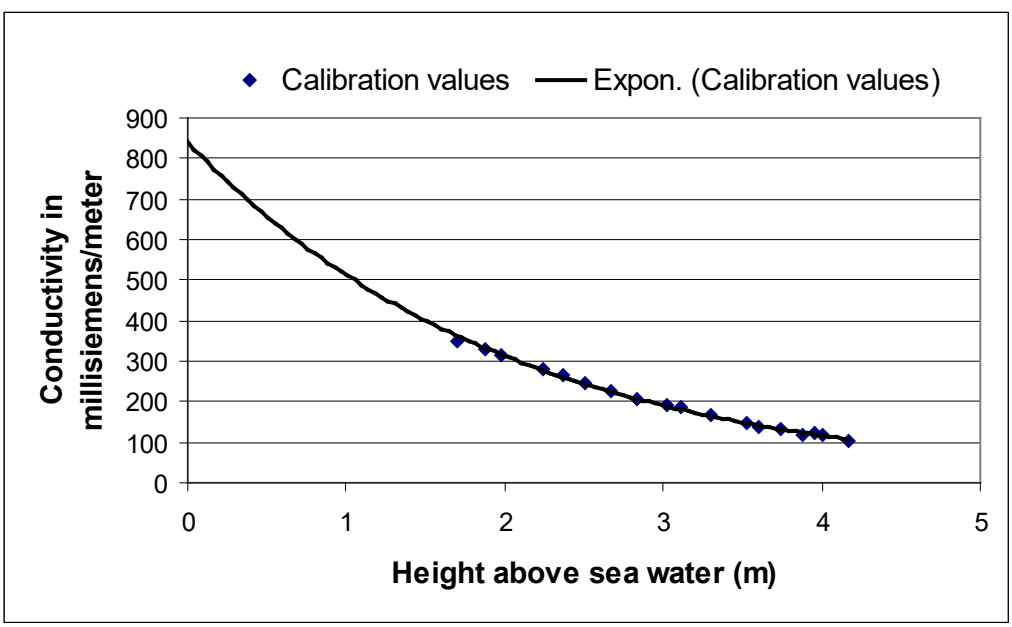


Figure 2. Plot of calibration values and fitted exponential model.

Data acquisition methods
EMI (electromagnetic induction) records of ice thickness (to be derived), utilizing a Geonics EM-31 induction meter, were conducted with the meter suspended from the ship's starboard A-frame, at heights varying from 2.5 to 4.0 meters. Conductance data (in millisiemens/meter) were acquired at 2 second intervals. Heights to the snow/ice surface were measured with a sonic ranger attached to the frame housing the EMI device. Data were recorded on a Campbell Scientific CX200 data logger (range measurements) and with an Allegro Windows CX handheld computer (conductivity data) running Geonics EM31 acquisition software. Due to design constraints with the CX200 data logger, range measurements were only acquired at 60 second intervals. Range measurements were adjusted for speed of sound variation due to temperature. Geolocation of EMI/ranger data pairs was accomplished through simultaneous logging of the ships GPS track at a mean positional accuracy of < 3.0 meters. A map of EMI data tracks, along with icecam video tracks, can be seen in Figure 3.

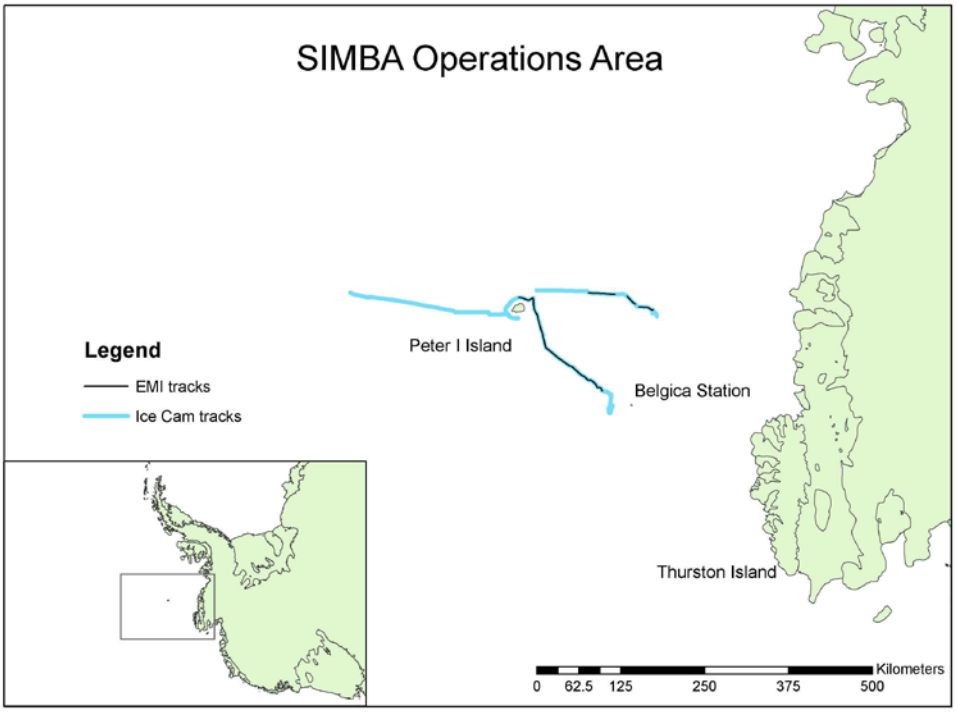


Figure 3. Map of SIMBA operations area with EMI and ice cam data tracks.

Palmer Station Track (outbound)
EMI records of ice thickness along an outbound track from Palmer Station commenced 8 September at 18:49 GMT, at 64.48S 64.03W and terminated 9 September at 04:00 GMT at 64.53S 65.00W. Approximately xx.xx km of ice thickness data were acquired along

this track. However, due to uncertainties of conductivity measurements in predominately pancake ice conditions (< 100% ice concentration), ice thicknesses for this track will not be reported in this cruise summary document. Future analysis of this data is warranted however.

Belgica Station Track (inbound)

EMI records of ice thickness along an inbound track to Belgica Station commenced 25 September at 13:00 GMT, at 69.78S 90.02W and terminated 27 September at 3:41 GMT at the conclusion of waystation 3 operations, due to high winds that persisted the remainder of the day. An estimated 90 kilometers of EMI data were collected along this inbound track. A frequency histogram of ice thickness measurements (preliminary) for this track can be seen in Figure 4.

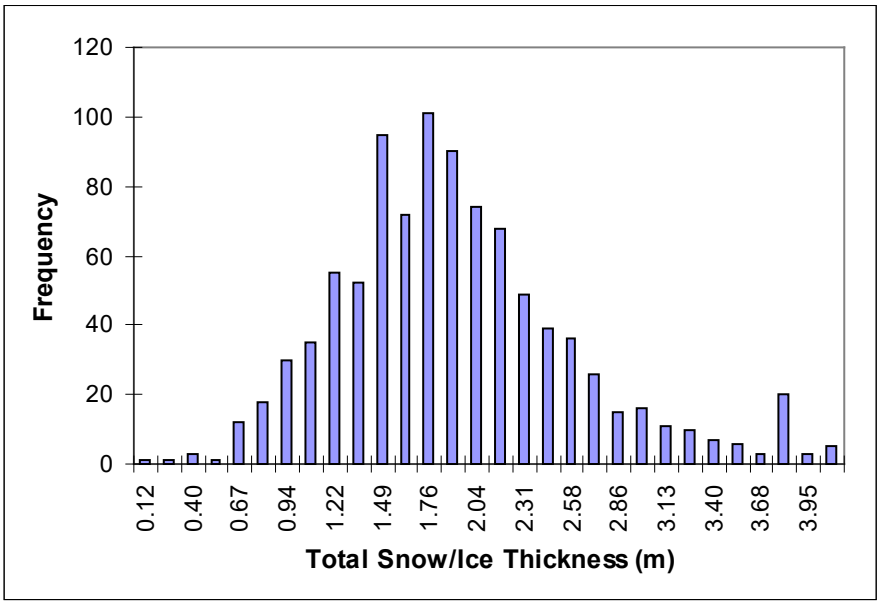


Figure 4. Histogram of ice thickness measurements (n = 957) along inbound track to Belgica Station.

Belgica Station Track (outbound)

During the journey out to the ice edge, the EM-31 was again deployed from the starboard A-frame to collect ice thickness data during transit. This transit began at approximately 69°55'S 93°45'W and extended to 68°50'S 90°12'W, a distance covered of 216 km. A digital surveillance camera was added to the instrumentation on the kayak to record images of the EM footprint (target ice) concurrent with the conductivity measurements. This video record will be used in future analysis to correct ice thickness determinations for varying ice concentration. A frequency histogram of ice thickness measurements (preliminary) for this track can be seen in Figure 5.

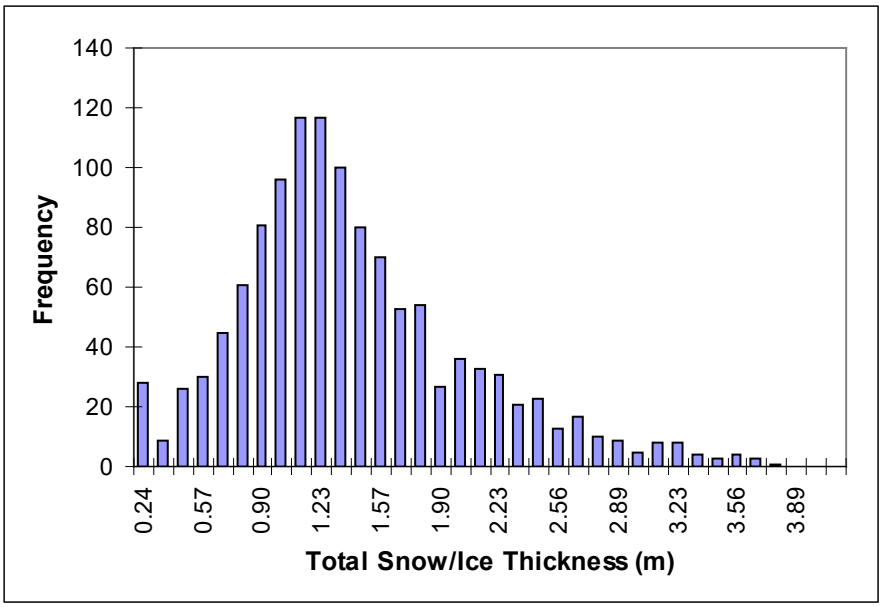


Figure 5. Histogram of ice thickness measurements (n = 1471) along inbound track to Belgica Station.

Ice Thickness and Concentration by digital surveillance imagery

Three separate photographic (video) records of ice observations were conducted along outbound tracks at Palmer Station and along both inbound and outbound tracks from Belgica Station, approximately coincidental in time with ASPECT ice observations. IceCam 2 recorded AVI time lapse video at 20 second intervals from the starboard bridge wing. The view angle of IceCam 2 is the starboard aft quarter, with the near frame of the field of view (FOV) being approximately 6 meters off the starboard beam, and the far view estimated at 500 meters distant. IceCam 1 recorded AVI time lapse video at 5 second intervals from a near-vertical FOV (approx. 5.4 m width at ship's water line). IceCam 1 was located at the starboard 01 deck midship (just forward of lifeboat) and corresponds to the ASPECT observers view of pack ice thickness from upturned ice fragments. The time span of inbound video recordings (commencing 25 September 05:00 GMT and terminating 27 September at 03:41 GMT) encompassed marginal ice and ice pack from just south of Peter I island, through 3 ice waystations to the SIMBA ice process station at 70.66 S 91.00W. The time span of outbound video recordings (commencing 24 October at 11:04 GMT and terminating on 27 October at 12:06 GMT) encompassed ice pack and marginal ice from Belgica Station to approximately 200 km north of Peter I Island. These video recordings will be processed and analyzed to groundtruth ASPECT ice observations.

Sea Ice Waystations

Waystation 1

Ice profile sampling at Waystation 1 (70° 14.72'S 90° 04.57'W) commenced 25 September at 18:35 GMT. Two 50 meter parallel profiles on ship's starboard were sampled at 1 and 5 meter incremental stations. Snow ice interface temperatures for line 1

were sampled every 1 meter utilizing thermistor rods and a plug-on digital meter. Thermistor rods were inserted to the snow ice interface and allowed to equilibrate for a minimum of 1 minute. For line 2, temperatures were sampled every 5 meters. Mean interface temperature for both lines was -1.98 °C, with a range of -1.7 to -2.4 °C. The presence of slush was assessed by digging a pit to the snow ice interface. Approximate thickness of the slush layer, if present, was measured at 1 meter increments for line 1 and at 5 meter increments for line 2. Slush was present in 58 of the 61 sampling sites, with a mean thickness of 0.091 m, and a maximum of 0.205 m. For this profile site the absence of slush was attributed to elevated topography due to ridging.

Three snow pits were excavated at this way station to assess the snow structure, temperature profile and obtain snow samples for density, salinity, and oxygen isotope ratios. A summary of result is presented in Table 1.

Table 1 – Waystation 1 Snow Pit Summary

Snow Pit	Snow Thickness (m)	Slush Thickness (m)	Air Temp (C)	Avg Snow Temp (C)	Snow/Ice interface Temp (C)	Slush Temp (C)	Average Density (g/cc)	Average Snow Salinity (psu)	Salinity Snow/Ice interface (psu)
1-1	0.300	0.160	-1.18	-1.24	-1.62	ND	0.373	0.05	14.2
1-2	0.240	0.000	-1.12	-1.49	-1.68	ND	0.406	0.00	ND
1-3	0.350	0.040	-0.82	-1.18	-1.65	ND	0.344	0.00	ND

ND = no data

Waystation 2

Ice profile sampling at Waystation 2 (70° 24.47'S 90° 29.00'W) commenced 26 September at 16:52 GMT. Eighty (80) meters of profile were sampled at a 5 meter spacing. The 30 meter profile was orthogonal to the 50 meter profile, beginning at the 50 meter endpoint. Mean interface temperature for this profile was -2.09 °C, with a range of -1.8 to -2.7 °C. The presence of slush was assessed by digging a pit to the snow ice interface. Approximate thickness of the slush layer, if present, was measured every 5 meters coincident with the temperature samples. Slush was present in 73 of the 81 sampling sites, with a mean thickness of 0.091 m, and a maximum of 0.170 m.

Three snow pits were excavated at this way station to assess the snow structure, temperature profile and obtain snow samples for density, salinity, and oxygen isotope ratios. A summary of result is presented in Table 2.

Table 2 – Waystation 2 Snow Pit Summary

Snow Pit	Snow Thickness (m)	Slush Thickness (m)	Air Temp (C)	Avg Snow Temp (C)	Snow/Ice interface Temp (C)	Slush Temp (C)	Average Density (g/cc)	Average Snow Salinity (psu)	Salinity Snow/Ice interface (psu)
2-1	0.690	0.070	-3.28	-1.92	-1.67	ND	0.327	0.02	ND
2-2	0.320	0.010	-2.83	-2.50	-1.53	ND	0.388	0.47	ND
2-3	0.400	0.010	-2.25	-2.35	-1.81	ND	0.428	1.25	ND

ND = no data

Waystation 3

Ice profile sampling at Waystation 3 (70° 38.13'S 90° 44.17'W) commenced 27 September at 4:55 GMT. Eighty (80) meters of profile were sampled at a 5 meter spacing. The 30 meter profile was orthogonal to the 50 meter profile, beginning at the 50 meter endpoint. Mean interface temperature for this profile was -3.10 °C, with a range of -2.8 to -3.4 °C. The presence of slush was assessed by digging a pit to the snow ice interface. Approximate thickness of the slush layer, if present, was measured every 5 meters coincident with the temperature samples. Slush was present in 25 of the 100 sampling sites, with a mean thickness of 0.030 m, and a maximum of 0.075 m.

Three snow pits were excavated at this way station to assess the snow structure, temperature profile and obtain snow samples for density, salinity, and oxygen isotope ratios. A summary of result is presented in Table 3.

Table 3 – Waystation 3 Snow Pit Summary

Snow Pit	Snow Thickness (m)	Slush Thickness (m)	Air Temp (C)	Avg Snow Temp (C)	Snow/Ice interface Temp (C)	Slush Temp (C)	Average Density (g/cc)	Average Snow Salinity (psu)	Salinity Snow/Ice interface (psu)
3-1	0.140	0.000	-4.44	-3.90	-3.00	ND	0.290	0.00	8.1
3-2	0.280	0.050	-4.00	-2.76	-1.49	ND	0.315	3.76	19.0
3-3	0.110	0.000	-3.95	-3.19	-2.09	ND	0.278	2.1	ND

ND = no data

<u>Drifter Buoy deployment</u>

Following the initial deployment of a single drifter buoy at Way Station 1, it was determined that the drifter buoys were functioning intermittently in an unstable manner. Upon further investigation and discussions with the manufacturer (Trident Sensors, Helen Cusack) it was discovered that the electronics are unstable below -5 °C (sporadic and/or cessation of transmission). An assessment of the temperature stability of the Iridium/GPS units for the drifter buoys was performed using three HOBO temperature dataloggers placed outside and within a buoy case. The case was deployed on the outside deck of the ship and allowed to transmit for approximately 5 days, during which time ambient air temperature ranged from -4 °C to -15 °C. The data record was sent to Cathy Geiger, the person responsible for monitoring drifter buoy tracks at CRREL and Helen Cusack. Preliminary results indicated that insulating the unit retains enough internally generated heat to maintain board temperatures 5 to 6 °C above ambient air temperature. It was determined that the temperature sensitivity could be partially addressed by enclosing the Iridium units in thermal insulation prior to deployment. However, the decision was made NOT to deploy the Iridium/GPS drifter buoys and to return them to the manufacturer for replacement or repair.

BELGICA DRIFT STATION

The Belgica drift station was reached on the afternoon of September 27 before the onset of adverse weather. A storm began overnight and continued through September 30 with high winds, blowing snow and low visibility. An initial attempt to set survey stakes on September 30 was thwarted by continued high winds. By October 1, the storm cleared and work on the ice began in earnest. Several independent sites were established across the ice floe where geophysical measurements were performed and snow conditions were assessed. A site layout diagram of Belgica Station showing the various sites and features is provided in Figure 6.

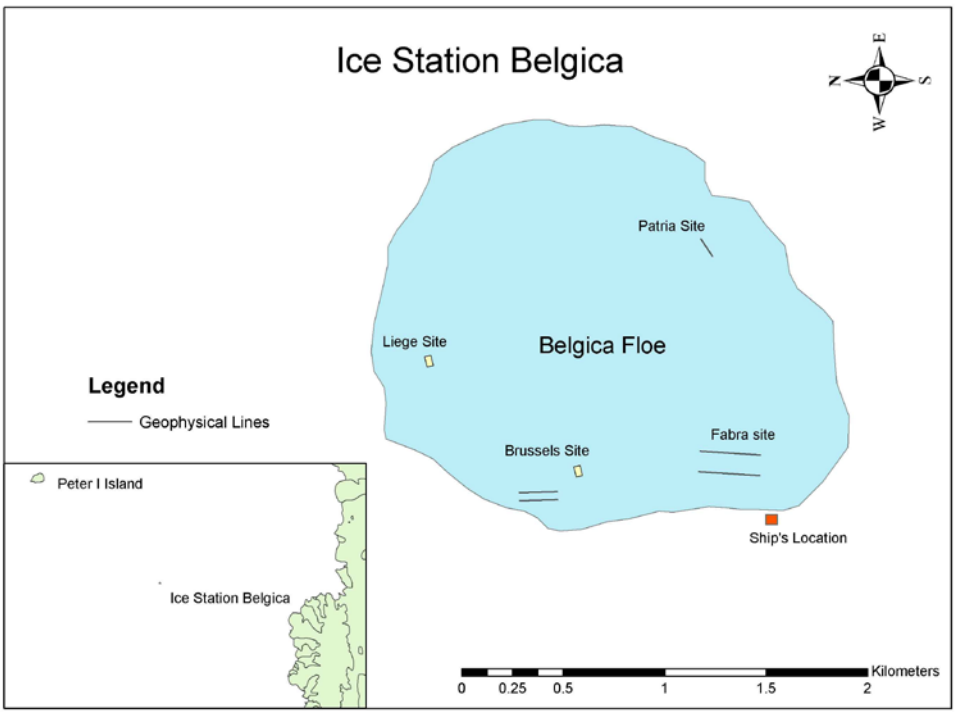


Figure 6. Layout of the Drift Station Belgica and various site features

Fabra Site

The first geophysical area, Fabra Site, was located approximately 200 meters off the starboard side of the NBP. The Fabra site typically contains thick snow cover over ridged and broken blocks of ice. Two geophysical transect lines were established approximately 100 meters apart and extended for 300 meters each. The endpoints of each geophysical line were marked with flags to allow repeated surveys of the same lines over time. Level surveys were performed at 1 meter increments along both transect lines to obtain snow surface elevation, as referenced to sea level benchmark. Snow depths

were also measured along the lines at 1 meter increments. The snow/ice interface was calculated by subtracting the snow depth from the surface elevation in each survey. Since the surface elevations are referenced to sea level, the snow/ice interface is also referenced to sea level. Positions along the geophysical lines that have a negative freeboard (ie. snow/ice interface below sea level) are susceptible to flooding. Snow pits were excavated in 15 locations along lines 1 & 2 in areas of negative freeboard to confirm the presence of slush (flooded snow) in these areas. Total snow and ice thickness along both geophysical lines was measured using a Geonics EM-31 conductivity meter. A 20m x 20m grid in which auger holes were drilled and ice thickness was gauged at 2 meter intervals was used for further calibration of the EM-31 to local ice conditions.

Surveys of the Fabra site were performed on October 1 &2, October 7, and October 21. The measurements were used to construct profiles for the geophysical lines. Statistics related to the measurements are given in Table 4. The surface elevation is reported in meters above sea level (ASL). The snow depth (in meters) is measured from the surface and subtracted from the surface elevation to give the snow/ice (S/I) interface in meters ASL. The EM ice thickness is derived from the total EM thickness (includes snow and ice) with snow depth subtracted. The % flooded represents the portion of the geophysical line with S/I interface below sea level.

Table 4 – Fabra Site Summary

Line	Date	Parameter	Mean	Std. Dev.	Max.	Min.	% Flooded
1A	10/01/07	Surface Elevation (m ASL)	0.659	0.338	1.673	0.073	55
		Snow Depth (m)	0.663	0.370	1.630	0.000	
		S/I interface (m ASL)	-0.006	0.367	1.261	-0.634	
		EM Ice Thickness (m)	1.794	0.703	3.674	0.437	
2A	10/02/07	Surface Elevation (m ASL)	0.673	0.266	1.564	0.213	70
		Snow Depth (m)	0.730	0.261	1.700	0.070	
		S/I interface (m ASL)	-0.057	0.282	1.004	-0.571	
		EM Ice Thickness (m)	1.672	0.678	3.436	0.606	
1B	10/07/07	Surface Elevation (m ASL)	0.669	0.321	1.539	0.079	51
		Snow Depth (m)	0.646	0.356	1.450	0.070	
		S/I interface (m ASL)	0.024	0.254	1.339	-0.529	
		EM Ice Thickness (m)	1.840	0.706	3.918	0.426	
	10/10/07	***Measured*** Ice Thickness (m)	2.328	1.251	5.010	0.600	
	10/11/07	***Measured*** Freeboard (m)	-0.027	0.143	0.270	0.270	
2B	10/07/07	Surface Elevation (m ASL)	0.681	0.253	1.478	0.271	69
		Snow Depth (m)	0.709	0.259	1.900	0.130	
		S/I interface (m ASL)	-0.028	0.239	0.865	-0.592	
		EM Ice Thickness (m)	1.724	0.626	3.401	0.620	
1C	10/21/07	Surface Elevation (m ASL)	0.667	0.320	1.469	0.049	74
		Snow Depth (m)	0.701	0.372	1.580	0.070	
		S/I interface (m ASL)	-0.034	0.211	1.354	-0.464	
		EM Ice Thickness (m)	1.623	0.629	3.448	0.392	
2C	10/21/07	Surface Elevation (m ASL)	0.640	0.256	1.530	0.219	80
		Snow Depth (m)	0.690	0.263	1.550	0.180	
		S/I interface (m ASL)	-0.049	0.191	0.888	-0.648	
		EM Ice Thickness (m)	1.501	0.580	3.385	0.591	

Plots of the profile for Lines 1 and 2 during the initial survey of October 1 and 2 are given in Figure 7.

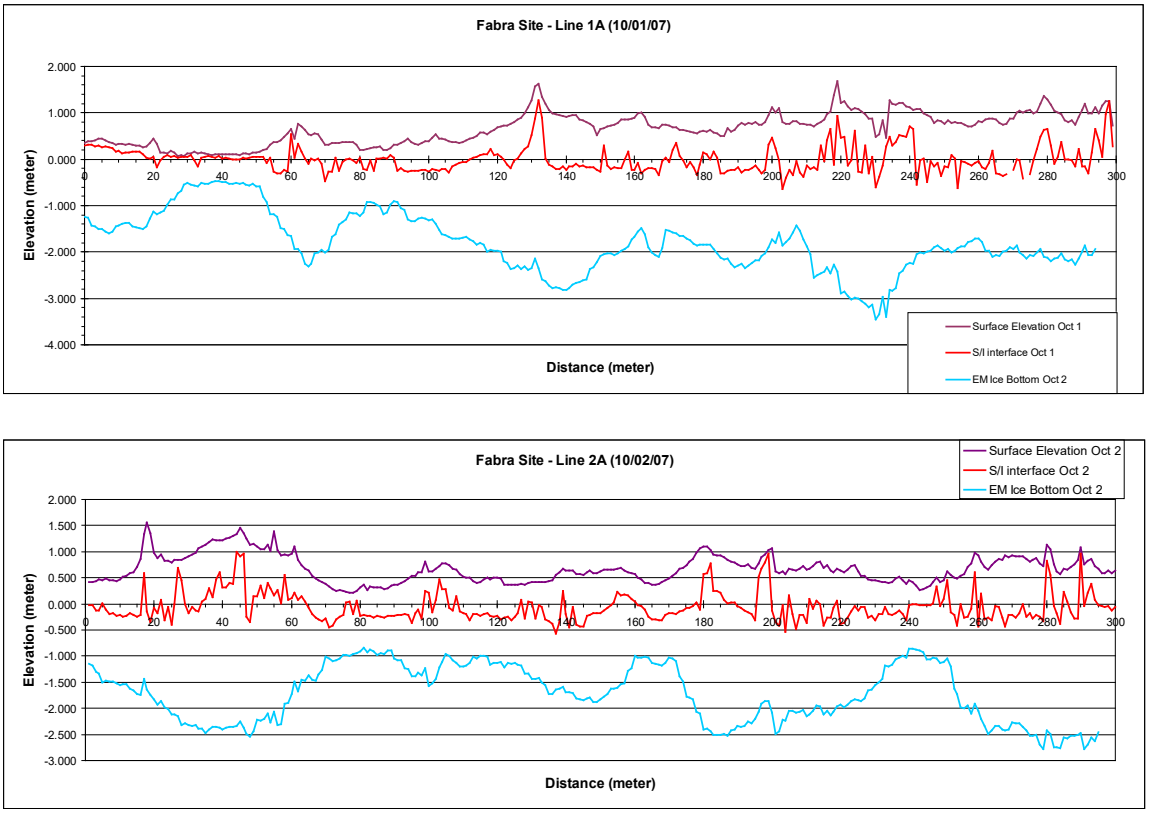


Figure 7. Initial Survey Profiles of Fabra Site on October 1 & 2, 2007

The Fabra site was re-surveyed approximately one week after the initial survey to assess temporal change. Plots for profile lines of the second survey of October 7 are given in Figure 8. On October 10 and 11, snow pits were excavated at 5 meter intervals along Line 1 and ice thickness augers were utilized to drill holes and measure ice thickness and freeboard. The measured values are given as individual points plotted as symbols in Figure 8.

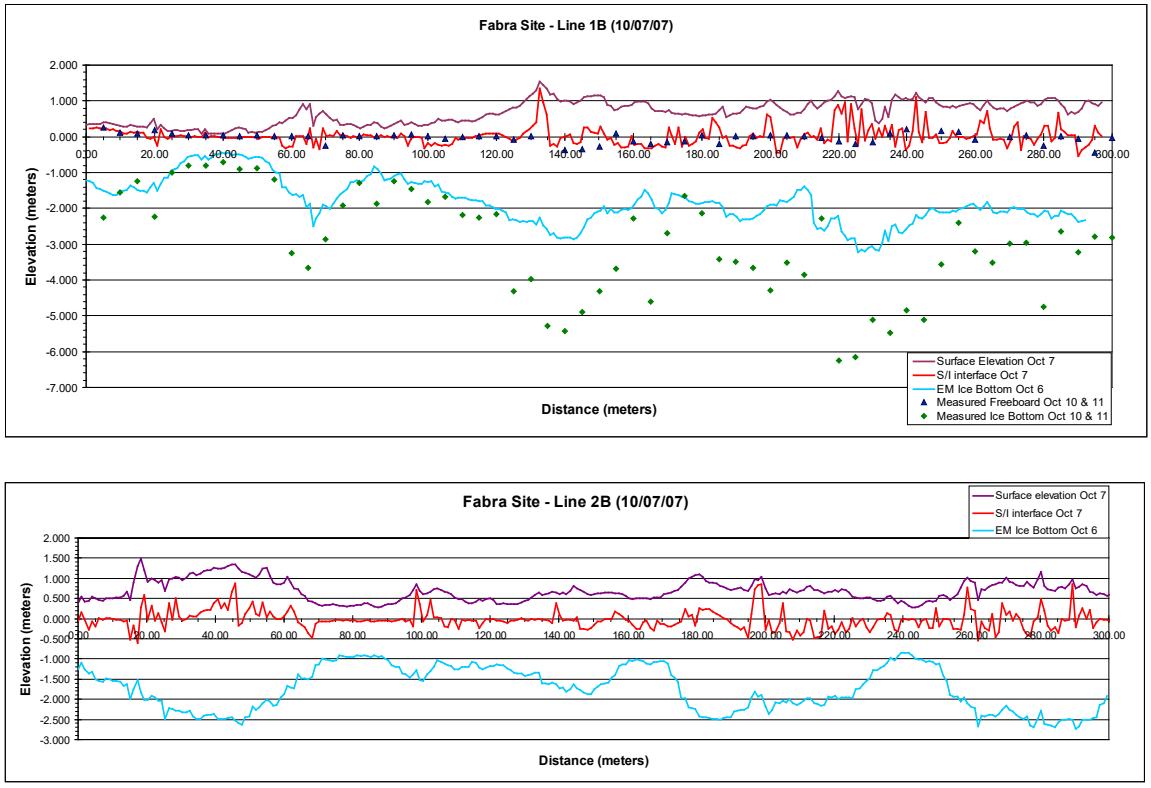


Figure 8. Survey Profiles of the Fabra Site on October 7, 2007

The data shows that the shape of the ice bottom is approximated by the EMI survey, however the EMI measurements significantly underestimate the ice thickness in heavily ridged areas. Factors affecting these measurements are likely attributed to the limitation in the configuration (transmitter/receiver spacing and energy) of the EM-31 device. Other potential effects may be the presence of flooded snow along the profile line and the ambiguities associated with an area averaged EM signal.

The final survey of the Fabra site, Lines 1 and 2, was performed on October 21 following a significant northern storm that resulted in snow accumulation and redistribution across the geophysical lines at the site. The storm resulted in additional flooding of the snow-ice interface along the geophysical lines. The profile plots for the final survey of the Fabra site are given in Figure 9.

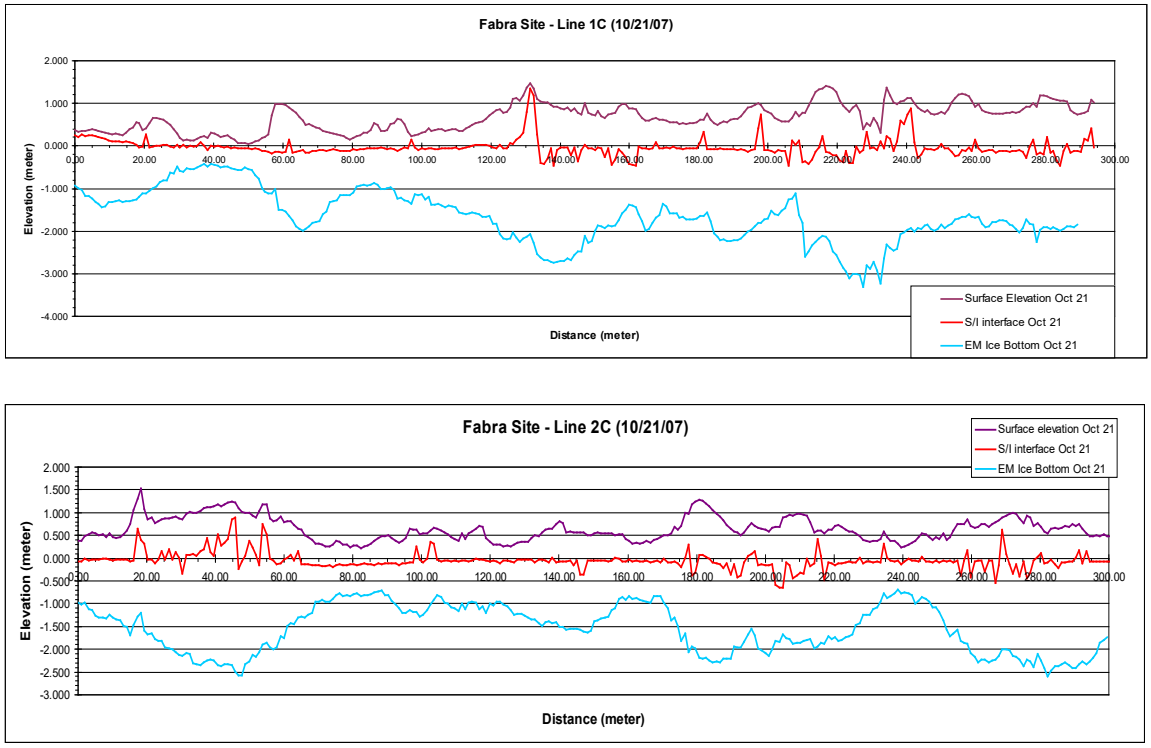
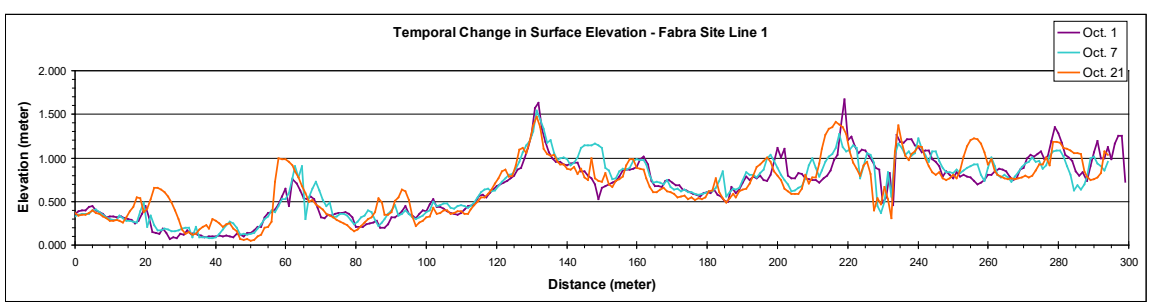


Figure 9. Final Survey Profiles for Fabra Site on October 21, 2007

A comparison of the temporal changes in the surface elevation of Lines 1 and 2 between the three separate survey dates are given in Figure 10. A preliminary statistical analysis using one-way ANOVA between the data sets indicates that there is no significant difference between the elevation profiles for Lines 1 and 2 over the three time periods. In addition, one-way analyses performed on snow depth measurements indicated that the snow depth profiles between Lines 1 and 2 were statistically different, however, the differences between time periods were not significant.



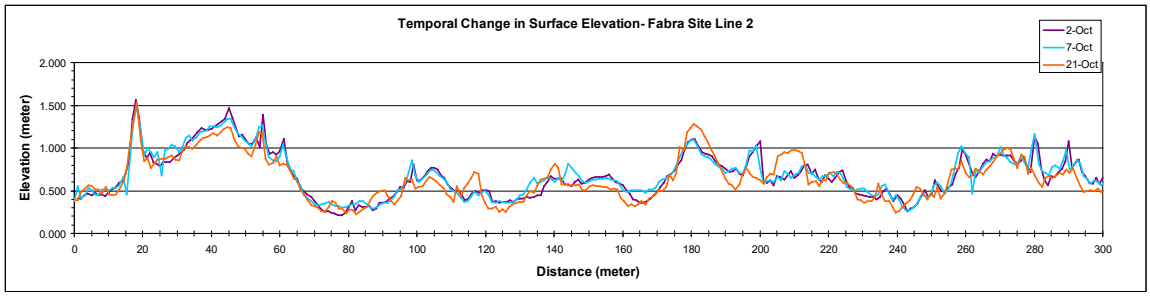


Figure 10. Comparison of Surface Elevations between Fabra Site Surveys

A total of 15 snow pits were excavated at the Fabra site on October 2 (Pits 1A & 2A), October 6 (Pits 1B - 1F & 2B – 2F), and October 16 (Pits 1G, 1H, & 2G). Snow Pit 1A and 1G are located in the same approximate position approximately 100 meters along Line 1 and 15 left of the line, however separated by 14 days. Snow Pits 2A and 2G are co-located approximately 200 meters along Line2 and 10 meters left, also separated by 14 days. Snow Pits 1B through 1F and 2B through 2F were excavated primarily to investigate the validity of the survey measurements indicating negative freeboard. The pits were located as follows:

- Pit 1B - 90 meters along Line 1 and 3 meters left
- Pit 1C – 100 meters along Line 1 and 3 meters left
- Pit 1D – 145 meters along Line 1 and 2 meters left
- Pit 1E – 185 meters along Line 1 and 2 meters left
- Pit 1F – 275 meters along Line 1 and 3 meters left
- Pit 1H – 170 meters along Line 1 and 5 meters left
- Pit 2B – 10 meters along Line 2 and 3 meters left
- Pit 2C – 90 meters along Line 2 and 3 meters left
- Pit 2D – 120 meters along Line 2 and 3 meters left
- Pit 2E – 170 meters along Line 2 and 3 meters left
- Pit 2F – 225 meters along Line 2 and 3 meters left

The snow pits were excavated to obtain snow temperature profiles, verify the presence of slush, examine snow structure, and obtain samples for analysis. Snow samples were analyzed for density, salinity, and O^{18} isotope concentration (analyses pending). A summary of snow properties is provided in Table 5.

Table 5 – Fabra Snow Pit Summary

Snow Pit	Snow Thickness (m)	Slush Thickness (m)	Air Temp (C)	Avg Snow Temp (C)	Snow/Ice interface Temp (C)	Slush Temp (C)	Average Density (g/cc)	Average Snow Salinity (psu)	Salinity Snow/Ice interface (psu)
1A	0.250	0.170	-4.38	-3.72	-1.91	-1.58	0.319	0.025	18.7
1B	0.300	0.210	ND	ND	ND	ND	ND	ND	ND
1C	0.450	0.240	ND	ND	ND	ND	ND	ND	ND
1D	1.050	0.160	ND	ND	ND	ND	ND	ND	ND
1E	0.550	0.280	ND	ND	ND	ND	ND	ND	ND
1F	0.740	0.200	ND	ND	ND	ND	ND	ND	ND
1G	0.450	0.000	-13.10	-8.10	-1.70	-1.65	0.318	0.443	17.4
1H	0.710	0.300	-12.36	-7.35	-2.00	-1.66	0.370	0.020	
2A	0720	0.450	-7.28	-6.43	-1.98	-1.78	0.362	0.043	20.5
2B	0.480	0.080	ND	ND	ND	ND	ND	ND	ND
2C	0.450	0.210	ND	ND	ND	ND	ND	ND	ND
2D	0.620	0.480	ND	ND	ND	ND	ND	ND	ND
2E	0.720	0.000	ND	ND	ND	ND	ND	ND	ND
2F	0.580	0.160	ND	ND	ND	ND	ND	ND	ND
2G	0.510	0.300	-12.84	-9.40	-2.23	-1.65	0.362	0.078	19.7

ND = no data

A time-series of temperature change in a borehole adjacent to Fabra snow pit 2G was obtained between October 16th and 22nd using 8 HOBO button dataloggers. The HOBO dataloggers were spaced roughly at 10 cm intervals, except for the snow-ice interface where the interval was condensed to 5 cm. At the time of retrieval (10/22/07), the snow pit sustained an additional 25 cm of flooding that was measured above the original snow-ice interface. A time series plot of the temperature profile from the button dataloggers is given in Figure 11. The snow temperature increased at the time of flooding to represent the temperature of sea water above freezing (-1.8°C). Based on the time series plot of temperature given below, the flooding of snow at the +25 cm level was sustained at approximately 15:00 hours on October 19 during warm northern storm that brought additional snow fall and wind redistribution of snow. The temperature of all intervals below the +30 cm level stabilize at approximately -1.8°C indicating the influx of ocean water into the snow pack. The temperature of intervals +30 and above reflect the warming trend in the upper snow pack. The estimated overall amount of flooding along Line 2 increased during this period from 69% to 80% as a result of this storm.

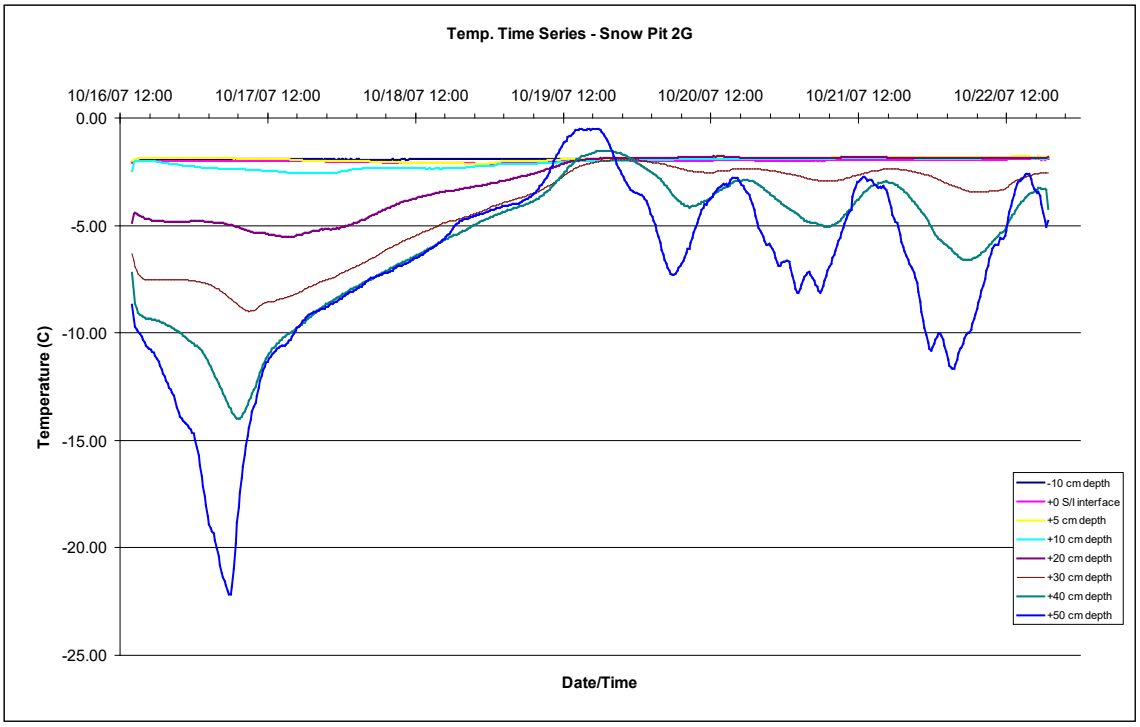


Figure 11. Time series of temperature in Snow Pit 2G during storm event

Attempts to characterize the presence and distribution of flooded snow (slush) utilizing electrical resistivity profiling were unsuccessful. The method involved injection of AC current (12V) at two electrodes 0.75 meters apart planted in the snow and measuring the electrical potential difference at two adjacent electrodes (planted 2.5 meters distant at a similar spacing). This technique is known as the dipole-dipole method of resistivity imaging, and in theory should resolve resistivity (or conductivity) contrasts between fresh snow and saline slush (if present). It was presumed that a slush layer could then be mapped both spatially and temporally over the Fabra site. Unfortunately, the extremely high resistivity (> 1 x 10^6 ohm-meters) of the near surface snow layers (due to dryness and air content) prevented the introduction of sufficient current (< 5 microwatts) to make the technique effective utilizing the available equipment.

A statistical characterization of ice deformation morphology at the Fabra site was undertaken in the 100 x 300 meter area between geophysical lines 1 & 2. Deformed ice features were characterized by measuring approximate area and height from surrounding mean snow surface elevation. Characterization of the entire study area was achieved by selecting a sample set of cross transects (n = 24) between lines 1 and 2, occurring at randomly selected locations along the geophysical transects. Each cross transect was 100 m in length and 5 m in width. Any ice deformity over 30 cm high and greater than 1 m^2 was surveyed using laser level and stadia rod. These data were statistically analyzed and frequency distributions generated according to ice deformity height. Mean height of deformities above surrounding snow elevation was 0.76 m. Frequency distribution was bimodal with modes occurring at 0.73 m and 1.34 m. Deformed ice accounted for 7.5 %

of the transect study area. A histogram showing the distribution of deformed ice features is given in Figure 12.

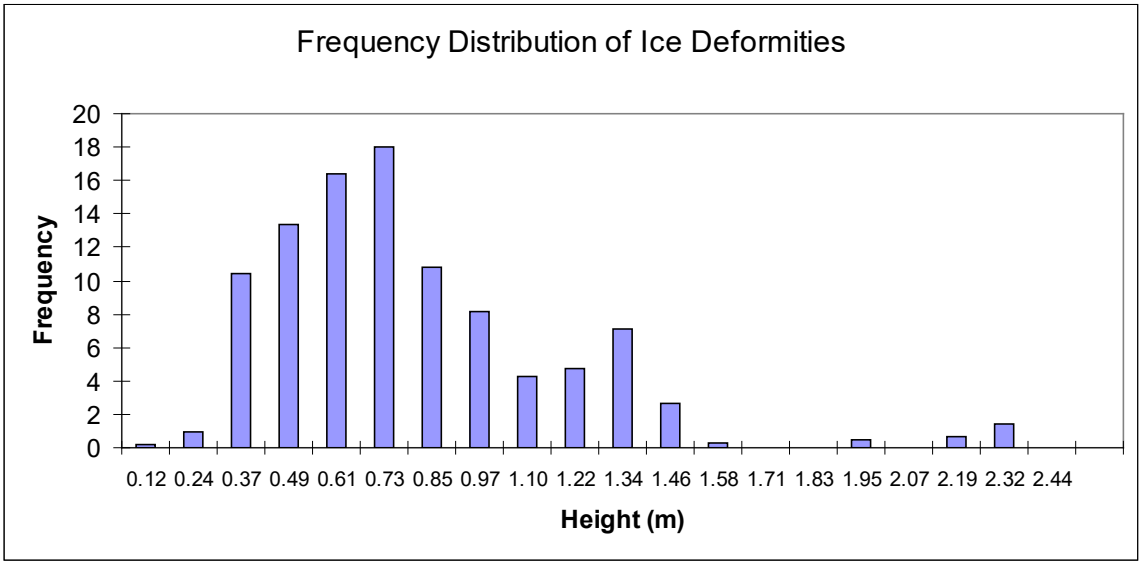


Figure 12. Distribution of Ice Deformities at Fabra Site

In addition, an assessment of the combined ice/snow thickness present along the 24 random transects at the Fabra site was performed using the EM-31. These data are pending further analysis. Once analyzed, these data will assist in characterizing total ice volume as well as ice-bottom morphology in the Fabra study area.

Brussels Site

The second site (Brussels Site) is located approximately 1 km from the bow of the NBP. The site typically contains thinner (less than 1 meter) and relatively level ice with thin snow cover. Two geophysical lines were established on October 3 at this site in the downwind location from the "clean" drilling operations. Again, level surveys of snow surface elevation, snow depth measurements and EM-31 ice thickness measurements were performed at 1-meter intervals. Additionally, ice auger holes were drilled and ice thickness was gauged at varying intervals along the geophysical lines. The measurements were again used to construct transect profiles for the geophysical lines. Additionally, snow depth measurements were obtained on three separate instances along geophysical Line 2. The measurements obtained on October 21 (2C) were limited to stations 174 through 200 meters. The snow depth measurements obtained on October 22 (2D) were offset approximately 10 meters to the left of Line 2 and extended from station 15 to 215 meters due to the removal of ice thickness gauges on the previous day. A summary of the site survey statistics is provided in Table 6.

Table 6 – Brussels Site Summary

Line	Date	Parameter	Mean	Std. Dev.	Max.	Min.	% Flooded
1A	10/03/07	Surface Elevation (m ASL)	0.124	0.024	0.219	0.079	4
		Snow Depth (m)	0.070	0.029	0.160	0.010	
		S/I interface (m ASL)	0.055	0.031	0.135	-0.065	
		EM Ice Thickness (m)	0.475	0.037	0.578	0.385	
		Measured Ice Thickness (m)	0.545	0.054	0.660	0.470	
		Measured Freeboard (m)	0.026	0.022	0.090	0.010	
2A	10/03/07	Surface Elevation (m ASL)	0.133	0.037	0.265	0.070	0.5
		Snow Depth (m)	0.081	0.034	0.190	0.020	
		S/I interface (m ASL)	0.053	0.022	0.197	-0.001	
		EM Ice Thickness (m)	0.477	0.033	0.592	0.376	
		Measured Ice Thickness (m)	0.585	0.057	0.690	0.490	
		Measured Freeboard (m)	0.039	0.036	0.110	0.010	
2B	10/07/07	Snow Depth (m)	0.111	0.041	0.220	0.010	ND
2C	10/21/07	Snow Depth (m)	0.086	0.025	0.130	0.030	ND
2D	10/22/07	Snow Depth (m)	0.143	0.079	0.425	0.030	ND

ND = no data

A plot of the profile for Lines 1 and 2 during the survey of October 3, 2007 are given in Figure 13. Snow pits and auger drilled thickness holes represent the measured ice thickness and freeboard given as symbols in the plots below.

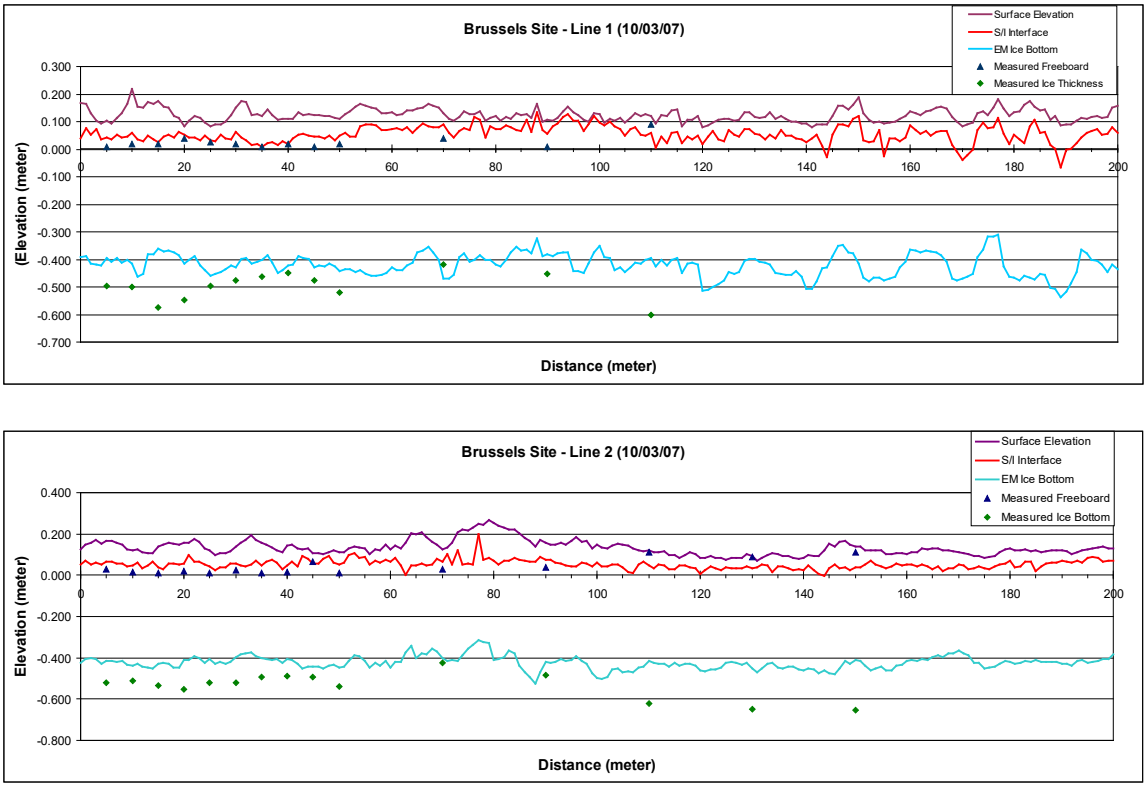


Figure 13. Survey Profiles for the Brussels Site on October 3, 2007

A total of 7 snow pits were excavated at the Brussels site on October 2 (Pit 3A), October 17 (Pits 3B & 3C), and October 20 (Pits 3D & 3E). The location of the various snow pits are as follows:

- Pit 3A – 60 meters along Line 1 and 10 meters left
- Pit 3B – 10 meters left of IMB #3 (toward the Scott tent)
- Pit 3C – 10 meters right of IMB #3 (away from the tent)
- Pit 3D – 10 meters left of IMB #1 (away from Line 2)
- Pit 3E – 10 meters from IMB #1 (parallel to Line 2)
- Pit 3F – 5 meters downwind of IMB #3 on wind plain
- Pit 3G – 5 meters downwind of IMB #3 on snow drift

The snow pits were excavated to obtain snow temperature profiles, verify the presence or absence of slush, examine snow structure, and obtain samples for analysis. Snow samples were analyzed for density, salinity, and O^{18} isotope concentration (analyses pending). A summary of snow properties is provided in Table 7 below.

Table 7 – Brussels Snow Pit Summary

Snow Pit	Snow Thickness (m)	Slush Thickness (m)	Air Temp (C)	Avg Snow Temp (C)	Snow/Ice interface Temp (C)	Slush Temp (C)	Average Density (g/cc)	Average Snow Salinity (psu)	Salinity Snow/Ice interface (psu)
3A	0.130	0.000	-8.80	-5.24	-2.95	ND	0.232	0.05	ND
3B	0.19	0.000	-11.86	-7.92	-4.95	ND	0.292	1.1	ND
3C	0.070	0.000	-11.87	-9.28	-8.06	ND	0.273	3.6	ND
3D	0.120	0.020	-2.36	-3.84	-3.96	ND	0.393	0.7	9.6
3E	.150	0.020	-3.62	-3.26	-3.96	ND	0.358	0.6	18.0
3F	0.110	0.000	ND	ND	ND	ND	ND	ND	ND
3G	0.430	0.000	ND	ND	ND	ND	ND	ND	ND

ND = no data

Patria Site

The Patria site is located on the east side of the floe approximately 2 km distant from the ship. Visual observations from the ship during our initial approach on Sept. 27 indicated that this side of the Belgica floe had substantially thicker ice and snow cover. This proved not to be the case, as the selected Patria site had a mean ice thickness of 0.75 m (augered) and a mean snow depth of 0.092 m, which is substantially less than the Fabra site.

The Patria site was initially surveyed on October 9, 2007. All relevant data, elevations, snow depth, ice thickness (auger holes and EMI) were collected along a 100 meter transect at 5 meter intervals (snow depth at 1 m intervals). A snow pit (5A) was excavated at the site to obtain snow temperature and density profiles and to obtain snow structure characteristics. Samples of snow were analyzed for salinity and O^{18} isotope (pending). The location of Pit 5A was approximately 15 meters right of the geophysical line near a large snow drift about 5 meters before the start of the line. Snow pit 5B was

excavated on October 22 and was located at the start (station 0) of the geophysical line and 3 meters to the right. A summary of snow pit data from the Patria site is given in Table 8.

Table 8 – Patria Snow Pit Summary

Snow Pit	Snow Thickness (m)	Slush Thickness (m)	Air Temp (C)	Avg Snow Temp (C)	Snow/Ice interface Temp (C)	Slush Temp (C)	Average Density (g/cc)	Average Snow Salinity (psu)	Salinity Snow/Ice interface (psu)
5A	0.710	0.300	-12.36	-7.35	-2.00	-1.66	0.323	0.17	4.20
5B	0.180	0.000	-4.31	-3.02	-2.36	ND	ND	ND	ND

ND = no data

The results of the elevation survey and depth measurements from the Patria site on October 9 are given in Figure 14.

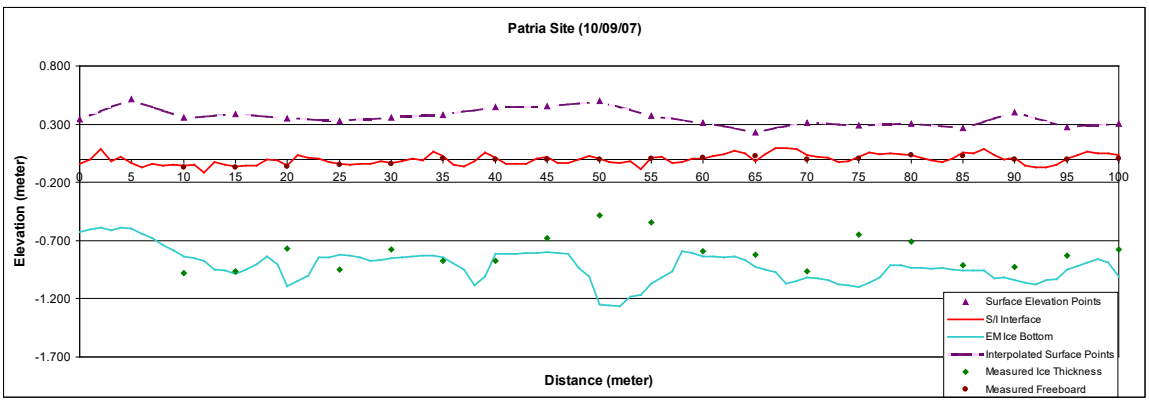


Figure 14. Profile of Patria Site Survey on October 9, 2007

An additional survey of surface elevations and snow thickness was performed at the Patria site on October 22. The survey and depth measurements were all performed at 1-meter intervals. The site work was cut short by an impending snow storm with very limited visibility that forced a return to the ship. Therefore, ice thickness measurements by auger were not performed and snow pit density profile for Snow Pit 5B was not obtained. The profile for the October 22 survey is given in Figure 15.

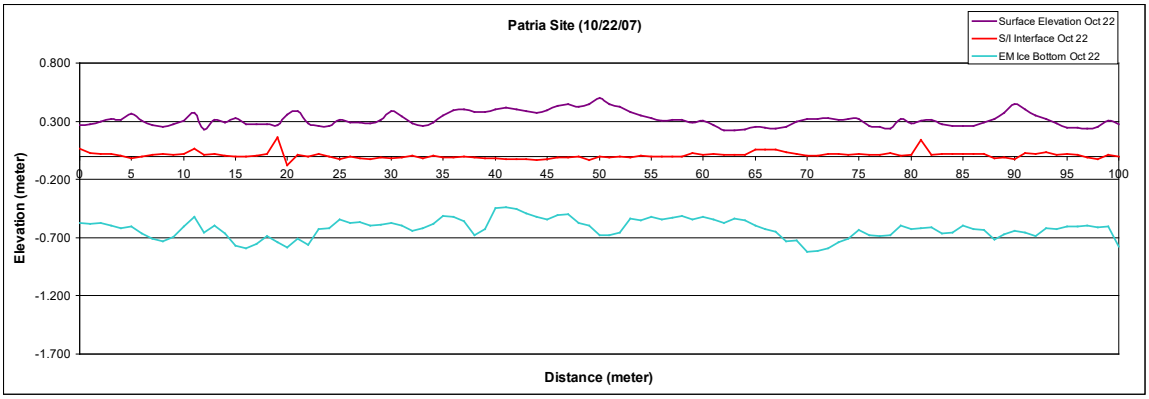


Figure 15. Profile from the Re-survey of the Patria Site on October 22, 2007
A summary of the survey statistics for the two profiles are provided in Table 9 below.

Table 9 – Patria Site Summary

Line	Date	Parameter	Mean	Std. Dev.	Max.	Min.	% Flooded
A	10/09/07	Surface Elevation (m ASL)	0.356	0.074	0.512	0.232	52
		Snow Depth (m)	0.360	0.093	0.550	0.170	
		S/I interface (m ASL)	-0.003	0.044	0.095	-0.114	
		EM Ice Thickness (m)	0.913	0.150	1.259	0.567	
		Measured Ice Thickness (m)	0.788	0.135	1.000	0.490	
		Measured Freeboard (m)	-0.009	0.033	0.035	-0.070	
B	10/22/07	Surface Elevation (m ASL)	0.316	0.062	0.497	0.219	44
		Snow Depth (m)	0.309	0.079	0.500	0.110	
		S/I interface (m ASL)	0.007	0.030	0.158	-0.080	
		EM Ice Thickness (m)	0.629	0.093	0.895	0.416	

Liege Site

No elevation or depth surveys were performed at the Liege site due to the near proximity of the "clean area" sampling. A total of 5 snow pits were excavated on October 6 (Pit 4A), October 17 (Pit 4B), and October 20 (Pits 4C – 4E). Snow Pits 4A & 4B were located in the same approximate position on the left flank of the Ice Mass Balance Buoy (IMB #2), however offset by 11 days. Snow Pit 4C was located on the opposite side of IMB #2 between it and the clean sampling area. Snow Pit 4D was located adjacent to the flag at the far end of the clean area (toward the ship) along the right boundary of the clean area. Snow Pit 4E was located 40 meters from the corner flag of the clean area on the opposite end (away from the ship) along the left boundary of the clean area and toward the meteorological towers (Katie's). A summary of the snow pit data from the Liege site is given in Table 10.

Table 10 – Liege Snow Pit Summary

Snow Pit	Snow Thickness (m)	Slush Thickness (m)	Air Temp (C)	Avg Snow Temp (C)	Snow/Ice interface Temp (C)	Slush Temp (C)	Average Density (g/cc)	Average Snow Salinity (psu)	Salinity Snow/Ice interface (psu)
4A	0.550	0.000	-7.49	-3.75	-3.26	ND	0.282	0.113	ND
4B	0.612	0.090	-12.00	-10.03	-2.53	-1.98	0.363	0.020	ND
4C	0.440	0.130	-4.26	-3.06	-2.01	-1.90	0.353	0.125	ND
4D	0.460	0.000	-3.77	-3.42	-3.08	ND	0.303	0.025	ND
4E	.250	0.000	-2.51	-3.01	-2.28	ND	0.370	0.200	5.2

ND = no data

Snow Wetness Calculations

For temperatures below the freezing point of fresh water (0°C), the snow wetness may be related to the volume of brine present in the snow sample. The phase relation presented by Cox and Weeks (1983) was used to calculate the volume of brine relative to the total volume (and thus snow wetness in %) based on the salinity and temperature of the snow samples. The following relation is based on the continuity equations for a multi-phase sea ice mixture.

$$V_b/V = (1 - V_a/V)\,[\rho_i\, S_{si}/\, F_1 - \rho_i\, S_{si}\, F_2] \qquad \text{Eqn 2}$$

Where:
ρ_i = density of pure ice = $0.917 - 1.403e^{-4}\,T$ (g/cm^3)
T = temperature (°C)
V_b = volume of brine (cm^3)
V_a = volume of air (cm^3)
S_{si} = salinity of sea ice (psu)
F_1 = empirical polynomial function, dependent on temperature
F_2 = empirical polynomial function, dependent on temperature

The empirical polynomial functions are computed as follows:

$$F_i = a_i + b_i\,T + c_i\,T^2 + d_i\,T^3 \qquad \text{Eqn. 3}$$

Where the constants are dependent upon different temperature range

Constants	$0 \geq T > -2$	$-2 \geq T \geq -22.9$	$-22.9 \geq T \geq -30$
a_1	-0.041221	-4.732	9899
b_1	-18.407	-22.4	1309
c_1	0.58402	-0.6397	55.27
d_1	0.21454	-0.0174	0.7160
a_2	0.090312	0.08903	8.547
b_2	-0.016111	-0.01763	1.089
c_2	$1.2291\ e^{-4}$	$-5.330\ e^{-4}$	0.04518
d_2	$1.3603\ e^{-4}$	$-8.801\ e^{-6}$	$5.819\ e^{-4}$

Based on the temperature, salinity, and gravimetric measurements performed on samples from the snow pits at Waystations 1-3, Fabra site (1 and 2), Brussels site (3), Liege site (4), and Patria site (5), the snow wetness calculations are provided in Table 11 below.

Table 11 – Snow Wetness Calculation Results

Snow Pit	Depth Interval (cm)	Temp (°C)	Density (g cm^{-3})	Salinity (psu)	F1	F2	Snow Wetness (%)
	0 - 5 cm	-1.51	0.620	14.2	28.34632	0.114452	15.720
	5 - 10 cm	-1.39	0.331	0.1	26.09672	0.112578	0.225
	10 - 15 cm	-1.35	0.360	0.0	25.34476	0.111951	0.000
	15 - 20 cm	-1.29	0.417	0.0	24.21513	0.111008	0.000
1-1	20 - 25 cm	-1.17	0.384	0.1	21.95082	0.109112	0.243
	0 - 5 cm	-1.63	0.409	0.0	30.58475	0.11631	0.000
	5 - 10 cm	-1.56	0.415	0.0	29.28049	0.115228	0.000
	10 - 15 cm	-1.52	0.414	0.0	28.53332	0.114607	0.000
1-2	15 - 20 cm	-1.34	0.384	0.0	25.15662	0.111794	0.000
	0 - 5 cm	-1.57	0.316	0.0	29.46707	0.115383	0.000
	5 - 10 cm	-1.43	0.365	0.0	26.84769	0.113204	0.000
	10 - 15 cm	-1.31	0.347	0.0	24.59188	0.111323	0.000
	15 - 20 cm	-1.18	0.324	0.0	22.13973	0.109271	0.000
	20 - 25 cm	-1.04	0.350	0.0	19.49241	0.107047	0.000
1-3	25 - 30 cm	-0.92	0.361	0.0	17.22047	0.105132	0.000
	0 - 5 cm	-1.69	0.295	0.1	31.60636	0.117157	0.197
	10 - 15 cm	-1.75	0.306	0.0	32.71738	0.118077	0.000
	20 - 25 cm	-1.80	0.356	0.0	33.64027	0.118841	0.000
	30 - 35 cm	-1.83	0.326	0.0	34.23863	0.119335	0.000
	50 - 55 cm	-1.94	0.290	0.0	36.29994	0.121037	0.000
2-1	60 - 65 cm	-2.29	0.386	0.0	43.58229	0.126752	0.000
	0 - 5 cm	-1.58	0.399	2.1	29.70019	0.115576	3.694
	5 - 10 cm	-1.64	0.372	0.0	30.67775	0.116388	0.000
	10 - 15 cm	-1.86	0.353	0.0	34.78985	0.11979	0.000
	15 - 20 cm	-1.98	0.371	0.0	36.93789	0.121563	0.000
	20 - 25 cm	-2.55	0.415	0.2	48.54672	0.130591	0.207
2-2	25 - 30 cm	-2.88	0.418	0.5	55.03372	0.135594	0.454
	0 - 5 cm	-1.84	0.459	4.7	34.42249	0.119487	6.349
2-3	10 - 15 cm	-1.97	0.415	0.1	36.75579	0.121413	0.137

	20 - 25 cm	-2.24	0.427	0.1	42.54181	0.125946	0.115
	30 - 35 cm	-2.68	0.410	0.1	51.17435	0.13262	0.099
	0 - 5 cm	-3.25	0.307	8.1	61.97675	0.140928	8.122
3-1	5 - 10 cm	-3.90	0.273	0.0	74.12531	0.150202	0.000
	-5 - 0		0.844	19.0			
	0 - 5 cm	-1.55	0.266	5.9	29.09382	0.115073	0.135
	10 - 15 cm	-2.32	0.384	5.1	44.12616	0.127173	0.062
3-2	20 - 25 cm	-3.78	0.294	0.3	71.83668	0.148461	0.003
3-3	5 - 10 cm	-3.19	0.278	2.1	60.84417	0.140059	0.022
	-5 - 0		0.939	18.7			
	0 - 5 cm	-2.14	0.316	0.0	40.45219	0.124326	0.000
	5 - 10 cm	-2.88	0.279	0.0	55.03372	0.135594	0.000
	10 - 15 cm	-3.88	0.356	0.0	73.66868	0.149855	0.000
1A	15 - 20 cm	-4.56	0.325	0.1	85.98818	0.159174	0.000
	-5 - 0		0.945	20.5			
	0 - 5 cm	-2.49	0.405	0.0	47.37297	0.129684	0.000
	10 - 15 cm	-4.15	0.363	0.1	78.5717	0.153576	0.000
	20 - 25 cm	-5.19	0.398	0.0	96.98497	0.167403	0.000
	30 - 35 cm	-6.25	0.381	0.0	114.8403	0.180546	0.000
	40 - 45 cm	-7.43	0.323	0.0	133.8939	0.194207	0.000
	50 - 55 cm	-7.89	0.415	0.1	141.0441	0.199219	0.000
2A	60 - 65 cm	-8.20	0.251	0.1	145.861	0.202556	0.000
	0 - 5 cm	-3.88	0.228	0.1	73.66868	0.149855	0.000
3A	5 - 10 cm	-5.24	0.235	0.0	97.75894	0.167979	0.000
	0 - 5 cm	-3.20	0.247	0.0	61.03317	0.140204	0.000
	5 - 10 cm	-3.17	0.208	0.0	60.5605	0.139841	0.000
	10 - 15 cm	-3.22	0.280	0.0	61.50526	0.140566	0.000
	15 - 20 cm	-3.29	0.316	0.2	62.72992	0.141505	0.001
	20 - 25 cm	-3.34	0.348	0.2	63.76308	0.142296	0.001
	25 - 30 cm	-3.34	0.326	0.1	63.76308	0.142296	0.001
	45 - 50 cm	-5.62	0.270	0.1	104.321	0.172838	0.000
4A	50 - 55 cm	-7.05	0.260	0.3	127.7627	0.189857	0.001
	0 - 5 cm	-2.19	0.469	4.2	41.44869	0.125099	0.049
	10 - 15 cm	-3.08	0.273	0.1	58.80643	0.138495	0.000
	20 - 25 cm	-4.22	0.402	0.3	79.83269	0.15453	0.001
	30 - 35 cm	-5.42	0.374	0.3	100.8827	0.170297	0.001
	40 - 45 cm	-5.37	0.252	0.2	100.0293	0.169664	0.001
	50 - 55 cm	-4.91	0.261	0.1	92.04806	0.16372	0.000
	60 - 65 cm	-4.29	0.268	0.1	81.22399	0.155582	0.000
5A	70 - 75 cm	-3.67	0.287	0.1	69.85739	0.146953	0.000
	-5 - 0 cm	-1.65	0.902	17.4			
	5 - 10 cm	-4.36	0.384	0.8	82.4317	0.156494	0.004
	10 - 15 cm	-5.99	0.416	0.8	110.4473	0.17734	0.003
	15 - 20 cm	-6.94	0.356	0.8	126.0768	0.188653	0.002
	20 - 25 cm	-7.94	0.307	0.6	141.8239	0.199761	0.001
	25 - 30 cm	-8.94	0.277	0.1	157.2005	0.21028	0.000
	30 - 35 cm	-10.43	0.240	0.0	179.5743	0.224914	0.000
1G	35 - 40 cm	-12.18	0.243	0.0	205.2486	0.240594	0.000
	5 - 10 cm	-3.16	0.381	0.0	60.27661	0.139624	0.000
	15 - 20 cm	-4.40	0.433	0.1	83.05644	0.156966	0.000
	25 - 30 cm	-5.83	0.361	0.0	107.7729	0.175379	0.000
1H	35 - 40 cm	-7.37	0.395	0.0	132.8642	0.193479	0.000

	45 - 50 cm	-9.05	0.279	0.0	158.9447	0.211451	0.000
	-5 - 0 cm	-1.65	0.957	19.7			
	0 - 5 cm	-3.44	0.283	0.0	65.54101	0.143657	0.000
	5 - 10 cm	-5.31	0.369	0.3	99.04561	0.168934	0.001
	10 - 15 cm	-6.61	0.411	0.4	120.6565	0.184759	0.001
	15 - 20 cm	-7.64	0.384	0.0	137.2064	0.196537	0.000
	20 - 25 cm	-9.01	0.339	0.0	158.3385	0.211045	0.000
	25 - 30 cm	-10.09	0.338	0.0	174.5359	0.221694	0.000
	30 - 35 cm	-10.71	0.405	0.0	183.7069	0.227522	0.000
	35 - 40 cm	-11.73	0.368	0.0	198.6713	0.236697	0.000
2G	40 - 45 cm	-12.34	0.364	0.0	207.5133	0.241917	0.000
	5 - 10 cm	-4.27	0.307	0.0	80.82058	0.155277	0.000
	15 - 20 cm	-6.63	0.361	0.1	120.9819	0.184994	0.000
	25 - 30 cm	-10.38	0.379	0.0	178.8348	0.224445	0.000
	35 - 40 cm	-12.49	0.411	0.0	209.705	0.243187	0.000
	45 - 50 cm	-13.71	0.389	0.0	227.5828	0.253193	0.000
4B	55 - 60 cm	-12.70	0.332	0.0	212.8477	0.244991	0.000
	0 - 5 cm	-5.77	0.380	2.9	106.7655	0.174639	0.011
	5 - 10 cm	-7.27	0.241	0.2	131.3553	0.192411	0.000
3B	10 - 15 cm	-8.60	0.255	0.2	152.0166	0.206773	0.000
3C	0 - 5 cm	-8.67	0.273	3.6	153.1638	0.207553	0.007
	5 - 10 cm	-2.05	0.307	0.2	38.75206	0.123007	0.002
	15 - 20 cm	-2.66	0.435	0.1	50.78623	0.13232	0.001
	25 - 30 cm	-3.35	0.375	0.1	63.85687	0.142368	0.001
4C	35 - 40 cm	-4.07	0.295	0.1	77.12548	0.15248	0.000
	5 - 10 cm	-3.09	0.318	0.1	58.94896	0.138604	0.001
	15 - 20 cm	-3.13	0.302	0.0	59.85037	0.139296	0.000
	25 - 30 cm	-3.33	0.359	0.0	63.48159	0.142081	0.000
4D	40 - 45 cm	-3.74	0.233	0.0	71.19339	0.147971	0.000
	0 - 5 cm	-2.52	0.423	5.2	47.9603	0.130138	0.047
	5 - 10 cm	-2.83	0.371	0.6	53.97633	0.134779	0.004
	10 - 15 cm	-3.03	0.352	0.0	57.80724	0.137727	0.000
4E	15 - 20 cm	-3.19	0.336	0.0	60.84417	0.140059	0.000
	0 - 5 cm	-3.95	0.384	9.6	75.03694	0.150895	0.052
3D	5 - 10 cm	-3.84	0.402	0.7	73.02848	0.149368	0.004
	0 - 5 cm	-4.09	0.417	18.0	77.57801	0.152823	0.102
3E	5 - 10 cm	-3.55	0.299	0.6	67.5893	0.145222	0.003