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GEOLOGICAL SURVEY OF CANADA
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Publications in this series have not been edited; they are released as submitted by the author.

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- Alex Normandeau, Chief Scientist, 2019Nuliajuk

1. Background and Objectives

Since 2012, the Baffin Bay Geohazards Activity of NRCan's Public Safety Geoscience Program has conducted research to improve the understanding of geological processes and hazards (geohazards) in Baffin Bay to support stakeholder decisions on the use of offshore areas and provide northern communities with better knowledge for improving public safety. The 2019 Preliminary Findings Report for the SEA in Baffin Bay states that there are knowledge gaps in the region regarding geohazards, seismicity, seabed characteristics (depth and sediment thicknesses), tsunamis and oil seeps. These knowledge gaps limit the assessment of the risk they pose to communities that are located at or near sea-level.

Study of the marine geology of a region provides critical information about the modern stability of the seabed, reveals evidence of past instability, and divulges specific constraints around the timing and triggering of past events, thus improving predictive capability of future events. For example, determining the past record of seismic activity preserved in marine sediments helps to better estimate earthquake recurrence and understand seismic risk.

Whereas much of the NRCan research from 2012 to 2018 focused on the offshore areas of Baffin Bay, relatively little effort has been spent examining the geohazard record preserved in fjords of Baffin Island. Fjords are well-known sediment traps that are more likely to record past geohazard events such as large earthquakes. Fjords are often located along pre-existing faults which may act as conduits, leading to seabed fluid seepage. In addition, fjords are constrained environments where mapping of past landslide distribution is much easier than in the offshore where data collection is expensive to acquire and the record is not as well preserved. Therefore, fjords represent cost-effective natural laboratories to study geohazard activity in Baffin Bay.

Fjords are known to be more susceptible to submarine and subaerial sidewall failures, producing some of the largest tsunamis on Earth. From the 14 largest tsunamis ever recorded, 10 occurred in glaciated environments such as fjords (Hingar et al., 2018) in environments similar to Baffin Bay. The 2017 Greenland tsunami serves as a reminder of the risk they pose and their dramatic consequences on northern communities.

During the past 7 years, NRCan has been funded by the Program for Energy and Resources Development (PERD) and Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC) to assess the recurrence of geohazards offshore eastern Baffin Island. During that time, a study of Pond Inlet was completed that suggests a recurrence rate of 1/1000 years for submarine landslides (Broom, 2019). In addition, simple numerical models were applied to assess the potential tsunami impact on the community for a landslide of the same magnitude as the 2017 Greenland event (Broom, 2019). A similar study is underway in Southwind Fjord, near Qikiqtarjuaq, where there is widespread evidence of submarine landslide deposits on the seabed (Normandeau et al., 2019a). During 2018-2019, NRCan produced a predictive map of where landslides are more likely to occur at the front or river mouths in fjords of all of eastern Baffin Island (Normandeau et al., 2019b).

Building on these results, clear knowledge gaps were identified near Pangnirtung and Qikiqtarjuaq where limited information of the seafloor is available, but where preliminary data suggest a high level of geohazard activity. Therefore, the *2019Nuliajuk* scientific cruise aimed at acquiring new data near these communities to refine the recurrence estimate of submarine landslides, some possibly linked to past earthquake events, and their potential for generating tsunamis.

The main objective of the R/V Nuliajuk (Fig. 1) *2019Nuliajuk* cruise was to refine estimates of the recurrence of marine geohazards in eastern Baffin Island. Specifically, the cruise aimed at:

1) Mapping the distribution of submarine landslides in fjords between Qikiqtarjuaq and Pangnirtung by acquiring new multibeam bathymetry data.
2) Collect sediment cores in the fjords to assess the stability of slopes near the communities. This stability analysis will allow us to understand what magnitude of earthquake was/is required to trigger a sediment failure.
3) Monitor active geohazards in Southwind Fjord and Pangnirtung Fjord through repeat multibeam bathymetric surveys and the deployment of a current profiler mooring.

Figure 1: The R/V Nuliajuk

2. Participants

Scientific participants of the *2019Nuliajuk* cruise consisted of three Geological Survey of Canada researchers, one M.Sc. student from Dalhousie University, and one hydrographer from the Marine Institute of the Memorial University of Newfoundland (Table 1, Fig. 2).

Table 1: Scientific participants of the 2019Nuliajuk cruise

First Name	Last Name	Affiliation	Role
Alex	Normandeau	Geological Survey of Canada (Atlantic)	Chief Scientist
Genevieve	Philibert	Geological Survey of Canada (Atlantic)	Physical Scientist
Angus	Robertson	Geological Survey of Canada (Atlantic)	Lead tech
Philip	Sedore	Dalhousie University	M.Sc. student
Kirk	Regular	Marine Institute, Memorial University	Hydrographer

Figure 2: Crew and science participants of the *2019Nuliajuk* scientific cruise. From left to right: Kirk Regular, Philip Sedore, Genevieve Philibert, Desmond Jordan, Allan Hayter, Mary Kelly, Evie Kilibuk, Alf Burton, Bob Bennett, Alex Normandeau, and Angus Robertson

3. SUMMARY OF ACTIVITIES

The cruise began in Qikiqtarjuaq, on Sept. 20th (Table 2, Fig. 3). The ship left Qikqitarjuaq in the morning of September 21st and headed for a small channel system on the south side of Broughton Island. Following the mapping of this channel, the vessel headed towards Padle Fjord. The aim was to map the fjord for the presence of marine geohazards. Western Padle Fjord was then mapped for the same purposes.

Following the mapping of Padle Fjord, the vessel transited to Southwind Fjord where a complete mapping of the fjord-head was repeated to observe any changes on the seabed. Following the repeat mapping, a mooring was deployed at the mouth of a submarine channel. This mooring will remain in the fjord for 1 year.

A 1 ½ day transit brought the vessel to Pangnirtung where most of the work was completed. A full bottom mapping of the fjord was completed, along with 3.5 kHz sub-bottom profiles, unmanned aerial vehicle (UAV) surveys and sediment cores. This data aims at understanding submarine geological hazards near the community of Pangnirtung.

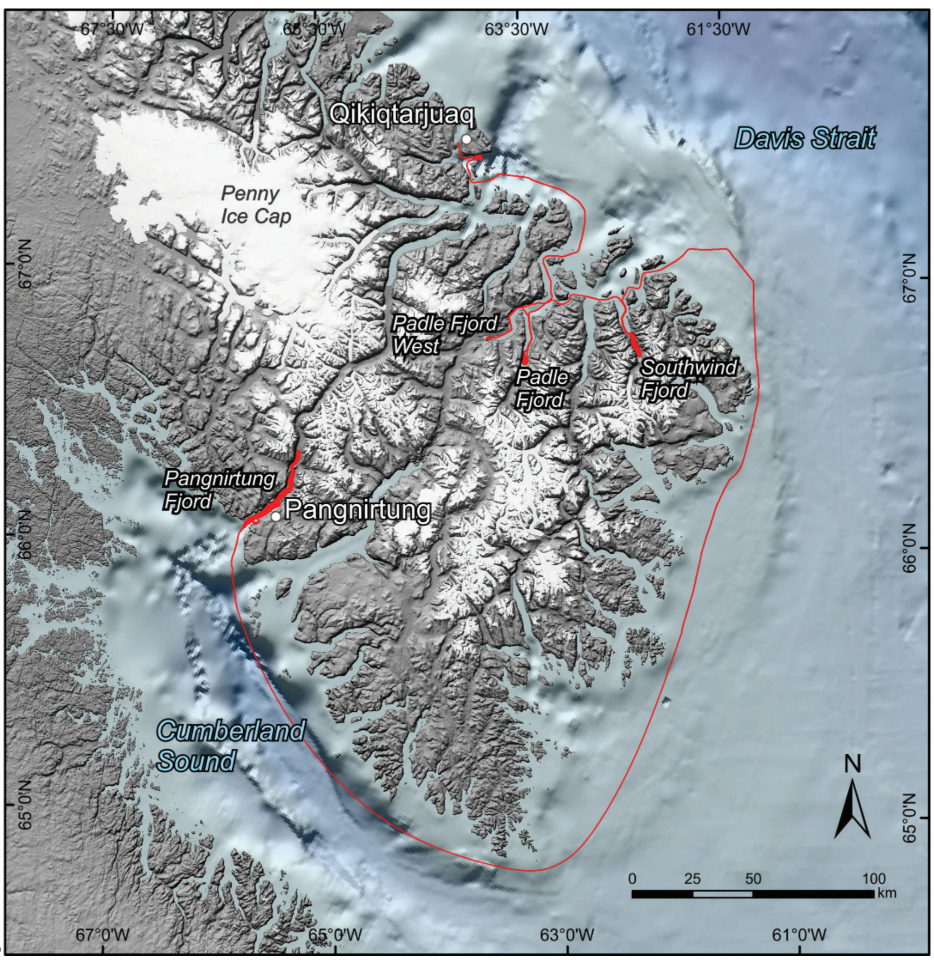

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Figure 3: Navigation lines of 2019Nuliajuk cruise

Table 2: Summary of activities

Date	JD	Location	VV	GC	BC	CTD	ADCP	Mooring	UAV	3.5 kHz	MBES	Notes
20 Sept.	263	Qikiqtarjuaq										Mobilization
21 Sept	264	Qikiqtarjuaq				1				X	X	
22 Sept.	265	Padle Fjord		2		4				X	X	
23 Sept.	266	Southwind Fjord	2			1	X	1	5	X	X	
24 Sept.	267	Transit								X	X	
25 Sept.	268	Transit				1				X	X	
26 Sept.	269	Pangnirtung		6	1	2	X		10	X	X	
27 Sept.	270	Pangnirtung		9		1			3	X	X	
28 Sept.	271	Pangnirtung		6		2				X	X	
29 Sept.	272	Pangnirtung		3		2			1	X	X	
30 Sept.	273	Pangnirtung				3				X	X	Demobilization
TOTAL			2	26	1	17		1	19			

4. PRELIMINARY RESULTS

4.1 Cruise statistics

The 2019Nuliajuk cruise allowed the collection of:

1) 26 gravity cores
2) 2 Van Veens grab samples
3) 17 CTD casts
4) 1 mooring deployment
5) 19 drone flight stations
6) 1713 km of 3.5 kHz CHIRP surveys
7) 1155 km of multibeam surveys

4.2 Key preliminary results

4.2.1 Qikiqtarjuaq

On the south side of Broughton Island, a small channel system comprises crescentic bedforms (Fig. 4). An initial multibeam survey completed in 2014 was repeated on the R/V Nuliajuk during this cruise. The repeated survey suggests that the bedforms have not migrated between the two years, indicating that turbidity currents likely have not occurred on the south side of the island between 2014 and 2019. Turbidity currents were suggested to occur but their recurrence appears to be limited. These turbidity currents are likely to be triggered when storms generate large waves along the coast. A sediment core collected on the CCGS Amundsen in 2019 will allow to reconstruct the storm activity of the area.

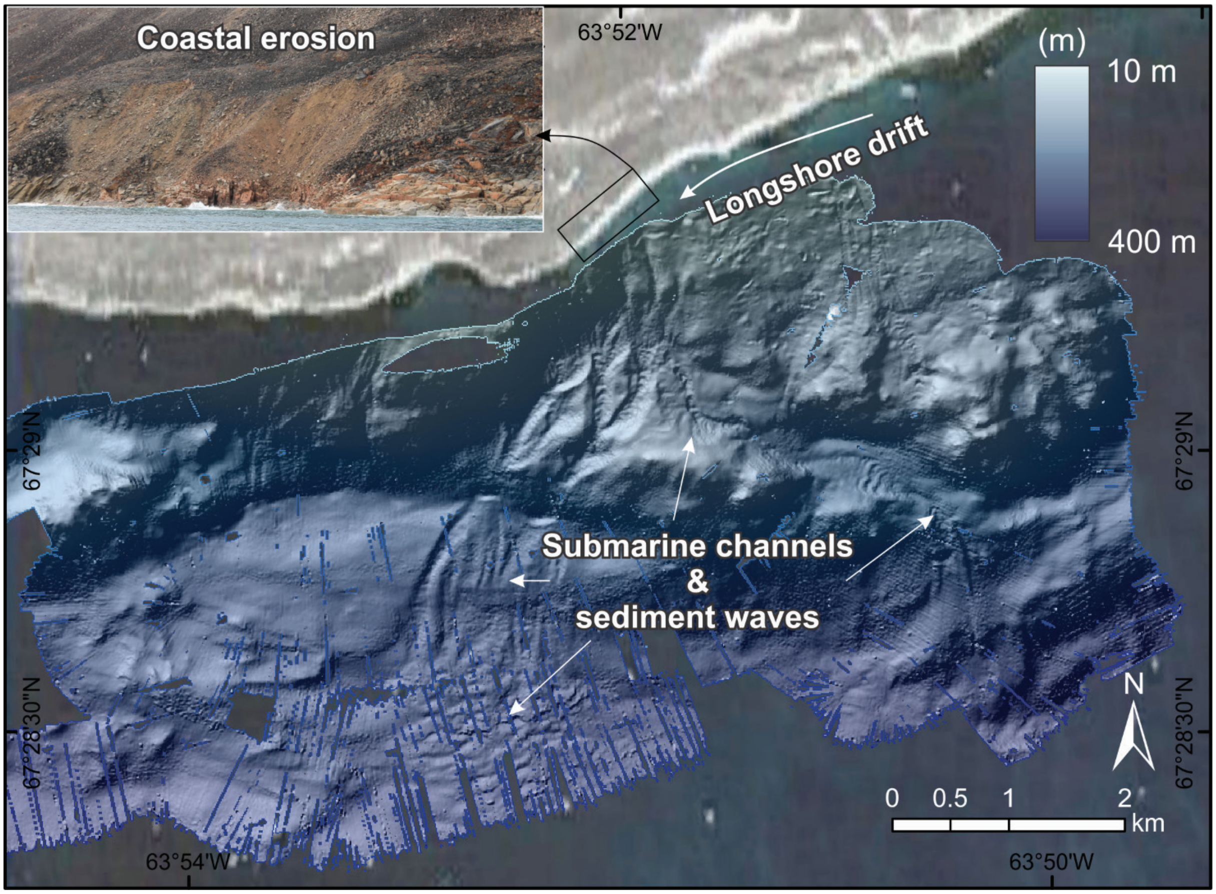

Figure 4: Longshore drift-fed submarine channels offshore Qikiqtarjuaq. Coastal erosion is evident on the coast and provides the sediment supply to the submarine channels, likely during storms.

4.2.2 Padle Fjord

Eastern Padle Fjord displays a large fjord-head delta (Fig. 5). Its underwater part consists of numerous submarine channels and crescentic bedforms that evolve downslope into more linear sediment waves. These bedforms are similar to those observed in other fjords around Cumberland Peninsula (Normandeau et al., 2019a). The presence of these bedforms suggests that turbidity currents are active on the delta and probably occur during the spring and summer. On the fjord sidewall, submarine landslides were also identified and appear relatively young due to their blocky appearance. Other landslides appear slightly buried suggesting multiple events of landslides occurred in the fjord.

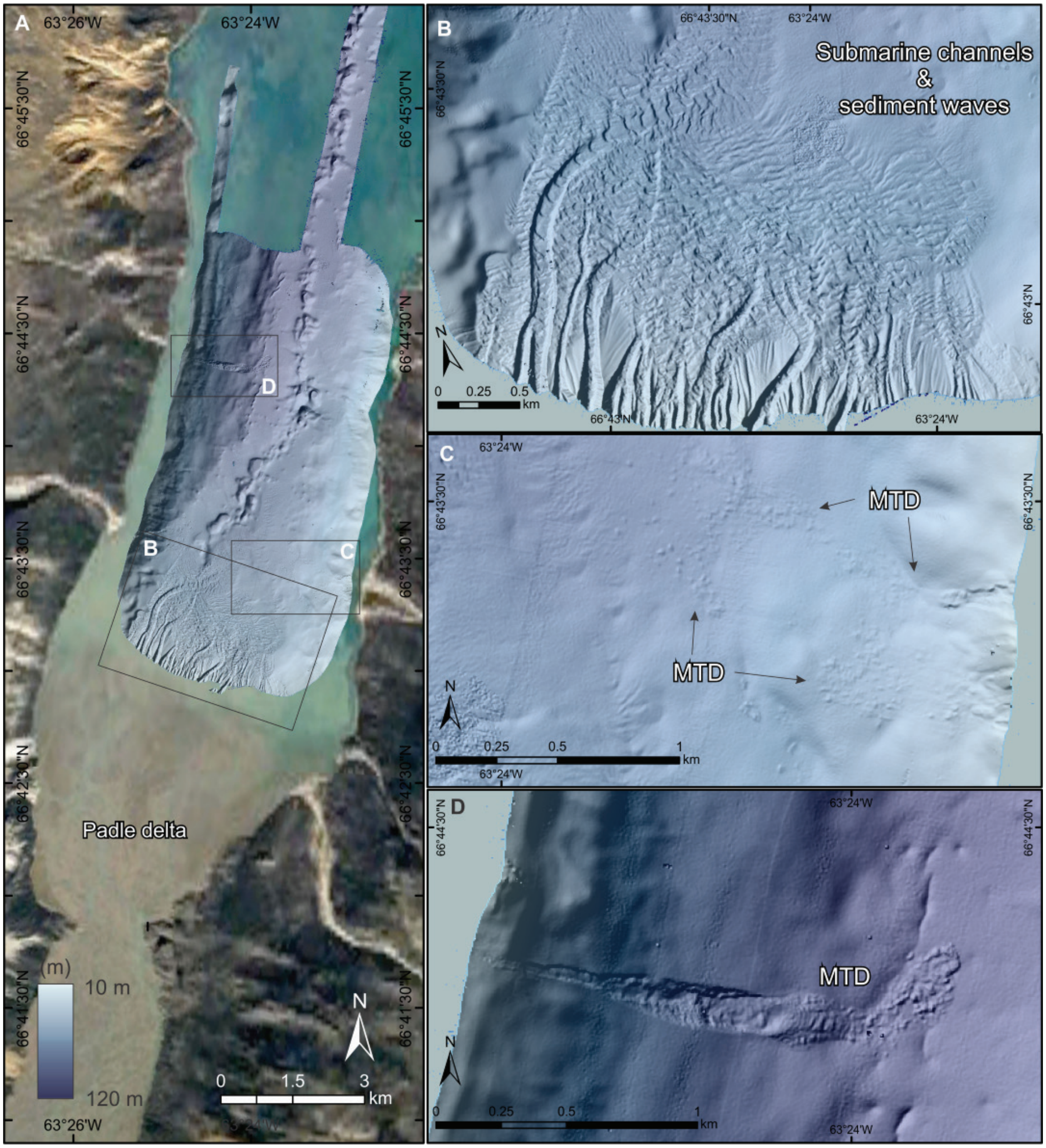

Figure 5: Examples of submarine landslides (MTD – Mass Transport Deposit) and submarine channels in Padle Fjord

4.2.3 Southwind Fjord

Including this year, Southwind Fjord has been mapped five times (2013, 2014, 2018 and twice in 2019). This dataset is unique in the Arctic and allows to observe changes on the seabed related to turbidity currents and submarine landslides. In the channel thalweg, at the head of the fjord, a comparison of the multibeam data from 2018 and 2019 reveals that the crescentic bedforms have migrated over 30 m during the past year (Fig. 6). In many cases, the migration appears to be more than ½ the wavelength of the bedforms, making it difficult to measure precise distances of migration. These changes on the seabed are clear evidence that turbidity currents are active on the delta front.

In addition to changes in the channel, the repeat multibeam bathymetry from 2013 and 2019 reveals the presence of a new landslide at the head of the fjord (Fig. 6B). Two other landslides also show evidence of reactivation between those two years. Therefore, not only are turbidity currents active in Southwind Fjord, landslides involving the displacement of large masses of sediment are also occurring.

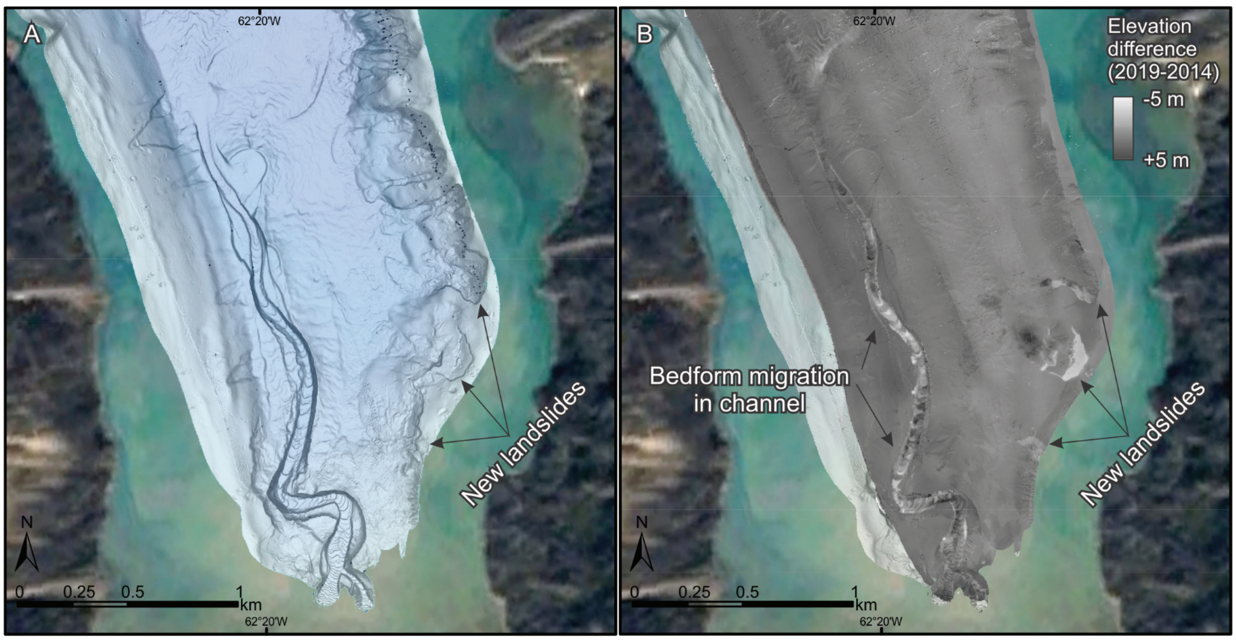

Figure 6: Channel and submarine landslides in Southwind Fjord. Right image shows a difference in elevation from 2019 to 2013 and reveals the presence of three new submarine landslides

4.2.4 Pangnirtung Fjord

A complete mapping of Pangnirtung Fjord was completed during this cruise and revealed the presence of numerous submarine landslides. Of particular note is a relatively large (1.5-2 km^2) landslide on the opposite side of Pangnirtung (Fig. 7). This landslide appears relatively old, being buried by Holocene sediment but is one of the largest in the fjord.

In addition, similarly to Southwind Fjord, crescentic bedforms at the head of the fjord were mapped (Fig. 8). Comparing the 2019 data to the previous data collected in 2013 shows that the bedforms have migrated upslope. Erosional channels were also observed. These result show that Pangnirtung Fjord, as Southwind and Padle Fjords, is a dynamic environment with turbidity currents and submarine landslide being a major component of the seafloor.

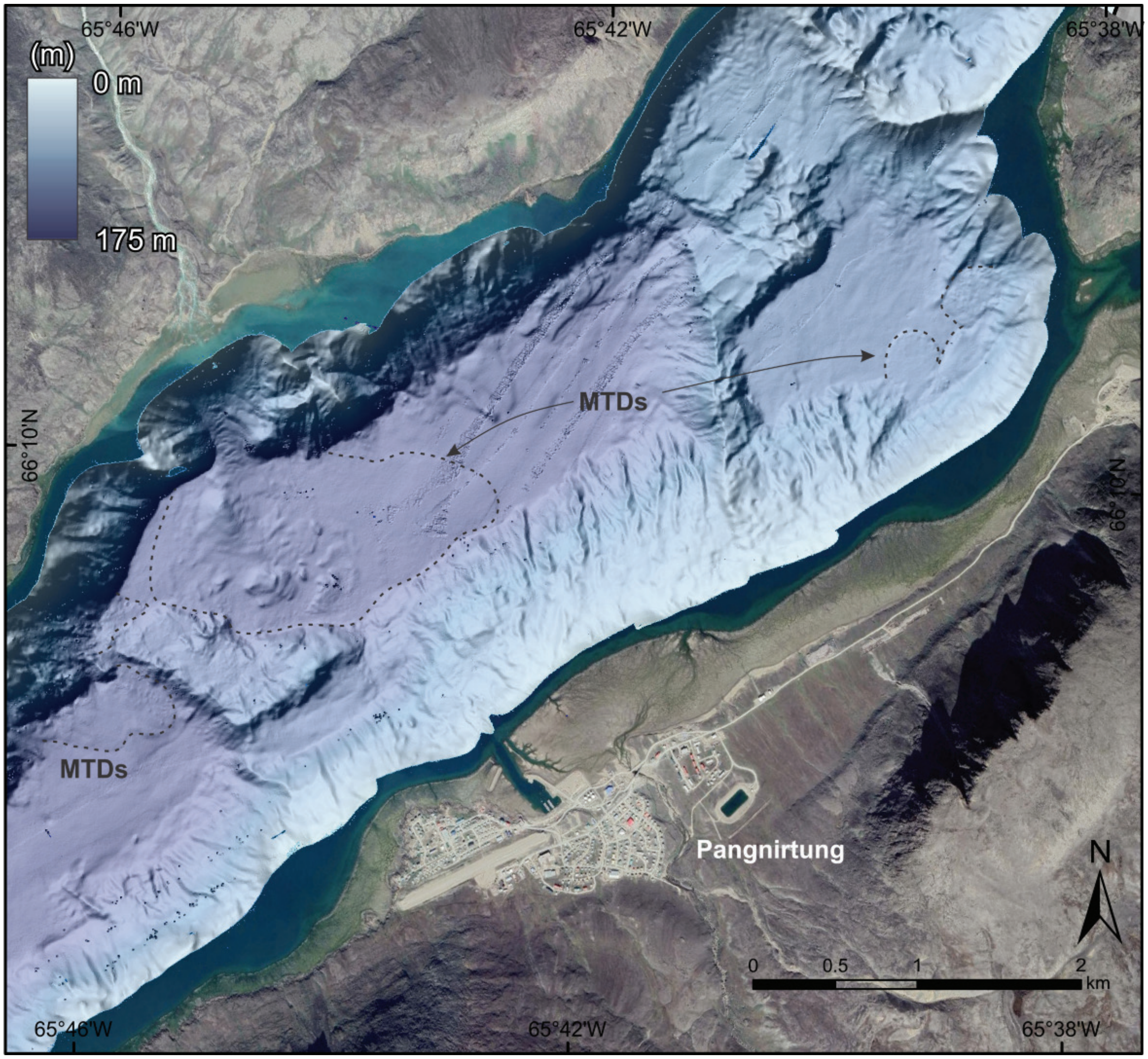

Figure 7: Evidence of Mass Transport Deposits (MTDs) in front of Pangnirtung

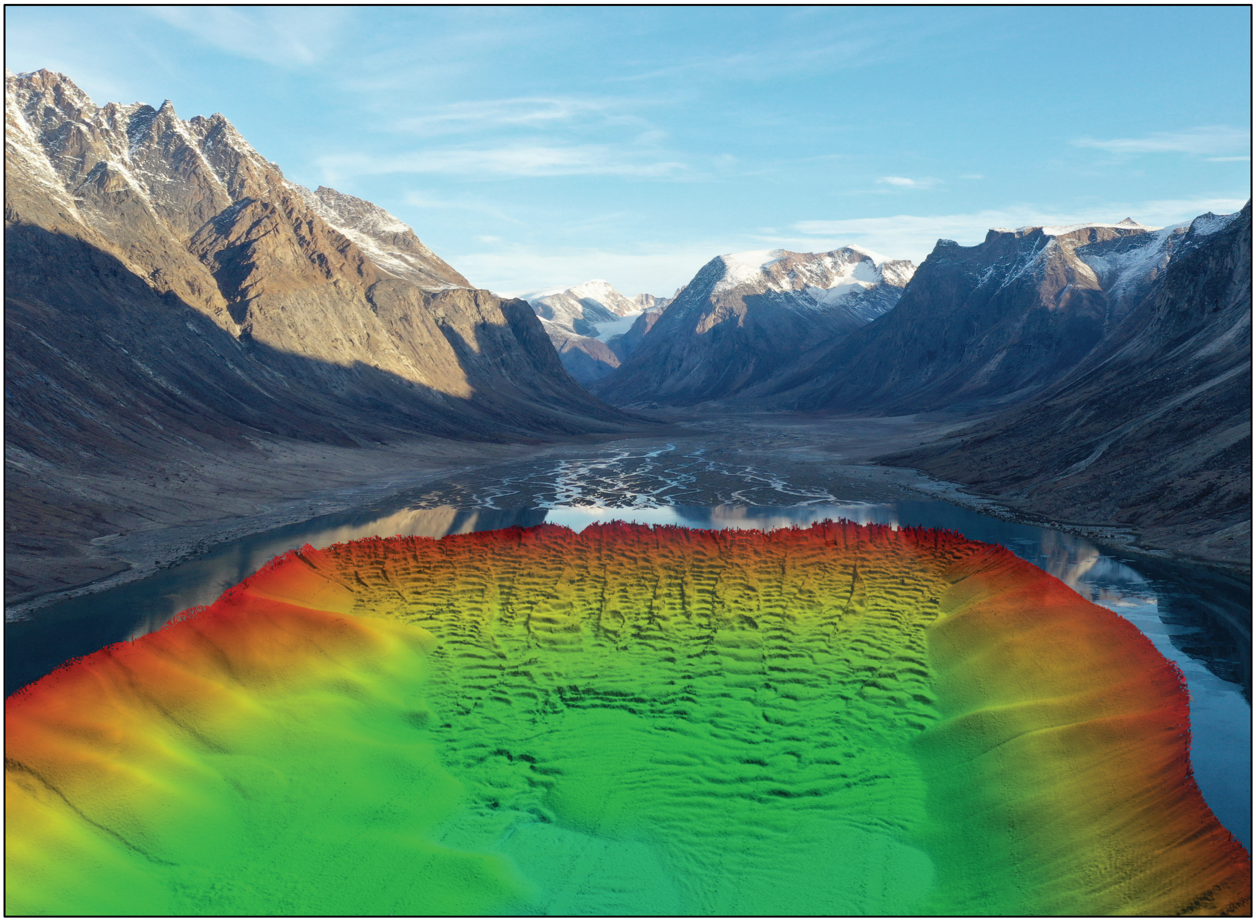

Figure 8: Illustration of bedforms at the head of Pangnirtung Fjord, on the delta front.

5. DAILY NARRATIVE

*All date/time in Eastern Standard Time. For exact UTC time, refer to Appendix A.

5.1 JD263 – Friday September 20, 2019 – Qikiqtarjuaq

Participants boarded the vessel at 1630. When onboard, a couple hours were dedicated to finding our equipment on the vessel and setting up the Wet Lab for sediment core processing. Kirk Regular, hydrographer on the cruise, arrived around 1800 and setup the multibeam system, the sub-bottom profiler and the hull-mounted ADCP. The MBES and Chirp systems appeared to behave well.

5.2 JD264 – Saturday September 21, 2019 – Qikiqtarjuaq

In the morning, the hull-mounted ADCP was tested and appeared to have some problems with some beams. These problems were never resolved although we collected some data with the system during the cruise. The acoustic release of the mooring was also tested and all appeared to behave well. At 1330, we departed Qikiqtarjuaq and began the cruise. We transited towards a longshore-drift fed submarine channel on the south side of Brouhton Island. Enroute, we did a heading calibration for the motion sensor. At 1500, we arrived on site and deployed the CTD for a sound velocity profile. We began surveys (MBES and 3.5 kHz) shortly after. We finished mapping south of Broughton Island at 1830 and began transiting towards a site where a rockfall was reported by community members. Reduced daylight made it difficult to observe the sidewalls and we thus continued our way towards Padle Fjord.

5.3 JD265 – Sunday September 22, 2019 – Padle Fjord

Rough seas were encountered over night in the offshore. We arrived at Padle Fjord around 0340, where a CTD cast was made. We began the surveys shortly after. At 1015, we arrived on site of the first gravity core. A CTD cast was done first, followed by the gravity core (001). The gravity core was completed at 1130. We resumed mapping the shallow water parts of Padle Fjord until 1300. We then did a second gravity core (002) in the deep basin, at the base of a landslide deposit. At 1330, we did a CTD cast and then began mapping along a subaerial landslide. No evidence of underwater instabilities were observed so we did not do a full coverage of the underwater part. Instead, the Unmanned Aerial Vehicle (UAV) was deployed in an attempt to map the subaerial landslide. At 1420, the UAV survey was completed and we began transiting towards Padle Fjord West. We began mapping Padle Fjord West at 1730. Shallow waters (less than 10 m) prevented us from doing an extensive survey. Only the head of the delta was mapped but did not reveal any specific features on the seabed. At 2230, the survey was completed and we began our transit towards Southwind Fjord.

5.4 JD266 – Monday September 23, 2019 – Southwind Fjord

We arrived in Southwind Fjord around 0400 and began mapping the fjord. The fjord was mapped until 1300. At 1100, the mooring was assembled and was deployed at 1317. At 1328, we used the Universal Deck Box (UDB) to communicate successfully with the acoustic release. We took range from four different positions to estimate the position of the mooring. We then passed over the mooring with the EM2040 multibeam system to locate the exact position. The mooring was clearly seen on the EM2040 and its exact position is known. A final communication with the acoustic release was done to have its status (95% battery, 1 degree tilt). At 1500, we deployed the UAV and began surveying the fjord sidewalls next to the delta. Five UAV flights were done to map the fjord sidewalls near the delta. The flights were completed when the sunlight became minimal, near 1645. Two grab samples in the channel at the delta head, were then completed at 1730. We then finished mapping the sides of the fjord seafloor until 2030 before beginning our transit towards Pangnirtung.

5.5 JD267 – Tuesday September 24, 2019 – Transit

Transit towards Pangnirtung. We considered mapping one of the fjords along the way but strong winds were expected in Cumberland Sound Thursday. Delaying our arrival in Pangnirtung might mean getting stuck in the storm. We therefore decided to transit directly to Pangnirtung.

5.6 JD268 – Wednesday September 25, 2019 – Pangnirtung Fjord

The morning was dedicated to transit towards Pangnirtung. We arrived at Pangnirtung at 1400. We visited the Hamlet office and talked with the Planning Officer. We gave posters describing the work we do to the Hamlet office and we visited the Hunters and Trappers Organisation (HTO), which was closed. We departed Pangnirtung towards 1700 and began mapping the fjord-head overnight.

5.7 JD269 – Thursday September 26, 2019 – Pangnirtung Fjord

At 0700, we mapped the fjord-head delta. At the same time, the UAV was deployed to start mapping the fjord sidewall while we were mapping. However, there was still some shade on the cliffs so we decided to remap those cliffs. At 0941, a gravity core was deployed in front of the delta. Three tries in a small depressions were unsuccessful so we changed position by 50 m offshore. It did not work either so we changed to the base of a landslide closer to the delta. This core was successful at 10:29 (0015). We then went on the slope near the landslide to have an idea of slope stability of normal sediments (0017-0020). At 1315, we began another gravity core, aiming at a glide plane of an older landslide, which was successful at 14:17. We tried coring the front of the delta again, but farther away at 14:46 (0024). Following this core, we tried a mini box core at the same location (0026). During all that time, 10 UAV stations along the delta fjord wall were done. We did the western wall in the morning and the eastern wall in the afternoon. We finished coring at 16:30 and began mapping shortly after.

5.8 JD270 – Friday September 27, 2019 – Pangnirtung Fjord

We continued mapping until 1000 and then transited towards the first core site of the day for 1030. A first attempt was done but the corer fell on its side. A second attempt, at much slower speed recovered a bit of sediment (0028). The liner was then recovered vertically instead of horizontally which was much better for preserving the surface. At 1130, a UAV flight was started with mild rain coming down. We arrived on the second core station of the day at 1145 and began coring with the smaller length barrel. After lunch, seven other cores were done and we began mapping at 1730.

5.9 JD271 – September 28, 2019 – Pangnirtung Fjord

We finished the main part of the mapping program overnight. We began coring at 0930 and recovered our first core at 1012. The conditions were windy during the day and tidal currents were relatively strong. Keeping position for the coring was difficult in these conditions. Gravity coring operations nevertheless continued until 1400. However, after several unsuccessful attempts to recover sediment cores, we decided to stop coring operations. Weather conditions were not favourable for coring since the corer would fall on its side at most attempts and recovery was minimal. We decided to finish mapping some of the outer bays and nearshore parts of the fjord near Cumberland Sound. Mapping progressed over night.

5.10 JD272 – Sunday September 29, 2019 – Pangnirtung Fjord

Mapping operations finished around 0900. Coring operations began shortly after and conditions were favourable. During the third gravity core, the rope holding the gravity core came out of the hawler and the gravity corer freefell. On the fourth attempt, the rope broke and we lost the gravity core to the bottom at 10:35. At 1200, we decided to run sub-bottom profile lines. Two lines running from Cumberland sound to the head of the fjord were done, which were very well imaged. CTD casts were also done at the head of the fjord, in depressions and outside depressions. CTD casts were also done near Cumberland Sound in the depression field to measure salinity near the bottom. Overnight, we began sub-bottom profiles running across the fjords.

5.11 JD273 – Monday September 30, 2019 – Pangnirtung Fjord

We finished the sub-bottom imaging at 0330 and went towards Pangnirtung for the high tide. We had to enter the marina at high tide for 0600. We disembarked at 0900 and went to the hotel. In the afternoon, Alex met with the Nancy Anilnilak (Senior Adminstrative Officer), David Kooneeliusie (Deputy Mayor) and George Qaqqasiq from the Hunters and Trappers Organisation (HTO). Preliminary results and factsheets were presented. At 1630, Alex went on the radio to explain the reasons the R/V Nuliajuk was conducting research in Pangnirtung over the last four days. On radio, Alex mentioned the maps produced by the GSC and that they would be available soon. He also mentioned the importance of the research: tsunami potential and safety of offshore infrastructure. Preliminary results show numerous landslides that appear relatively old and some minor recent ones but that their tsunamigenic potential was not yet evaluated although there was nothing alarming in the data seen so far.

6. EQUIPMENT AND PROCEDURES

6.1 Knudsen 3260 Echo-Sounder

During the cruise, a hull-mounted 3.5 kHz transducer, transceiver and recorder were used to track bottom and gather sub-bottom profiles when transiting, surveying and sampling. The echosounder was used simultaneously as the multibeam echosounder. No significant problems were encountered with this system for the duration of the cruise.

The raw KEB files were converted into SEG-Y files using the conversion utility tool from Knudsen. The SEG-Y were then combined by day and speed corrected using Combine_Segy tool.

Metadata (cruise number, instrument and frequency) was added to the file names. The combined SEG-Y were then converted into JPEG2000 and exported to SHP.

6.2 EM-2040 multibeam echosounder

The Kongsberg EM2040 is a single head hull-mounted system (Table 3). It was run at 300 kHz during the entire cruise with HD equidistant, meaning that 400 beams, separated by equal distance, were used. Its swath width is 120° although it was often reduced to less than 100° in deeper waters. Throughout the *2019Nuliajuk* cruise, the EM2040 multibeam echosounder proved to be a functioning system up to a limit of approximately 300 m water depth. Between 300 and 400 m data was collected but at much reduced quality. Beyond 400 m, no bottom tracking was available. Since the EM2040 was used at the same time as the 3.5 kHz sub-bottom profiler, significant cleaning in Caris HIPS was required.

Table 3: Specifications of the EM2040

Beams	400 (HD Equi-Distant)
Frequency	200kHz - 400kHz (used 300 kHz)
Swath	Greater than four times water depth
Max Swath Angle	120 degrees
Depth Range	10m-300m

CTD casts were done to correct the data for sound velocity changes in the water column. An Xchange CTD from AML was used. It measured depth, conductivity, temperature and sound velocity. Sound velocity was used for multibeam bathymetry correction while the other parameters were used to get water column conditions at the different locations. Detailed CTD casts are available in Table 4.

Table 4: CTD casts during 2019Nuliajuk

Date	Time (UTC)	Latitude	Longitude	Region	Comment
2019/09/21	19:32	67.4834	-63.9049	Qikiqtarjuaq	
2019/09/22	08:09	66.8626	-63.36	Padle Fjord	No GPS lock. Position from time.
2019/09/22	15:02	66.7238	-63.3974	Padle Fjord	
2019/09/22	18:16	66.7403	-63.3969	Padle Fjord West	
2019/09/22	22:58	66.8083	-63.7358	Padle Fjord West	
2019/09/23	16:26	66.7628	-62.3357	Southwind Fjord	
2019/09/25	22:33	66.3043	-65.5413	Pangnirtung Fjord	
2019/09/26	10:12	66.3693	-65.4972	Pangnirtung Fjord	
2019/09/26	21:04	66.3372	-65.5096	Pangnirtung Fjord	

2019/09/27	18:25	66.2352	-65.5533	Pangnirtung Fjord	
2019/09/28	03:35	66.1757	-65.6697	Pangnirtung Fjord	No GPS lock. Position from time.
2019/09/28	21:18	66.1380	-65.7812	Pangnirtung Fjord	No GPS lock. Position from time.
2019/09/29	20:04	66.3652	-65.4950	Pangnirtung Fjord	
2019/09/29	20:29	66.3641	-65.4864	Pangnirtung Fjord	No GPS lock. Position from time.
2019/09/30	00:09	66.1058	-65.9413	Pangnirtung Fjord	
2019/09/30	00:24	66.1058	-65.9233	Pangnirtung Fjord	
2019/09/30	00:46	66.1014	-65.8673	Pangnirtung Fjord	No GPS lock. Position from time.

6.3 Coring

Sampling was undertaken from the aft starboard quarter of the main deck. Three samplers were used including an OSIL Van Veen grab, a small annular box core and a GSCA gravity core (Pledge & Robertson, 2018). A small DMW marine knuckle crane on the top deck was used to position the samplers over the side and had a hydraulic winch with wire running through a small block that provided the lift point. A 5/8" poly rope was used through a hydraulic net hauler to provide the deployment and recovery means for each sampler and run through the crane block.

A minimum of 2 vessel crew and 2 science crew were required on the deck during the operations. An additional crew member on the upper deck was useful for providing signals to the crane operator who did not have direct visual contact with the primary deck crewmen below.

Sampling was performed in Padle, Southwind and Pangnirtung Fjord. The grab sampler worked as expected and was used 2 times with nearly full recovery at the first station and approximately half at the second. Subsamples were taken in small bags for grain size analysis back in the sedimentology laboratory. The small annular box core was deployed at two stations and only recovered a small sample that was difficult to transfer to a core tube so was put aside. The predominant sampler used was the GSCA gravity core with 2 different barrel lengths and variable head weight. Initially we used 6 x 22 kg weights in the core head with a 228 cm aluminum barrel. We had mediocre success with deployment often noticing that we had sediment on one side of the bright yellow corehead weights and little if any on the barrel and cutter. The assumption was that the system was either encountering coarse material on the seabed impeding penetration and the core falling over or that the angle of attack to the seabed was less than perpendicular and it was starting penetration but due to the poor angle and speed was not able to penetrate enough to maintain a stable orientation and was falling over. We noticed greater success in sediment recovery with shallower water depth leading us to believe that the deployment rope was having a negative impact on the gravity core attitude when more line was deployed in the water column. We removed three weights from the core head and switched to a shorter 172 cm barrel in an attempt to have the weight closer to the cutter to lessen the centre of gravity during penetration but didn't have measurable improvements. Deployment speeds were varied as well but difficult to measure and have consistency as we were not using a real oceanographic winch or wire. During the last day of coring (September 29th) the deployment rope parted during recovery so we unfortunately had to leave the core assembly on the seabed. It was felt that we needed a dedicated smaller diameter coring line and a better winch system as there are inconsistencies and some safety concerns with many hands on the rope.

One improvement that was discovered was being able to recover the core system to the deck and maintaining a vertical orientation throughout rather than laying the gravity core down on the deck horizontally. This was done in order to preserve the orientation of the sediment and worked very well. On assembly the core catcher was taped to the liner then pushed into the barrel so that it would not separate letting the sediment out. The core string was held vertically at the aft starboard corner by the upper deck crane in order to perform this.

A total of ~13 m of sediment was obtained from 26 gravity cores. All cores were processed according to standard GSC Atlantic core procedures (Mudie et al., 1984). All core sections were kept in sequence, from the bottom to the top. The section ends were carefully capped to minimize disturbance to the sediment surface. The top end cap was labelled with the cruise number, station number, section label and as top. The base of the core is designated with the letter A and the top of the base section is designated as B. Each section was taken into the Wet Lab and stored vertically. Each core, starting with the base section AB, was processed using the following procedure. The core liner was labelled with an up arrow, cruise number, station number, section label and the top and base of the section were labelled with the appropriate letter. The section length was measured and recorded.

The sealed core sections were stored upright in the WetLab. The WetLab is temperature controlled and the cores were kept at ~10°C. All station location information, core section lengths, extruded pieces and cutter/catcher lengths, sediment description, core performance information and all relevant field information were documented (Appendix A). Geographical and stratigraphic locations of cores are found in Appendix B and C.

6.4 Mooring

6.4.1 Mooring design

The mooring consisted of a 825 lbs train-wheel, 5 m of chain to the acoustic release, followed by the following instruments (Fig. 9):

1- Five HOBO temperature sensors were spread out on the line to measure variability in temperature near the bottom. They were delayed start to February 1, 2020, at 10:00am UTC and should run for approximately 301 days, at 10 minutes interval, which will bring the end to approximately November 2020. They can operate in temperature between -40° to 70°, have an accuracy of ±0.21°C from 0° to 50°C and a resolution of 0.02°C at 25°C.

2- Halfway up on the line, a Seametrics CT2X measures both temperature and conductivity. This sensor aims at measuring the flux of freshwater coming from the melting glacier through turbidity currents. The CT2X sensor was installed in a foam casing for frost protection. It was delayed start to Oct. 1 2019, 10:00am. It will run at an interval of 1 day for 213 days, which brings it to May 1st 2020. Then, it will run at an interval of 10 minutes for 500 days or until battery runs out. The CT2X ranges from 10 mS/cm to 300,000 mS/cm

3- At 19 m above bottom, a RBR concerto3 CTD-Tu was installed and measures conductivity, temperature, depth and turbidity. The conductivity ranges from 0 to 85 mS/cm at an accuracy of 0.003mS/cm and a resolution of 0.001 mS/cm. The temperature sensor has a range of -5℃-35℃, an accuracy of 0.002℃ and a resolution of <0.00005℃.

4- At 21 m above bottom, a Nortek Signature 500 ADCP is positioned to look downward. The ADCP has five beams but is set-up to use only 4 beams since the line interacts with the 5th beam. The ADCP is set-up in Burst mode 4 beams with no averaging. Profile range was set to 24 m with a cell size of 1m. Measurement intervals were set to 25 sec for 400 days.

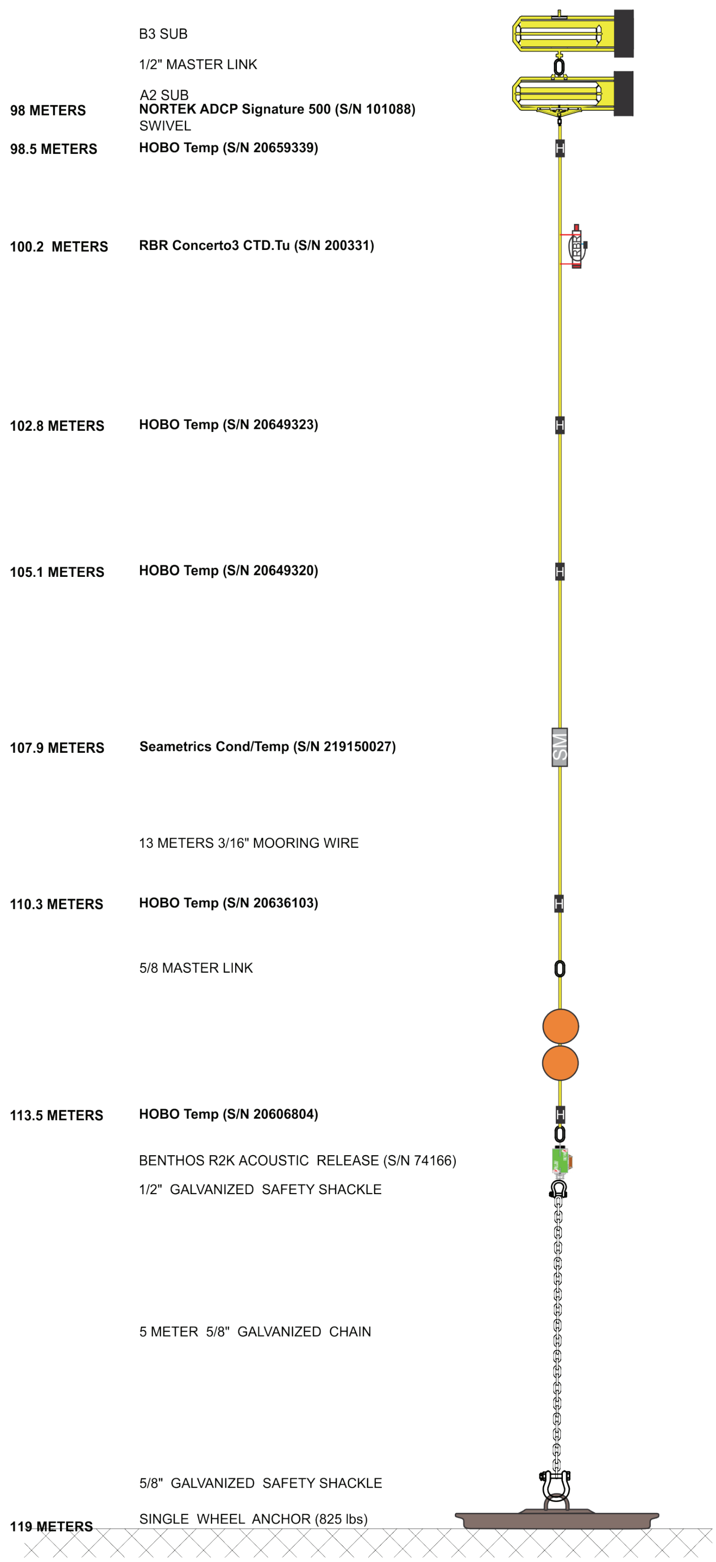

Figure 9: Mooring design combining the downward-looking ADCP, 5 HOBO temperature sensors, 1 RBRConcerto CTD-Tu and 1 Seametrics CT2X CT.

6.4.2 Mooring deployment

The deployment of the mooring was accomplished from the starboard aft-deck of the R/V Nuliajuk. The two buoys (B3 and A2 subs) were gently lowered over the side. Once over the side, the vessel increased speed to about 2 knots. While advancing, the remainder of the mooring was gently lowered over the side until only the train wheel was left on board. When the vessel was within 100 m of the deployment location, the train wheel was lowered over the side using a rope from the upper deck winch. When on location, the train wheel was lowered into the water and the rope was cut using a knife. The train wheel then sank to the bottom with the mooring.

Once deployed, the position of the mooring on the bottom was measured using two techniques. The first technique consisted in measuring the range of the acoustic release using a UDB on 3 or 4 positions (Fig. 10). Triangulation allowed a relatively precise position to be measured (Table 5-6). The second technique consisted in tracking the buoys using the EM2040 (Fig. 11). This technique allowed a sub-meter precision on the mooring location. Both technique yielded 4 m difference in position (Table 6). The EM2040 is considered a more precise location.

Table 5: Position and range estimated by the Universal DeckBox

ID	Latitude	Longitude	Range (m)	Horizontal range (m)	Time (UTC)
R1	66.761017	-62.340867	141	83	17:25:08
R2	66.76175	-62.337167	159.5	111.55	17:30:45
R3	66.763	-62.34055	199.2	163.35	17:35:12
R4	66.761217	-62.339367	122.5	44.83	17:40:57

Table 6: Position estimated using the water column display of the EM2040 and the ranging of the acoustic release

ID	Latitude	Longitude	Depth (m)	Time (UTC)
Mooring from MBES	66.76176	-62.339705	119	17:18
Mooring from ranging	66.76167	-62.339767	119	

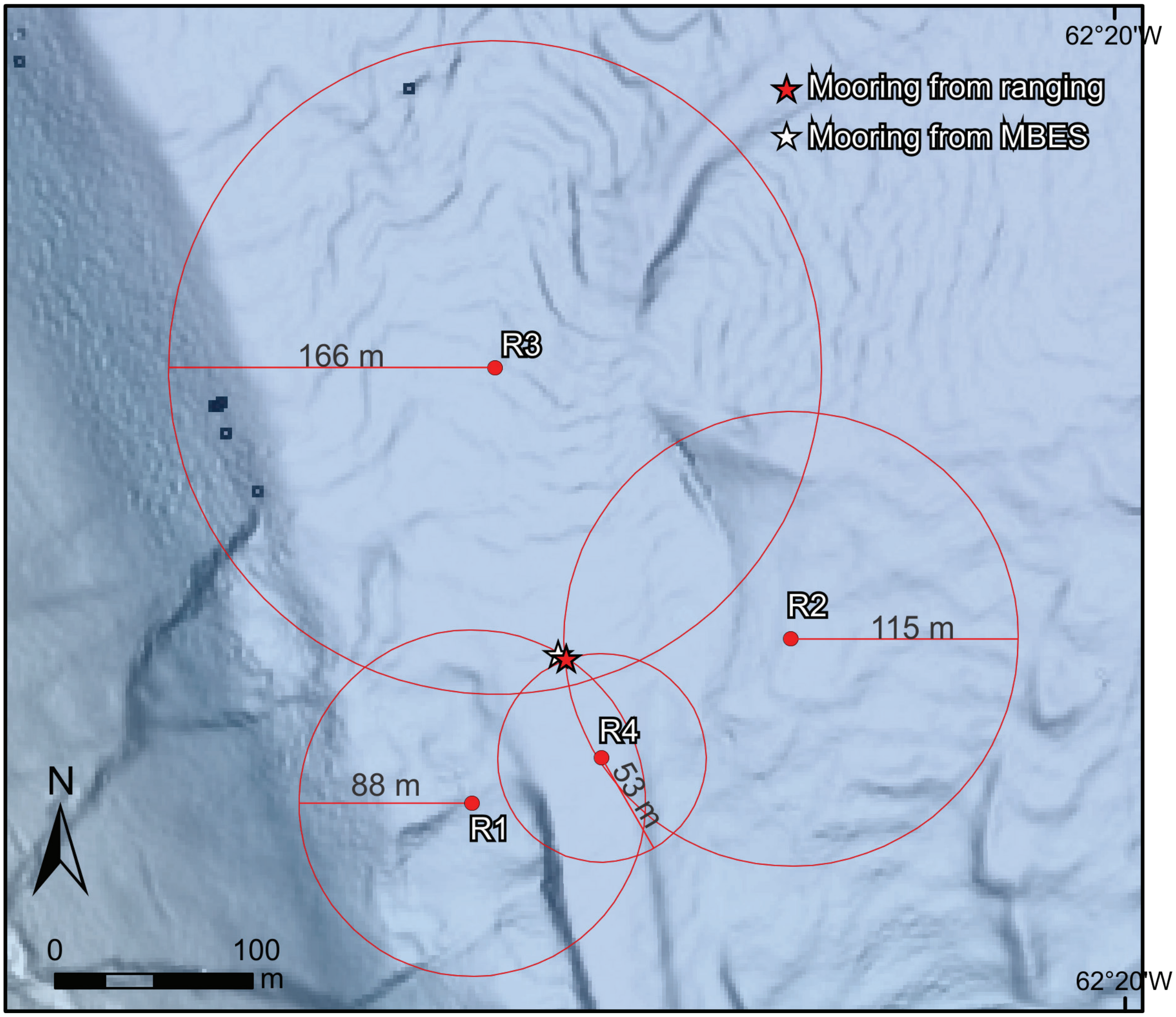

Figure 10: Estimated position of mooring from EM2040 and from ranging

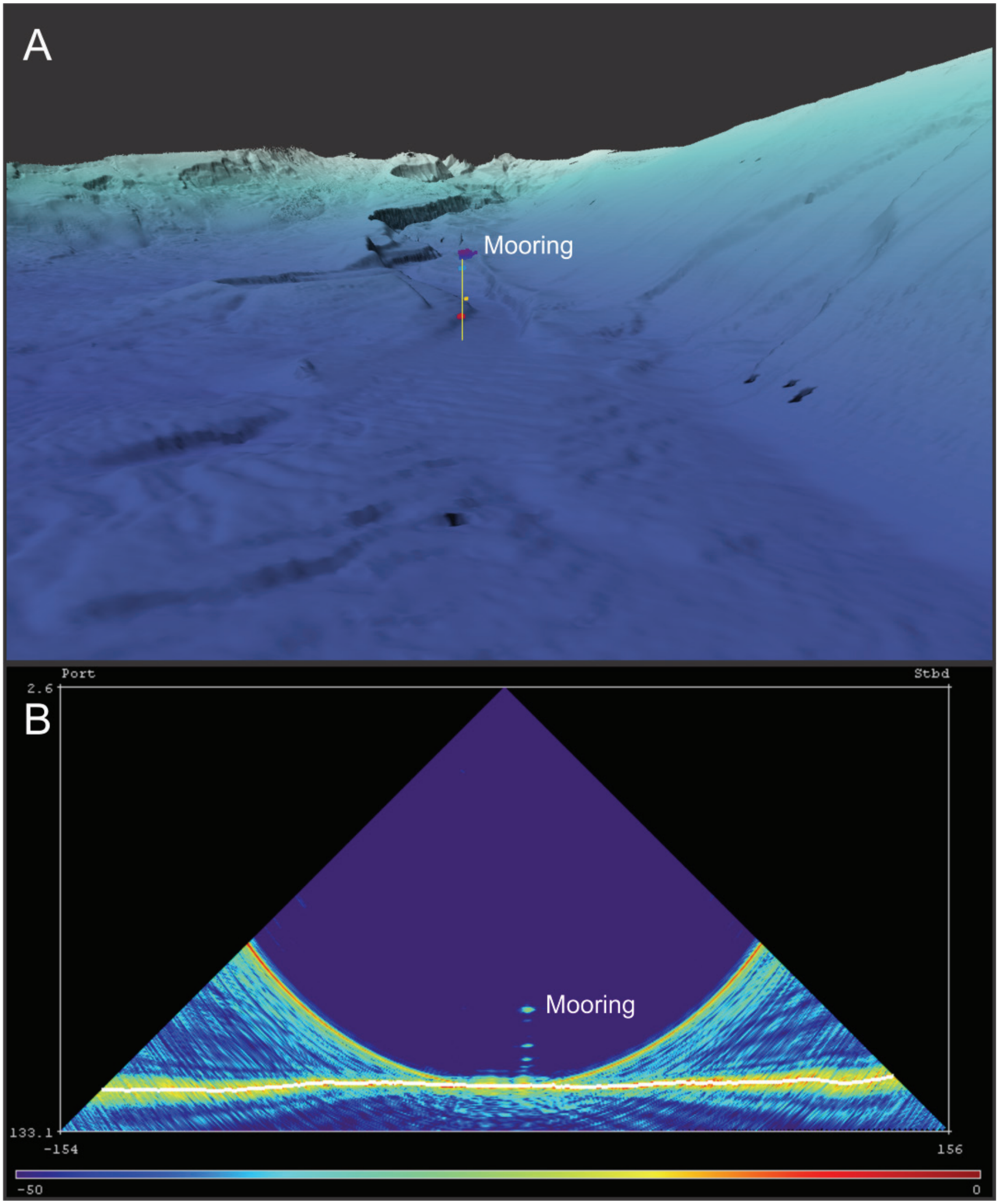

Figure 11: Mooring imaged by the EM2040. A) 3D view of the mooring imaged by the EM2040 – Yellow line added to show position of the mooring on bottom. B) Cross profile view of the raw imagery from the EM2040 showing the mooring 20 m above bottom.

6.5 UAV Flights

The GSC-A DJI Phantom 4 and Mavic 2 Pro (Fig. 12) aircrafts were flown on several flights from the upper and front deck of the vessel with good success. The coldest temperatures flown in were just above 0°C with winds of 15 kts. The aircraft performed well in this environment as did the flight battery. Pix4D capture was used in conjunction with an iPad mini to fly all flights in manual free flight mode.

Aerial surveys were conducted in all three Fjords from the vessel deck under full manual control. A DJI Phantom 4 Pro was used on a few flights but was encountering frequent compass issues. The back up aircraft was a Mavic 2Pro and it was used on the majority of flights. DJI Go 4 was used initially to carry out manual flights using oblique camera angles and manual shutter control but there were focus issues and the flights returned fewer than expected stills usually around 100 per flight. We then switched to PIX4d Capture and the automatic shutter function was set to trigger every 15 m in movement horizontally or vertically typically getting over 300 stills per flight.

Some challenges were experienced due to flying over water and having to allow extra battery reserve. Also, due to the challenge of landing on the vessel and the fact the vessel position was always different from the starting point plenty of battery reserve was required to time the aircraft landings. Strong wind was encountered as well that had to be monitored in order to maintain safe flights.

On the last day of flying we tried several flights from the vessel while it was moving and had deck crashes with both aircrafts and the Mavic 2 Pro started to show some compass errors. The aircraft armed but takeoff attitudes were not normal and the aircraft did not respond properly to remote commands. A total of 20 mapping flights were undertaken in the three fjords (Appendix D).

Figure 12: The Mavic 2 Pro in Southwind Fjord

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Mudie, P.J., Piper, D.J.W., Rideout, K., Robertson, K.R., Schafer, C.T., Vilks, G., Hardy, I.A. (1984) Standard methods for collecting, describing and sampling Quaternary sediments at the Atlantic Geoscience Center. Open file 1044, 47 pp.

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APPENDIX A: STATION SUMMARY

Table A7: Summary of core stations

2019Nuliajuk Core Summary													
Vessel: Nuliajuk						**Chief scientist: Alex Normandeau**					**Date: September 21 to September 30, 2019**		
Station No.	**Sample Type**	**Day / Time (UTC)**	**Latitude**	**Longitude**	**Location**	**Acoustic Target**	**Water Depth (m)**	**Corer length (cm)**	**App. Penetration (cm)**	**Core length (cm)**	**No. of Sections**	**Bagged**	**Comments**
001	Gravity	265 / 1505	66.723817	-63.397083	Baffin Bay - Padle Fjord	Stratified	77.7	2.3	135	85.5	1	no	n/a
002	Gravity	265 / 1718	66.73922	-63.3961	Baffin Bay - Padle Fjord	Transparent Stratified	111	2.3	163	119	1	no	n/a
015	Gravity	269 / 1429	66.367078	-65.497098	Baffin Bay - Pang Fjord	Stratified	61	2.3	230	111	1	1	Disturbed horizontally on the sides of the core due to water moving into the liner.
017	Gravity	269 / 1542	66.36989	-65.503538	Baffin Bay - Pang Fjord	Stratified	27	2.3	207	89.5	1	no	Disturbed horizontally on the sides of the core due to water moving into the liner.
020	Gravity	269 / 1737	66.371148	-65.50126	Baffin Bay - Pang Fjord	Stratified	36.5	2.3	110	85	1	no	Disturbed horizontally on the sides of the core due to water moving into the liner.
022	Gravity	269 / 1817	66.364073	-65.494122	Baffin Bay - Pang Fjord	Stratified	80	2.3	156	25	1	no	Disturbed horizontally on the sides of the core due to water moving into the liner.
024	Gravity	269 / 1846	66.361083	-65.493517	Baffin Bay - Pang Fjord	Stratified	87	2.3	204	96	2	1	Section BC is disturbed.
026	Box	269 / 2011	66.361422	-65.493103	Baffin Bay - Pang Fjord	Stratified	87	2.3	n/a	13	1	no	n/a
028	Gravity	270 / 1457	66.300633	-65.527517	Baffin Bay - Pang Fjord	Stratified	67	2.3	n/a	31	1	1	New method where we lifted the corer with the crane to extract the core vertically and minimize perturbations. Method applied the next cores.
030	Gravity	270 / 1550	66.279327	-65.537513	Baffin Bay - Pang Fjord	Stratified	87	1.75	147	103	1	no	Used shorter barrel (5'8") with 6 weights on top.
031	Gravity	270 / 1703	66.280232	-65.552828	Baffin Bay - Pang Fjord	Stratified	44	1.75	87	29	1	no	Used shorter barrel (5'8") with 6 weights on top.
034	Gravity	270 / 1746	66.260178	-65.547673	Baffin Bay - Pang Fjord	Stratified	110	1.75	120	89	1	1	Used shorter barrel (5'8") with 6 weights on top.

035	Gravity	270 / 1920	66.239003	-65.550998	Baffin Bay - Pang Fjord	Stratified	101	1.75	n/a	23.5	2	1	Section AB is sediment from the core cutter that were cohesive and kept their structure so they were pushed into a liner to preserve the stratigraphy. 3 gravels that fell from the core catcher after capping section AB were put in a bag. Used shorter barrel (5'8") with 6 weights on top.
036	Gravity	270 / 2004	66.227028	-65.57465	Baffin Bay - Pang Fjord	Stratified	113	1.75	95	11	0	1	Sediment bagged from the core catcher and base of the liner. The core was too short to cut the liner, so sediment were put in a bag to preserve the few remaining liners for better cores. Used shorter barrel (5'8") with 3 weights on top.
037	Gravity	270 / 2032	66.238832	-65.560567	Baffin Bay - Pang Fjord	Stratified	65	1.75	101	74	1	no	Very soupy on top. We let it settle during an hour before draining the water and caping it. Used shorter barrel (5'8") with 3 weights on top.
038	Gravity	270 / 2105	66.239893	-65.560745	Baffin Bay - Pang Fjord	Stratified	57	1.75	44	8	1	1	Very short core. Section AB was pushed into a short liner to preserve the few remaining liners for better cores. Plus sediment from the core catcher were put in a bag. Used shorter barrel (5'8") with 3 weights on top.
039	Gravity	270 / 2131	66.24374	-65.560828	Baffin Bay - Pang Fjord	Stratified	61	1.75	128	30	1	1	Used shorter barrel (5'8") with 5 weights on top.
040	Gravity	271 / 1412	66.158628	-65.707868	Baffin Bay - Pang Fjord	Stratified	70	1.75	59	20	1	1	Used shorter barrel (5'8") with 5 weights on top.
041	Gravity	271 / 1439	66.164393	-65.718175	Baffin Bay - Pang Fjord	Stratified	145	1.75	103	64	1	1	Used shorter barrel (5'8") with 5 weights on top.
042	Gravity	271 / 1512	66.158917	-65.75927	Baffin Bay - Pang Fjord	Stratified	140	1.75	73	30.5	1	1	Used shorter barrel (5'8") with 5 weights on top.
043	Gravity	271 / 1555	66.174225	-65.664755	Baffin Bay - Pang Fjord	Stratified	108	1.75	131	47	1	1	Used shorter barrel (5'8") with 5 weights on top.
044	Gravity	271 / 1712	66.134585	-65.80121	Baffin Bay - Pang Fjord	Stratified	156	1.75	116	11	1	1	Used shorter barrel (5'8") with 5 weights on top.
045	Gravity	271 / 1736	66.13495	-65.800612	Baffin Bay - Pang Fjord	Stratified	154	1.75	112	0	0	1	Just a bag with the sediment from the core catcher. Liner was empty. A gravel was blocking the core catcher. Used shorter barrel (5'8") with 5 weights on top.

046	Gravity	272 / 1306	66.140505	-65.784785	Baffin Bay - Pang Fjord	Stratified	158	1.75	54	0	0	1	Sediment bagged from the core catcher and base of the liner. The core was too short to cut the liner, so sediment were put in a bag to preserve the few remaining liners for better cores. Used shorter barrel (5'8") with 6 weights on top.
047	Gravity	272 / 1349	66.125497	-65.863072	Baffin Bay - Pang Fjord	Rough and incoherent	66	1.75	126	103	1	0	Used shorter barrel (5'8") with 6 weights on top.
048	Gravity	272 / 1412	66.121208	-65.893797	Baffin Bay - Pang Fjord	Rough and incoherent	98	1.75	59	25	1	2	A lot of foam put into the liner because half the liner was empty (horizontally). Bag 1/2 is the core cutter (so deeper section, hence older) and bag 2/2 is the core catcher (so more recent then bag 1/2). Used shorter barrel (5'8") with 6 weights on top.

Table A8: Summary of grab stations

2019Nuliajuk Grab Summary									
Vessel: Nuliajuk				Chief scientist: Alex Normandeau					Date: September 21 to September 30, 2019
Station No.	**Sample Type**	**Day / Time (UTC)**	**Latitude**	**Longitude**	**Location**	**Acoustic Target**	**Water Depth (m)**	**No. of Samples**	**Comments**
010	Van Veen	266 / 2102	66.74405	-62.32588	Baffin Bay - Southwind Fjord	Rough and incoherent	49	2	--
011	Van Veen	266 / 2115	66.74188	-62.32709	Baffin Bay - Southwind Fjord	Rough and incoherent	20	1	--

Table A9: Summary of mooring station

2019Nuliajuk Grab Summary							
Vessel: Nuliajuk				Chief scientist: Alex Normandeau			Date: September 21 to September 30, 2019
Station No.	**Sample Type**	**Day / Time (UTC)**	**Latitude**	**Longitude**	**Location**	**Water Depth (m)**	**Comments**
004	Mooring	266 / 1717	66.76176	-62.62339705	Baffin Bay - Southwind Fjord	119	--

Table A10: Summary of Unmanned Aerial Vehicle stations

2019Nuliajuk UAV Summary

Vessel: Nuliajuk | **Chief scientist: Alex Normandeau** | **Date: September 21 to September 30, 2020**

Station No.	Sample Type	Day / Time (UTC)	Latitude	Longitude	Location	No. of Photos	Comments
003	Phantom 4 Pro White	265 / 1815	66.7614	-63.40336	Baffin Bay - Padle Fjord	102 photos 2 videos	Flying over a landslide.
005	Mavic 2Pro	266 / 1833	66.743	-62.3216	Baffin Bay - Southwind Fjord	49 photos 3 videos	Western side of the fjord.
006	Mavic 2Pro	266 / 1903	66.743	-62.3216	Baffin Bay - Southwind Fjord	63 photos 2 videos	Western side of the delta and fjord head.
007	Mavic 2Pro	266 / 1936	66.743	-62.3216	Baffin Bay - Southwind Fjord	92 photos 3 videos	Eastern side of the delta and fjord head.
008	Phantom 4	266 / 2002	66.74387	-62.32104	Baffin Bay - Southwind Fjord	31 photos 3 videos	Eastern side of the fjord.
009	Phantom 4	266 / 2023	66.74375	-62.32056	Baffin Bay - Southwind Fjord	91 photos 1 video	Eastern side of the fjord.
012	Mavic 2Pro	269 / 1122	66.37431	-65.47937	Baffin Bay - Pangnirtung Fjord	360	Western side of the fjord head.
013	Mavic 2Pro	269 / 1152	66.36067	-65.5044	Baffin Bay - Pangnirtung Fjord	230	Western side of the fjord head.
014	Mavic 2Pro	269 / 1239	66.37582	-65.49461	Baffin Bay - Pangnirtung Fjord	94	Delta
016	Mavic 2Pro	269 / 1514	66.369956	-65.503354	Baffin Bay - Pangnirtung Fjord	337	Western side of the delta and fjord head.
018	Mavic 2Pro	269 / 1541	66.36989	-65.503538	Baffin Bay - Pangnirtung Fjord	339	Western sidewall of the fjord.
019	Mavic 2Pro	269 / 1709	66.37119	-65.50137	Baffin Bay - Pangnirtung Fjord	396	Western sidewall of the fjord.
021	Mavic 2Pro	269 / 1741	66.37102	-65.50144	Baffin Bay - Pangnirtung Fjord	355	Eastern side of the delta and fjord head.
023	Mavic 2Pro	269 / 1810	66.3641	-65.49427	Baffin Bay - Pangnirtung Fjord	250	Eastern sidewall of the fjord.

025	Mavic 2Pro	269 / 1844	66.36096	-65.49389	Baffin Bay - Pangnirtung Fjord	327	Eastern sidewall of the fjord.
027	Mavic 2Pro	269 / 2053	66.33837	-65.50721	Baffin Bay - Pangnirtung Fjord	291	Eastern sidewall of the fjord.
029	Mavic 2Pro	270 / 1523	66.30049	-65.5289	Baffin Bay - Pangnirtung Fjord	296	Eastern sidewall of the fjord and valley.
032	Mavic 2Pro	270 / 1559	66.229327	-65.537513	Baffin Bay - Pangnirtung Fjord	211	Eastern sidewall of the fjord and valley.
033	Mavic 2Pro	270 / 1700	66.280232	-65.552828	Baffin Bay - Pangnirtung Fjord	274	Western sidewall of the fjord.
049	Phantom 4 Pro White	272 / 1810	66.21984	-65.50837	Baffin Bay - Pangnirtung Fjord	116	Western sidewall of the fjord

APPENDIX B: GEOGRAPHIC LOCATIONS OF STATIONS

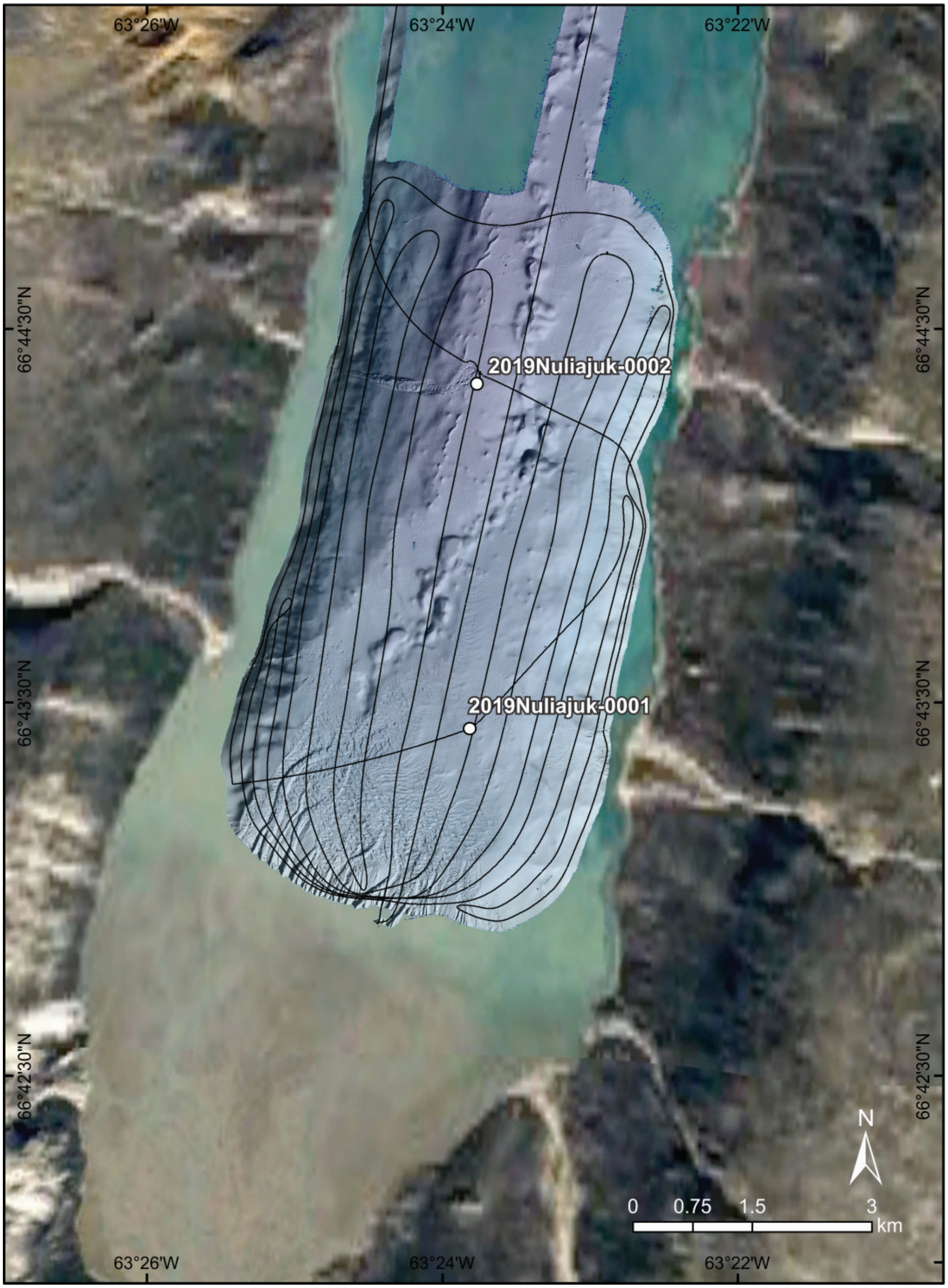

Figure B13: Location of cores Nuliajuk-0001 and 0002 and 3.5 kHz sub-bottom profiles collected in Padle Fjord

Figure B14: 3.5 kHz sub-bottom profiles in western Padle Fjord.

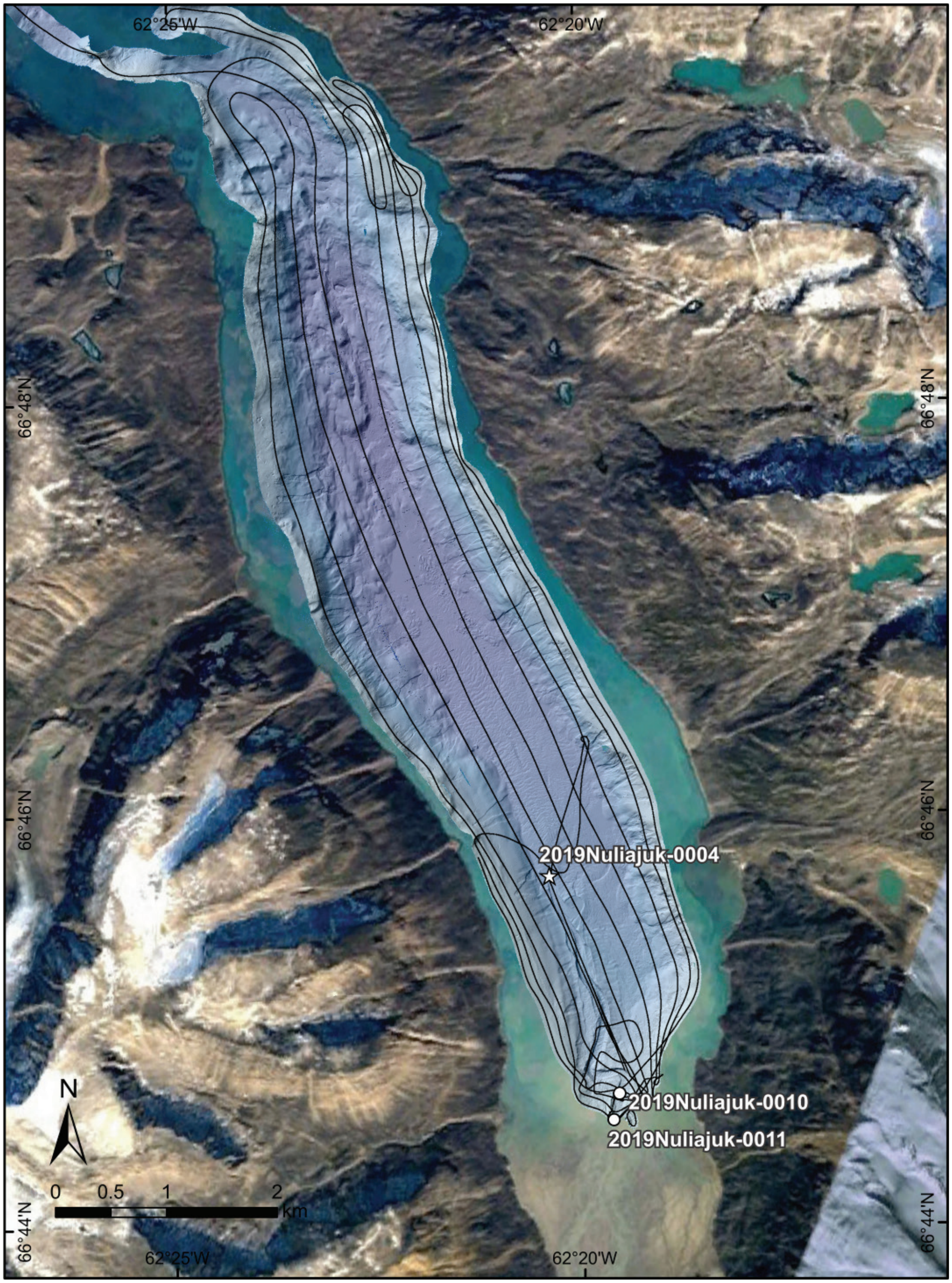

Figure B15: Location of stations Nuliajuk-0004 to 0011 and 3.5 kHz sub-bottom profiles collected in Padle Fjord.

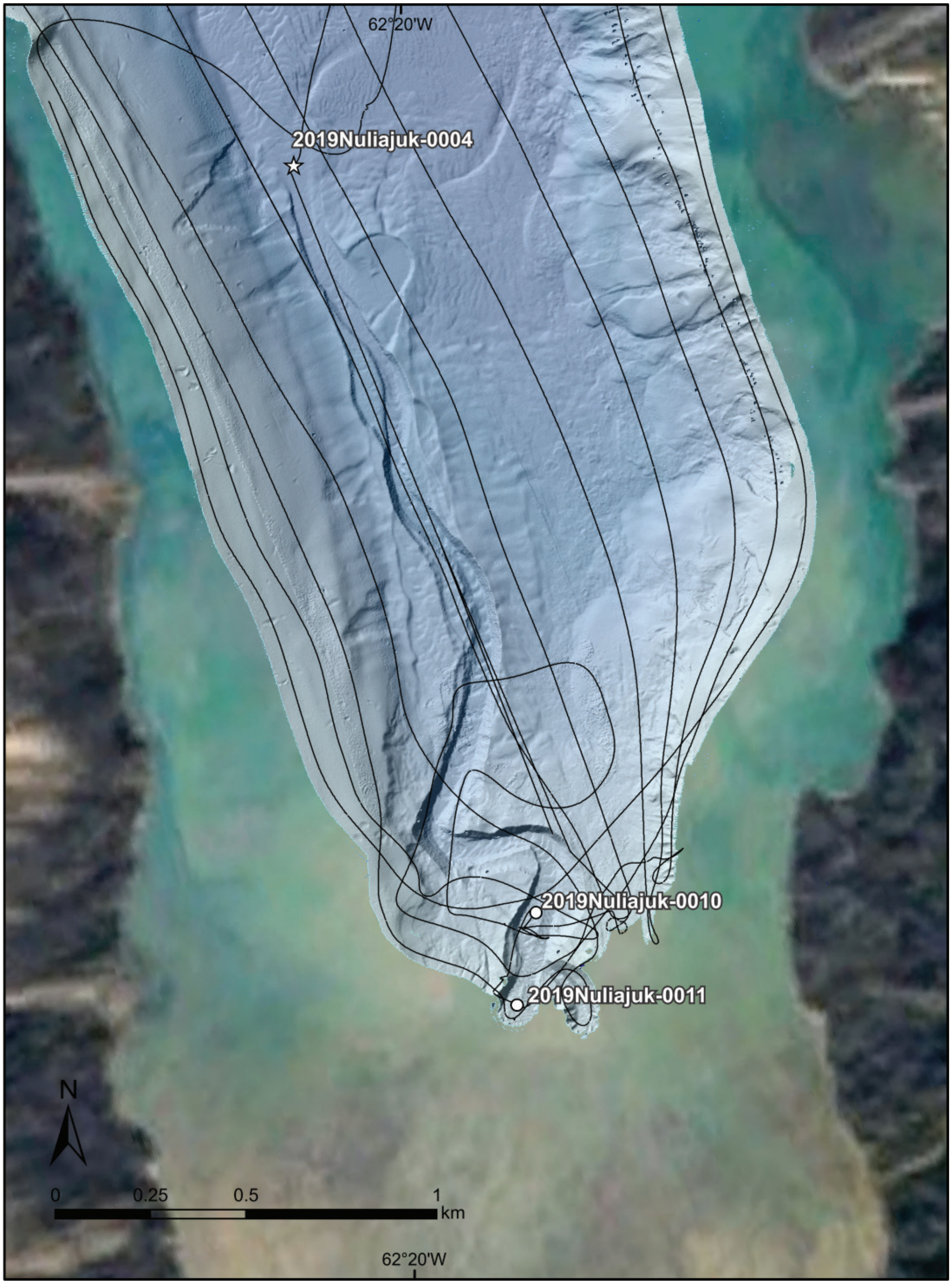

Figure B16: Location of mooring Nuliajuk-0004 and grab samples 0010 and 0011 and 3.5 kHz sub-bottom profiles collected in Southwind Fjord

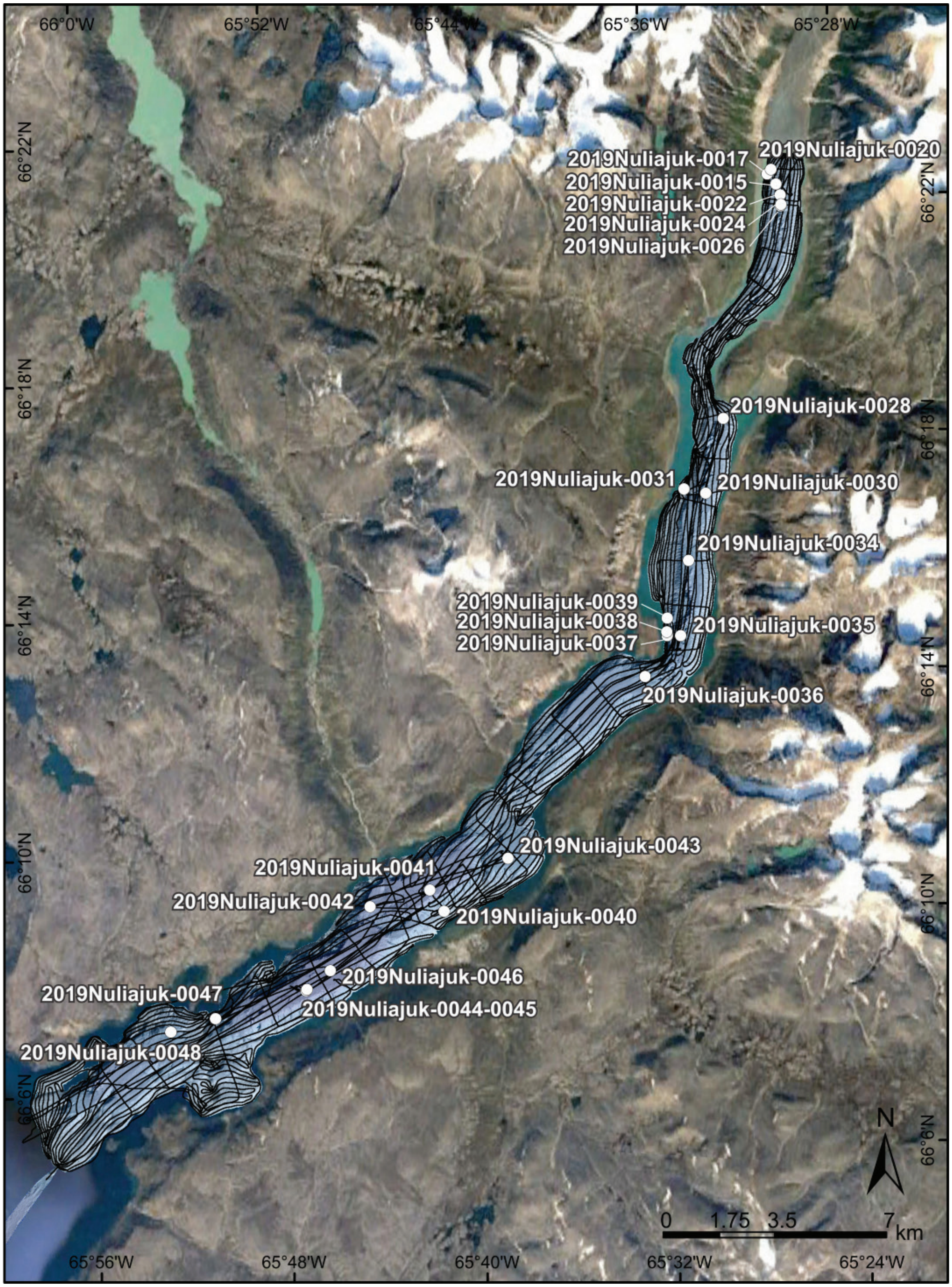

Figure B17: Location of cores and 3.5 kHz sub-bottom profiles collected in Pangnirtung Fjord

Figure B18: Location of cores 0015 to 0026 and 3.5 kHz sub-bottom profiles collected in Pangnirtung Fjord

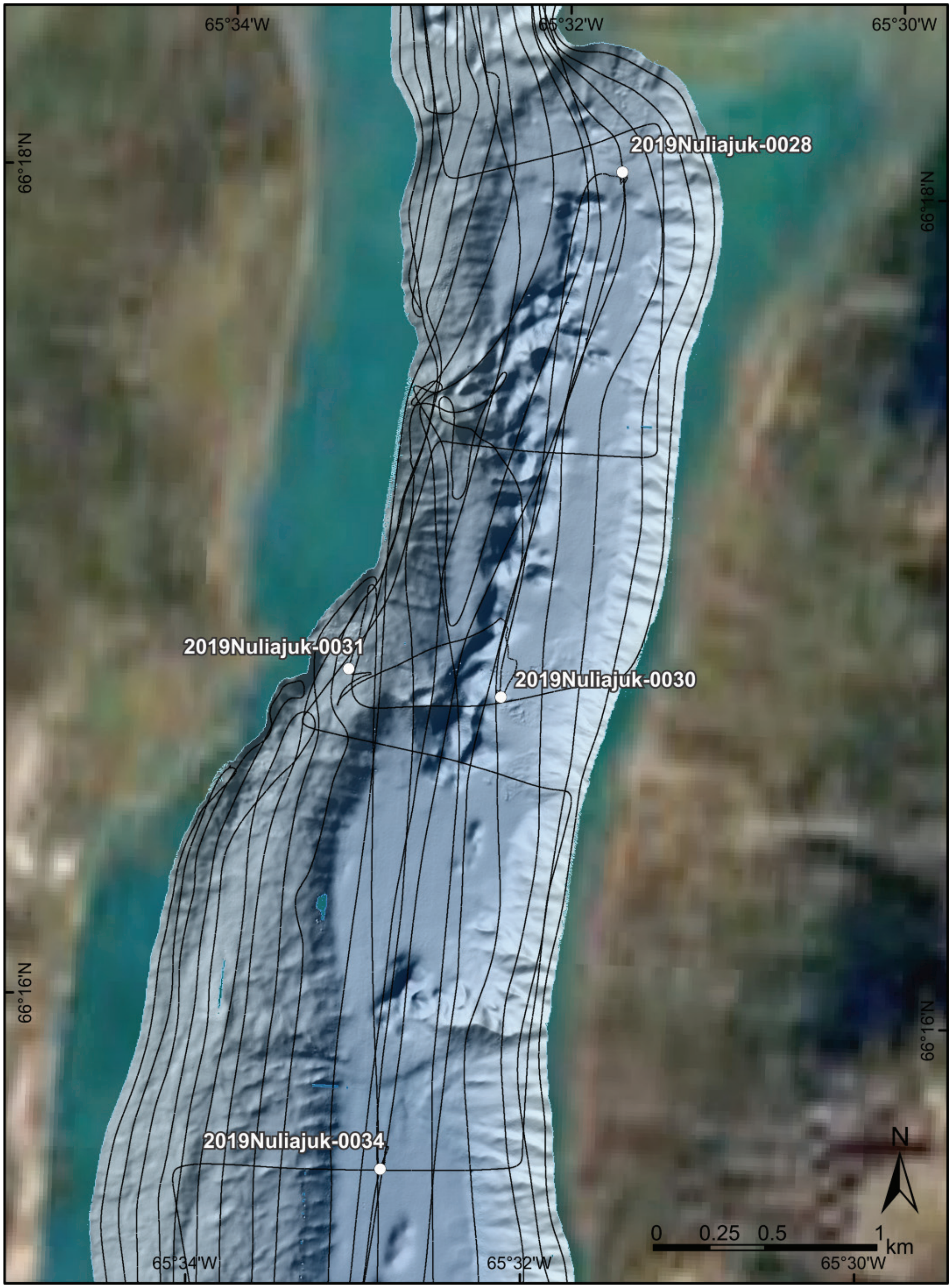

Figure B19: Location of cores 0028to 0034 and 3.5 kHz sub-bottom profiles collected in Pangnirtung Fjord

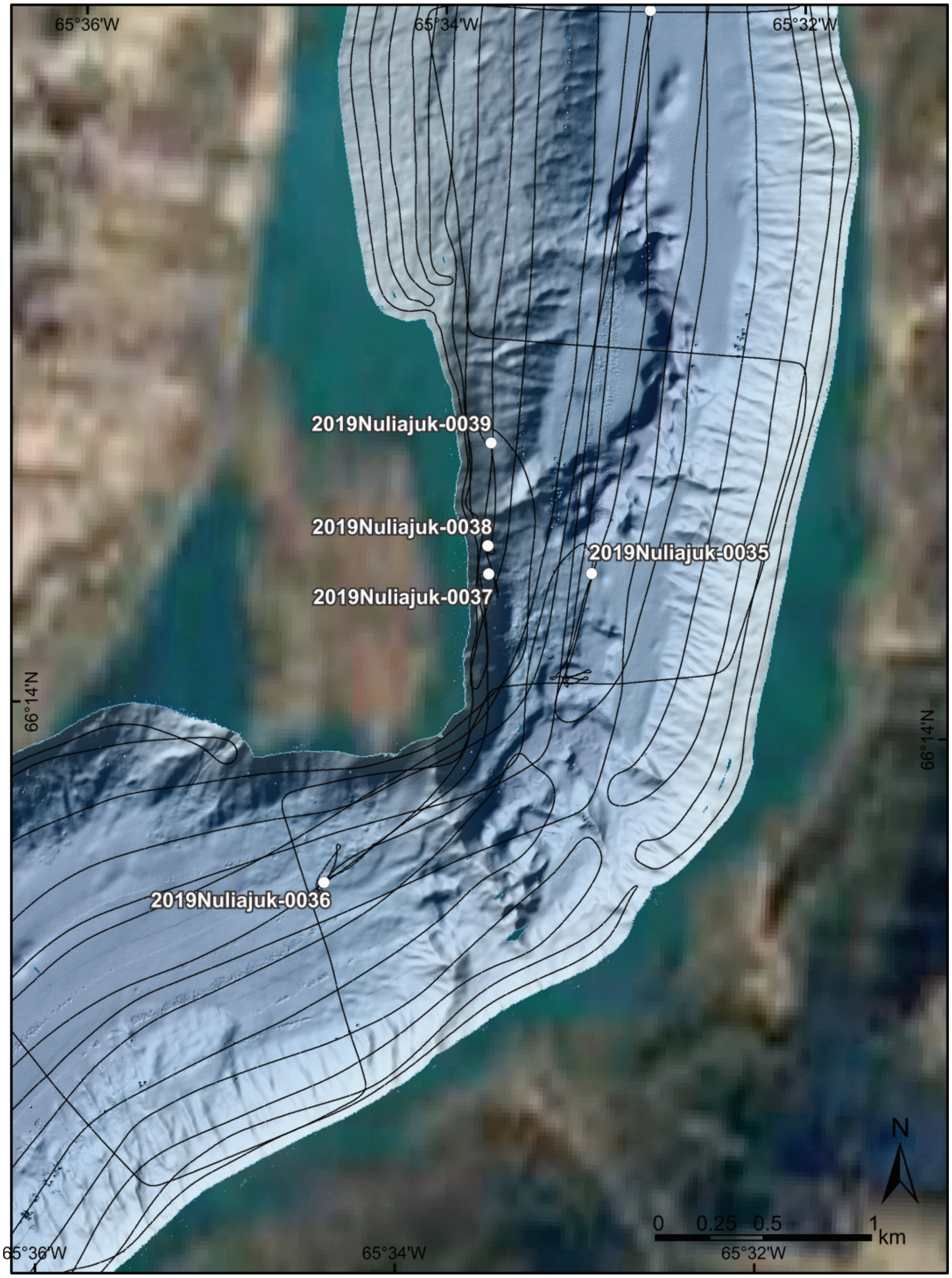

Figure B20: Location of cores 0035 to 0039 and 3.5 kHz sub-bottom profiles collected in Pangnirtung Fjord

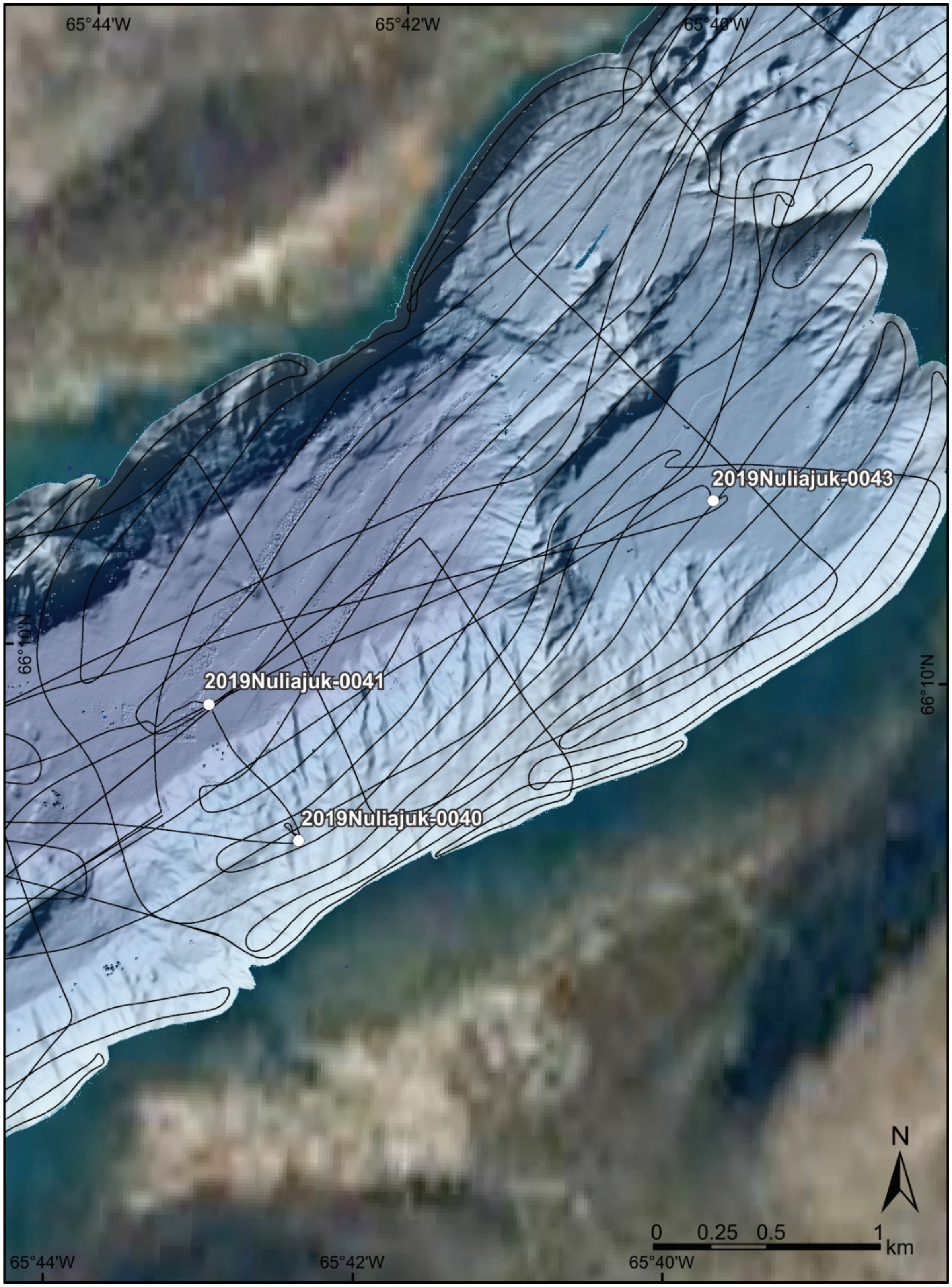

Figure B21: Location of cores 0040 to 0043 and 3.5 kHz sub-bottom profiles collected in Pangnirtung Fjord

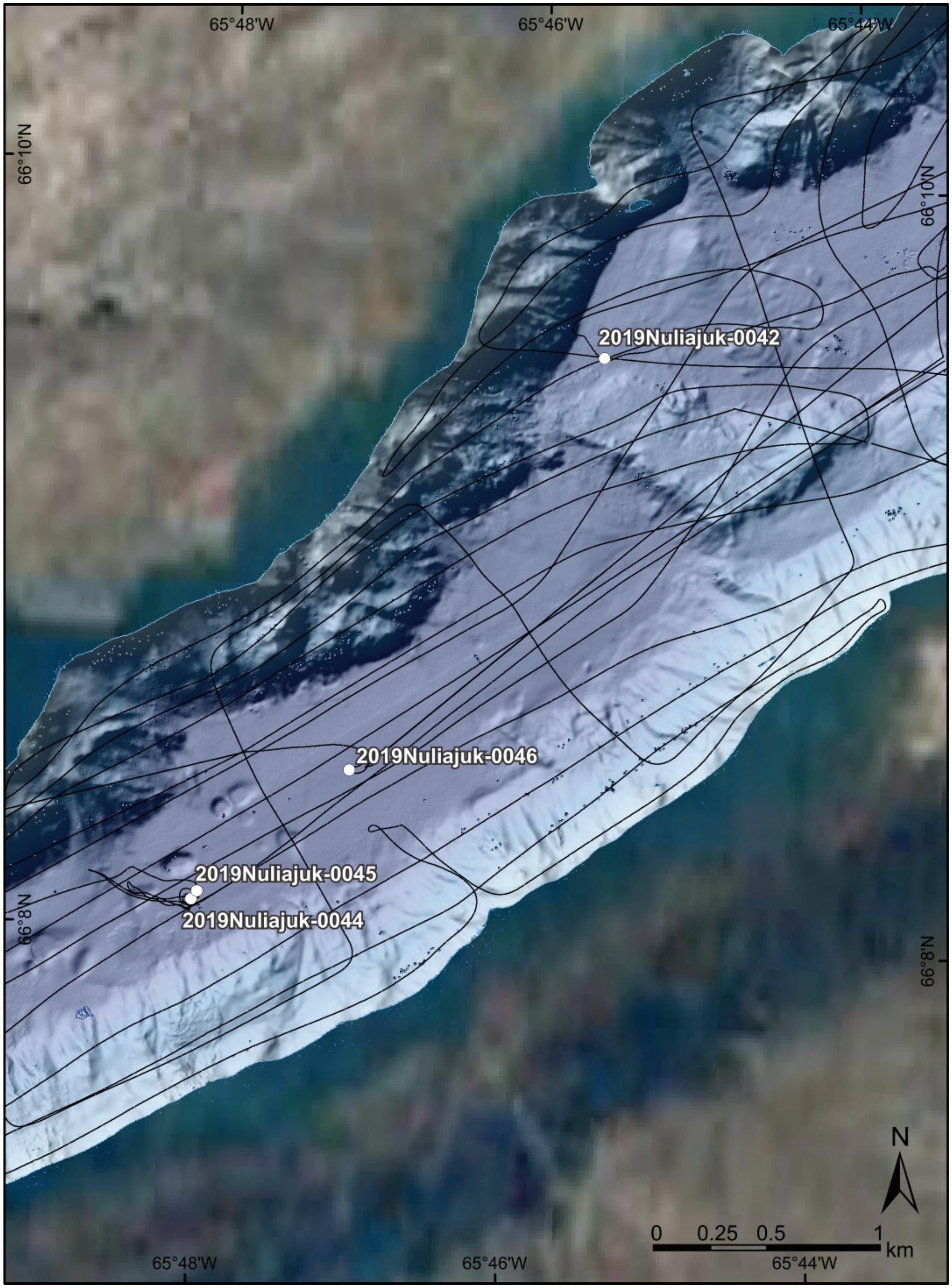

Figure B22: Location of cores 0042 to 0046 and 3.5 kHz sub-bottom profiles collected in Pangnirtung Fjord

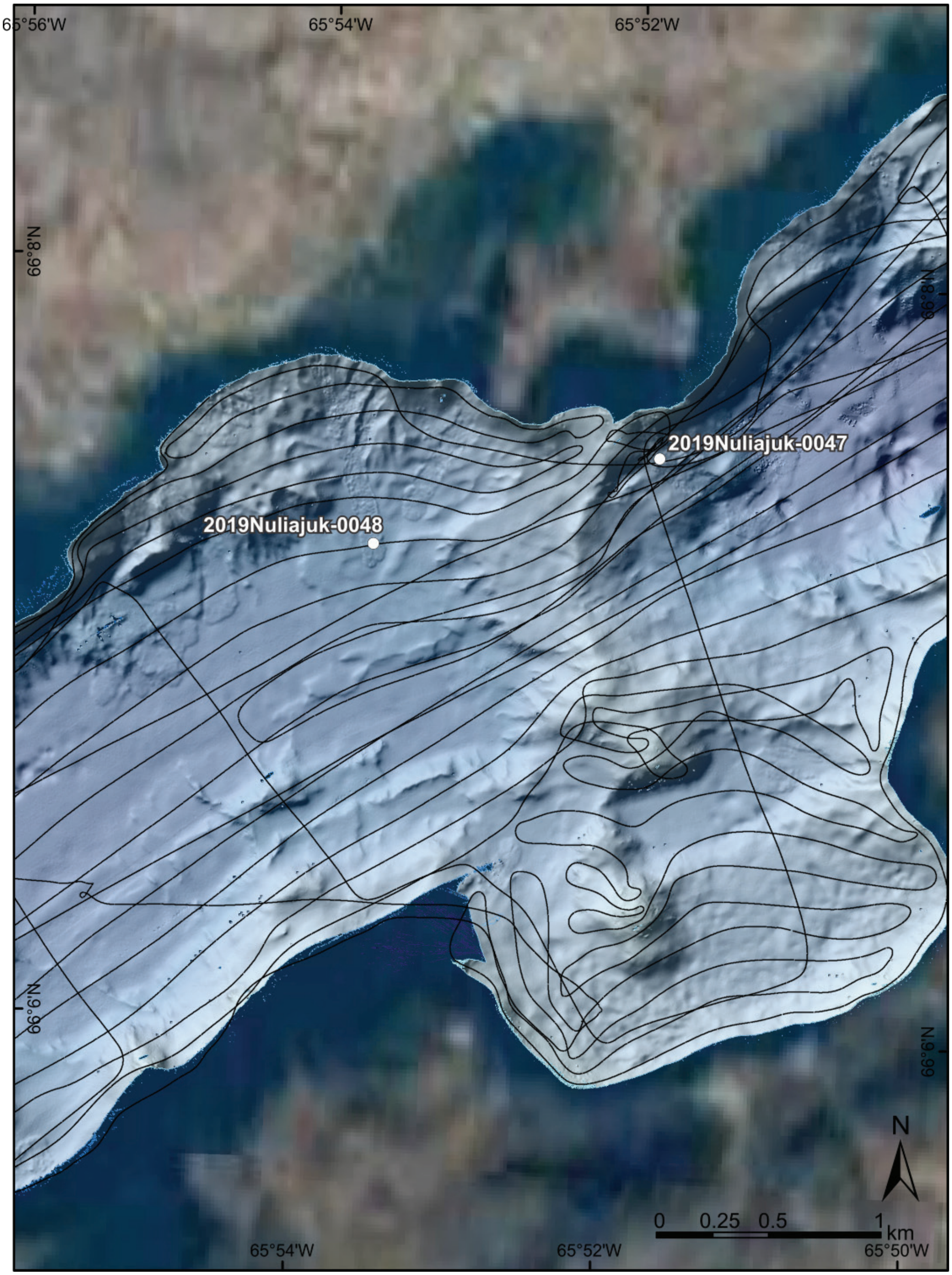

Figure B23: Location of cores 0047 and 0048 and 3.5 kHz sub-bottom profiles collected in Pangnirtung Fjord

APPENDIX C: STRATIGRAPHIC POSITIONS OF SEDIMENT CORES

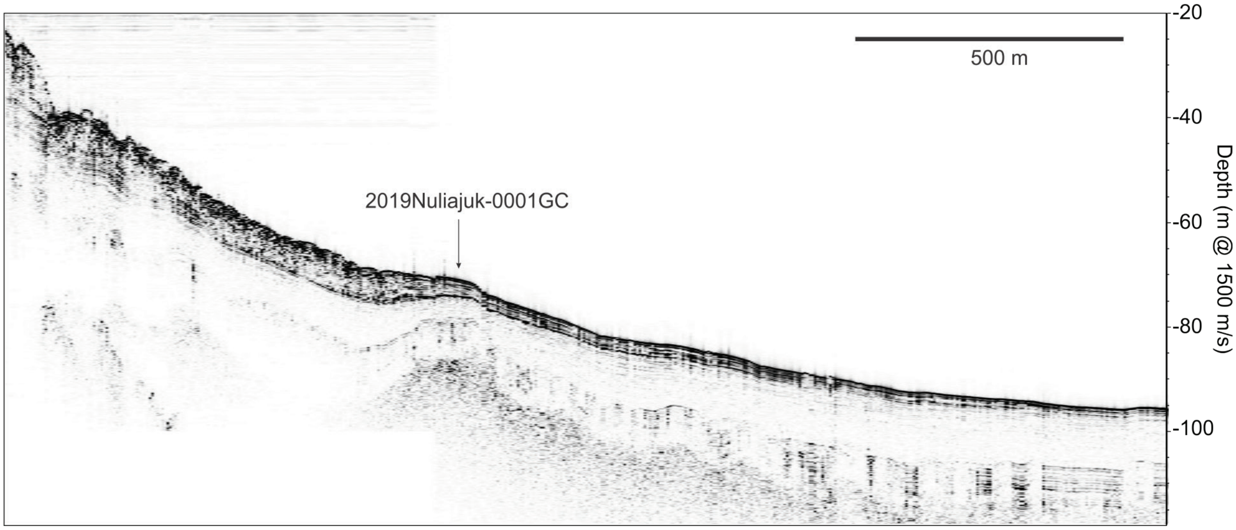

Figure C24: Stratigraphic position of core 2019Nuliajuk-0001GC in Padle Fjord

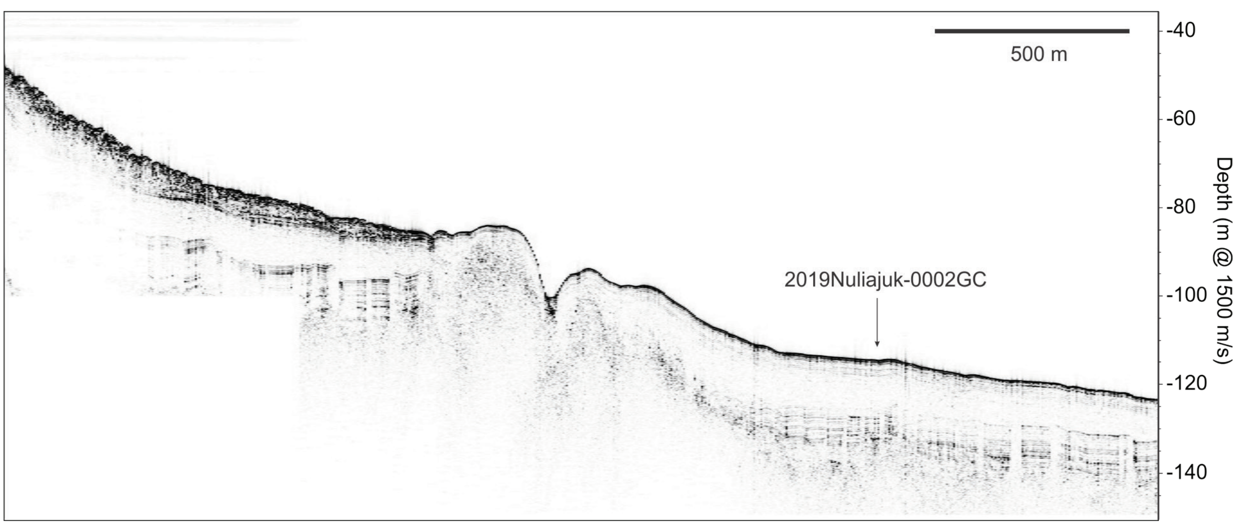

Figure C25: Stratigraphic position of core 2019Nuliajuk-0002GC in Padle Fjord

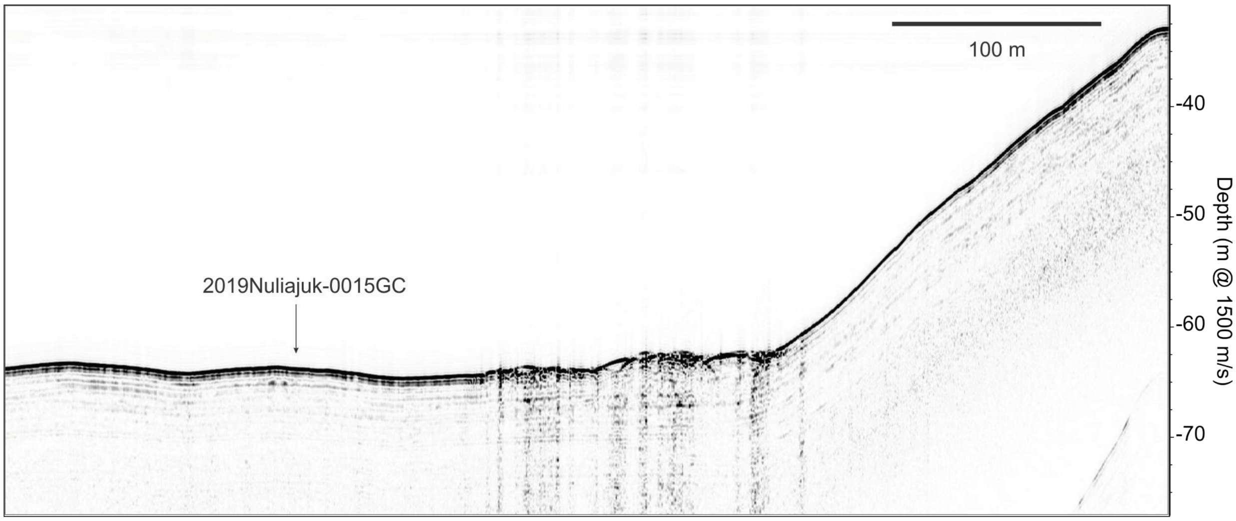

Figure C26: Stratigraphic position of core 2019Nuliajuk-0015GC in Pangnirtung Fjord

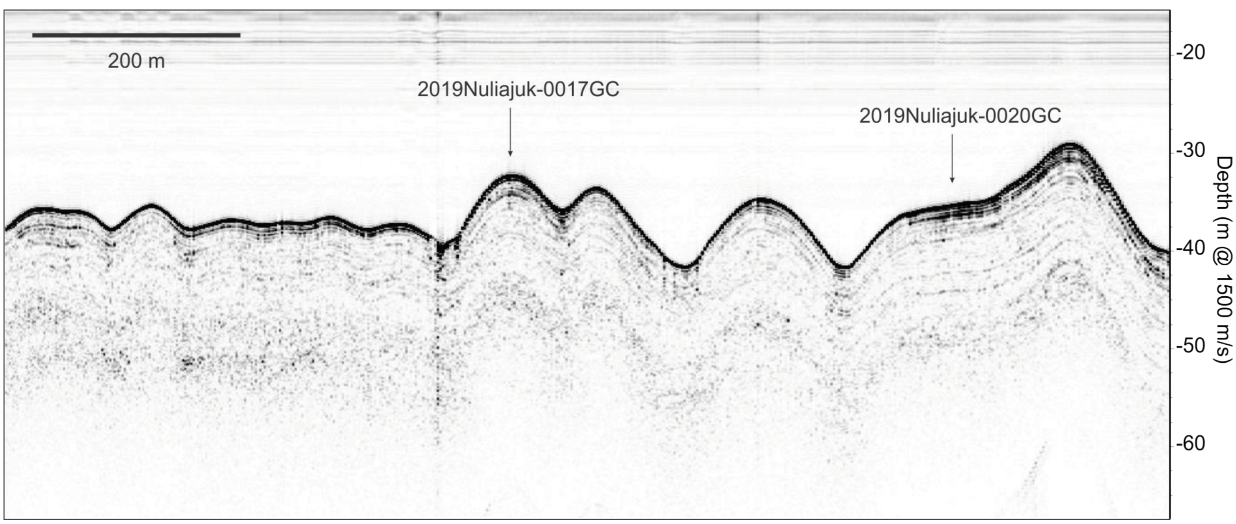

Figure C27: Stratigraphic position of core 2019Nuliajuk-0017-0020GC in Pangnirtung Fjord

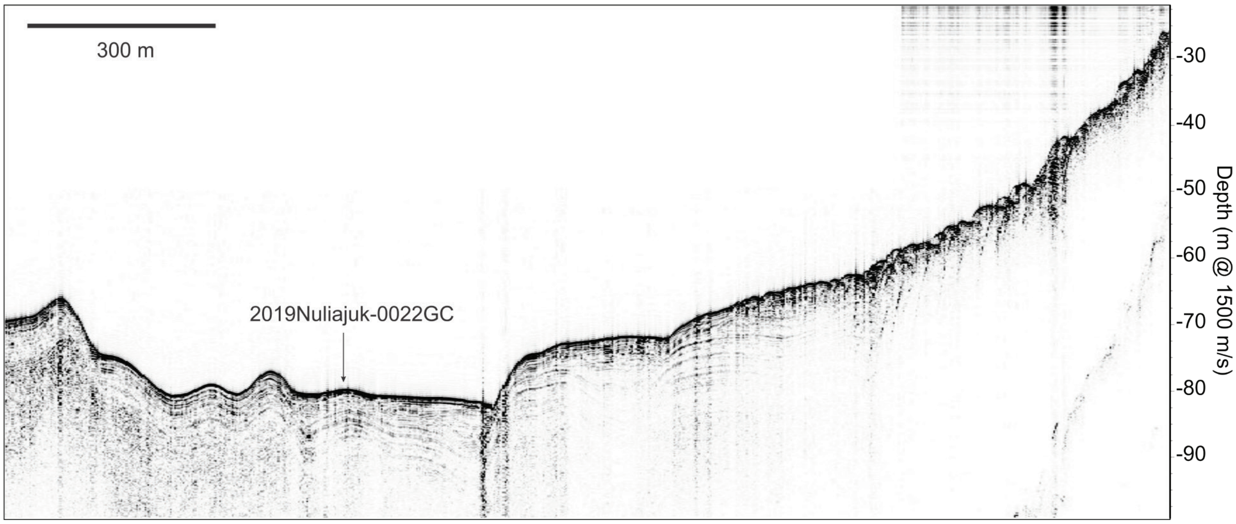

Figure C28: Stratigraphic position of core 2019Nuliajuk-0022GC in Pangnirtung Fjord

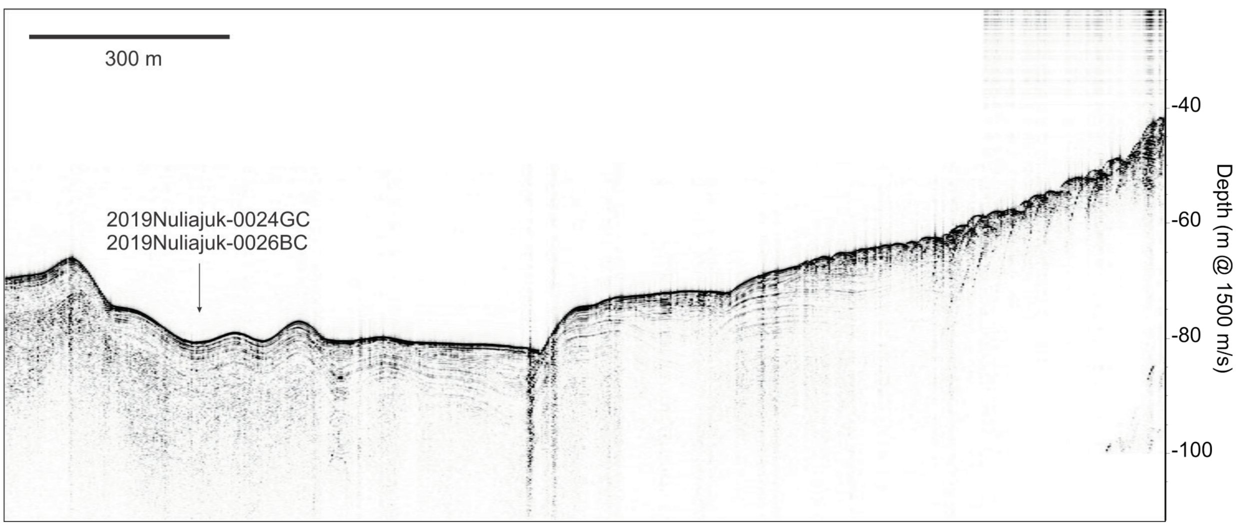

Figure C29: Stratigraphic position of core 2019Nuliajuk-0024GC and 0026BC in Pangnirtung Fjord

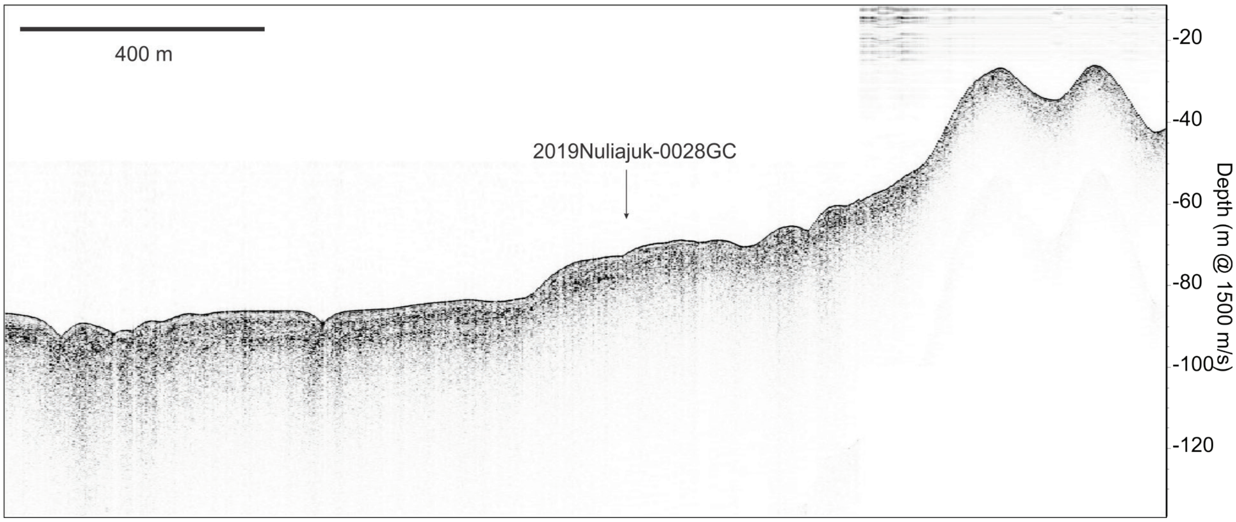

Figure C30: Stratigraphic position of core 2019Nuliajuk-0028GC in Pangnirtung Fjord

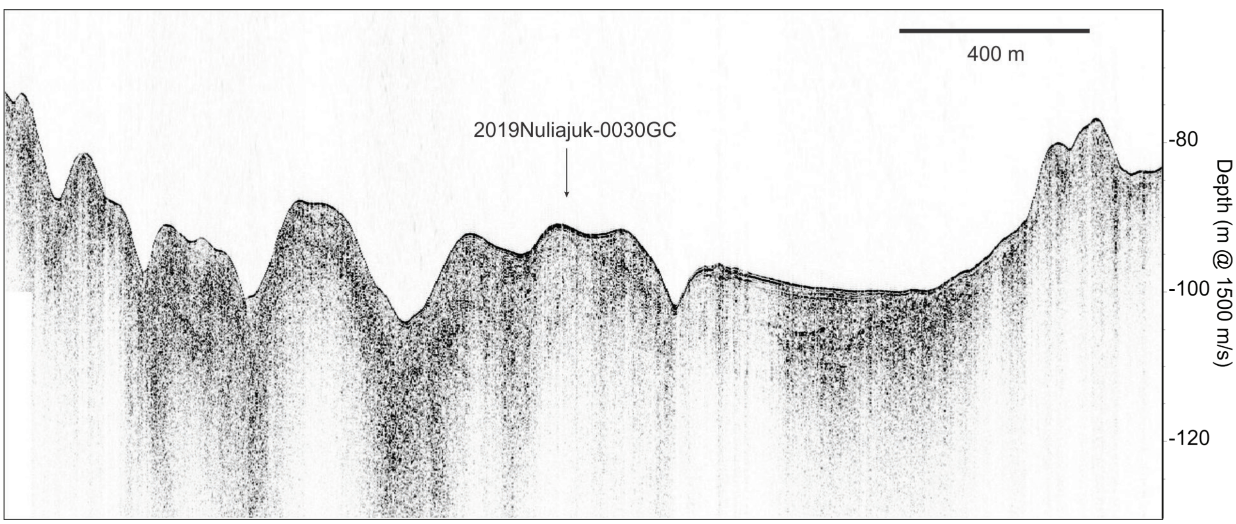

Figure C31: Stratigraphic position of core 2019Nuliajuk-0030GC in Pangnirtung Fjord

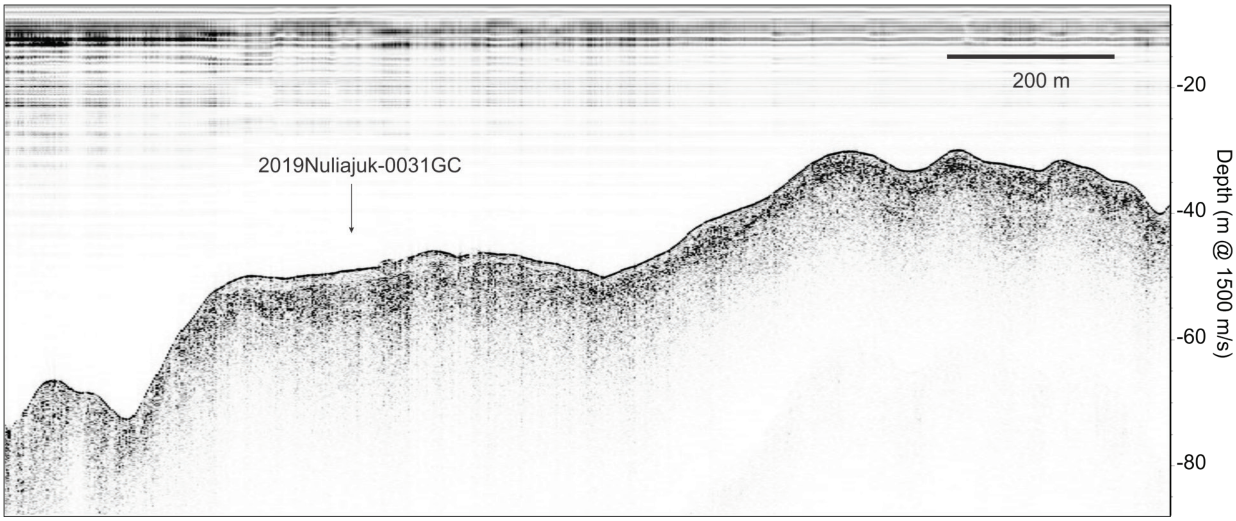

Figure C32: Stratigraphic position of core 2019Nuliajuk-0031GC in Pangnirtung Fjord

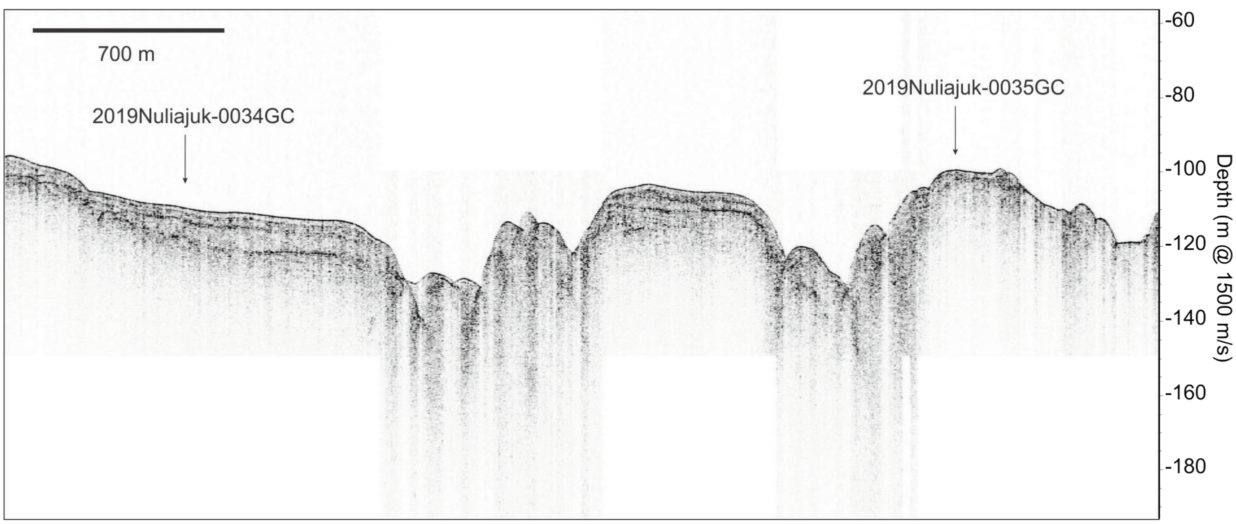

Figure C33: Stratigraphic position of core 2019Nuliajuk-0034-035GC in Pangnirtung Fjord

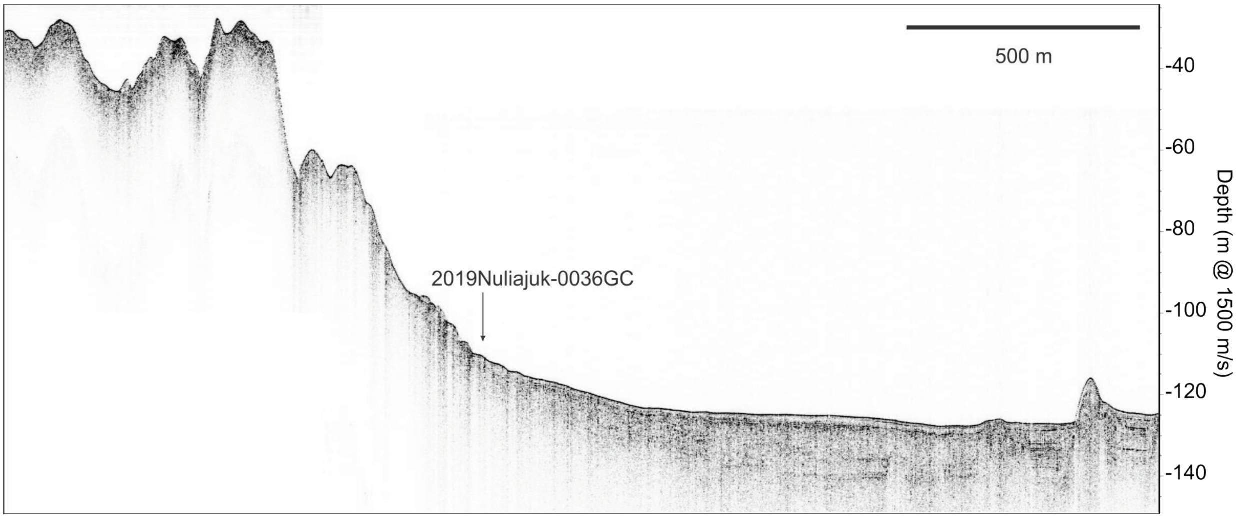

Figure C34: Stratigraphic position of core 2019Nuliajuk-0036GC in Pangnirtung Fjord

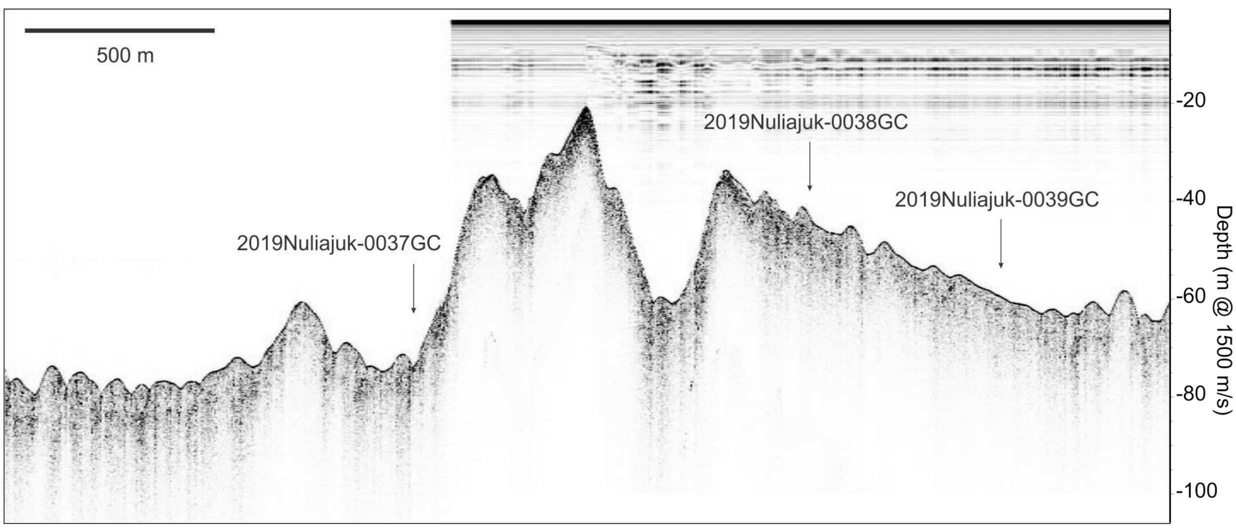

Figure C35: Stratigraphic position of core 2019Nuliajuk-0037-38-39GC in Pangnirtung Fjord

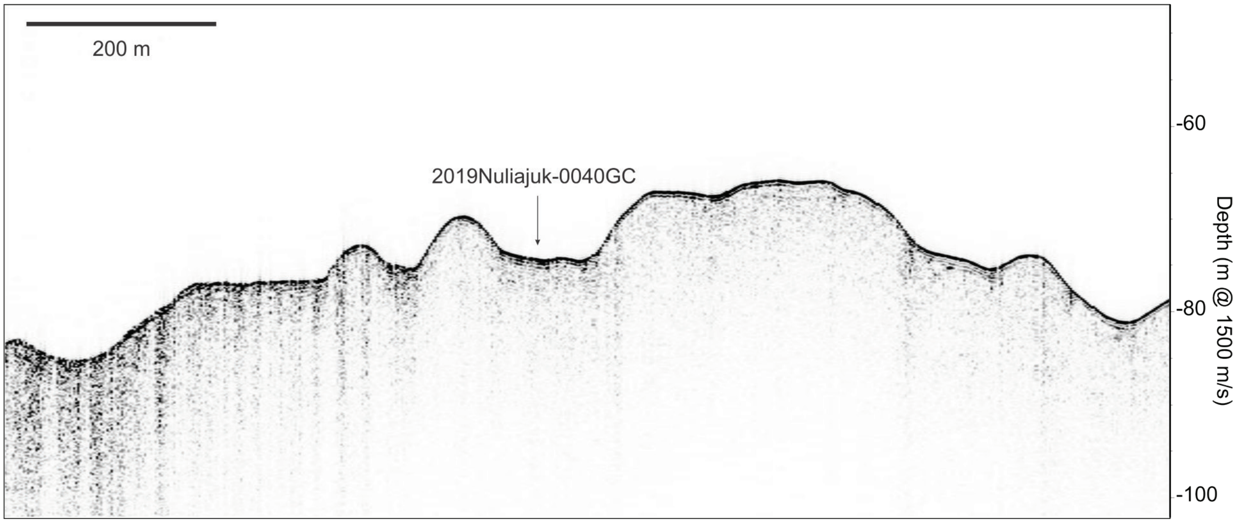

Figure C36: Stratigraphic position of core 2019Nuliajuk-0040GC in Pangnirtung Fjord

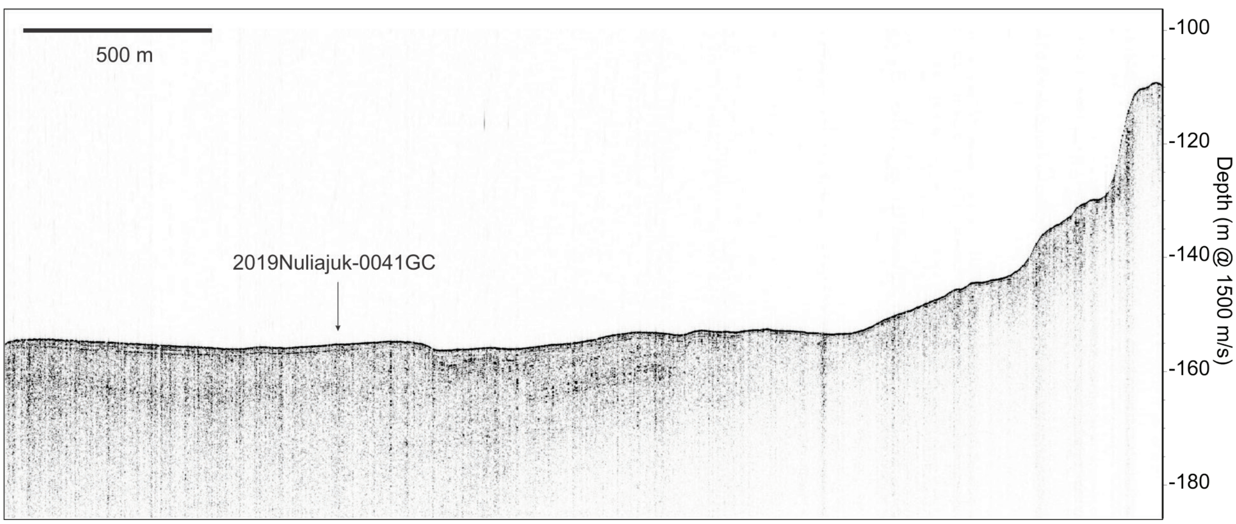

Figure C37: Stratigraphic position of core 2019Nuliajuk-0041GC in Pangnirtung Fjord

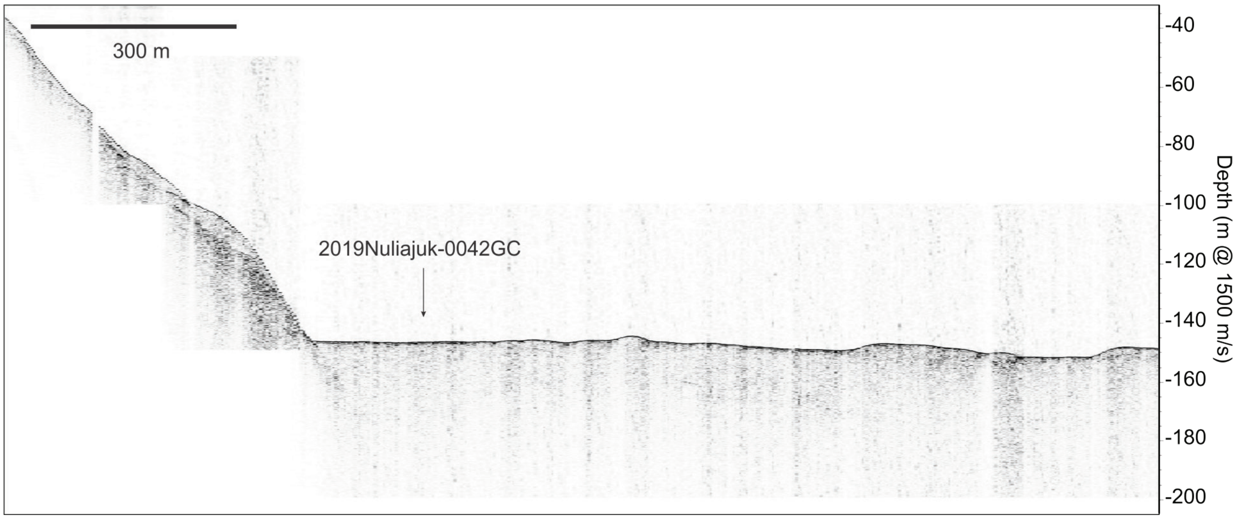

Figure C38: Stratigraphic position of core 2019Nuliajuk-0042GC in Pangnirtung Fjord

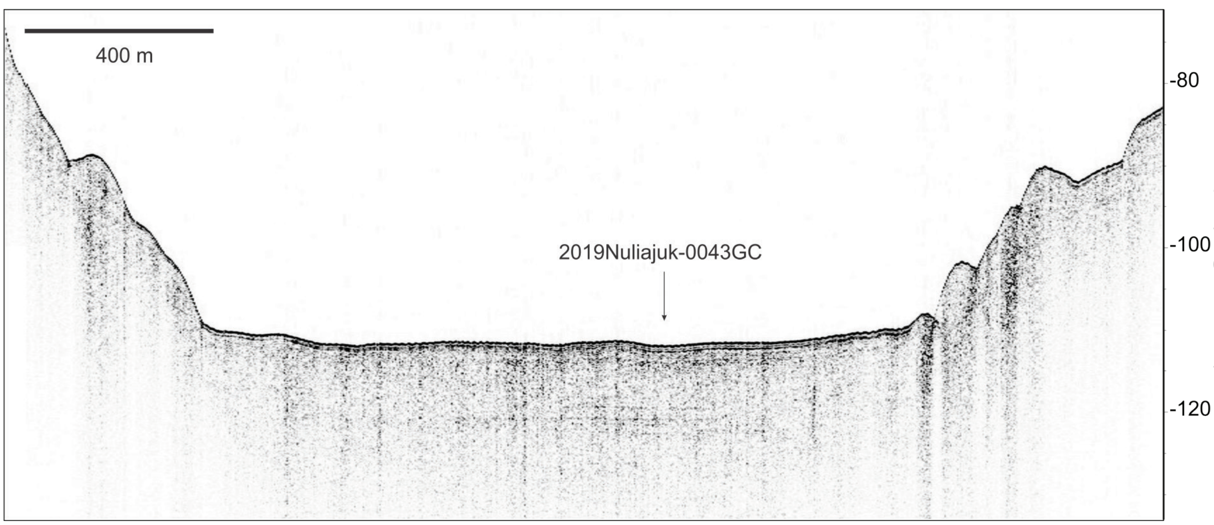

Figure C39: Stratigraphic position of core 2019Nuliajuk-0043GC in Pangnirtung Fjord

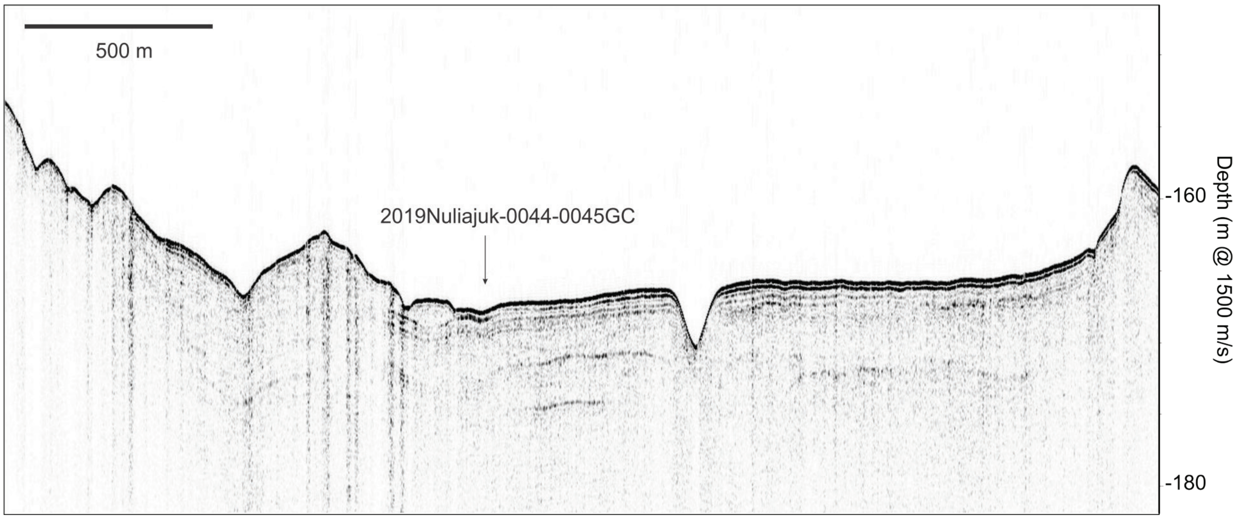

Figure C40: Stratigraphic position of core 2019Nuliajuk-0044-45GC in Pangnirtung Fjord

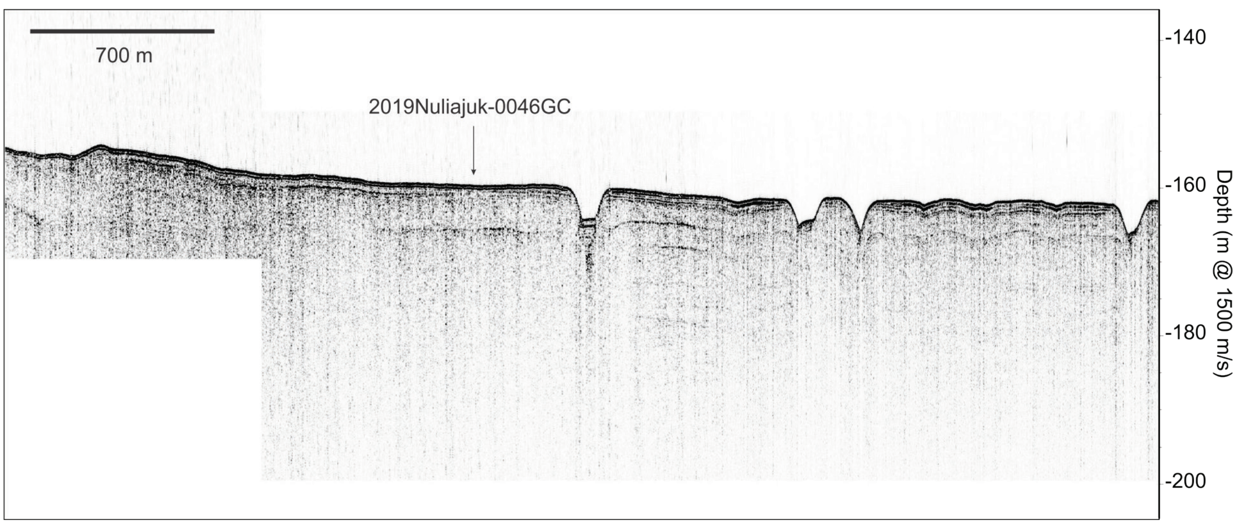

Figure C41: Stratigraphic position of core 2019Nuliajuk-0046GC in Pangnirtung Fjord

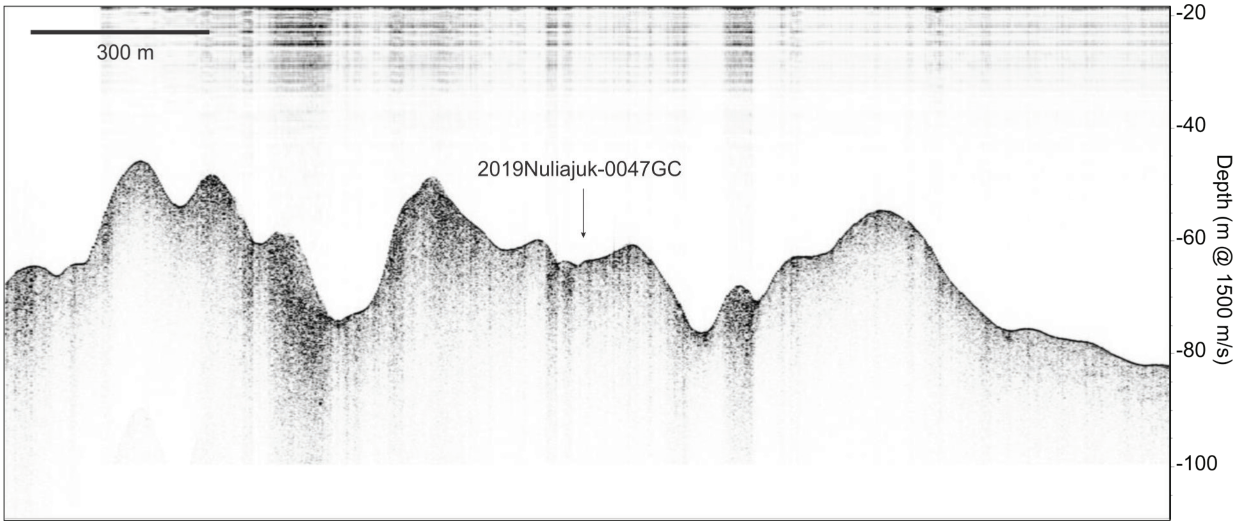

Figure C42: Stratigraphic position of core 2019Nuliajuk-0047GC in Pangnirtung Fjord

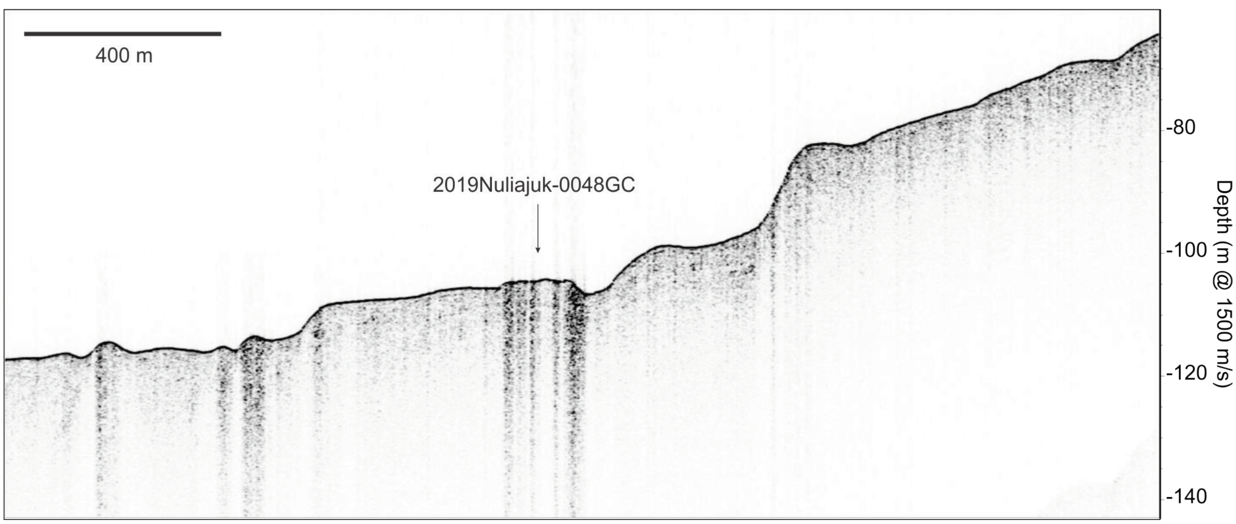

Figure C43: Stratigraphic position of core 2019Nuliajuk-0048GC in Pangnirtung Fjord

APPENDIX D: UAV FLIGHTS LOCATION

Figure D44: Location of UAV flight station 0003 in Padle Fjord.

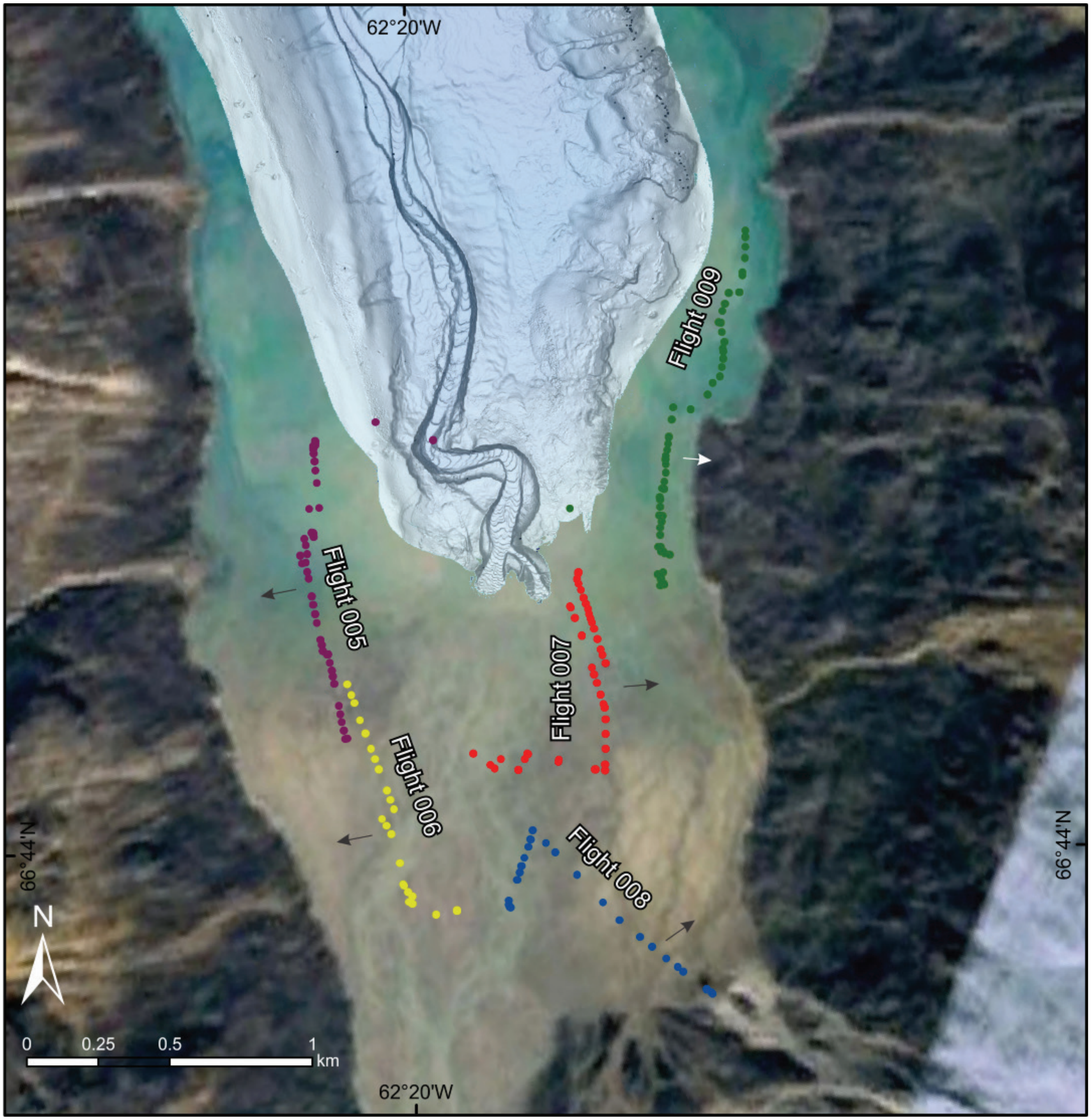

Figure D45: Location of flights stations 0005-0009 in Southwind Fjord

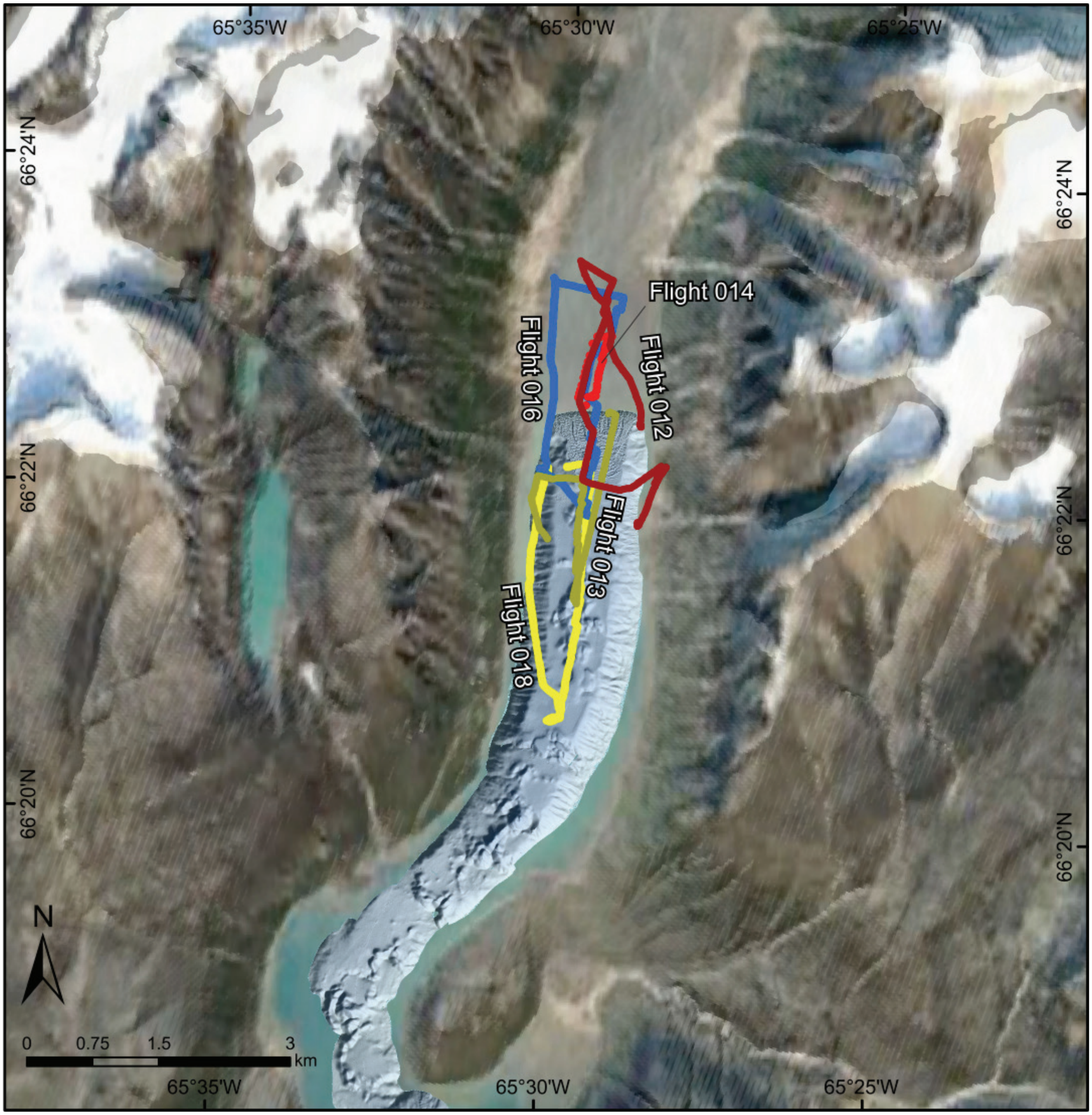

Figure D46: Location of flights stations 0012-0018 in Pangnirtung Fjord

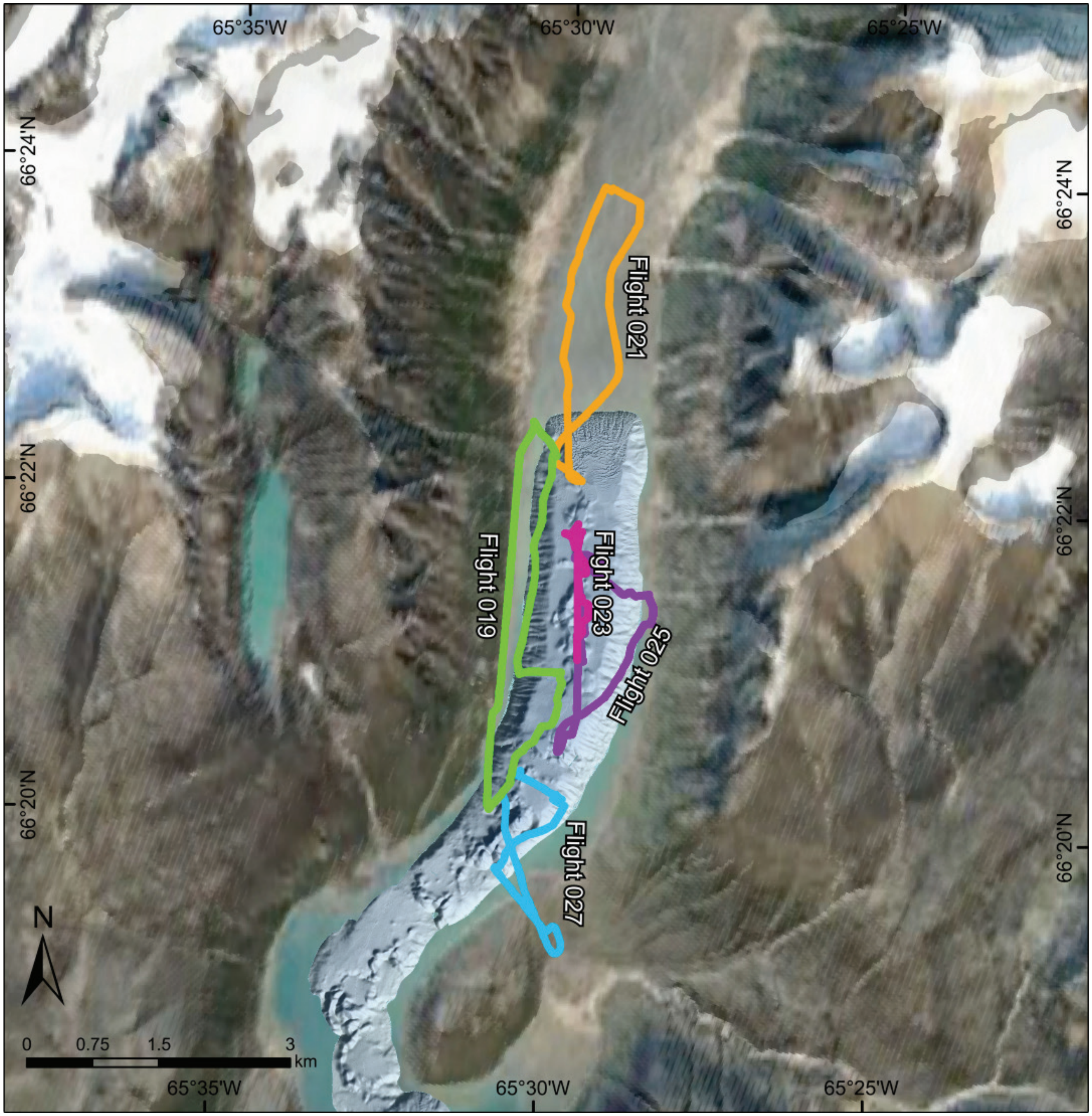

Figure D47: Location of flights stations 0021-0027 in Pangnirtung Fjord

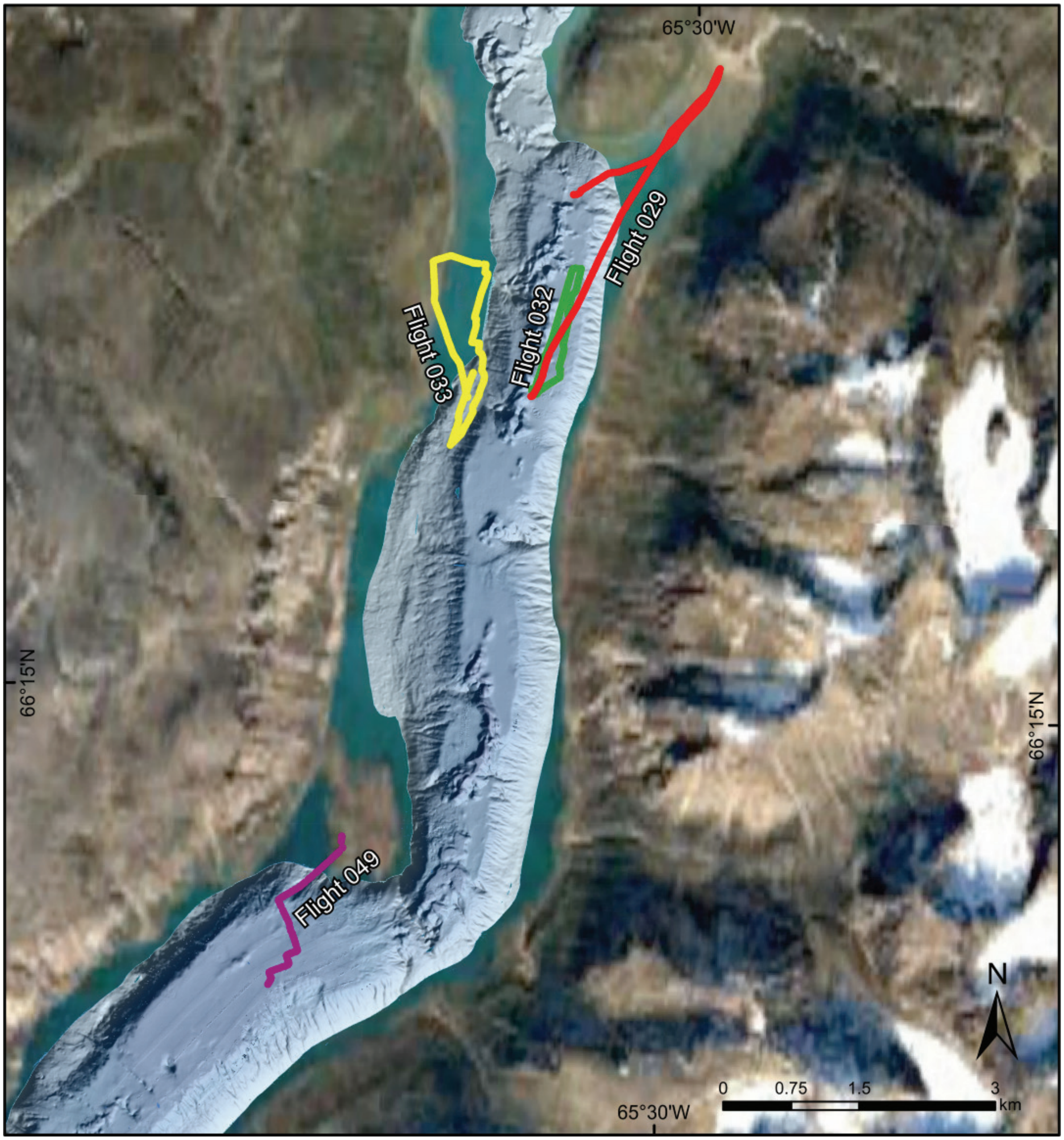

Figure D48: Location of flights stations 0029-0033 in Pangnirtung Fjord