Meltwater drainage through the Mackenzie Mountains, Canada, during the last deglaciation

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ACKNOWLEDGEMENTS

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1.0 MEET THE TEAM

Team photo at the end of the expedition, just before float plane pick up. From left to right: Ben Stoker, Sophie Norris, Helen Dulfer.

EXPEDITION LEADER: BEN STOKER

Ben is a PhD student at the Department of Physical Geography and Geoecology at Charles University, Prague, Czechia. His PhD is titled, 'The dynamics of the northwestern Laurentide Ice Sheet margin', and the main objectives are to determine the maximum extent of the Laurentide Ice Sheet in the Northwest Territories, Canada, to reconstruct the timing and rate of deglaciation, and to understand the mechanisms that caused the retreat of this ice sheet sector. He combines both desk-based and field-based methods in his PhD, including the mapping of glacial landforms from elevation models and satellite imagery and field investigations to collect samples to constrain the timing of ice sheet retreat. This expedition forms part of his PhD research. Throughout Ben's time in academia, he has undertaken fieldwork in Ireland, Svalbard, and the Canadian Subarctic.

DR. SOPHIE NORRIS

Sophie is an assistant professor at the University of Victoria in British Colombia, Canada. Her research is mostly focused on the reconstruction of the past ice sheets which were located over North America during the last glaciation and understanding how past climatic changes influenced the timing and style of these glaciations. As part of this research, she has tried to understand how large floods relating to the drainage of glacial lakes can shape the landscape. She has undertaken multiple field expeditions across Canada (including the Canadian Prairies and Canadian Arctic), Iceland, and in Svalbard.

HELEN DULFER

Helen is also a PhD student at the Department of Physical Geography and Geoecology at Charles University. Her PhD is titled, 'Reconstructing the central sector of the Cordilleran Ice Sheet'. This project is focused on reconstructing the timing and style of glaciation in the Canadian Cordillera in British Colombia and the Yukon.

This involves remote sensing work using satellite imagery to map the glacial landforms of the region and field methods to understand the timing of the ice sheet retreat. Helen has considerable experience in remote, mountainous environments through her work and her hobbies. She has undertaken field campaigns in remote northern Canada, Svalbard, and Arctic Norway.

2.0 SCIENTIFIC BACKGROUND

The Laurentide Ice Sheet (LIS) was the largest of the Pleistocene Northern Hemisphere ice sheets at the Last Glacial Maximum (LGM; ~26-19 ka). It was centred on the Canadian Shield, with a southern margin that stretched to 36° N (see Figure 1 below). The LIS coalesced with the Cordilleran Ice Sheet in the west and in the north it connected through the Innuitian Ice Sheet to the Greenland Ice Sheet (Dyke et al., 2002). At its maximum extent the LIS reached an ice volume of about 19.8 – 22.4 x 10^6 km3, which relates to a global sea level equivalent of between 49.4 – 55.8 m (Licciardi et al., 1998; Clark and Mix, 2002; Dyke et al., 2002) and is similar to the modern-day Antarctic Ice Sheet. The influence of the Laurentide Ice Sheet was wide-ranging; the growth of the Laurentide Ice Sheet led to the diversion of drainage systems within northern North America, including the Mackenzie Valley (Lemmen *et al.,* 1994), and to the disruption of global climate through cyclical events of high ice flux into the North Atlantic (Heinrich Events; Hemming, 2004).

Depending on the drainage route, the input of freshwater to the ocean can disrupt ocean circulation (Marshall and Clarke, 1999; McManus *et al.,* 2004; Tarasov and Peltier, 2005). Meltwater Pulse 1A (MWP-1A) occurred at ~14.6 ka and represents the largest documented rise in sea level (14 – 18 m over 340 years, which is ~10 times the current rate of sea level rise) but its source remains a contentious issue (Deschamps et al., 2012). Recent modelling efforts have suggested that the collapse of a saddle between the north-western sector of the Laurentide Ice Sheet and the Cordilleran Ice Sheet may have constituted the dominant source of MWP-1A (Gregoire et al., 2012; Gomez et al., 2015; Gregoire et al., 2016). During the last deglaciation, the drainage of the NW Laurentide Ice Sheet was directed through the Mackenzie Mountains or dammed in large proglacial lakes that drained through various routes in the Mackenzie Valley (Lemmen *et al.,* 1994; Duk-Rodkin and Hughes, 1995; Tarasov and Peltier, 2005). Understanding the timing and routing of ice sheet drainage through this region has important implications for deciphering the relationship between ice sheet drainage and global ocean-climate links (Marshall and Clarke, 1999; McManus *et al.,* 2004; Tarasov and Peltier, 2005).

There has been considerable effort to reconstruct the climatic implications of drainage from the North American ice sheets (e.g. Baker, 1973; Lord and Kehew, 1987; Teller *et al.,* 2002; Fisher *et al.,* 2009). In particular, research has focused on the drainage of topographically-dammed, large proglacial lakes during deglaciation (Lemmen *et al.,* 1995; Norris *et al.,* 2019). However, the most recent studies of the deglacial drainage system for the NW Laurentide Ice Sheet date back to the 1990s, based on aerial imagery and field mapping (Lemmen *et al.,* 1994; Duk-Rodkin and Hughes, 1995). These studies identified three main, large proglacial lakes that drained through the Mackenzie Valley region and carved a series of large spillways (Lemmen *et al.,* 1994; Figure 2 and 3). In addition, a series of smaller lakes also likely formed during deglaciation, as the Laurentide Ice Sheet retreated from its maximum position with its western margin high in the eastern slopes of the Mackenzie Mountains. This early research into the drainage systems of the NW Laurentide Ice Sheet did not reconstruct in detail a series of extremely large meltwater channels cut into the eastern slopes of the Mackenzie Mountains (see the cross profiles in Figure 2). These meltwater channels are below the maximum extent of the last glaciation and occur in series – they thus do not record the long term drainage of meltwater but rather large magnitudes of meltwater discharge during a period of rapid ice sheet retreat. These channels may thus record the potential drainage route for the NW Laurentide Ice Sheet contribution to Meltwater Pulse 1A.

This series of large meltwater channels in the eastern Mackenzie Mountains provides an opportunity to research high-magnitude drainage during the early stages of deglaciation, likely related to the NW Laurentide Ice Sheet contribution to Meltwater Pulse 1A (Figure 2 and 3). This projects aims to understand the timing and size of the floods that created these large channels and to understand the nature of the flood event and how that shapes the landscape.

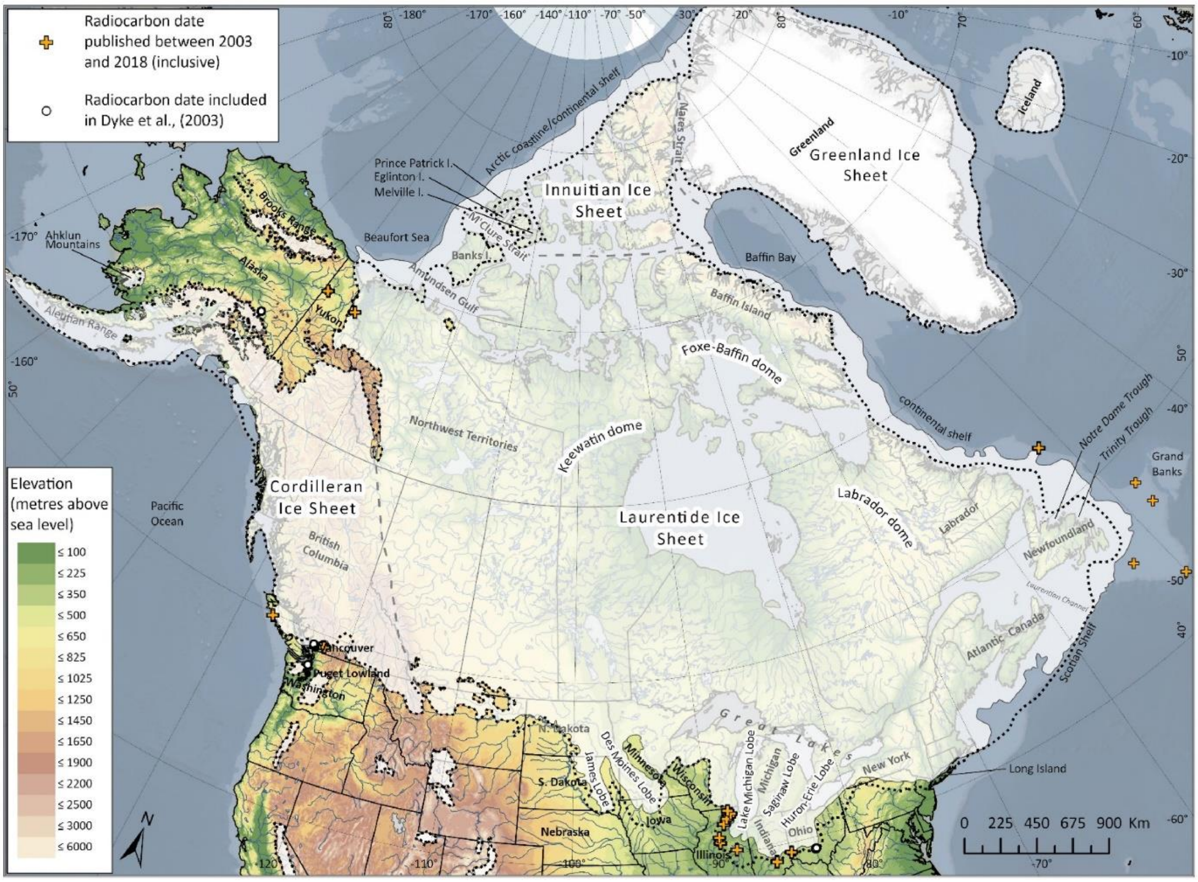

Figure 1. This figure is taken from Dalton et al (2020) and depicts the North American Ice Sheet complex at ~18,000 years ago. The study site of this field expedition is located in the Northwest Territories and described further in the following sections.

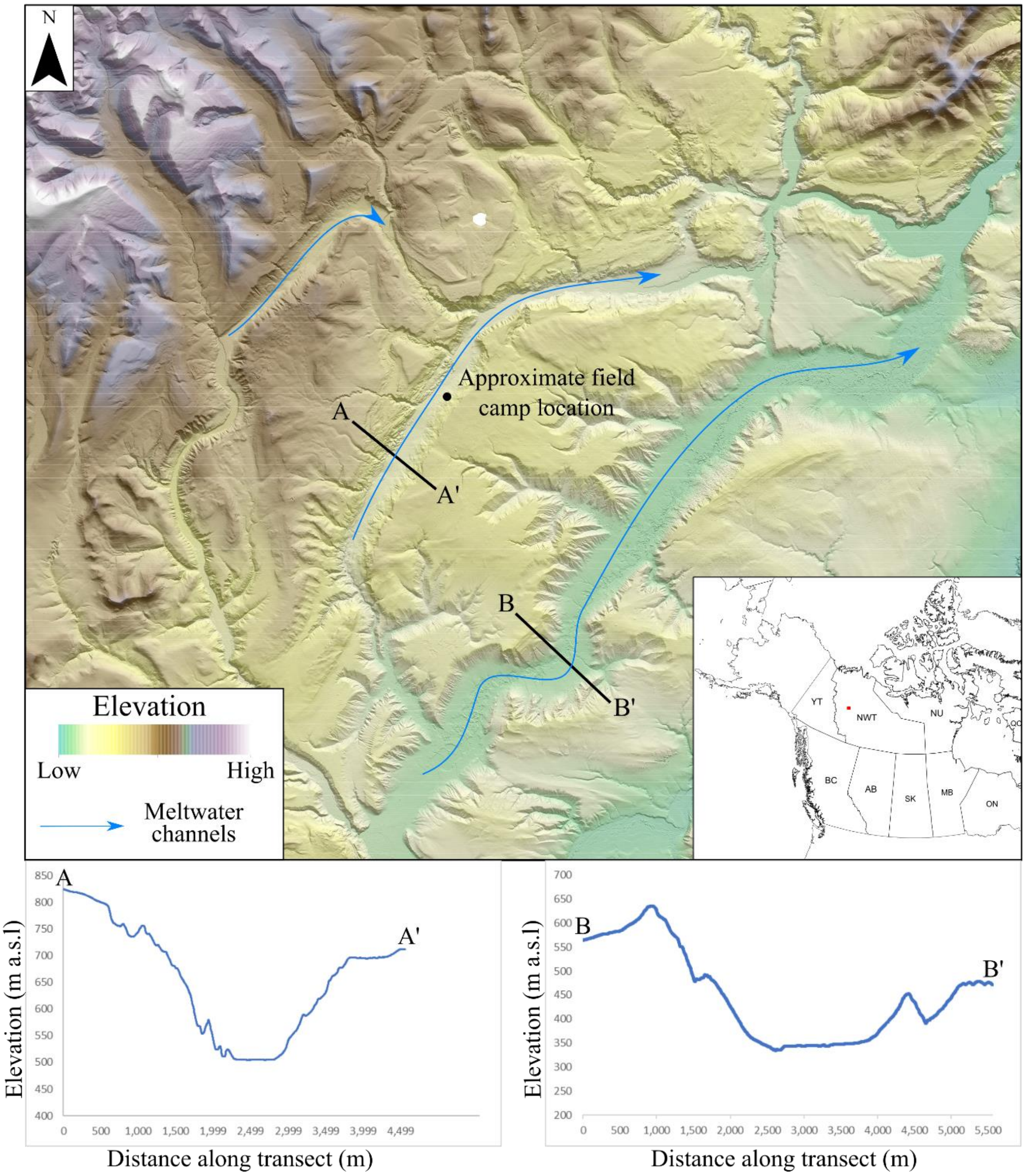

Figure 2. Hillshade elevation model of the expedition site. The study area is shown by the red square on the inset map. The location of the meltwater channels, which are the focus of this project, is indicated by blue arrows. The location of a field camp location that was proposed during the planning stages is shown by a black dot in the central meltwater channel. The lower panels show elevation cross-profiles of two of the channels along the two black lines on the map.

Figure 3. Oblique image from a helicopter looking to the north along a large meltwater channel in the Mackenzie Mountains. The image shows the eastern channel from Figure 2, at the location of the elevation transect (B-B'), which provides scale for the photograph (Fig. 1). This channel likely carried large volumes of water during the early stages of ice sheet retreat in the region ~15,000 years ago.

3.0 EXPEDITION SUMMARY

View down the meltwater channel from our campsite.

The team travelled to the Mackenzie Mountains, Northwest Territories, via Norman Wells, to investigate a series of large channels that formed by the drainage of meltwater from the Laurentide Ice Sheet during the last deglaciation (approximately 15,000 to 13,000 years ago). The Mackenzie Mountains are the northern extension (~61°N – 66°N) of the Canadian Rockies, composed of a series of different ranges which includes the Backbone Ranges in the core and the Canyon Ranges on the eastern side. Keele Peak (2,972m), the largest mountain in the range, is located in the Backbone Ranges in the central Mackenzie Mountains. The Nahanni National Park Reserve in the southern Mackenzie Mountains, home to the Cirque of the Unclimbables and the Lotus Flower Tower (2,570m), is arguably the most desirable location for mountaineering expeditions due to the stunning granite rock faces which are considered among the 'most aesthetically beautiful rock faces in the world'. Our expedition focused on the less visited, and possibly more remote, Canyon Ranges in the central Mackenzie Mountains. In summer, this region is accessible only by float plane and helicopter from Norman Wells (~100km away) and is notorious for the healthy mosquito population.

We had an six-day period between float plane drop-off and pick-up to complete the planned scientific activities, including any potential lost days for bad weather and for travelling. Unfortunately, our float plane charter into the field had to be adjusted due to bad weather, meaning we had two less days in the field than we expected. This is because float plane travel in to the mountains is impossible during periods of low cloud and poor visibility for safety reasons. This meant that our original plan, which included a day moving the camp location to a separate channel, had to be amended. To make best use of our time we simply took day trips from our base camp location near the float plane drop-off site and we successfully managed to complete the key scientific objectives. This included collecting four samples for cosmogenic nuclide dating to constrain the timing of channel formation and field observations which have helped us understand the processes of channel formation. This expedition also gave us the opportunity to prepare and undertake expeditionary research in a remote mountainous region.

4.0 PLANNING

MACKENZIE MOUNTAINS

The eastern Canyon Ranges of the Mackenzie Mountains are an incredibly remote and wild environment. The only access to the region is by helicopter or float plane. Some tributaries of the Mackenzie River may allow access to certain areas by boat once the summer thaw of the river ice is finished. The nearest townsite is Norman Wells, which is approximately 100km straight line distance from our field site. The Canol Heritage Trail is the only hiking trail in the region. It is approximately 220 miles long (350 kilometres) and constitutes one of the hardest long distance hiking trails in Canada. It follows the former Canol Road that was controversially built by the USA during the Second World War to service an oil pipeline. The road has now fallen into disrepair and in many places is barely visible.

The Mackenzie Mountains is home to two national park areas, the Nahanni National Park Reserve of Canada and the Náátsʼįhchʼoh National Park Reserve. The region we visited does not fall within the boundaries of either of these national parks, but all research expeditions in the Northwest Territories must receive approval of a research permit from the Aurora Research Institute to ensure that sensitive, natural environment is protected.

OUR EXPEDITION PLAN

This main aims of this project are to understand the drainage network created as glacial meltwater drained through the Mackenzie Mountains during the last deglaciation, and how this freshwater flux to the Arctic Ocean may have impacted ocean circulation.

The expedition targeted sites in the central channel with two main objectives (Fig. 2). These objectives are: to reconstruct past flow characteristics (flow discharge and velocity) and understand the processes responsible for channel erosion and landform creation. Firstly, information on past flow level indicators needed to be collected in the field (e.g. fluvial landforms and wash limits) for model calibration. Maximum boulder sizes could provide an estimate of the shear stress and allow flow discharge to be calculated using basic flow equations. Secondly, field observations of the fluvial landforms around the area are essential. Prospective sites included a series of raised bedrock features and streamlined landforms. These sites could give us an insight into the erosional and depositional processes that operated during channel formation. We also planned to take samples from any available locations for cosmogenic nuclide dating or optically stimulated luminescence dating, to constrain the timing of channel formation. Future desk-based work will use this geological data to constrain numerical models and quantify the past channel discharge. In turn, this will allow us to understand how the freshwater flux impacted ocean circulation.

5.0 DIARY

PART 1 – PREPARATION AND GETTING THERE

The majority of travel into the Mackenzie Mountains happens through Norman Wells, which is home to multiple helicopter and float plane companies offering travel options to hunters, hikers, and scientists. The team members arrived in Norman Wells from various locations around the world. Helen and Ben arrived from Edmonton where they were undertaking a research visit at the University of Alberta and Sophie arrived from Halifax, Canada. During the week leading up to the departure day, lots of planning and preparation was necessary. This included the organisation of: food supplies to ensure self-sufficiency in the field for a week, scientific equipment (shovels to excavate sediments exposures, angle grinder to collect rock samples), as well as field safety equipment (satellite phones, bear protection equipment). Any hazardous goods that were required (including camping gas) had to be shipped up in advance. All team members successfully arrived in Norman Wells with a couple of days to spare and all the necessary equipment. We spent our nights in the Sahtu Dene Inn next door to colleagues from the University of Alberta which allowed for plenty of evening activities after the preparation work was done, including games of cribbage, Yahtzee and euchre.

PART 2 – FLOAT PLANE DROP-OFF

On June 20th, we visited the offices of North Wright Airways to discuss our charter into the Mackenzie Mountains. Our original schedule would have seen us arrive at the field site on June 21st. Unfortunately, the weather forecast was not great, with low visibility and the possibility of thunderstorms. This resulted in our field plans being delayed by a day and our departure date set for June 22nd and pick-up scheduled for June 28th. This would still give us plenty of time to complete our scientific objectives, assuming the weather was more cooperative during our field camp. First thing on the morning of June 22nd we left Norman Wells for the Mackenzie Mountains. The journey took approximately 30 minutes in our Pilatus Porter, including a quick reconnaissance circle around the field site to check for any dangerous wildlife.

On arrival, we set up our camp site right next to the drop off location and followed standard bear safety protocols. This included keeping our three sleeping tents well away from (~100m) our food storage location and cooking area. After a quick lunch, we headed out in the afternoon for a short reconnaissance trip to check for possible routes out of the channel to prepare for the next days work. In the area of our campsite there was no evidence of recent bear activity, but there was plenty of moose tracks and scat suggesting that moose regularly travel through this area.

PART 3 – THE SCIENTIFIC WORK

To complete our scientific objectives, we hiked to sites that were from 2 – 5 km away from our base camp (Figure 4). The distances travelled each day were relatively short, but the rough terrain, dense vegetation, and hot weather made hiking difficult, and it was necessary to allow for plenty of time for scientific activities and sampling. Any future scientific expeditions in the area that aim to visit sites more than 5 km away from a base camp should consider a camp move.

On the first day, we hiked up to the upstream end of the hanging channel. At lower elevations, vegetation cover can be fairly dense and make hiking difficult, but generally it becomes less dense at higher elevations. Although, none of the area is fully above the treeline so vegetation cover is present across the whole site. As we reached the hanging channel, we noticed a spread of boulders (~1m) that were left behind by the ice age floods. We measured the size of boulders and we can use these boulder sizes to calculate the past flood discharge using simple flow equations. We also managed to sample four boulders for cosmogenic nuclide dating to constrain the timing of channel formation. This involved using an angle grinder, and a hammer and chisel to remove the top few cm from the surface of a boulder. While this is a destructive process and does remove material from the environment, the impact is minimal and the scar on the rock surface is barely visible after a couple of years.

Although the following days did not involve anymore sampling to constrain the timing of channel formation, they still provided scientifically valuable information on the processes of channel formation. This included a trip to the downstream end of the hanging channel and the adjacent area which was not affected by the flood flows and two trips (upstream and downstream) in the lower channel where we were camped. Through our observations we began to piece together a two-stage model of flooding that likely occurred following the drainage of a glacial lake. This likely involves an initial stage of broad flood flows across the whole landscape which scoured the surface and removed the initial glacial deposits, leaving behind only bedrock ridges and scattered boulders as erosional remnants. The flood became channelized during the later stages to create the large channels we see today. This follows the classic two-stage flood that has been attributed to glacial lake outburst floods in the past. While the absence of large boulders in the main channels indicates the large flood magnitudes that occurred during the second phase of channelised drainage that efficiently transported away any sediment.

Despite evidence that this channel acts as somewhat of a ‘highway’ for animals to travel the area, we were lucky to have limited experiences of the Canadian wildlife. Every evening when we sat to eat at our campground we were greeted by a raptor which would circle us. This raptor had made the steep, rocky walls of the channel it's home and clearly wasn't comfortable in sharing the area with us. The only other encounter with wildlife happened at night when I was woken up by rustling around our tents. After the sound had passed, I peered out of my tent to check our food supply and couldn't see any evidence of our visitor so I went back to sleep. The next day, there were moose tracks around our tents and around 30m from our camp there was an area of flattened forest where the moose had clearly slept. On our hike that day we were lucky to see the moose, from a good distance.

PART 4 – PICK UP

Having completed our scientific objectives early, we managed to organise an earlier pick up on the afternoon of June 27th. This gave us plenty of time to organise our samples, pack up our camping equipment and then wait. In the early afternoon we could start to hear the drone of the float plane coming. After a few loops of the area to test the weather conditions and make sure the lake was clear of obstacles the plane landed and came to pick us up.

6.0 THE FINAL ROUTE (MAP)

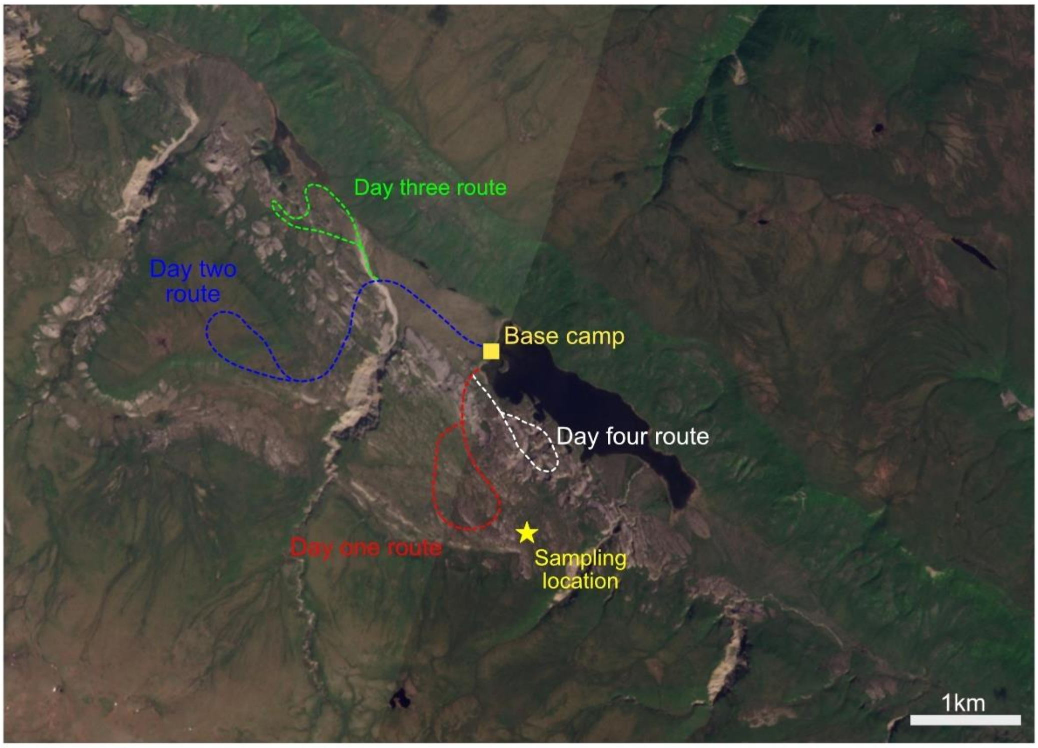

Figure 4. Satellite image showing the field site. Dashed lines indicate the approximate route taken on each day of the trip.

7.0 FUTURE WORK

The field-based element of this project was successfully completed at the end of this expedition. The remaining project work will revolve around lab and desk based methods. The samples we collected for cosmogenic nuclide dating have been sent to Dalhousie University where they will be processed over the following year. Additionally, we must complete the hydraulic modelling to calculate past flood flow discharges. The final aspect of the project will be to bring all the scientific data and to reconstruct the past drainage network, the processes that shaped it, and the timing and magnitude of these events.

8.0 MACKENZIE MOUNTAINS SPECIFICS

PERMITS

It is necessary to get a permit from the Aurora Research Institute, Inuvik, prior to any scientific research in the Northwest Territories. You must apply for your research permit at least three months prior to any planned fieldwork and it can be done through an online system.

MAPS

In the planning phase we consulted with a range of maps, this includes Google Earth, PlanetLabs satellite imagery and the ArcticDEM elevation dataset. Surficial geological maps and geological maps from the Geological survey of Canada were also used.

EQUIPMENT TRANSPORTATION

We transported the majority of our equipment up to Norman Wells prior to our arrival. There are many services based in Edmonton that can organise this, we used Buffalo Airways for air cargo. There is also an option to send equipment by cargo boat, but early in the season this faces possible delays due to river ice on the Mackenzie River.

FOOD AND EQUIPMENT

The majority of food was bought in advance in Edmonton, this includes freeze-dried meals. There are two supermarkets in Norman Wells which allowed us to purchase perishable items. These supermarkets can often have a limited selection due to issues with transporting goods to Norman Wells when the winter road is closed.

COMMUNICATION

In the field, we had an Iridium satellite phone for communication in emergency situations. Due to the remote location, we often found the satellite phone unreliable when sending messages and used it only for phone calls. To send messages, we used a Garmin InReach. Every evening we sent a message to check-in with our emergency contact and update them with our plan.

RISKS

The usual risks apply when travelling in backcountry areas with regards to exposure, heat stroke, or risk of injury from falling. We carried a satellite phone and always travelled in our group in case of any incident. The Mackenzie Mountains also host a healthy bear and wolf population. Instances of bear or wolf attacks are low, especially on larger groups, but each team member always carried a personal bear spray and we regularly used an air horn to prevent any surprise meetings.

MEDICAL ARRANGEMENTS

In case of emergencies, we had a satellite phone to contact the Royal Canadian Mounted Police to organise a rescue. While the region is incredibly inaccessible, Norman Wells is very close by helicopter travel. In case of less time-sensitive incidents, we could contact North Wright Airways, our float plane charter provider.

9.0 MOUNT EVEREST FOUNDATION SPECIFIC QUESTIONS

OBSERVATIONS ON THE ACCURACY, OR OTHERWISE, OF GOOGLE EARTH IMAGES

Google Earth images are a true representation of the area. Not only does it well depict the topography and terrain, but with some experience you can also identify the variations in vegetation which may help identify easier routes through less densely vegetated areas.

SUGGESTIONS FOR NEW ROUTES OF NEW SUBJECTS FOR STUDY IN THE AREA

Due to its remote nature, the region is very poorly understood. There are many opportunities in the region for future scientific work. A potentially interesting project could take advantage of either the Canol Heritage Trail for the limited hiking access it provides or the many rivers of the Mackenzie Mountains through a kayaking expedition. This work could potentially aim to collect further samples to constrain the timing of glaciation in the region, which is currently poorly understood. Either of these projects would present a very serious, long-term expedition that may inhibit any scientific objectives.

NOTES ON ACCESS, PORTERS, OR OTHER ISSUES OF INTEREST TO FUTURE VISITORS

North Wright Airways were incredibly responsive and knowledgeable about the region. We would highly recommend their safe and friendly approach to anyone in the region.

DETAILS OF ANY INJURY OR ILLNESS TO EXPEDITION MEMBERS AND/OR PORTERS

Beyond minor allergic reactions to mosquito bites there were no injuries or illnesses.

DETAILS OF WASTE DISPOSAL

All human waste was buried in deep trenches. All other waste was packed and brought back to Norman Wells for disposal.

A SUMMARY OF EXPEDITION ACCOUNTS, INCLUDING INCOME AND EXPENDITURE (WHERE VALUES HAVE BEEN CONVERTED FROM ANOTHER CURRENCY THEY ARE APPROXIMATE)

Income	
Source	Amount
Mount Everest Foundation (22-17)	2000
Grant Agency of Charles University (122220)	~8500
Total	10,500

Outgoings	
Expenditure	Amount
Accommodation	~2,000
Flights	~1,800
Float plane charter	~2,300
Food	~150
Laboratory analysis of samples	~4,250
Total	10,500

10.0 REFERENCES

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