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Mapping of Massive Ground Ice Using Ground Penetrating Radar Data in Taylor Valley, McMurdo Dry Valleys of Antarctica

Kartläggning av massiv markis med hjälp av markradar i Taylor Valley, Antarktis

Alexandra Drake

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Abstract

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Alexandra Drake

The distribution of massive ground ice in the ground in Taylor Valley of the McMurdo Dry Valleys, Antarctica, is quite unknown, and could provide answers to questions such as where the ice comes from, if it has been affected and removed by proglacial lakes and how landscapes underlain by massive ground ice responds to climate change. It could also be a source for atmospheric information in the past and hence a key in climate research. The main goal with this project was therefore to map the distribution of massive ground ice mainly in Taylor Valley, but also in the adjacent Salmon Valley and Wright Valley, using ground penetrating radar to see how the distribution varied and if there was any spatial patterns.

The technical computing programme MATLAB was used for editing of the raw radar data, merging of GPR profiles and digitalization of reflectors for possible massive ground ice and several compilations of different files. The data obtained from MATLAB was imported and interpreted using the geographic information system ArcGIS. A series of histograms showing the distribution of massive ground ice depending on the parameters elevation, slope and aspect were made by using the spreadsheet application Microsoft Excel.

The results showed that the distribution of massive ground ice was more common at elevations up to 200 m, at the mouth of the valleys and also more frequent in Taylor Valley than in Wright Valley. There was a slightly higher amount of massive ground ice at northeast-east aspects, probably due to different incoming solar radiation. The lack of, or not that prominent, differences for slope and aspect can be due to lack of data, a not enough detailed digital elevation model or that it have existed for a too short period of time to display big differences caused by effects from these parameters. The higher frequency of massive ground ice in Taylor Valley can be due to a thicker sediment cover when compared with the situation in Wright Valley. The distribution of massive ground ice at different slopes seems to follow the distribution of radar measurements, whereas the origin of the massive ground ice and sediment cover can be responsible for the distribution across different elevations. The reason why massive ground ice still occurs despite the existence of Glacial Lake Washburn that previously occupied Taylor Valley could be that the glacial lake did not remain for a sufficiently long time to melt all the massive ice.

Massive ground ice is very common in a zone that is believed to be very susceptible for future warming, which means that changes that already have been observed in areas rich in massive ground ice can continue to happen and changes in other areas with massive ice can be enabled. The ice can thus play a major role in the development of the landscape in the McMurdo Dry Valleys depending on the amount of warming.

Keywords: McMurdo Dry Valleys, Taylor Valley, massive ice, ground penetrating radar, Glacial Lake Washburn, climate change

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Populärvetenskaplig sammanfattning

Kartläggning av massiv markis med hjälp av markradar i Taylor Valley, Antarktis

Alexandra Drake

Markis kan hittas i mark som har temperaturer under 0°C under åtminstone 2 år i följd och därav klassas som permafrost, skillnaden mellan markis och permafrost är däremot att permafrost inte behöver vara just is utan kan enbart vara kall mark. För att markis ska klassas som massiv is så ska andelen is i marken vara minst 250 % jämfört med vikten på torr jord. Utbredningen av sådan massiv is i Taylor Valley i McMurdos torrdalar på Antarktis är inte helt känd, och kunskapen om att veta vart den finns (om den finns) skulle kunna ge svar på frågor som vart den kommer ifrån, om den har påverkats och smält bort av isuppdämda sjöar och hur landskap som är grundade av massiv markis påverkas av klimatförändringar. Isen skulle även kunna vara en informationskälla för tidigare atmosfäriska förhållanden. Huvudsyftet med detta arbete var därför att kartlägga utbredningen av massiv is främst i Taylor Valley, men även i de närliggande dalarna Salmon Valley och Wright Valley, och undersöka hur utbredningen varierar beroende på olika landskapsegenskaper som påverkar dess förekomst.

Datorprogrammet och programspråket MATLAB användes för att editera rådatat från radar-mätningarna i området, samt för att sammanföra och digitalisera horisonter för möjlig massiv markis i radarfigurerna och för ett antal sammanställningar av olika filer. Data erhållet från MATLAB importerades till det geografiska informationssystemet ArcGIS där det kunde visualiseras i kartor och tolkas. Ett antal histogram skapades i kalkylprogrammet Microsoft Excel för att visa frekvensen av massiv markis vid olika höjder, sluttningsvinklar och olika väderstrecksriktningar.

Resultaten visade att det var mer vanligt med massiv is höjder upp till 200 m, vid mynningarna av dalarna samt i Taylor Valley jämfört med Wright Valley. Det var en aning mer vanligt med massiv markis vid nordöst-östliga sluttningsriktningar, vilket antagligen beror på olika mängder inkommande solstrålning till de olika riktningarna. Avsaknaden av, eller inte så märkbara, skillnader för olika sluttningsvinklar och riktningar kan bero på att mängden data var för liten, att höjdkartan inte var tillräckligt detaljerad eller att isen inte har funnits tillräckligt länge för att bli påverkad av dessa parametrar. Anledningen till att det finns mer massiv markis i Taylor Valley än i Wright Valley kan vara att det skyddande sedimenttäcket är tunnare i Wright Valley än i Taylor Valley. Frekvensen av massiv markis vid olika sluttningsvinklar verkar bero på det totala antalet mätningar gjorda, fler mätningar leder till en högre frekvens av markis, medan dess ursprung samt det antagna tunnare sedimenttäcket på högre höjder kan vara anledningen till de olika frekvenserna av massiv markis vid olika höjder. Anledningen till varför det fortfarande finns massiv markis trots existensen av den isuppdämda sjön Washburn som tidigare fanns i Taylor Valley, och att isen således inte helt har smält bort på grund av sjön, kan vara att den fanns under en för kort tid så att de långsamma termodynamiska processerna som skulle orsaka smältningen inte hann agera tillräckligt länge för att smälta all is.

Den massiva markisen är vanlig i en zon som tros vara väldigt mottaglig för framtida uppvärmning, vilket betyder att landskapsförändringar som redan har observerats i områden med mycket massiv markis kan fortsätta att ske samtidigt som andra områden med massiv markis kan börja förändras. Isen kan därför spela en stor roll i landskapsutvecklingen i McMurdos torrdalar beroende på hur mycket varmare det blir i området.

Nyckelord: McMurdos torrdalar, Taylor Valley, massiv markis, markradar, Glacial Lake Washburn, klimatförändringar

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1. Introduction

The continental ice sheet on Antarctica represents approximately 90 percent of the world's continental ice (Ford, 2015), and how this ice responds to global climate change is an important issue in climate studies today (Swanger et al. 2011). The human impact on the environment of Antarctica is the least among all the continents, and it is considered to be an important area for understanding global climate (Guglielmin et al., 2011). Massive ground ice and ice-rich sediments are sources where information about paleoclimatic and paleohydrological information can potentially be obtained. These can be found on Antarctica in permanently frozen ground, where the ice lenses can be up to several meters thick (Lacelle et al., 2010). An example of where studies of massive ground ice like this have been conducted is the Arctic, where scientists are starting to see a connection between the distribution of massive ground ice, limits of previous glaciations and environmental conditions (Lacelle et al., 2007; Froese et al., 2008).

Published studies of massive ground ice on Antarctica are concentrated to a few sites in the McMurdo Dry Valleys located in Southern Victoria Land (Lacelle et al., 2010; Levy et al., 2013a). A record of interactions between previous glaciations and the land surface has been preserved over the last ~14 million years, revealed in the geomorphology of the landscape (Sugden et al., 1993; Fountain et al., 2014). Changes in this landscape have been observed over the past decade; ablation of glaciers and thermal erosion of streams are two examples where the latter have not been observed during earlier observations of the last 50 years. Fountain et al. (2014) noticed that one thing that all of these changes have in common is that they occur in areas where sediment covers massive ground ice. They suggest that the changes are climatically induced and they proposed a conceptual model for the occurrence of buried massive ice which was used together with other models in order to predict regions in the McMurdo Dry Valleys that are at risk of rapid gemorphological change due to climate change. There are however few published data of massive ground ice which makes the definitive associations between ground ice and geomorphic features limited. It is also not established where the massive ground ice in Taylor Valley comes from since the extent of it is quite unknown. Fountain et al. (2014) claim that it is a product of past incursions of the Ross Ice Shelf, alpine glaciers or buried stream icings that later have been covered with debris. Mapping of the distribution of massive ice can therefore be useful when trying to predict the response of the landscape to climate changes (Fountain et al., 2014).

Massive ground ice under a lake can be affected further by the sun-warmed lake water which melts the ground ice, something that would affect the distribution of it (Fountain et al., 2014). Taylor Valley was once occupied by a large proglacial lake called Glacial Lake Washburn which was over 300 m deep, as shown by shorelines reaching up to 336 m above sea level along the slopes in the valley, and was dammed by a grounded ice lobe in the McMurdo Sound (Hendy et al., 2000). It existed during the Last Glacial Maximum (LGM) which occurred 26.500 to 19.000-20.000 cal. years ago and into the Holocene (Hendy et al., 2000; Wagner et al., 2006; Clark et al., 2009). Because of this, the massive ground ice that eventually existed underneath this lake is believed to have melted away, leaving a distribution that more or less follows outside the outline of this lake. More information about Glacial Lake Washburn will be covered in section 3.

Mapping of the massive ground ice in Taylor Valley can therefore provide an answer to the question if it has been affected (disappeared) by the previous Glacial Lake. The mapping can then be of help to understand the distribution of the massive ground ice, e.g. if it is more common in any place (Ng et al., 2005). The distribution makes it possible for further investigations of where the massive ground ice come from, which then can provide a picture of the response of different ice sources around the area to climate forcing in the past and possibly how it will respond in the future (Ng et al., 2005). Massive ground ice covered with debris should be able to survive for millennia since the debris acts as protection against solar radiation and warm temperatures, which can make the massive ice a possible place to obtain information about the atmosphere in the past, something that is a major key in climate research (Swanger et al., 2010).

2. Aim

The objective with this project is to study the distribution of massive ground ice in the Dry Valleys and provide more information over its spatial occurrence in the area by compiling and interpreting collected ground penetrating radar data. The radar data are mainly from Taylor Valley, but some is from the adjacent Salmon Valley and Wright Valley as well. These compiled data will then be the material for trying to answer the following questions:

- Is there any spatial pattern of the distribution of massive ground ice?
- Is the presence of massive ground ice limited to the area formerly not covered by Glacial Lake Washburn?
- What is the origin of the massive ground ice?

These questions will be answered by comparing the data of the distribution of massive ground ice with elevation data, slope data and aspect data over the area in order to see if there are any correlations between the distribution and frequency of ground ice and these properties. The distribution of the massive ice will also be compared with the limits of Glacial Lake Washburn that previously occupied the valley in order to see if there is any correlation between them. The ice is more likely to be of glacial origin if it is only found outside the area formerly covered by the lake.

An interpretation of the origin of the massive ground ice can be done by looking at the distribution; the ice is more likely to be of glacial origin if it is only found outside the area formerly covered by Glacial Lake Washburn. It is probably segregation ice (moisture that accumulates in small locations in the ground) if the ice is found in this area. The work will be done in different steps described below.

1) Process the raw radar data in the computer program MATLAB using scripts for this purpose.
2) Go through the radar figure of each profile and digitize reflectors where it looks like it can be massive ground ice.
3) Compile all the digitized data in MATLAB and import it to ArcGIS where it can be interpreted and compared with terrain parameters.
4) Create maps over the area in ArcGIS, showing where there is massive ground ice with different underlays (aerial photograph, digital elevation model) and plots in Microsoft Excel that shows the distribution of massive ground ice (digitized data) against relevant information like elevation, slope and aspect. The maps and plots will be the end results.

3. Background

3.1 McMurdo Dry Valleys

The McMurdo Dry Valleys of Southern Victoria Land (77–78°S, 160– 184°E) is the largest area free of surface ice on Antarctica, with an area of approximately 4800 km^2 where the snow free area is about 2000 km^2 (Doran et al., 2002; Fountain et al., 2010). The valley system is located between the East Antarctic Ice Sheet and the Ross Sea in the central parts of the Transantarctic Mountains (Fig. 1 and 2; Swanger et al., 2010). Taylor Valley has a more southern location and is the smallest of the three main valley systems that constitutes the McMurdo Dry Valleys, where the Victoria and Wright Valley systems are the other two (Bockheim et al., 2008). The area is surrounded by glaciers where the largest ones extend all the way to the valley floor and terminate in 20 m high ice cliffs (Fountain et al., 1999). The glaciers in Taylor Valley are mainly polar alpine which flow on the north and south side of the valley. The exception is Taylor Glacier, the largest glacier, which flows into the valley from the west as an outlet glacier of the East Antarctic Ice Sheet (Fountain et al., 1999). Much of the flow of the East Antarctic Ice Sheet towards the McMurdo Sound is blocked by the Transantarctic mountain range, where the ablation is greater than the accumulation at the valley floors which prevents the valleys from becoming covered with ice and snow (Fountain et al., 1999). The dry condition in the valleys are a result of dry air brought in by katabatic winds that descend from the East Antarctic Ice Sheet, providing conditions that allows sublimation rather than melt (Fountain et al., 2010).

The landscape consists not only of surrounding glaciers, but also of ephemeral streams, ice-covered lakes, arid rocky soils and ice-cemented soils, within an elevation range that extends from sea level to more than 2000 m a. s. l. The streams and lakes are primarily fed by melt from the glaciers during summer since the amount of precipitation in the area is very low (Doran et al., 2002). There are 3 major lakes; Lake Hoare, Lake Fryxell and Lake Bonney, and at least 24 ephemeral streams in the 35 km long Taylor Valley, where the valley floor is characterized by sandy gravel with large parts of exposed bedrock (Fountain et al., 1999).

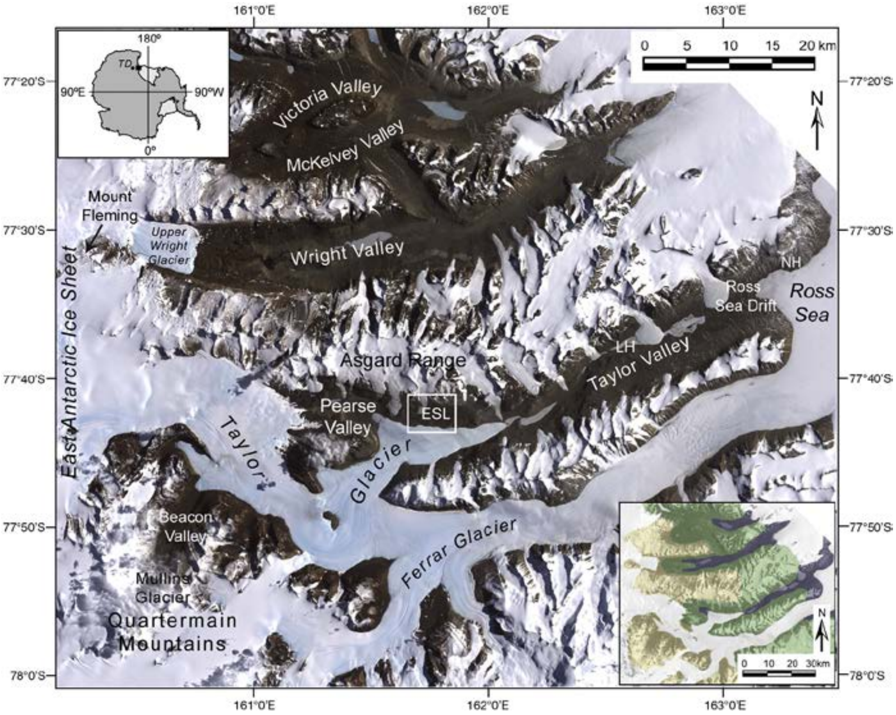

Figure 1: The location of Taylor Valley in the McMurdo Dry Valleys on Antarctica (Swanger et al., 2010). Reproduced for academic use and illustrative purpose only.

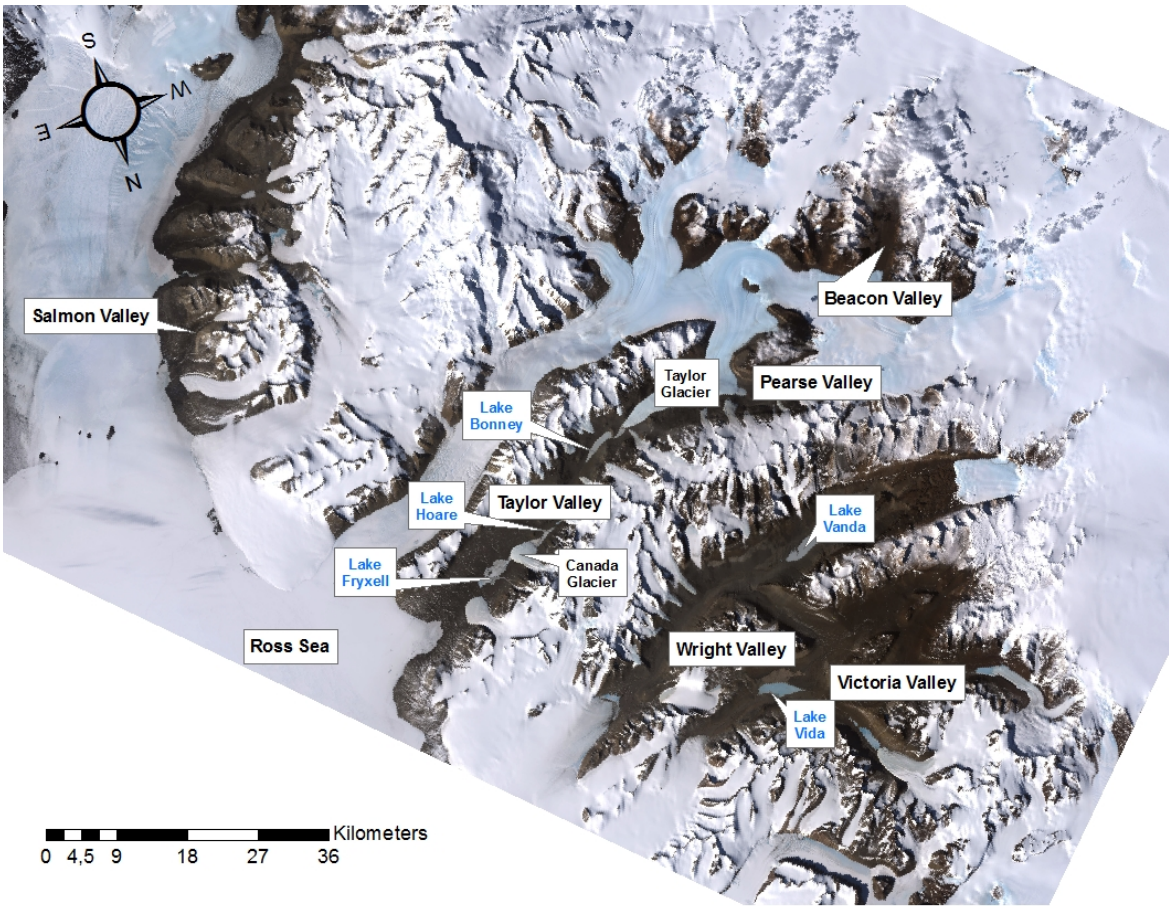

Figure 2: Overview of the location and direction of the area from ArcGIS as help for understanding later figures. Salmon, Taylor, Beacon, Wright and Victoria Valley are the valleys marked; Lake Fryxell, Hoare and Bonney are the marked lakes in Taylor Valley as well as the glaciers Canada Glacier and Taylor Glacier. Note: Orientation of Figure 2 is reversed of Figure 1.

3.1.1 Geology

A geologic map over the Dry Valleys can be seen in Figure 3, it shows that the bedrock consists of a basement complex of late Precambrian to Cambrian igneous and metamorphic rocks of the Skelton Group which was formed and/or deformed during the Ross Orogeny in the Early Palaeozoic (Marchant & Denton 1996a; Federico et al., 2006; Martin et al., 2015). This basement is overlain by nearly flat-lying sandstones, siltstones and conglomerates of the Devonian to Triassic age Beacon Supergroup (Marchant & Denton, 1996). The Ferrar Dolerite was intruded to these groups during the Jurassic as well as Cenozoic volcanics. Sediments from the Beacon supergroup and Ferrar Dolerite occur in the western parts of Taylor Valley. The Cenozoic volcanics of the McMurdo Group can be seen as sporadic deposits in the upper parts of the valley in the same figure. Granitic plutons intruded the Skelton group during the end of the Ross Orogeny between late Precambrian and early Palaeozoic to form the Granitic Harbor Intrusive Complex (Martin et al., 2015). The valley bottoms of Taylor Valley and the other valleys consist mainly of regolith or tills from the Quaternary which cover the bedrock (Ortlepp, 2009). Uplift of the rift flank of the West Antarctic Rift System, containing these groups, resulted in the Transantarctic Mountains and conditions for the creation of the McMurdo Dry Valleys were set (Sugden et al., 1995). The West Antarctic Rift System was formed at a plate boundary that separated East and West Antarctica, and has been active repeatedly due to the separation of Antarctica and Australia (Sugden et al., 1995; Eagles et al., 2009). The uplift is believed to have occurred due to combined thermal uplift after extensional rifting of this system and flexural uplift after isostatic unloading and underplating; the process when magma gets trapped on the way up through the crust causing thickening of the crust (Sugden et al., 1995).

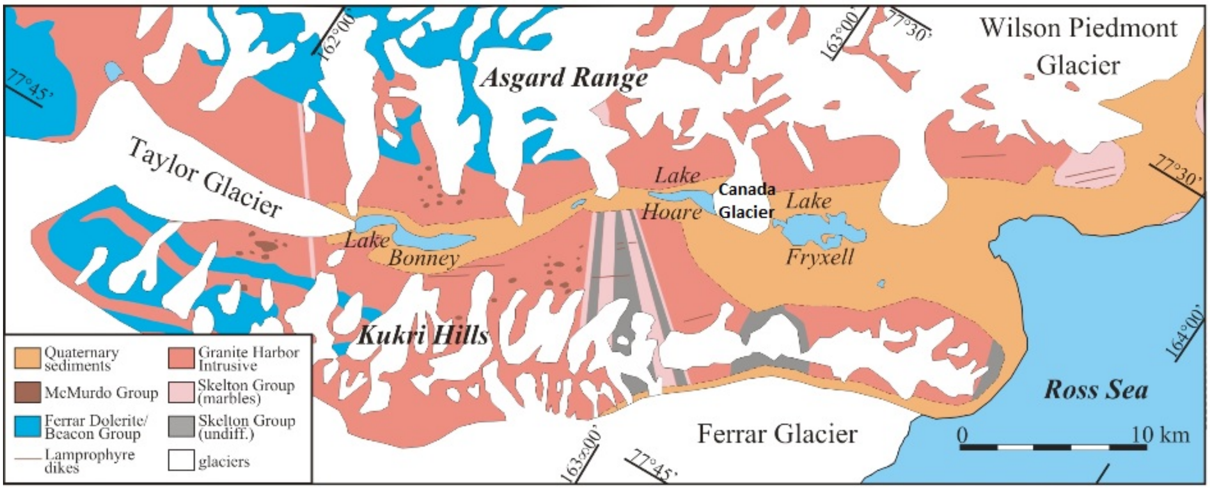

Figure 3: Geology and lakes of Taylor Valley. (After Porter & Beget, 1981 as referenced in Ortlepp, 2009) Reproduced for academic use and illustrative purpose only.

Denton et al. (1993) discuss how the Dry Valleys were formed, they believe that the main features of the McMurdo Dry Valleys were formed before the middle Miocene in a climate regime that existed before the dry cold desert environment of today, by fluvial and glacial downcutting followed by subsidence of approximately 400 m. This caused the sea to flood the valleys, leaving evidence such as fjord sediments. The subsidence was followed by tectonic processes which caused a surface uplift of about 300 m since the last 3.5 Ma, an uplift supported by evidence from surface deposits and sediment cores. The uplift led to drainage of the fjord, and the valley-floors could successively reach the present-day mean elevation of 270 m. This theory was presented as an opposing theory to the suggestion that the valleys were created only by glacial erosion and salt weathering in a more fluctuating climate, a theory that also is discussed by Denton (1993).

It is hence not only glacier erosion that could have created the McMurdo Dry Valleys. Fluvial erosion due to surface subsidence and/or uplift have probably played a major role as well in the landscape evolution (Porter & Beget, 1981 as referenced in Lyons et al., 2000).

3.1.2 Climate

A study based on climate observations in the McMurdo Dry Valleys between 1986 and 2000 by Doran et al. (2002a) explains the general climate of Taylor Valley and the Dry Valleys. They found that the climatic conditions vary spatially between the valleys (Table 1). The mean annual air temperature at the valley floor ranged from -23.1°C to -14.8°C in the central parts of Taylor Valley, which is higher than the mean annual temperatures at Wright Valley and Victoria Valley. The lowest mean annual temperature of -30°C can be found in Victoria Valley. The reason for this variation between the valleys can be the influence of katabatic winds, as Taylor Valley receives stronger and more than Victoria Valley. The winds are also affected by obstacles in the valleys, which can explain the warmer mean air temperatures at the head of Taylor Valley than at the mouth. The absolute maximum and absolute minimum temperatures measured during this period were 10.0°C at Lake Hoare and -60.2°C at Lake Fryxell, both in the lower to central parts of Taylor Valley.

Katabatic winds from the Polar Plateau with the highest wind speeds observed are more frequent during the winter months (March to November), together with increased temperatures and decreased humidity as they warm adiabatically when descending from the polar plateau. They control the winter season climate, resulting in the variation of the mean annual temperature. Coastal winds from the east are dominant in the austral summer (December, January, February) resulting in temperature variations that depend on the distance from the coast. The climate of the summer season contrasts with that of the winter season mainly because of the influence of solar radiation and the reduced frequency of katabatic winds (Clow et al., 1988). Clow et al. (1988), Marchant & Denton (1996) and Doran et al. (2002a) discuss the precipitation and environment in Taylor Valley; the amount of precipitation is very low, the mean annual precipitation is <100 mm water equivalent of snow. The amount of potential evaporation ranges from 150 to >1000 mm per year, hence greatly exceeding the amount of precipitation. These properties, together with a low surface albedo due to the dark colored bedrock and lack of snow cover, produce an extremely arid environment which is classified as a hyper-arid, cold-desert climate.

		Explorer's Cove	Lake Fryxell	Lake Hoare	Lake Bonney
Period of station record	start	21 Nov 1997	28 Oct 1987	12 Dec 1985	24 Nov 1993
	end	25 Jan 2000	25 Jan 2000	24 Jan 2000	25 Jan 2000
Station elevation, m asl		26	20	72	60
Distance from coast, km		4	9	15	25
Air Temperature, °C	avg mean annual	−19.6	−20.2	−17.7	−17.9
	max mean annual	−19.2	−16.7	−14.8	−16.2
	min mean annual	−20.2	−23.1	−19.8	−19.1
	absolute maximum	7.3	9.2	10.0	9.0
	absolute minimum	−49.0	−60.2	−45.4	−47.9
Degree days above freezing	mean annual	16.9	25.5	24.6	34.3
Soil temperature at 0 cm, °C	avg mean annual	−19.2	−18.4	−19.6	−17.1
	absolute max	17.2	22.7	25.7	22.6
	absolute min	−44.6	−52.0	−46.7	−49.4
Soil temperature at 5 cm, °C	avg mean annual	NA	−16.7	NA	−16.7
	absolute max	NA	10.2	NA	15.3
	absolute min	NA	−47.5	NA	−46.4
Soil temperature at 10 cm, °C	avg mean annual	NA	−17.5	−18.8	−16.6
	absolute max	NA	7.0	4.2	16.7
	absolute min	NA	−45.0	−37.8	−46.0
RH, %	avg mean annual	74	69	66	62
	absolute max	100	100	100	100
	absolute min	<12.4	<15.5	<19.2	<12
Wind speed, m/s	avg mean annual	2.5	3.1	2.8	3.9
	absolute max	32.2	37.8	36.3	35.6
solar flux, W/m^2	avg mean annual	106.7	100.1	83.6	94.1
	max mean annual	108.9	113.7	93.2	102.9
	min mean annual	97.1	83.0	71.4	76.1
	average summer solar noon	504.6	514.8	471.2	497.0

Table 2: Climatic variations in Taylor Valley. (Doran et al., 2002a) Reproduced for academic use and illustrative purpose only.

Marchant & Denton (1996) distinguished three microclimatic zones in the Dry Valleys based on the varying precipitation, wind direction, relative humidity and soil-moisture content. The differences in these parameters control the geomorphology as well, which therefore also can be divided into these zones. Zone 1, the coastal zone in Taylor Valley, extends from the sea level including areas at the coast with elevations up to 1000 m and descends along with the valley floor to approximately 100 m elevation at Lake Bonney in the inner parts of Taylor Valley. The climate in Zone 1 is relatively mild which allows geomorphological features like gelifluction lobes, solifluction terraces, ephemeral ponds, lakes and rivers, debris flows and fluvial channels to form.

Zone 2 is the intermediate zone/transition zone where the climate is more variable than in zone 1 with a relative humidity that can range from 10% to 70% compared with the more stable average of 75% in zone 1. These differences are due to alternating katabatic winds from the polar plateau and winds from the Ross Sea, where the katabatic winds are more dominant and leaves zone 2 with a dryer climate with less precipitation than zone 1. The climate in zone 2 hampers soil moisture of the kind that can be found in zone 1 as the ground is dry, making soil movement rare and probably only active during extreme climatic events, like unusually heavy precipitation. Zone 2 extends westward in Taylor Valley above zone 1, but also includes high elevation areas near the coast where the lower limit is 1000 m.

The ice-free areas above 800 m elevation along the western rim of the Dry Valleys represents zone 3; the inland and most western zone. Here the dry katabatic winds are most dominant, leaving the area drier than the other two zones with almost no precipitation, only some snow from the polar plateau that accumulates on glaciers and snow banks in lee areas. Easterly moist winds are prevented to reach into this zone due to the katabatic winds, and any soil processes like in the other zones are precluded because of the low moisture content and low soil temperatures in the ground. The slopes instead seem to be stable on timescales of million years, with landscape features like sand-wedge polygons that are linked by ventifact pavements and talus relicts without marks like channels and mudflows (Marchant & Denton, 1996).

3.1.3 Geomorphologic processes

There are three main processes that affect the morphology of the Dry Valleys; the katabatic winds, active layer cryoturbation and cold-based glaciers (Marchant & Head, 2007). Fountain et al. (2014) bring up the fact that the presence of buried massive ice also affects the morphology of the landscape, where they have observed notable changes over the past decade.

The katabatic winds, which are more common during the winter period, contribute to create warmer temperatures during this season since they warm adiabatically when they move down from the higher altitudes. They transport snow from the polar plateau, redistribute sand grains and erode the bedrock (Lancaster, 2002; Marchant & Head, 2007). The sand grains can abrade, erode and shape rocks and exposed surfaces when travelling with the high speed katabatic winds, creating ventifacts as well as boulder plains where the finer sediments have been removed by the wind and sand bodies where finer sediment have been accumulated (Knight, 2005; Swanger et al., 2010).

Marchant & Head (2007) discuss the effect of active layers. An active layer allows water to penetrate into the ground since it experiences ground temperatures above 0°C. Wet active layers in the Dry Valleys are mainly found in the coastal areas/zone 1 where visible ice and/or liquid water can be found, whereas dry active layers with minimal moist content are common in the inland areas/zone 2 and 3. Ice wedge polygons can be found in areas with a wet active layer since liquid water can penetrate into the ground and later freeze to ice. Sand wedge polygons and sublimation polygons are more common in areas with a dry active layer as the amount of liquid water is much less/does not exist. Sand wedge polygons are created when cracks are filled with fine grained sand instead of ice. Sublimation polygons form almost in the same way, except that it is cracks in buried ice that gets filled with fine grained sand from overlying sediments. Figure 4 below illustrate examples of some of the differences in the landscape between these three zones.

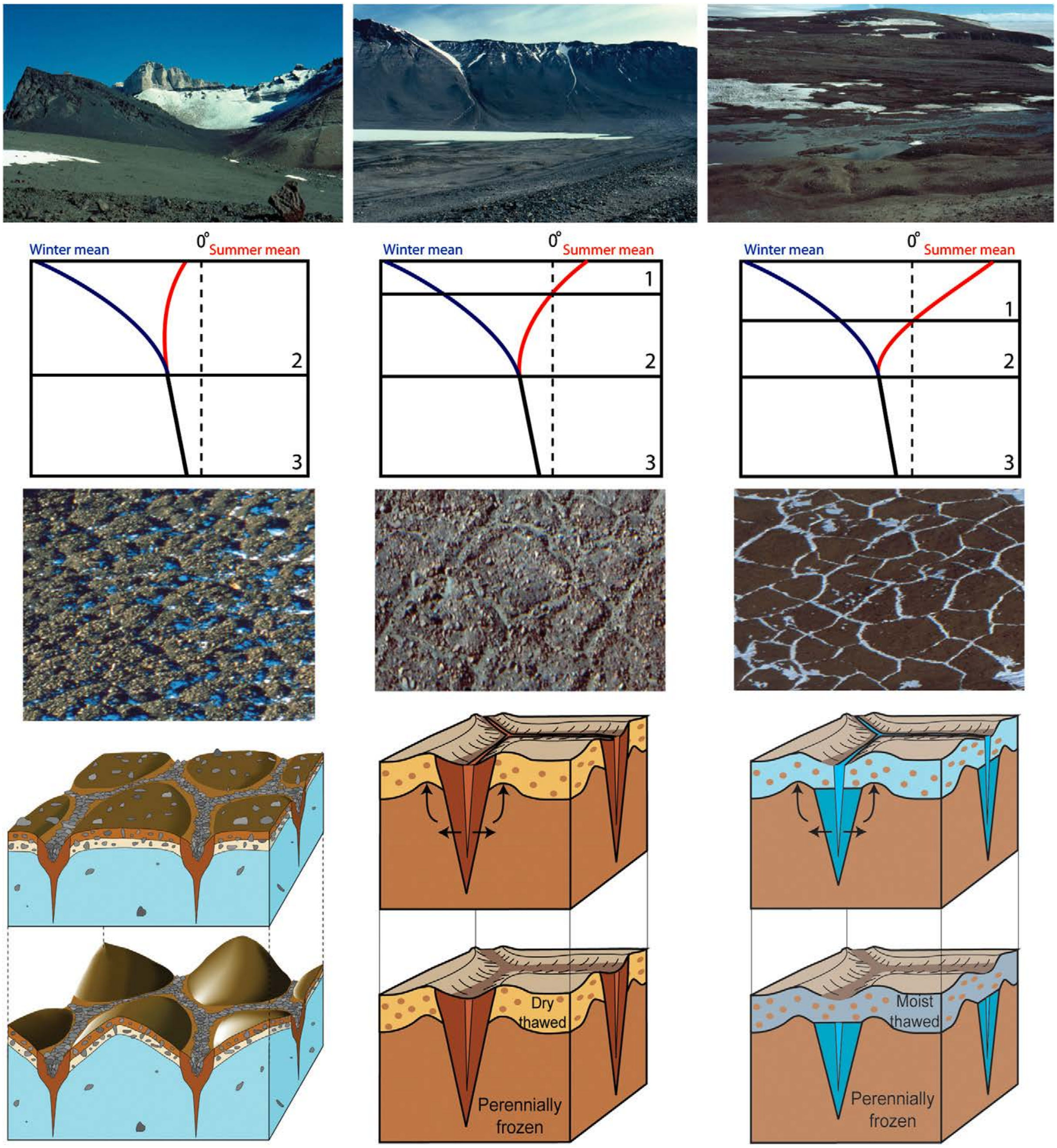

Figure 4: Typical landscapes, vertical thermal profiles and different polygons for each of the three zones. Column 1 represents zone 3, column 2 represents zone 2 and column 3 represents zone 1. Zone 3 never experiences ground temperatures above 0°C and the polygyns formed are sublimation polygons. Zone 2 experiences ground temperatures above 0°C during the summer and sand-wedge polygons are common. Zone 1 also experiences ground temperatures above 0°C during the summer, but more than zone 2 which makes it possible for an active layer to form. Ice-wedge polygons are common in this zone. (Marchant & Head, 2007) Reproduced for academic use and illustrative purpose only.

The cold-based glaciers only flow by internal deformation, and erode several times less than a wet-based glacier which slides across the bedrock surface. Cold-based glaciers in the Dry Valleys tend to preserve the landscape instead of eroding it because of this low erosion rate due to the cold bases (Marchant & Head, 2007).

The changes in the landscape that Fountain et al. (2014) found were ablation of glaciers, incision of rivers, streams that have experienced downcutting and undercutting and formation of gulleys. Ablation of glaciers and fluvial erosion by relative small streams were observed in Taylor Valley. The streams had very high flow during the austral summer 2001-2002, which was observed by Doran et al. (2008), but remained stable during this time with no thermal effect on the ice in the ground. The fluvial erosion was instead observed during the past two austral summers leading to morphological changes in the landscape supposedly activated by the climate together with the other changes as well (Fountain et al., 2014). All of the changes occurred in areas where massive ground ice was present and they suggest that these changes are climatically induced due to increased solar radiation during the summer instead of a decadal trend of cooling of the summer air temperature over the area. Higher radiation leads to increased absorbation of energy in low albedo areas, such as snow free areas, which leads to warming of the ground and potential melting of massive ground ice.

The temperature over Antarctica is expected to increase further during the years to come, which could trigger further melt of the massive ice in the ground and consequently possibly more geomorphic changes to the landscape (Convey et al., 2009; Fountain et al., 2014).

3.1.4 Glacial history and Glacial Lake Washburn

Taylor Valley has been affected by three types of glaciations that have left different deposits of varying age and composition (Bockheim et al., 2008). These are advances of alpine glaciers along the valley walls, advances of outlet glaciers from the East Antarctic Ice Sheet like Taylor Glacier, and advances of grounded ice in the Ross Embayment (Lyons et al., 2000; Bockheim et al., 2008). Local alpine glaciers and Taylor Glacier are currently at, or close to, their maximum extension from the LGM (Denton et al., 1989). The Ross Ice Shelf became grounded in the McMurdo Sound at the LGM and started acting as an ice sheet which caused the ice to thicken and flow inland towards the McMurdo Dry Valleys (Conway et al., 1999; Hendy, 2000). This ice sheet was able to terminate on land in Taylor Valley since the alpine glaciers in that area terminated far inland, which made the coastal parts of the valley susceptible to this inflow of ice from the embayment (Conway et al., 1999). The advancement of the Ross Sea ice sheet resulted in an ice lobe that covered much of the mouth-area in Taylor Valley up to an elevation of 350 m above sea level. This ice lobe dammed meltwater into the exposed valley, creating large proglacial lakes (Hall et al., 2000; Hendy, 2000). Evidence for such proglacial lakes can be found in the valleys as fossil beachlines, dated lacustrine sediments and relict deltas (Hendy, 2000). The advancement and retreat of the Ross Sea ice sheet into Taylor Valley left large deposits at the mouth of the valley which are concave out towards the Ross Sea and slope inward, leaving the geomorphology of Taylor Valley with higher elevations at the mouth than further inland (Hall et al., 2000).

Glacial Lake Washburn was a proglacial lake that was created in Taylor Valley when the ice from the Ross Ice Shelf got grounded and advanced inland. The ice lobe from the Ross Sea that dammed and created Glacial Lake Washburn reached its maximum extent at 350 m a. s. l. between 12.700 and 14600

^{14}C yr. BP (15.000-18.000 cal. yr BP, (Wagner et al., 2006)) based on dating of a moraine deposit at this level, which is believed to have been formed by the ice lobe. The maximum depth of the lake itself was at least 250 m at the central parts of Taylor Valley (Higgins et al., 2000). Dated deltas in Taylor Valley show that Glacial Lake Washburn existed between approximately 23.800 to 8340 ^{14}C yr. BP and reached its maximum lake level at 18.500 ^{14}C yr BP (Hall & Denton, 2000). The location of Glacial Lake Washburn in Taylor Valley can be seen in Figure 5. It extended from the coast to the Bonney basin furthest into the valley where it was delimited by Taylor Glacier (Denton et al., 1989; Hall et al., 2000). The extent can be compared to the distribution of Quaternary sediments (light orange colour) in Figure 3. The lake experienced some level fluctuations during its existence, fluctuations that likely are explained by climate variations that led to changes in the amount of meltwater and evaporation (Wagner et al., 2006). Deglaciation of the lobe of grounded ice that dammed Taylor Valley did not occur until early to mid-Holocene time due to internal dynamics of the ice sheet that could have been triggered by sea-level changes (Hall & Denton, 2000). Wagner (2006) suggests that evaporation was the factor that initiated lowering of Glacial Lake Washburn, and the fact that Glacial Lake Washburn experienced times of evaporation to low levels is supported by evaporates mentioned by Hendy (2000) and by relict deltas. Wagner et al. (2006, 2011) claim that the final lowering of Glacial Lake Washburn after the Pleistocene/Holocene transition not only occurred due to the retreat of the Ross Sea ice sheet but also by a change in the hydrological cycle forced by climatic conditions in the form of evaporation as well, induced by colder temperatures instead of a large drainage event. This is supported by their data that showed increasing salinity of the lake water during lake-level lowering since higher salinity point towards less freshwater/meltwater in the lake. Evidence for a gradual drying-up of Glacial Lake Washburn is provided by the fact that the sediments changed from deep-water facies to a shallower facies in the Holocene without evidence for a big drainage event. The lake-level lowering was probably discontinuous with at least one big re-filling of the basin (Wagner et al., 2006; Whittaker et al., 2008; Wagner et al., 2011). The lowering of Glacial Lake Washburn marks the start of the history for the three lakes that exist in Taylor Valley today, which are believed to be remnants of this proglacial lake (Hendy, 2000).

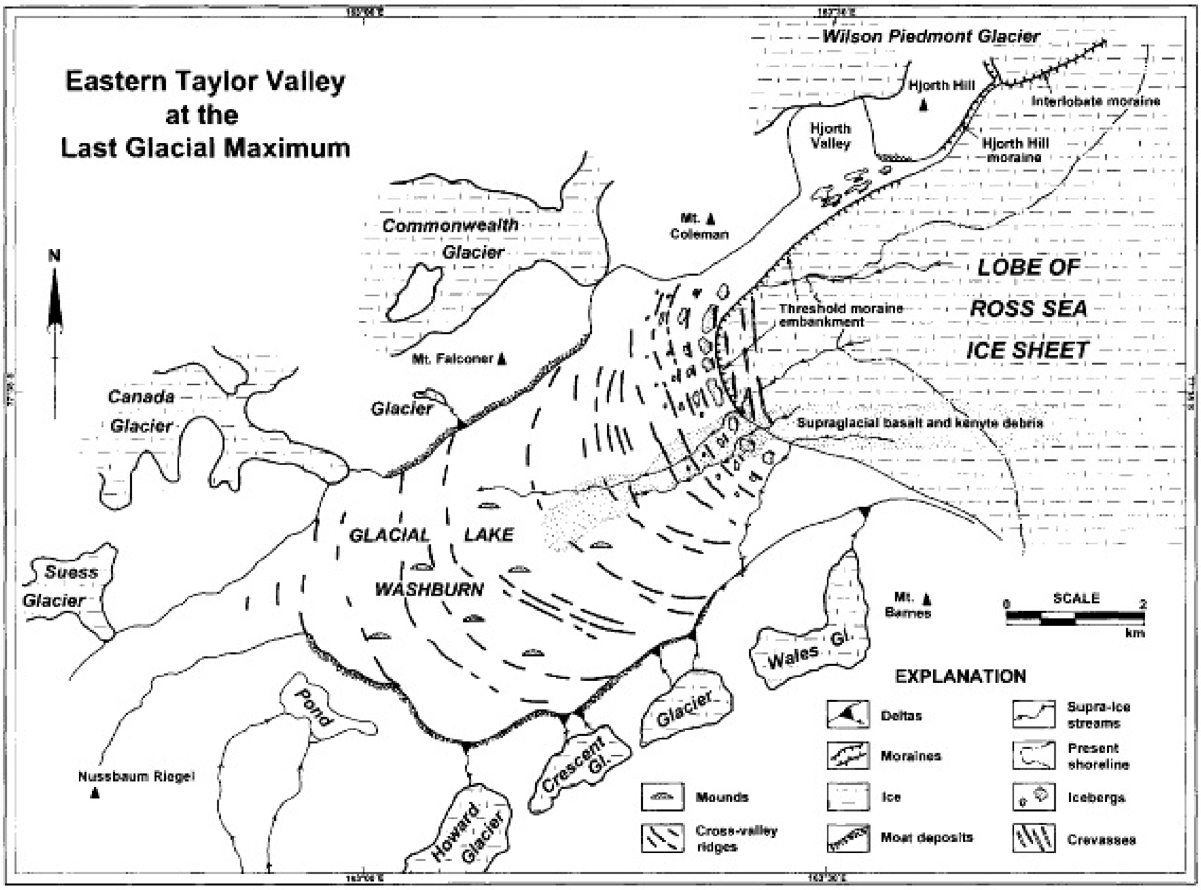

Figure 5: Extent of Glacial Lake Washburn. (Hall et al., 2000) Reproduced for academic use and illustrative purpose only.

3.2 Formation of massive ice

Ground ice can be found in most of the permafrost regions since the definition refers to any type of ice that forms in freezing or frozen ground. The difference between ground ice and permafrost is that permafrost is not depending on what kind of material the ground consists of, as long as it remains at or below 0°C for at least two years. It does not have to be ice, ice may or may not be present (National Research Council of Canada, 1988, p. 63; Waller, 2009). Massive ground ice is further defined by having an ice content of at least 250% compared to dry soil-weight and is used to describe phenomena like ice wedges, pingo ice, buried ice and large ice lenses. The difference between massive ground ice and buried massive ground ice is that the buried ice was formed or deposited on the ground surface and later buried by coverage of sediments. Massive ground ice in the form of buried glacier and sea ice therefore falls under this category (National Research Council of Canada, 1988, pp. 46-47). The term massive ground ice will here be used in a generic, non-specific way, since the origin of the ground ice in the Dry Valleys is not clear. Waller (2009) explains the different origins of massive ground ice; it could be glacier ice that has been preserved within permafrost after the ice retreat, or segregation ice formed as a result of the sustained water flow to permafrost areas with high sub-permafrost pore water pressures which generates a pressurized aquifer. The large ice bodies can be developed as the water reaches the freezing front and freeze. The preservation of massive ground ice then depends on a number of factors which influence its stability after it has been formed (Kowalewski et al., 2006). An overview of these factors can be seen in Figure 6 below, where some of them are the air temperature, solar radiance, surface albedo, precipitation and geothermal heat (Kowalewski et al., 2006).

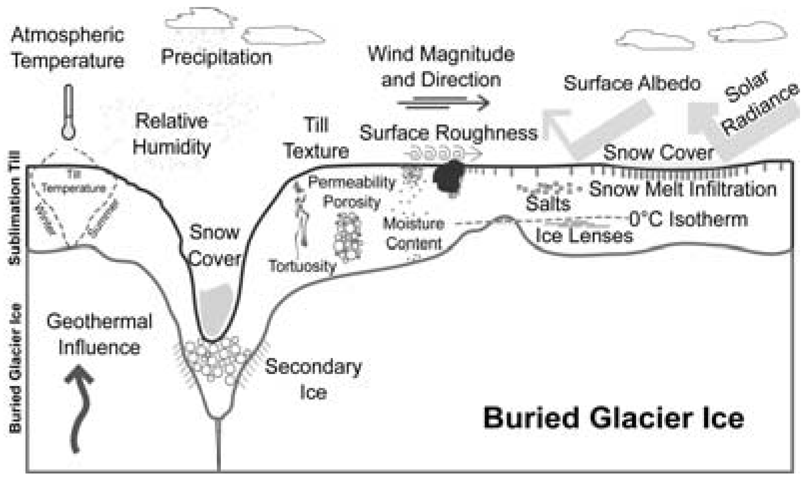

Figure 6: Overview of parameters affecting the massive ground ice. (Kowalewski et al., 2006) Reproduced with permission from Antarctic Science.

It is important to distinguish between these two different origins since they can provide different information, and to understand how it forms can help understanding where it may exist. Buried glacial ice can provide palaeoglaciological information, and other massive ground ice types (e.g., ice wedges) can provide information about the climatic regime when they were formed (Waller et al., 2009).

The differences in climatic parameters in the Dry Valleys have affected the origin of the massive ground ice and where it exists. Near-surface ground ice in zone 1, the coastal thaw zone, is believed to be segregation ice, formed when meltwater penetrates into the ground to open pore spaces and freezes. Massive ice in the more stable upland areas is instead believed to be buried glacier ice since the cold and dry climate does not produce enough meltwater to create extensive segregation ice (Marchant et al., 2007). As mentioned in section 3.1.4 Taylor Valley has been affected by three types of glacier advances that can have left deposits of massive ground ice. The massive ground ice here has also been affected by Glacial Lake Washburn, which should have caused the deposits of ice to melt based, as explained below.

Figure 7 (Fountain, 2014) illustrates a schematic of how buried massive ground ice is developed from a glacier and terminated. The starting point (a) shows the uncovered glacier that later gets covered by moraines and rock avalanches along the ice edge towards the valley sides in (b). The uncovered glacier then ablates resulting in ice-cored deposits of rock debris along the valley sides (c). The glacier can also have enough rock material intergrated in the ice which then results in a mantle of debris as the ice ablates (d). This accumulation of debris on the glacier surface slows the ablation and preserves the ice. Panel (e) shows sediment-covered stream icings that also can be preserved as thin random deposits on the valley floor. The buried ice can be melted away if a lake forms over the deposit (f), like Glacial Lake Washburn for example. This happens due to the fact that the water absorbes solar radiation which raises the temperature in the lake water, this temperature increase is then the cause for melting of the underlying ice deposits (Hendy, 2000; Fountain et al., 2014). The water absorbs solar radiation even if it is covered by ice since not all of the radiation is reflected by the ice surface, the temperature in the water can also increase by the influx of meltwater (Hendy, 2000).

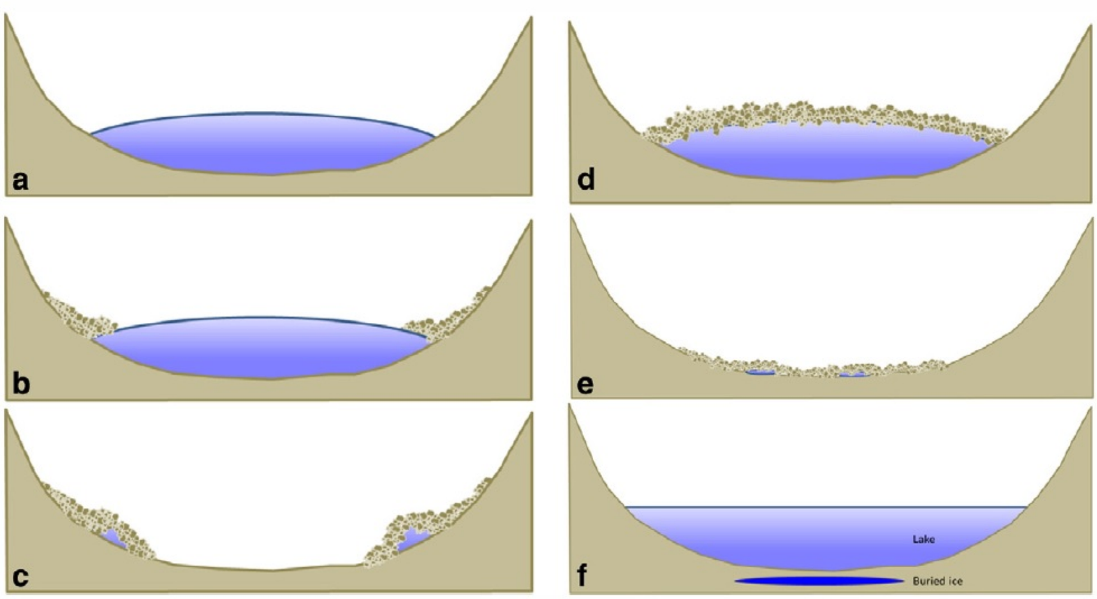

Figure 7: Schematic of how buried massive ground ice is formed and terminated, see text for description. (Fountain et al., 2014) Reproduced for academic use and illustrative purpose only.

3.3 GPR as a tool for the study of ground ice

Ground penetrating radar (GPR) is a geophysical method with similar principles as reflection seismic, and uses non-invasive electromagnetic pulses in order to get a reflection of the subsurface instead of acoustic waves which is the case in reflection seismic (Blindov, 2006, p. 227; Lønne & Lauritsen, 1996; Woodward & Burk, 2007). Blindov (2006, p. 227) as well as Woodward & Burk (2007) explain how GPR works; the electromagnetic pulses are transmitted from an antenna and propagate into the ground where they get refracted and reflected when encountering layer boundaries or buried objects with different electromagnetic properties than the surrounding, for example at a boundary between sediment and massive ground ice. The parameters that describe the electromagnetic property of a medium are its electric permittivity (how an electric field affects and is affected by a dielectric medium) and electric conductivity (the ability of a medium to conduct an electric current). The reflected pulse and direct pulse then return to a receiver antenna at the surface. The result is recorded and often displayed as a plot of signal amplitude against the two-way travel time which usually can provide a preliminary interpretation directly in the field.

A GPR system consists of one antenna that transmits the electromagnetic pulses at frequencies usually between 20 and 1000 MHz, one pulse generator that generates the electromagnetic pulses and one receiver antenna that receives the returning signals (Blindov, 2006, p. 239; Woodward & Burk, 2006). A schematic of a GPR system can be seen in Figure 8 below.

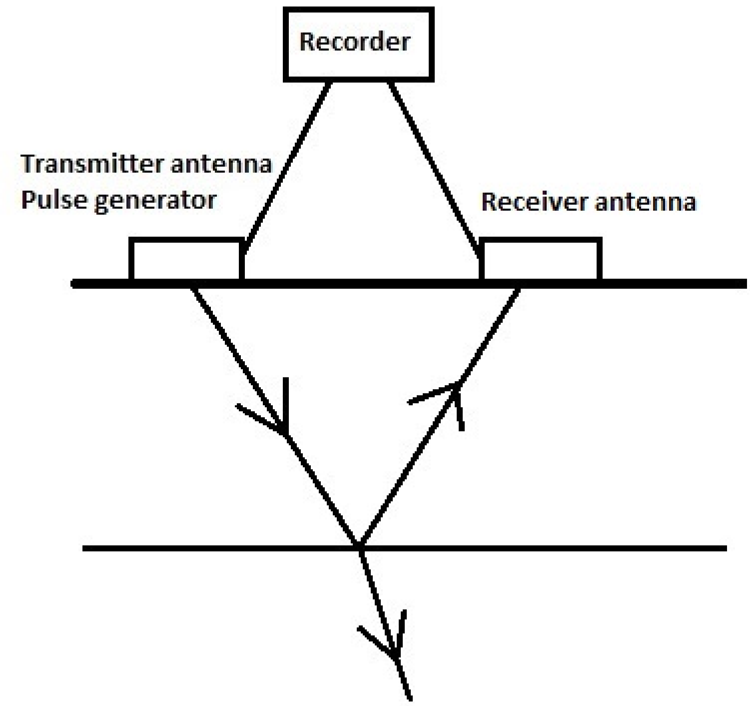

Figure 8: Setup of a GPR-system.

GPR has been used in glaciology for a variety of missions; some examples are mapping of the glacier bed (Arcone et al., 1992; Flowers & Clarke, 1999), investigations of the internal layer structure in snow (Hagen et al., 1999; Arcone et al., 2005) and ice (Vaughan et al., 1999), mapping of englacial structures like crevasses (Glover & Rees, 1992; Arcone, 2002) and shear zones (Goodsell et al., 2002) and investigations of discrete hydrological pathways (Moorman & Michel, 1998; Irvine-Flynn et al., 2006). The use of GPR for detection of massive ground ice has also been done in some earlier studies; some of which are described in the next section.

3.4 Previous research of particular relevance

Dallimore and Davis (1992) performed a study in the coastal area of the Canadian Beaufort Sea where they used two radars operating at different frequencies, 100 MHz and 30 MHz, in order to evaluate the performance of GPR as a method for detection and mapping of massive ground ice. The radar with lower frequency was used after the one with a higher frequency for detailed investigations of interesting parts. The conclusion based on their results was that the technique was very valuable and useful for this kind of field work, especially for correlation between boreholes. Lønne & Lauritsen (1996) also used GPR but in a study of the structure of a push moraine on Svalbard where they found three sets of reflectors where one of them was interpreted as buried ice blocks. Three dimensional GPR has been used for detecting subsurface ice as well, for example by Munroe et al. (2007) when they investigated the subsurface structure of ice-wedge polygons in Alaska.

Massive ground ice has been detected in the Dry Valleys by using GPR (Arcone et al., 2002b; Fitzsimons et al., 2008; Fountain et al., 2014). Arcone et al. found it in eastern Taylor Valley when they investigated permafrost, and Fitzsimons et al. (2008) found it when they investigated the apron of ice and debris in front of Victoria Upper Glacier in Victoria Valley. Fountain et al. (2014) describe a survey from Garwood Valley in the Dry Valleys where they used GPR in order to detect massive ground ice. They found massive ground ice under a relict delta within an intrusion from the Ross Sea (Fig. 9), the amount of data was however not enough in order to investigate if there was any association between the geomorphic features and the frequency of buried massive ice. These studies were performed only at a few locations and the main goal was not to find buried massive ice. Hence, they do not give a complete view of the distribution of massive ground ice in the area.

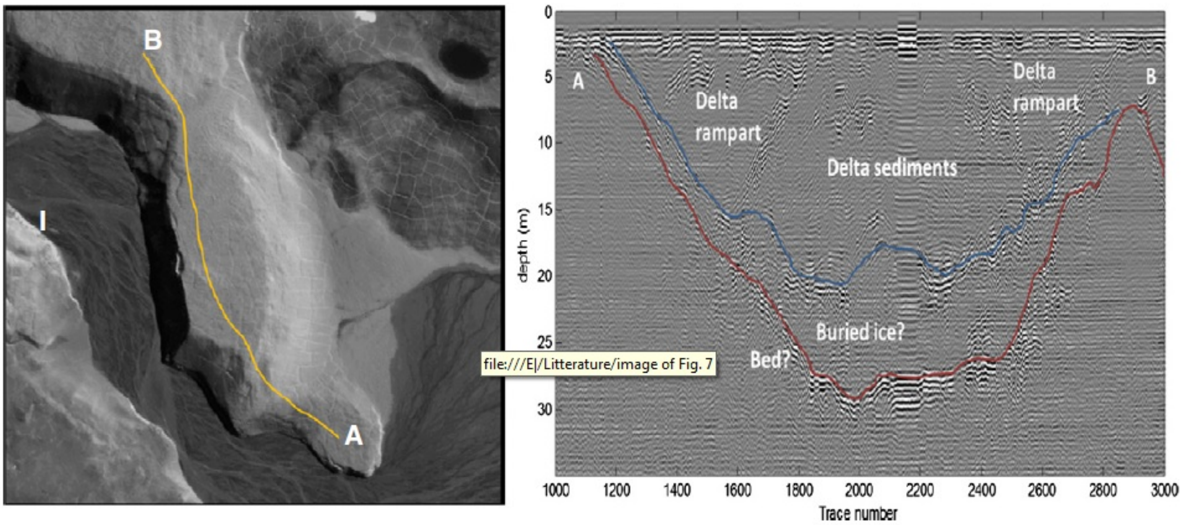

Figure 9: Interpretation of radar data from Garwood Valley. (Fountain et al., 2014) Reproduced for academic use and illustrative purpose only.

Bockheim et al. (2007) investigated massive ground ice in the Dry Valleys without the usage of GPR. They used a dataset with shallow (<1.5 m) excavations in order to map the distribution of permafrost in the Dry Valleys. They found that massive ground ice was present in at least 2% of the area, mainly in alpine drift of late Holocene age. They mention however the fact that massive ground ice that may be of older age occurs sporadically. This result is however only based on permafrost drill-core samples of a shallow depth. More ice may exist at greater depths – something that could be detected with GPR.

Swanger et al. (2010) found massive ground ice in central Taylor Valley when hand-digging small excavation pits in a survey of viscous flow lobes in the area. They performed a shallow seismic refraction survey in order to determine the thickness and extent of the ice. The result showed that the ice was approximately 14 to 30 m thick and was most likely an ice-cored moraine where the core consists of old glacier ice.

Marchant et al. (1996) isotopically dated volcanic ash-fall deposits in the Dry Valleys that did not show any signs of reworking or chemical weathering. The dating of these deposits indicated ages between approximately 4 and 15 Ma, where the ash in Beacon Valley was around 10 Ma. The lack of noticeable changes of the ashes and the high ages point towards stable weathering conditions since the past 15 million years with no significant landscape change. Sugden et al. (1995b) reported the discovery of buried glacier ice in Beacon Valley that they suggest has survived for at least 8 million years, this based on isotopic analysis and interpretation of volcanic ash in overlying glacial till which Marchant et al. (1996) performed later as well. Kowalewski et al. (2007) developed a vapor diffusion model based on metrological data in order to quantify the summertime vapor flow through this till in Beacon Valley, which showed results that supported the long-term survival of massive ground ice in hyper-arid conditions that can be found in the stable upland zone of the Dry Valleys.

Fountain and coworkers (2014) documented landscape changes in the Dry Valleys that seem to have appeared over the past decade, a landscape that otherwise show indications of being stable for millions of years. This survey also shows that the massive ground ice in the Dry Valleys is subject to melting which contributes to the observed rapid landscape changes, and that the amount of ice can be a contributing factor to the amount of change that occurs. Fountain et al. also conducted research to provide a preliminary map showing at what risk different areas in the McMurdo Dry Valleys are for future landscape changes due to a warming climate (Fig. 11). This map shows that most of the geomorphology in Taylor Valley is classified as coastal thaw zone, which was considered to be the zone most susceptible for landscape changes due to warmer temperatures.

Levy et al. (2013b) found massive ground ice revealed by erosion by the Garwood River in Garwood Valley. This river has eroded down through several meters of ice-cemented till, lacustrine and fluvial deposits, leading to the exposure of this ice, which also was observed by Fountain et al. (2014) (Fig. 10).

At present, the relative scarcity of published data of the occurrence of massive ground ice in the Dry Valleys makes it hard to establish if a possible connection exists between the presence of massive ground ice and geomorphic features, and how it might respond to climate and affect the landscape further (Fountain et al., 2014). This is the reason why one aim with this thesis is to provide more data of the occurrence of massive ground ice for future surveys.

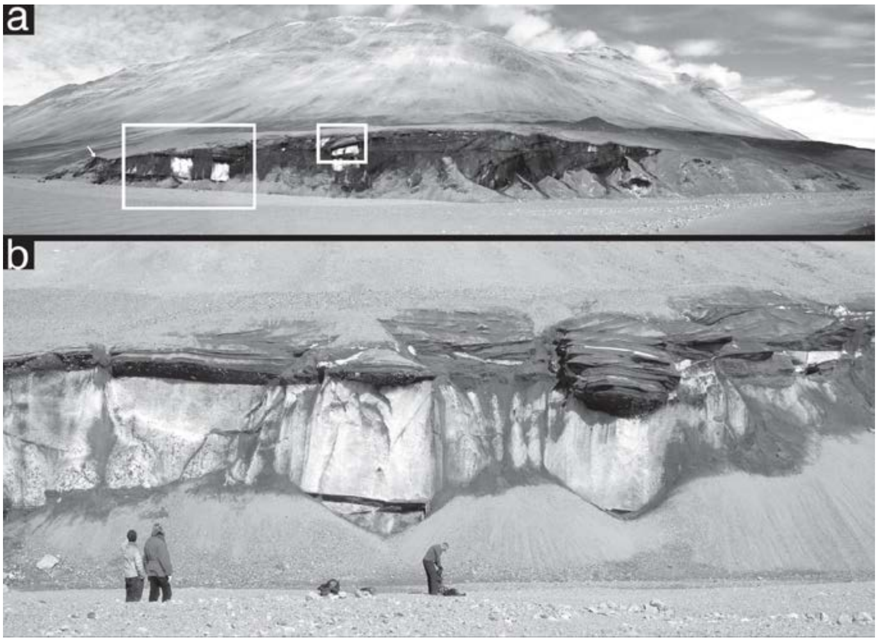

Figure 10: Exposure of massive ice due to erosion by Garwood River. (Levy et al., 2013b) Reproduced for academic use and illustrative purpose only.

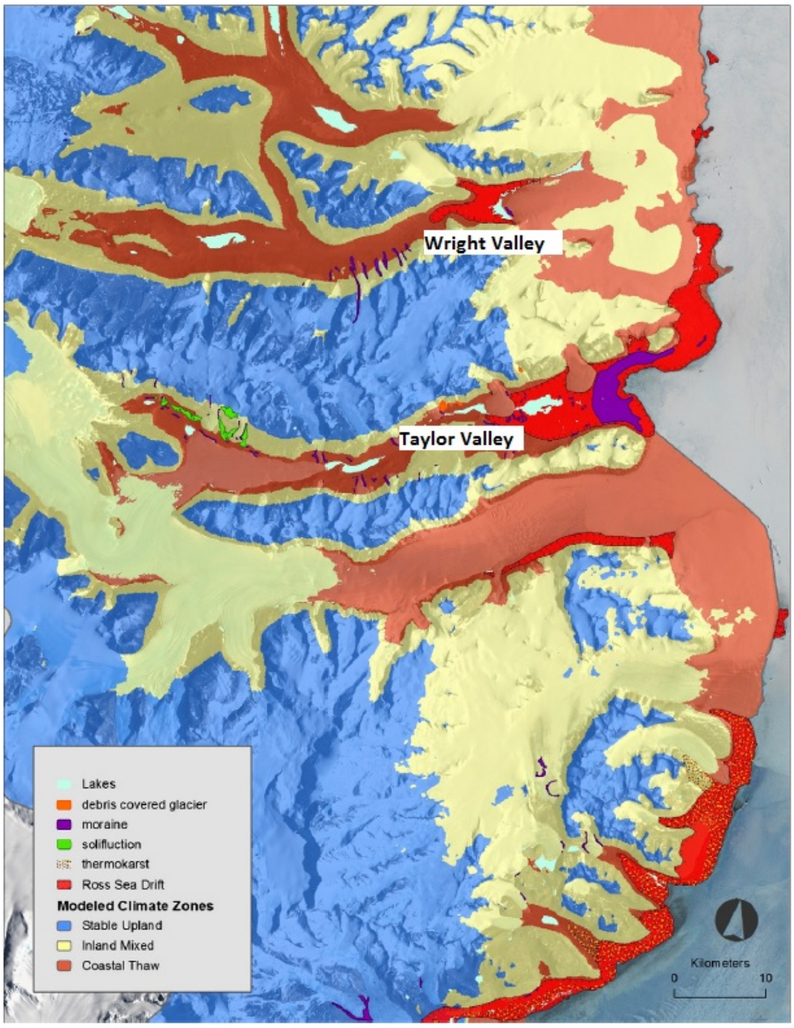

Figure 11: Map showing at-risk landscapes in the McMurdo Dry Valleys. (After Fountain et al., 2014), reproduced for academic use and illustrative purpose only.

4. Methodology

4.1 Data acquisition

The data from approximately 160 km of transects of GPR data for this project were collected from the middle to the end of December 2014 by Maciej Obryk and Andrew Fountain, Oregon University, and Rickard Pettersson, Uppsala University. The instruments used were a ProEx GPR system, from Malå Geoscience, that recorded a true position every 0.25 second and a Trimble R7 differential two-frequency Global Positioning System (GPS) using a base station at McMurdo station for providing permanent GNSS (Global Navigation Satellite System) data that saved the position every second. A 100 MHz unshielded antenna was used for the GPR, and the sampling was done with 8-fold measurements which means that 8 measurements were made with the average value saved. Both the ProEx and Trimble R7 collected GPS data, but the GPS data used in this project are from the Trimble R7. Preliminary data processing was done using the geospatial data software Trimble Business Center version 2.8 with a base station locked at McMurdo station.

4.2 Editing of data

The raw GPR data needed to be edited since there were times when the scientists carrying the measurement equipment stood still while the measurements continued. This created parts in the radar data that needed to be erased in order to be able to create coherent GPR profiles. A MATLAB script was used for sorting out and removing parts like this graphically. Each radar trace was given a GPS position and the coordinate system was converted from WGS-84 date to Polar Stereographic projection. The elevation was converted as well, to EGM-96 geoid elevation in order to geolocate the data and plot their position in time and space. The script did some processing as in the form of bandpass filtering of the 100 to 300 MHz interval in order to remove noise and frequencies outside of that range.

The script created three figures which can be found in Appendix 2.1 to 2.3, where the first one shows how the x- and y-coordinates (latitude and longitude) change with time. The second one shows a plot called TimeView with the change in y-coordinate over time, and one plot called MapView which shows the location of the selected GPR profile in the valley as x- and y-coordinates. The third, and last, figure shows a simple GPR profile where the editing was done. The script automatically detected and marked some of the gaps and stop/pauses that could be removed; these sections could be adjusted manually before removal**.** Some errors in the GPS files were found during the editing due to communication problems between GPS and computer, which prohibited running the script with some radar files. These errors were corrected manually and examples of them can be found in Appendix 1.

Another script was used to compile all the edited files to a text file in order to be able to import and work with the edited data in ArcGIS.

4.3 Processing of data using Geographic Information System

Version 10.2.2 of the Geographical Information System (GIS) software ArcGIS was used in order to examine the edited GPR profiles. This was done to see if they were consistent with the GPS data from the GPR (GPR profiles) as well as to find which profiles that form a cohesive single profile, and hence needed to be merged with each other, and how the joints between the profiles looked like.

4.3.1 Import data to ArcGIS

A LANDSAT 7 satellite picture over the area provided from the McMurdo Dry Valleys Long Term Ecological Research program was imported from ArcCatalog as background, together with a shapefile with the GPR profiles. The text-file with the edited data was then imported to ArcMap, different options for this commando can be found in Appendix 3.1. The South Pole Stereographic map projection system was chosen for display.

The imported data were exported to a point dataset shapefile to obtain an object-ID field in order to be able to work with and edit features in the data. This point data were converted to polylines by using an extension to ArcGIS called ET GeoWizards. Different options when working with this extension can be found in Appendix 3. The output was polylines which can be seen in Figure 12.

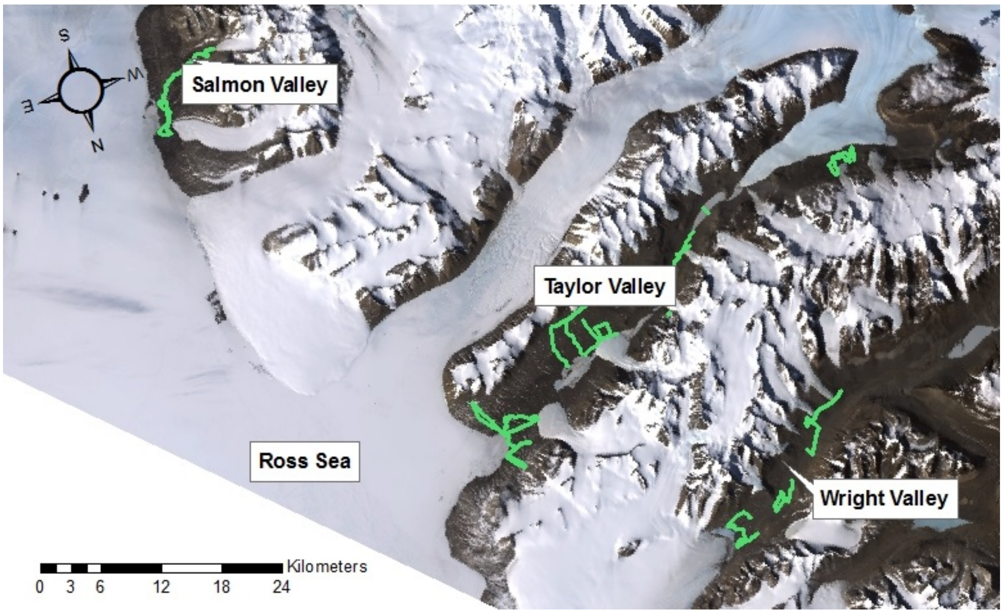

Figure 12: Created polylines of edited data (green lines) in ArcGIS.

The value 1000 was added to the ID number of the different GPR profiles which enabled the polylines to be sorted in ascending order based on the ID number. Each GPR profile was then given a specific colour in *Symbology* whereby they appeared in ascending order with a specific colour which made it possible to examine each GPR profile in the map (Fig. 13).

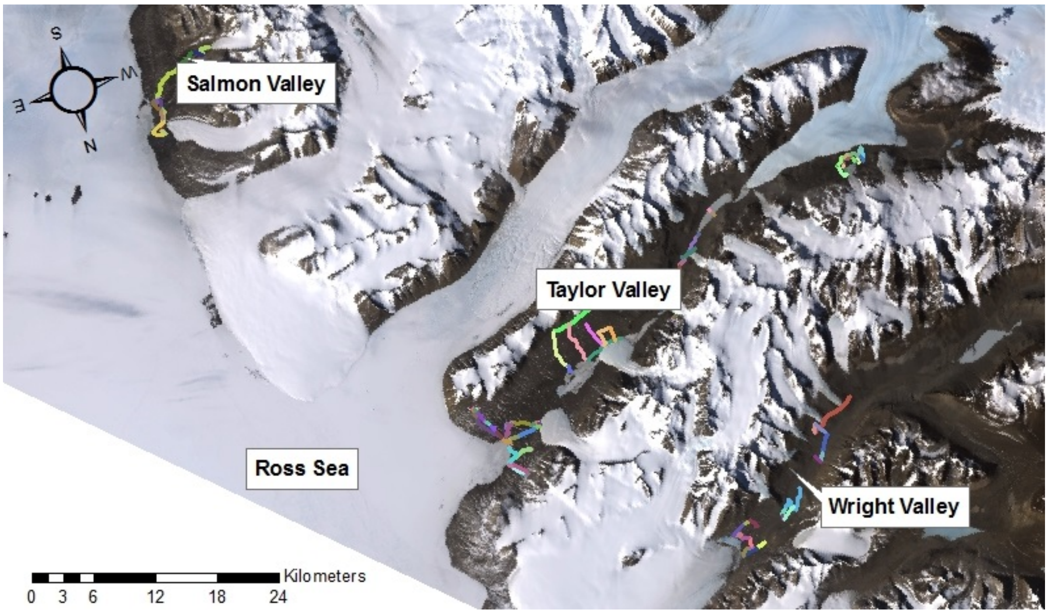

Figure 13: Polylines sorted as different GPR profiles with one colour for one profile.

4.3.2 Verification of editing & merging of sections

The sorted GPR profiles were verified in ArcGIS (after the editing in MATLAB) by checking each profile for how well they correlated with the GPS data from the external GPS (Fig. 13). Some re-editing was necessary where long distances appeared between edited profiles whereas the GPS data continued, which indicated that too much data may had been cut away during the editing. It was also needed if edited sections crossed each other, or if big clusters of points appeared which indicated that too little data had been removed. Examples can be seen in Appendix 4. The re-editing was done in MATLAB in the same way as the original editing. The re-edited profiles were then compiled in MATLAB and imported to ArcGIS together with the profiles that did not need any new editing as a new layer.

The merging of the GPR profiles, which was done using MATLAB, was performed when they had been re-edited. This was done to create coherent longer profiles to make interpretation of the data easier and to make the continued work with the files easier since the number of them became less. No merging of profiles was done if the gaps were 20 m or larger since the amount of missing data then probably would affect the outcome result, creating bad joints between the profiles.

The position of the merged profiles was then inserted to ArcGIS together with the single ones to show the final profiles. The verification of the merged GPR profiles was done later during the digitalization. The difference between un-merged and merged GPR profiles at the mouth of Taylor Valley can be seen in Figures 14 and 15. A map over the whole area with the result after the second editing and after merging of profiles can be found in Appendix 5.1 and 5.2.

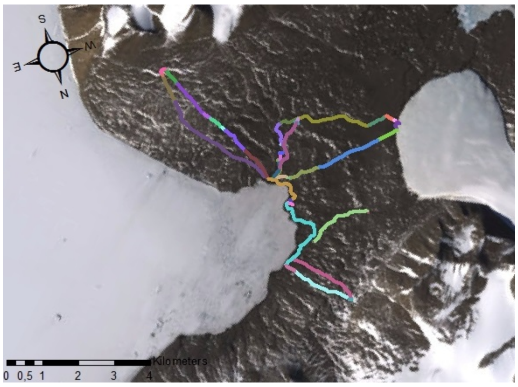

Figure 14: GPR profiles at the mouth of Taylor Valley after second editing.

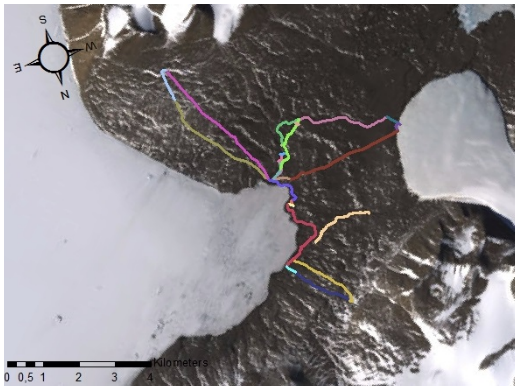

Figure 15: Profiles at the mouth of Taylor Valley after merging.

4.4 Extraction of information about massive ground ice

Extraction of information about where the ground ice appeared, and processing of the data, was done in different steps in order to present where possible massive ground ice exists in Taylor Valley. The data extraction was done in MATLAB, and later mapped in ArcGIS.

4.4.1 Digitalization in MATLAB

The main processing was to digitalize reflectors that could show massive ground ice. This was done using a script in MATLAB, with GPR profiles being processed one at a time. The script calculated the depth of the profile in travel time as well as meters above sea level for a topographic corrected figure. This figure showed the changes in elevation for the profile so the depth of the digitized reflectors could be determined. The script did processing in the form of different filtering; removal of very low frequencies, amplification of the frequency around the transmitter frequency and removing of background data that did not vary. The result when running the script was three figures where the first one was used as a help for the interpretation. This figure showed the distance in meters and a topographic corrected surface in meters above sea level along the profile (Fig. 16). The second figure was similar to the first one, but showed the distance in number of traces instead of distance in meters (Fig. 17). These figures were used as help when correlating the third figure to the topography. The third and last figure showed the number of samples along one trace on the y-axis and the number of traces along the x-axis (Fig. 18).

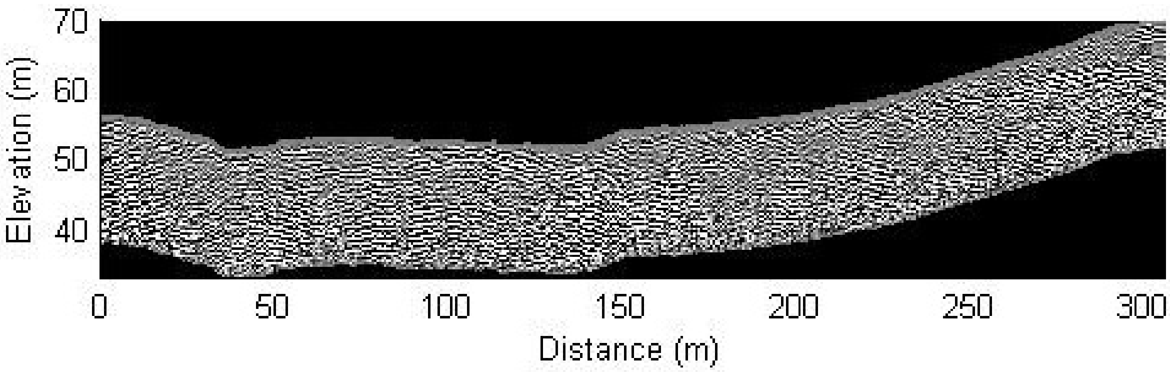

Figure 16: Radar figure for one profile with elevation along the y-axis and distance in m along the x-axis.

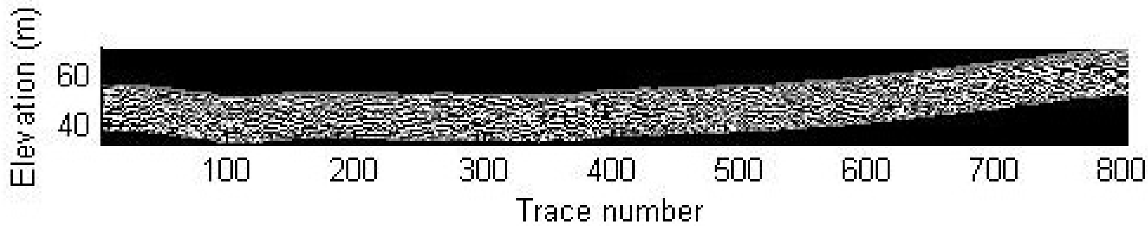

Figure 17: Radar figure for one profile with elevation along the y-axis and trace number along the x-axis.

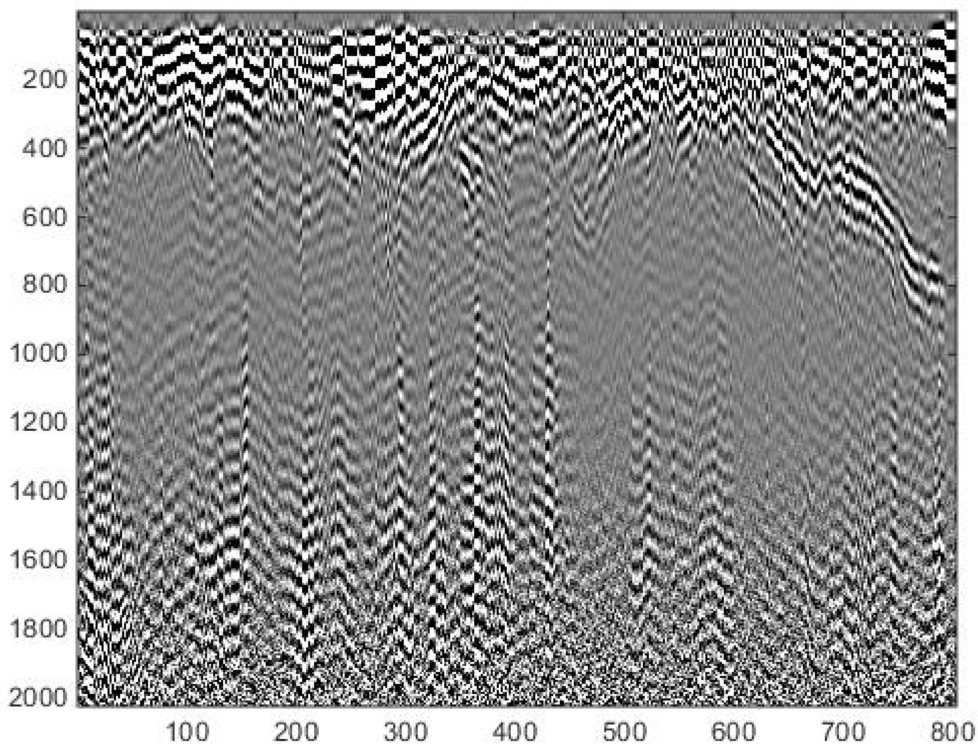

Figure 18: Radar figure for one profile where extraction of information was made, with number of samples along one trace on the y-axis and the number of traces along the x-axis.

The digitalization was done manually by marking reflectors of interest in the third figure after magnification for easier determination of the reflectors. The difference between a non-magnified and magnified figure from this step can be seen by comparing Figures 19 and 21 in section 5.1.

All digitalizations were then compiled by another MATLAB script to a text file with the parameters id, time, latitude, longitude, elevation, x, y and z-coordinates that could be added to the ArcGIS-project.

4.5 Histograms

A series of histograms were done based on the slope, aspect and elevation in order to get an overview of where the digitalizations of massive ground ice existed in the valley and to see if they followed any spatial pattern. The histograms were done in Microsoft Excel with exported data for elevation, slope and aspect from ArcGIS. The slope raster and aspect raster were created in ArcGIS from a 30 m digital elevation model (DEM) over the area by using the tools *Slope* and *Aspect.* The DEM was, similar to the satellite picture, obtained from the McMurdo Dry Valleys Long Term Ecological Research program.

The histograms for slope and aspect were done by applying a bin range that was the upper levels of classifications for these attributes obtained from ArcGIS and the exported data for slope/aspect as input range. An Excel extension called Daniels XL Toolbox was downloaded in order to merge several histograms to show a better comparison between the data of massive ground ice and all data.

The data for the elevation histogram needed some more work in GIS; the elevation values from the DEM did not show any specific boundaries in the classification to use as bin numbers for grouping in a histogram. This was solved by applying classes for the DEM in ArcGIS manually. The number of classes was set to 22 in order to get a clear separation in the histogram at the lower elevation as well since there were more radar measurements and digitalizations done at these lower elevations. The intervals were therefore set to be smaller up to 100 m elevation and then increase together with the increasing elevation up to 3500 m.

5. Results

5.1 Extraction of information and mapping of massive ground ice

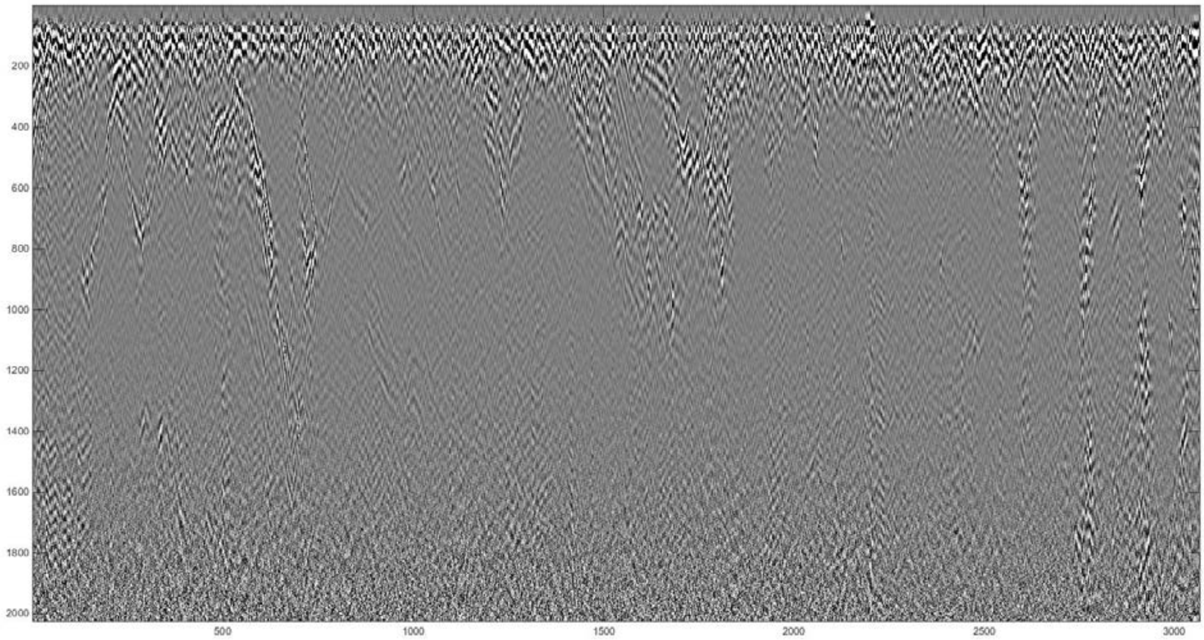

Figure 19: Radar figure over one profile where information of massive ground ice could be extracted.

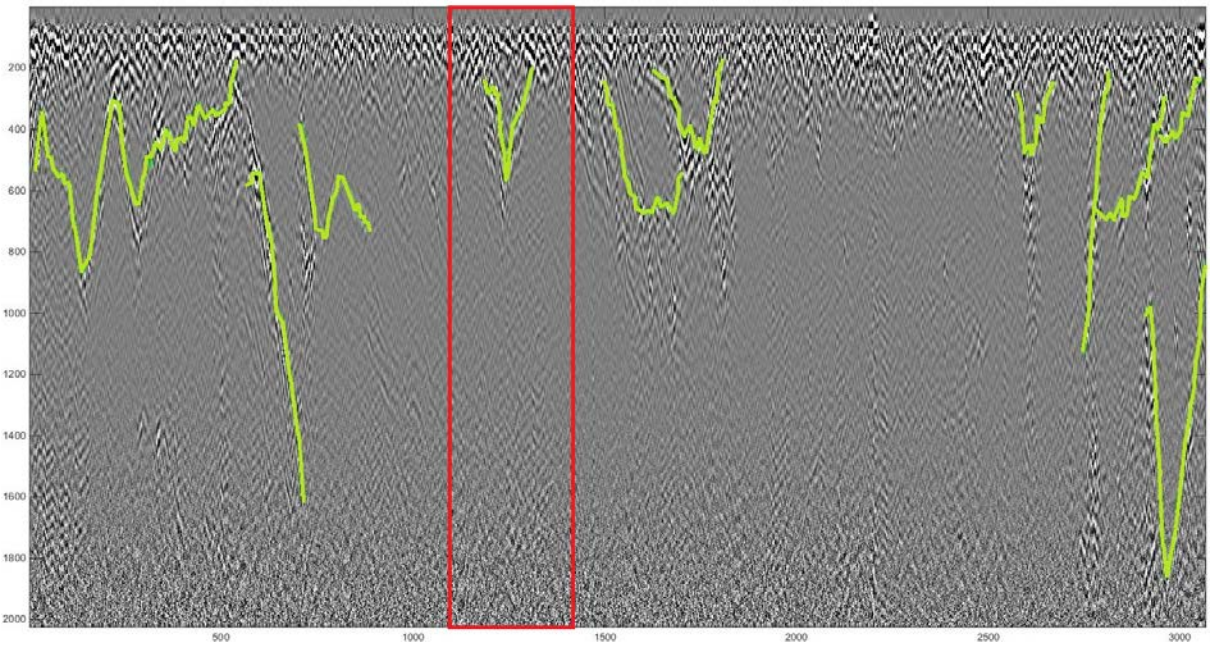

Figure 20: Radar figure over one profile with marked reflectors indicating massive ground ice. The red rectangle shows which part that have been magnified for Figures 21 and 22.

Figure 19 above is the result from running one file in MATLAB with the script for extracting information, showing the figure where digitalization of massive ground ice could be made. Figure 20 is from the same file, but with the indicators of massive ground ice marked as lime green lines. The red rectangle represents which part that have been magnified for Figure 21 and 22 which shows more details and one reflector that can be a result from massive ground ice; this reflector is digitalized in Figure 22.

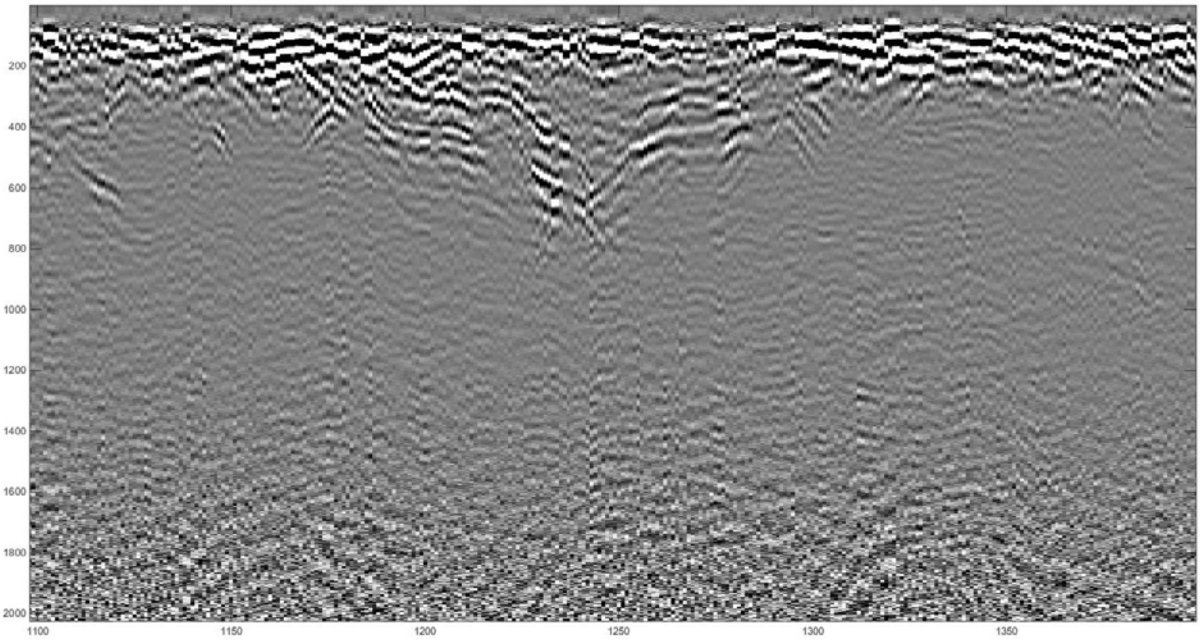

Figure 21: Magnified part of Figure 19 showing more details and one reflector that possibly could be massive ground ice.

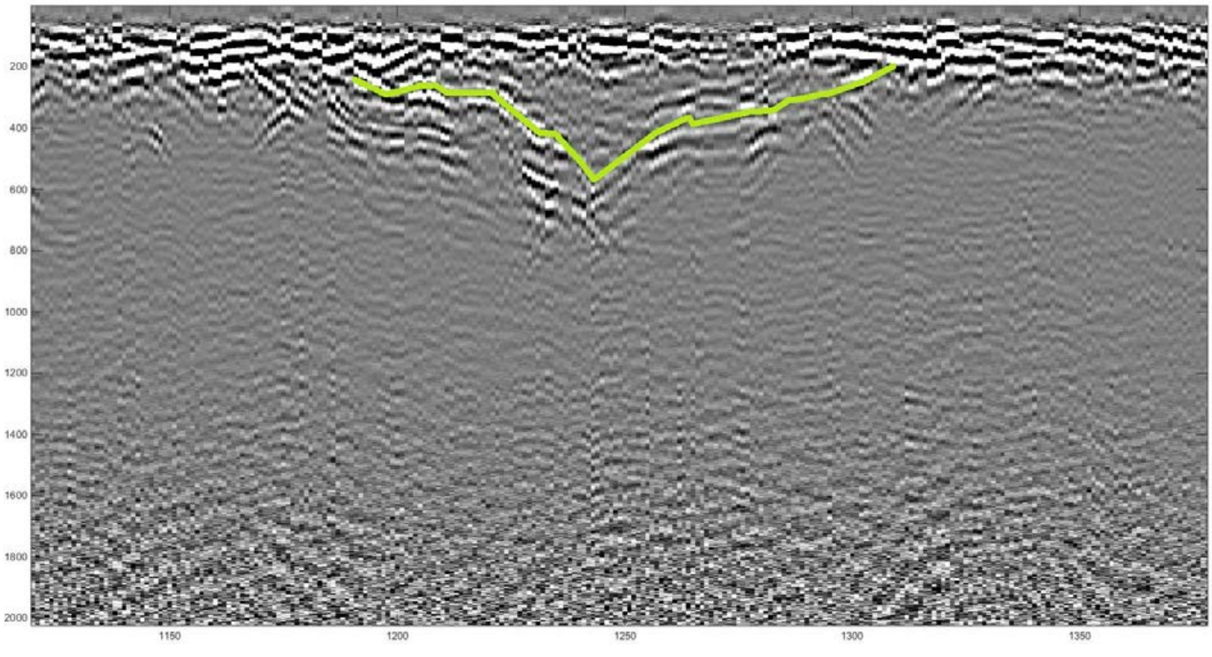

Figure 22: Magnified part of Figure 19 showing more details and one marked reflector that possibly could be massive ground ice.

Figure 23 shows the distribution of massive ground ice where the yellow lines represent the massive ground ice. A similar map but with all the profiles as well can be seen in Figure 24, and a magnified version of this figure can be found in Appendix 5.3 Maps showing massive ground ice and profiles, but with the DEM, slope and aspect respectively as background can be found in Appendix 5 as well. Figures

25 to 27 below shows close ups of the distribution of massive ground ice at the mouth of Taylor Valley, Wright Valley and Salmon Valley, respectively.

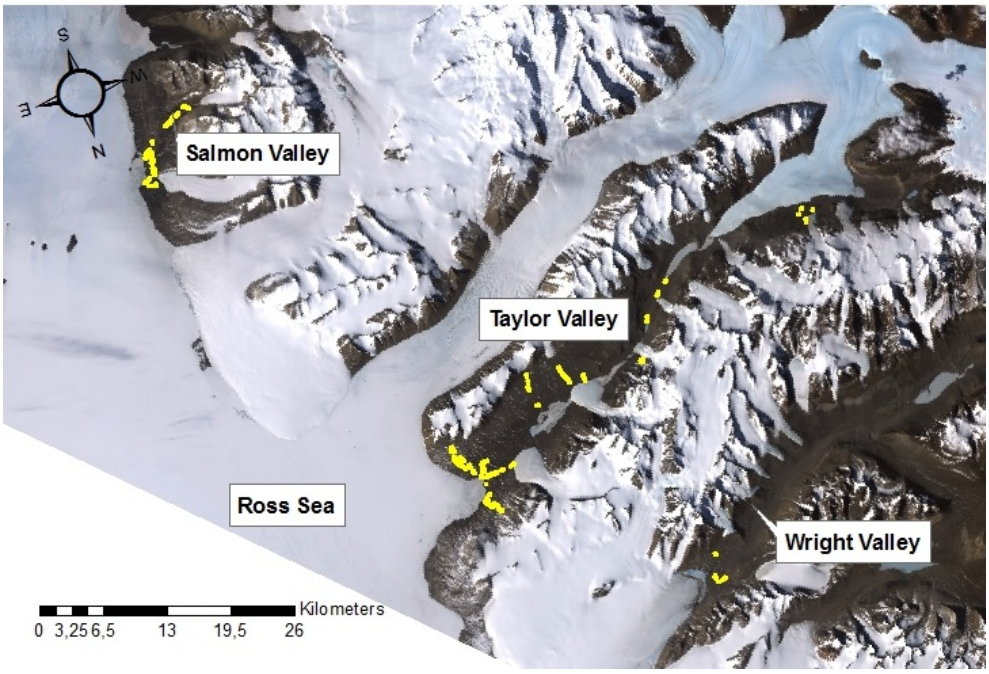

Figure 23: Distribution of massive ground ice, shown as yellow lines, in the area.

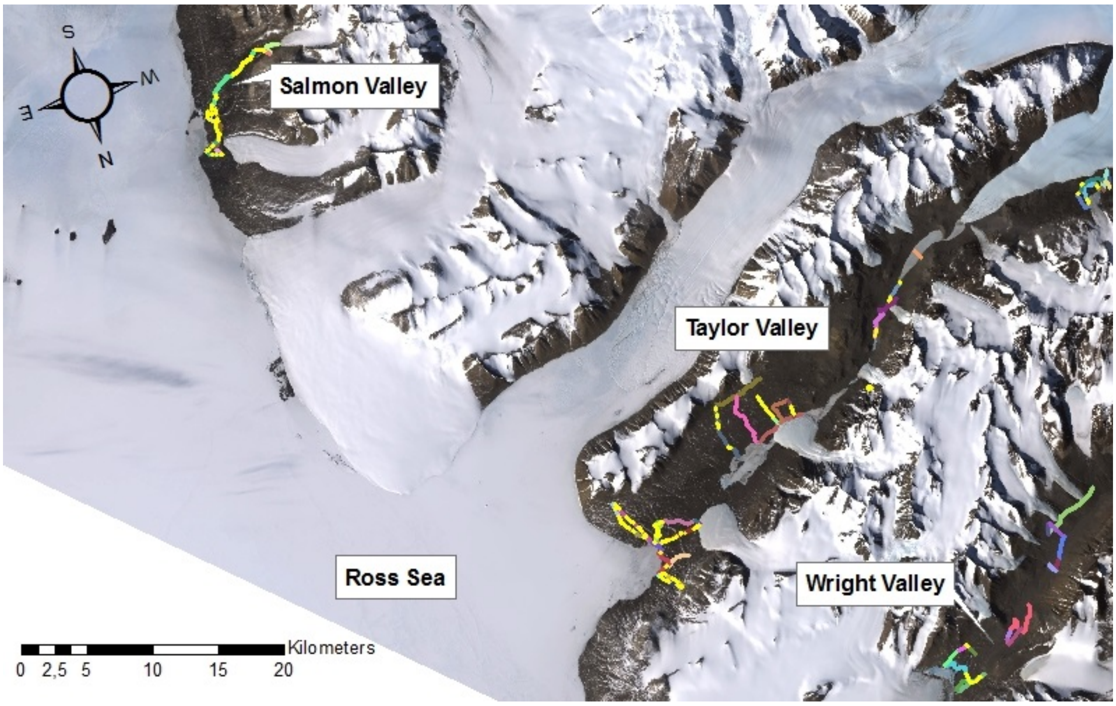

Figure 24: Massive ground ice shown as yellow lines overlying all of the profiles in the area which are shown as mixed colours.

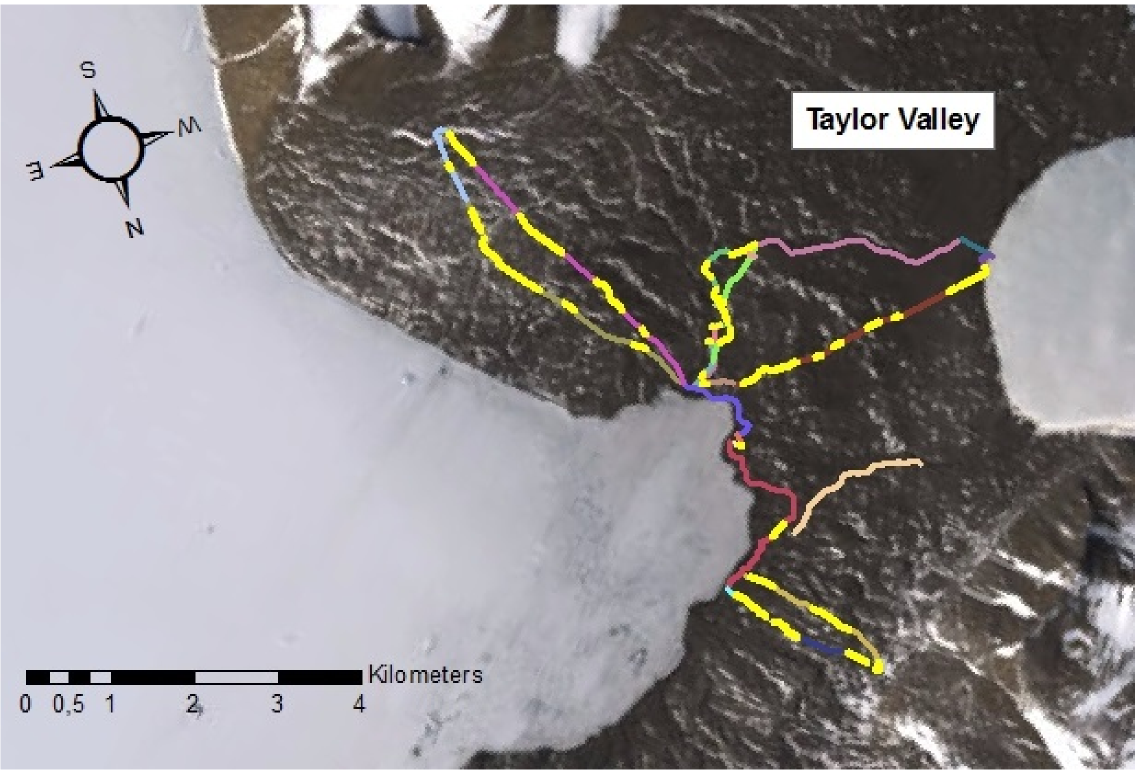

Figure 25: Distribution of massive ground ice (yellow lines) and radar profiles (mixed colours) at the mouth of Taylor Valley.

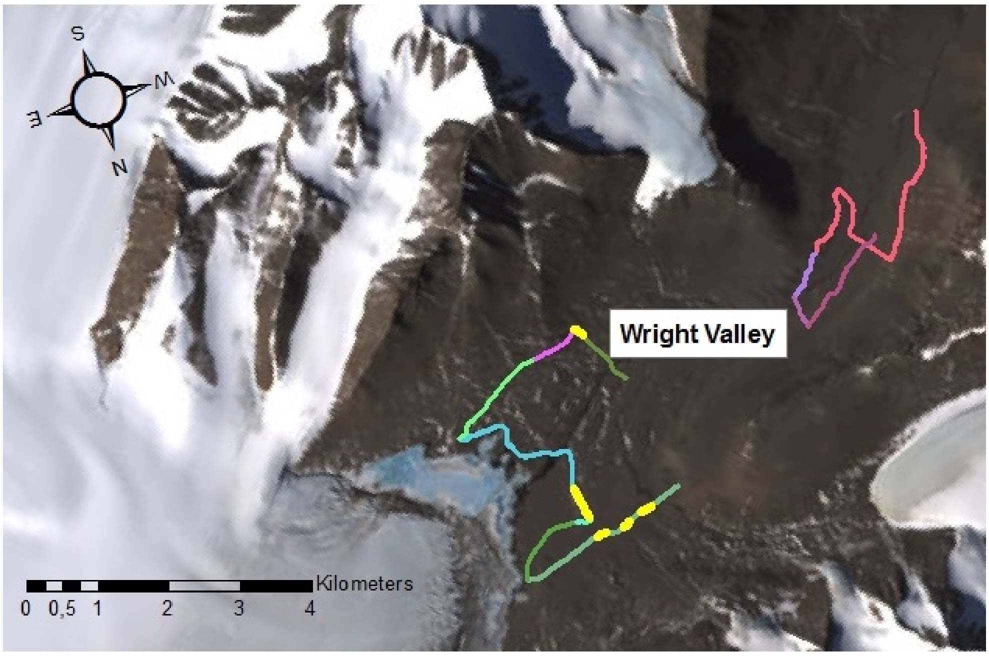

Figure 26: Distribution of massive ground ice (yellow lines) and radar profiles (mixed colours) at the mouth of Wright Valley.

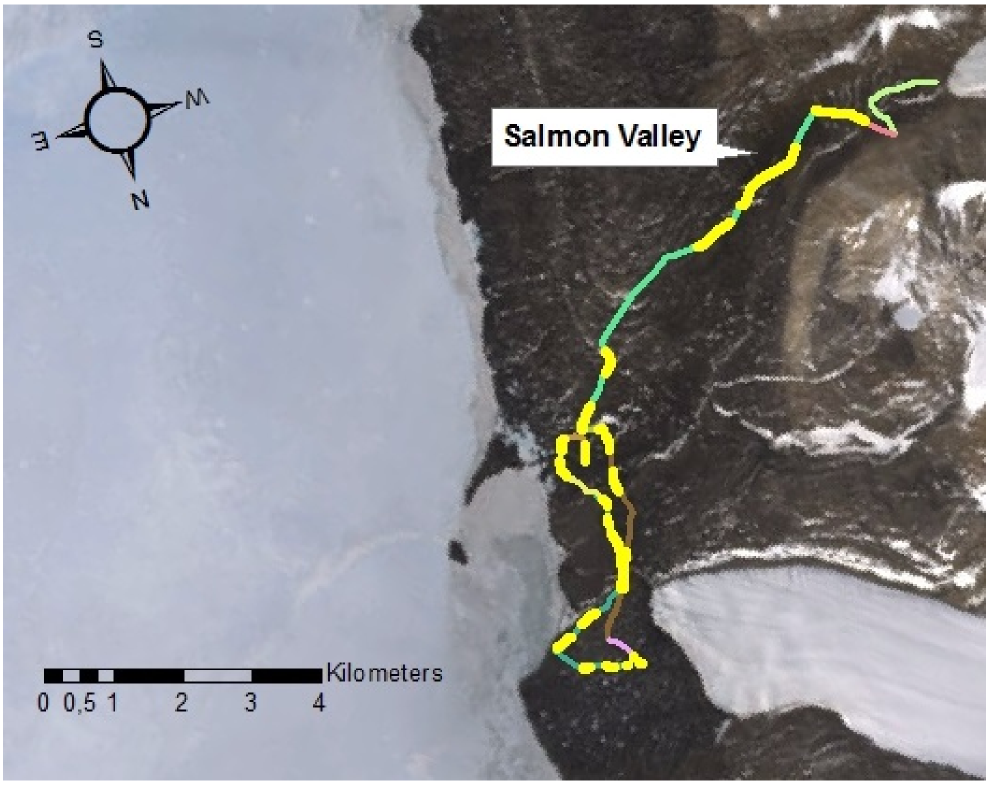

Figure 27: Distribution of massive ground ice (yellow lines) and radar profiles (mixed colours) in Salmon Valley.

Figures 23 and 24 show that there is more massive ground ice at the mouth of the valleys than further in, there is also less massive ground ice than GPR profiles at the centre of Taylor Valley, and no massive ground ice under Lake Bonney closest to Taylor Glacier in Taylor Valley. Massive ground ice also seems to be more frequent in Taylor and Salmon Valley compared to Wright Valley.

Figures 25 and 26 show that there is more massive ground ice at the mouth of Taylor Valley than at the mouth of Wright Valley, whereas massive ground ice in Salmon Valley (Fig. 27) occurs along almost the whole profiles.

5.2 Histograms for spatial patterns

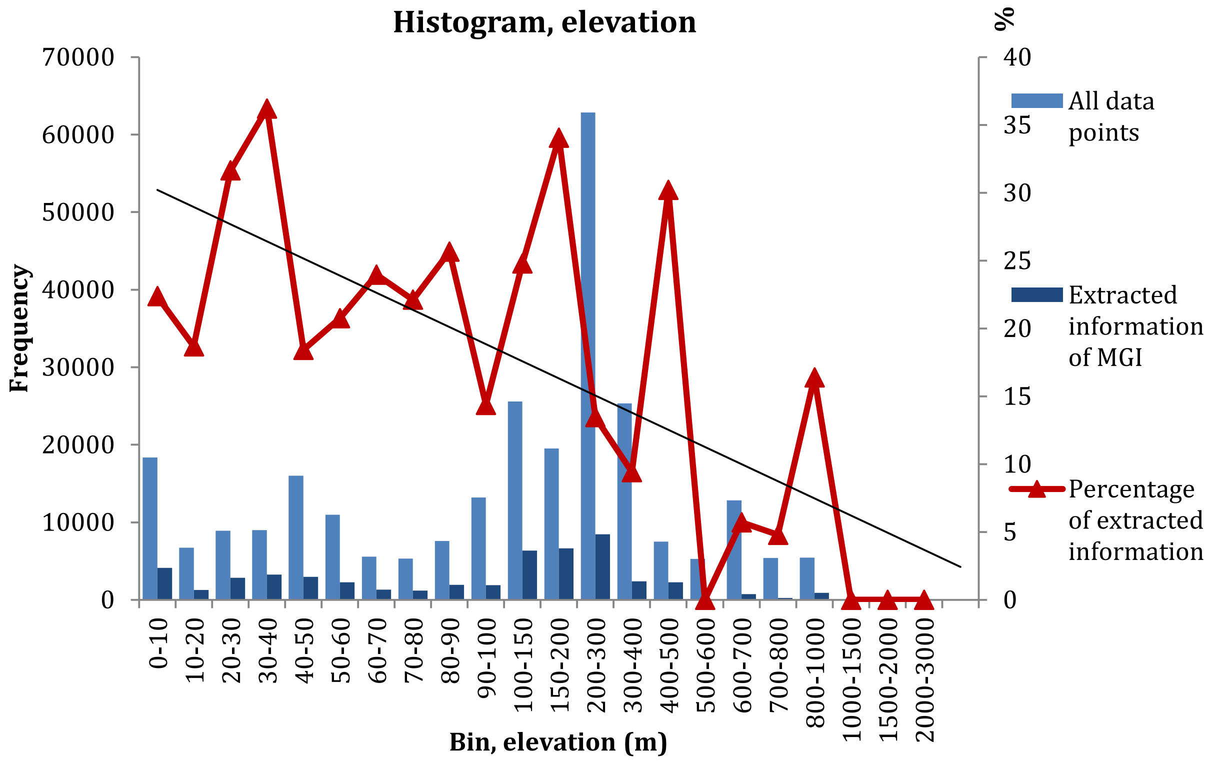

Figure 28: Frequency distribution of massive ground ice and total amount of data as a function of elevation in the study area.

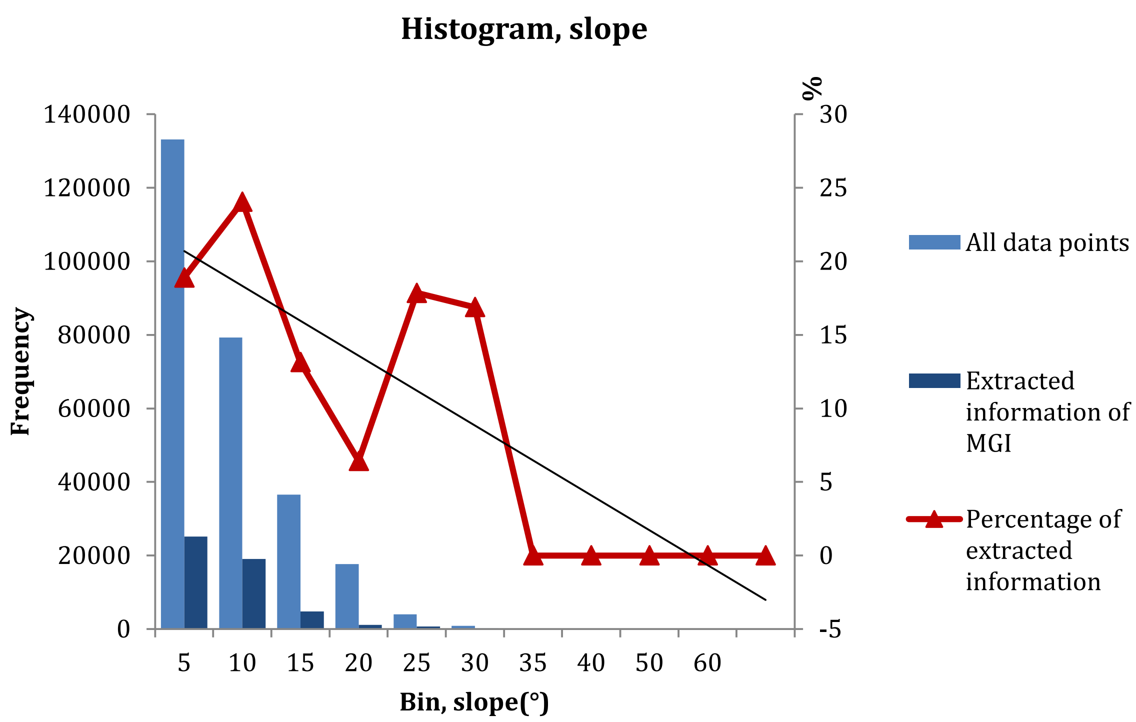

Figure 29: Frequency distribution of massive ground ice and total amount of data as a function of slope angle in the study area.

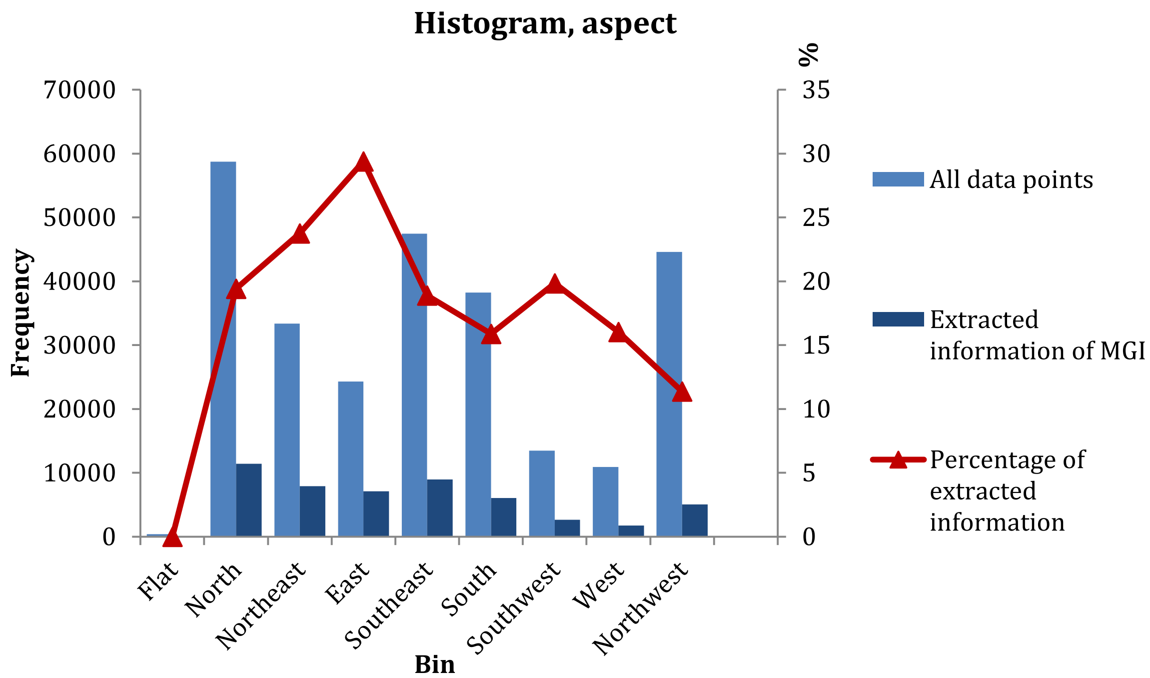

Figure 30: Frequency distribution of massive ground ice and total amount of data as a function of slope aspect in the study area.

The three histograms above in Figures 28 to 30 show the frequency of massive ground ice at different elevations, slopes and aspects. The light blue bars represent the data for all profiles, whereas the darker blue bars represents the data from profiles with only massive ground ice. The red line represents the percentage of massive ground ice relative to the total amount of data.

Figure 28 shows that there is an overall decreasing trend of massive ground ice with increasing elevation and that the lowest amounts of massive ground ice can be found at high elevations. This can be seen in Figure 23 and 24 as well, where the frequency of massive ground ice seems to decrease further in to the valleys where the elevation increases. There is however a slight increase of massive ground ice over intermediate elevations between 90 and 200 m after remaining relatively stable between 40 to 90 m.

The slope histogram in Figure 29 shows an overall decreasing trend of massive ground ice with increasing slope angle. The frequency of massive ground ice seems however to often follow the varying pattern for all of the data, where it decreases with decreasing amounts of total data.

The histogram for aspect in Figure 30 shows that massive ground ice is more frequent at northeast-east aspects than at the others.

6. Sources of errors

6.1 Preparatory processing

The radar figure for the GPR profile run in the script for editing could sometimes show grey fields (Appendix 2.6) which made it hard to distinguish if something needed to be removed or not. These grey fields were removed if marked by the script as suggested parts to remove. The figures in Appendix 2.1 and 2.2 from this editing script were used as help for determining which parts to remove if this was unclear just based on the radar figure. Flat parts of the Y-coordinates in the first figure (see Appendix 2.1 for example) indicated that data could be removed, the same was indicated if the Y-coordinates had been constant for some time in the TimeView of the second figure (see Appendix 2.2 for example). The still standing could be seen in ArcGIS as well as clusters along the GPR profile (Appendix 4.2 and 4.3). These clusters appeared as the lack of movement affects the precision in the GPS processing and because you probably still move a little bit even if you are "standing still".

However, too much or too little data could have been removed during this step despite the help from the figures from the editing script and visual help from ArcGIS, which could have affected the delineations of where massive ground ice exist.

6.2 Extraction of information

The difference between reflectors for massive ground ice and bedrock was not always easy to distinguish in the GPR profiles; even though reflectors for massive ground ice often were shorter with a clear start and end compared to bedrock reflectors that usually extended over large parts of the profile. This affected the first histograms because long reflectors that most likely were bedrock had been digitalized. Most of these digitalizations could be deleted after further check-up, which improved the end result. However, there are still some profiles where the digitalizations could be bedrock rather than massive ground ice. The long profile in front of Canada Glacier in Taylor Valley is such an example, where the whole profile is marked as massive ground ice, something that could indicate that too much data have been extracted.

The figures for some profiles showed large grey areas (Appendix 2.7), which could be a result from a weaker signal than usually that made the gain processing in the script to amplify deeper reflectors more than shallow ones. This would then result in this pattern where the upper parts where shown as a more homogeneous grey colour although these parts were not weaker than the lower. This pattern made it harder to distinguish the reflectors and some information of massive ground ice could therefore have been missed during the digitalization.

Poor/obvious joints between merged GPR profiles in the elevation-corrected figure (Fig. 16) could be an effect of some error in the elevation data from the GPS, but did not affect the digitalization if they were not obvious in the figure where they were made.

Some of the polylines that were supposed to show the distribution of the massive ground ice went over spaces where there were no points of data from the extraction. This made the distribution of massive ground ice to look more extensive that it actually was. This could be a result of having several digitalizations split up along one profile, and that these segments got connected with a straight line and that ArcGIS made a polyline of each profile; connecting end/start points of each segment although they should not be connected. This was solved by modifying the MATLAB-script that compiled all digitalizations to split them up more than before which made it possible to make proper polylines.

6.3 Amount of data

The amount of data could affect the possible errors, especially when working with the data for the histograms. The possible errors will have a bigger influence on the result if the amount of data worked with here is small compared to the number of errors that may exist. For example, a long profile with reflections from bedrock instead of massive ground ice will influence the result further if the amount of data is relatively small whereas a bigger amount of data would reduce the error more.

7. Discussion

7.1 Spatial pattern of massive ground ice from histograms

7.1.1 Elevation

The red line in Figure 28 reflects the percentage of measurements where massive ground ice was detected and the overall pattern of this line indicates how the occurrence of massive ground ice varies at the different elevations. It shows a decreasing trend of massive ground ice with elevation, which also can be seen by the trend line for the percentage values; massive ground ice gets less abundant with increasing elevation.

The spatial pattern with an increasing percentage of massive ground ice over intermediate elevations can be discussed together with the distribution of massive ground ice, where the massive ground ice seem to be more common at the mouth of the valleys. The elevation at the mouth of Taylor Valley is higher than further inwards due to the deposits from the Ross Sea Ice Shelf advance, which would explain the higher frequency of massive ground ice at these elevations.

The overall decreasing percentage of massive ground ice with elevation could be an indication of the origin of the ice. The alpine glaciers in Taylor Valley are believed to currently be at their maximum extent, which would mean that they have not retreated enough to leave big deposits of massive ground ice in the form of buried glacier ice. Buried glacier ice is instead believed to mostly exist in the valley mouth as remnants from the Ross Ice Shelf, and around Taylor Glacier as remnants from fluctuations of this glacier. The massive ground ice found at higher elevations along the valley sides and further into the valley could therefore be segregation ice instead, however this is only speculated. The decreasing amount of massive ground ice with altitude could then be a result of the colder temperatures at higher elevations which limit ground moisture and melting, which result in conditions that are not advantageous for the development of segregation ice. The alpine glaciers that could be possible contributors of ground moisture in the form of meltwater exist at these elevations, making the size and distribution of massive ground ice smaller here than at elevations and places where buried glacier ice is the main source for the massive ground ice.

The lesser frequency of massive ground ice at elevations above 200 m could also be due to the fact that Glacial Lake Washburn reached up to approximately 300 m. It is possible that the amount of massive ground ice was considerably smaller at these elevations than lower elevations already before this lake came into existence, if it consisted of segregation ice. The lake could then have been able to melt more of this ice than of the glacier ice if the total amount and size of segregation ice was low from the start. The slow thermodynamic processes that causes melting of the ice did not have to act on big deposits like buried glacier ice. This would then contribute to the result shown here, with a decreasing percentage of massive ground ice with elevation. Slow thermodynamic processes can also be a reason why the massive ground ice (both segregation ice and buried glacier ice) still exists. These processes act very slowly, and Glacial Lake Washburn could have existed for too short a time for these processes to affect all the massive ground ice. The environment has also been, and is, very cold, which slow these processes even further. This may however change with a changing climate.

The reason why there is so little massive ground ice at higher elevations can also be due to less sediment as a result of harsher conditions with more and stronger winds in similar directions. Katabatic winds are an example of such winds which remove a lot of the protecting sediment cover. Glaciers can generate katabatic winds, and they usually get more frequent with increasing elevation. The harsher conditions due to the winds can therefore get more prominent as the elevation increases, leaving the sediment cover to be thinner and thinner. The massive ground ice decreases with elevation where glaciers becomes more prevalent, something that can be seen in Appendix 5.8 and justifies this conclusion. There is very little evidence of massive ground ice compared to total radar data in Pearse Valley close to Taylor Glacier, which can be a result of the katabatic winds and sediment thickness. A thin sediment cover can possibly be too thin to preserve or contain massive ground ice, considering that the overlying thickness of it protects the deposit of massive ground ice as well. Field observations in Wright Valley indicate that the sediment cover in this area is very thin; something that then can be the reason for the low frequency of massive ground ice and support the theory that the thickness of sediment cover influences the massive ground ice. It is also possible that the glaciers have not advanced and retreated enough in this area to deposit a lot of ice or sediment deposits for protection.

A lot of massive ground ice at lower elevation can be found in Salmon Valley where it covers long parts of the profiles. The fairly high frequency of massive ground ice at 10m could therefore be the result of this massive ground ice from Salmon Valley.

7.1.2 Slope

The histogram showing the distribution of massive ground ice for different slope angles (Fig. 29) shows no significant pattern, it seems to follow the distribution of all the data at the different slope angles. This can be seen by the red line representing the percentage of massive ground ice relative to all data, which decreases in the same pattern as the data bars. The reason why the percentage of massive ground ice increases in the beginning and in the end of the histogram is because that the difference between all radar measurements and the extracted data gets smaller, which leads to a higher percent of massive ground ice. It is therefore the overall pattern of the red line and staples that are most reliable. This accompanying pattern makes it hard to say if the slope plays any major role in determining where massive ground ice exist. However, extraction of data for massive ground ice has been done at all elevations where measurements have been done, which mean that the ice at least can exist at these slopes. It is difficult to guess if there is any massive ground ice at the higher slope values because no measurements have been done there. Higher slope angles only exist at the upper parts of the valley sides where the glaciers and mountains starts (Appendix 5.7) in the study area, and these steep slopes and glaciers makes it hard to conduct GPR measurements at those places.

The age of the ice (time of deposition) could also be a reason for this pattern, that it is not old enough to show any effects of different slope angles. The slow thermodynamic processes would then have not been ongoing for a sufficient long time to show a difference in distribution depending on the slope angle.

The decreasing pattern could also be explained by the presence or lack of overlying sediment. The amount of massive ground ice at steeper slopes could be influenced by the amount of this, as it protects the underlying ice. Sediment is usually limited in these slopes, which would expose the ice for conditions that could cause melting. This could affect massive ground ice at flatter slopes for the same reason as well, sediments are usually more likely to stay and get deposited easier at lower slope angles, which then would provide more protection for the ground ice.

7.1.3 Slope aspect

The histogram showing the distribution of massive ground ice at different slope aspects (Fig. 30) indicates that massive ground ice is more frequent in northeast-east facing slopes since the red line, showing the distribution of massive ground ice relative to all radar data, increases in value over those intervals compared to the others. The reason for this difference between the aspects can be that the slopes get different amounts of solar radiation depending on which direction they are facing. Glaciers can also be more abundant at a certain aspect which provides different prerequisites for massive ground ice to get deposited in the first place, compared to aspects where glaciers could be less abundant. The different amounts of solar radiation depending on the aspect can have resulted in this distribution pattern by either melting the glaciers differently and hence provide different amounts of meltwater to form segregation ice, or just provide different conditions for the massive ground ice already deposited, i.e. the amount of glaciers is not the controlling factor.

One other explanation for the difference in distribution of massive ground ice, even if the difference is not that large, can be that the deposits of massive ice are of different age, i.e. the effect of slope direction would have affected older deposits more than younger. An older deposit of massive ground ice would have been exposed for the slow melting thermodynamic processes longer than a younger deposit, something that depends on the amount of solar radiation and heat which further depends on the aspect.

However, the histogram in appendix 6.1, that shows four points of the compass and flat aspect (northeast, northwest, southeast and southwest have been added to north and south respectively), indicates that there is no major differences in the distribution pattern of digitations between north, south or west facing slopes and that there is just a slight increase over east facing slopes.

This quite homogenous pattern could be explained by the same reason mentioned for the distribution of massive ground ice at different slopes, i.e. the massive ice is not old enough to show enough effects that would be because of different slope aspects. The DEM used could also have been not clear enough to separate between different aspect values. The slope raster and aspect raster does however point towards the opposite with their quite cohesive values without major changes around a certain pixel.

One other parameter that could have affected the result is the amount of data as mentioned in section 6.3; more data could maybe have resulted in more distinguished differences between the slope aspects. More data would also have had a positive effect on the number of uncertainties among the digitations and hence the result since only a few profiles digitalized in the wrong way would influence the end result in a bad way if the amount of data is too little. The amount of data and the digitalization process is a source of error for the distribution of massive ice at different slope angles, elevations and general in the valleys as well.

7.2 Origin and distribution of the massive ground ice

It is hard to know if the mapped massive ice is glacier ice or segregation ice just by looking at the distribution of massive ground ice alone, it did not show a specific pattern along with the limit of Glacial Lake Washburn. The spatial pattern alone is not sufficient to discriminate between the two genetic types of ice. Massive ground ice at intermediate and high elevations along the valley side is suggested to be segregation ice since the alpine glaciers are believed to be at their maximum extent today and the lower percentage of massive ground ice supports the unfavorable conditions for the creation of segregation ice. The massive ground ice around Taylor Glacier and at the valley mouth is instead suggested to be buried glacier ice from Taylor Glacier and advancement of the Ross Sea Ice Shelf with some segregation ice as well due to freeze/thaw cycles.

There are profiles in the middle part of Taylor Valley where little to no GPR evidence of massive ground ice was found. This can mean that Glacial Lake Washburn occupied this part of the valley for an enough long time to manage to melt massive ground ice that otherwise would have existed here, or that less massive ground ice have been deposited here.

The main process for the disappearance of Glacial Lake Washburn is believed to have been evaporation, not a major drainage event due to retreating ice. This could have made it possible for the ice lobe to occupy its position longer and to retreat slowly during and after disappearance of the lake, leaving ground ice deposits at the valley mouth, in areas that were not affected by the water for a sufficient time to melt this ice. This would then provide better survival odds for the massive ground ice. Sediment from the retreating ice lobe deposited above the massive ground ice could also act like further protection.

Radar measurements were done over one lake in Taylor Valley; Lake Bonney, which is the furthest into the valley. No information of massive ground ice was extracted here (see Appendix 5.3). However since the radar was not able to penetrate to the bottom of the lake, it is unclear if massive ground ice exists here or not. A lack of massive ground ice could be due to the fact that the lake has managed to melt massive ground ice that could have existed there before. Lake Bonney has existed for a longer time than Glacial Lake Washburn since it is believed to be a remnant from it, and thus have had a longer time to possibly achieve this.

Most of the massive ground ice exist in the area that is classified as the coastal thaw zone and some in the inland mixed zone (Fig. 11), where the coastal thaw zone is believed to be most susceptible for landscape changes due to warming according to Fountain (2014). This means that the distribution of massive ice supports the zone division after how big the risk for landscape change is since a landscape with ice underneath can go through major changes if this ice disappears. Most of the massive ground ice mapped in these valleys will probably experience a change towards warmer temperatures and thus be at risk of change considering that most of it exists in these zones. The changes in the landscape underlain by massive ice, which already has been seen at various places in the McMurdo Dry Valleys, will thus most likely continue to happen. Places underlain by massive ice where no change have appeared can instead start to transform if the conditions continue to be like they are, or switches towards conditions that enables even more changes to the massive ground ice and the landscape.

7.3 Future work

The methods used here for mapping the distribution and spatial patterns of massive ground ice worked well, it gave a clear visual picture of the result. However, there is always room for improvement. More data spread over a wider area would make it possible to see where the massive ground ice exists and how it varies in this area, both in distribution and spatially. More time and knowledge for the extraction of information could also improve the result since it would reduce the risk of errors in the form of wrongly digitalized reflectors. A more detailed DEM could enhance and distinguish the data for elevation, slope and aspect and data of solar radiation could be used to support or challenge the idea that it affects the distribution of massive ground ice.

The origin of the massive ground ice could be established further when knowing where it exists through for example sampling and isotopic analysis of it.

8. Conclusions

In this study the occurrence of massive ground ice in three of the McMurdo Dry Valleys, Antarctica, was investigated using ground penetrating data. Taylor Valley was the main area of investigation, but the adjacent Salmon Valley and Wright Valley were included in the study as well. The distribution of massive ground ice was mapped and compared with elevation, slope, slope aspect and other possible landscape properties that could control its occurrence.

Raw data from approximately 160 km of GPR transects were edited in MATLAB to remove parts with still standing. The edited data have further been verified and studied in ArcGIS to find possible GPR profiles to merge, creating coherent profiles. These profiles have been merged using MATLAB and verified in ArcGIS together with the profiles that did not have to be merged. Radar figures for the profiles have been created in MATLAB where digitalization of interesting reflectors showing massive ground ice was made, followed by interpretation of the digitized data and comparison with the total radar measurements in ArcGIS and Excel.

The distribution of massive ground ice is more common at elevations up to 200 m, something that can be coupled with the origin of the ice. The alpine glaciers along the valley sides in Taylor Valley are believed to currently be at their maximum extent, massive ground ice in these areas is therefore suggested to be segregation ice since the glaciers have not retreated enough to leave deposits of buried glacier ice. The conditions for creation of segregation ice is also less favored at higher elevations, thus creating less massive ground ice. This supports the results with decreasing massive ground ice with increasing elevation. The lack of massive ice in Wright Valley and at higher elevations can also be due to thinner sediment cover, resulting in less sediment for protection and containment of massive ground ice.

The distribution of massive ice was not more prominent at a certain slope angle but evenly distributed depending on the amount of measurements made. It can however be possible that it exists less massive ground ice at high slope angles due to less sediment cover and harsher conditions for segregation ice to form. Massive ground ice was more prominent at northeast-east slope aspects, which can be due to different amounts of solar radiation that affect the massive ice.

Different ages of the ice could be a factor of the distribution as well, older ice can have been affected more by different parameters and processes than younger; resulting in this difference in distribution. The lack of, or not that prominent, difference in distribution that is visible for slope and a bit for aspect can be a result of ice not old enough to show any effects of the different parameters and processes. The amount of data can be too small as well and the DEM used could have been too undetailed for displaying clearer differences. These factors, together with the extraction of information of massive ground ice in MATLAB, are possible sources of errors.

The spatial pattern of the massive ground ice compared to Glacial Lake Washburn is not sufficient to alone discriminate between the two genetic types of ice. Segregation ice is however suggested to be found at intermediate and higher elevations along the valley sides whereas buried glacier ice is suggested to be found at the valley mouth and around Taylor Glacier.

The higher distribution of GPR profiles than massive ground ice and lower amount of it in the central parts of Taylor Valley than at the mouth suggests that Glacial Lake Washburn managed to melt some of the massive ground ice but not all due to too short existence. The lack of a distribution of massive ground ice along with and above the extent of Glacial Lake Washburn and why massive ground ice still exist in areas that have been occupied by this lake can be explained by the fact that melting of ground ice by water is a slow thermodynamic process and that the lake did not exist for a sufficient time to melt all the massive ice. A lot of massive ground ice at the mouth of Taylor Valley can be a result of deposition of massive ground ice after the disappearance of the lake, or deposits not affected by the lake water due to the short existence of the lake and by the protection of sediment deposits from the retreating ice lobe and lake. The lack of radar penetration to the bottom of Lake Bonney resulted in the absence of massive ice under this lake, but can support the idea that a lake can melt underlying massive ground ice if the time is long enough, if it really does not exist massive ground ice here.

Most of the massive ground ice can be found in the coastal thaw zone which is believed to be most exposed for landscape changes due to warming. The massive ice can thus experience future warming and continue the changes to landscapes underlain by ice that are already seen and enable changes in new similar areas.

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10. Appendices

10.1 Appendix 1

Appendix 1 consists of different errors that occurred in the GPS file of the raw radar files and how they have been fixed.

1	1	2014-12-09	20:57:33	77.61049913283	S	163.59750168683	E	343.565	M	0.7
2	3	2014-12-09	05:73:4.	77.61049913800	S	163.59750121933	E	343.542	M	0.7
3	5	2014-12-09	20:57:35	77.61049917933	S	163.59750100200	E	343.55	M	0.7

Appendix 1.1: Time error in one raw radar file, marked by the red box.

1	1	2014-12-09	20:57:33	77.61049913283	S	163.59750168683	E	343.565	M	0.7
2	3	2014-12-09	05:73:34	77.61049913800	S	163.59750121933	E	343.542	M	0.7
3	5	2014-12-09	20:57:35	77.61049917933	S	163.59750100200	E	343.55	M	0.7

Appendix 1.2: Corrected time error in one raw radar file, marked by the red box.

841	1689	2014-12-20	04:18:45	77.68578622833	S	162.58111749767	E	134.519	M	0.7
842	1690	2014-12-20	04:18:46	77.68578571450	S	162.58112986367	E	134.326	M	07
843	1692	2014-12-20	04:18:47	77.68578153417	S	162.58113734500	E	134.014	M	0.7

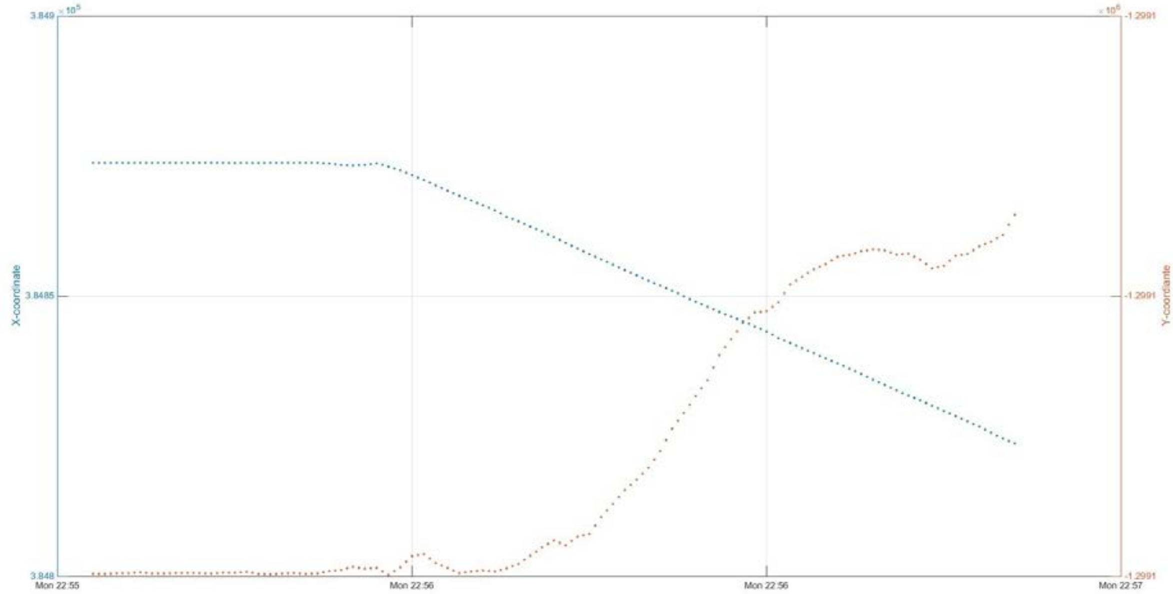
Appendix 1.3: Error of the correction number in one raw radar file, marked by the red box.

841	1689	2014-12-20	04:18:45	77.68578622833	S	162.58111749767	E	134.519	M	0.7
842	1690	2014-12-20	04:18:46	77.68578571450	S	162.58112986367	E	134.326	M	0.7
843	1692	2014-12-20	04:18:47	77.68578153417	S	162.58113734500	E	134.014	M	0.7

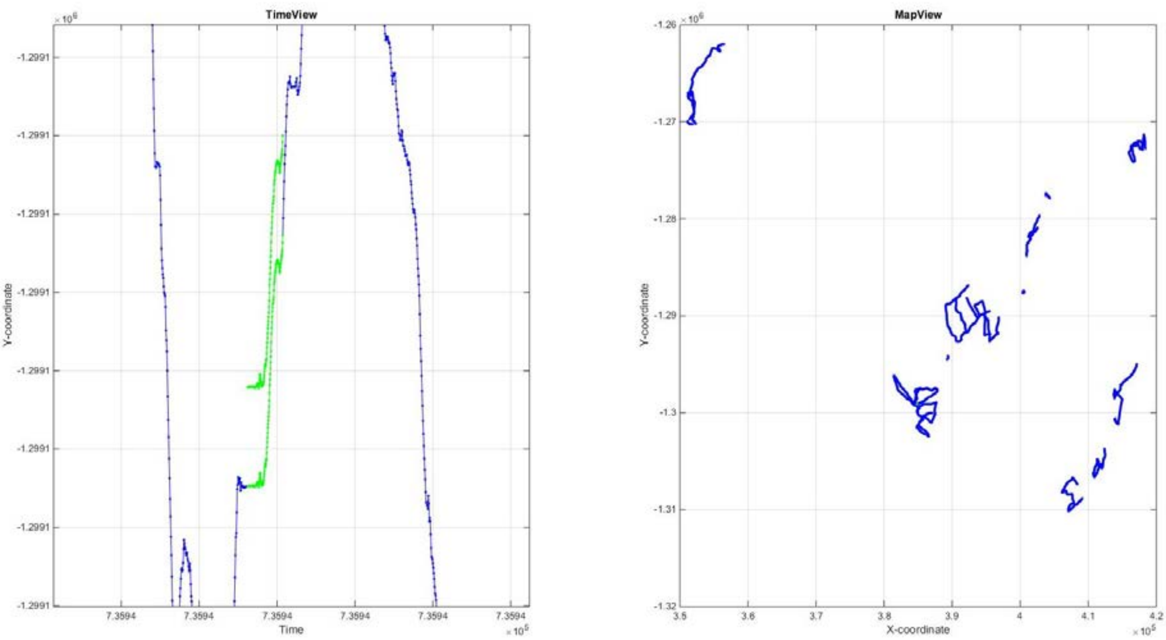
Appendix 1.4: Corrected error of the correction number in one raw radar file, marked by the red box.

10.2 Appendix 2

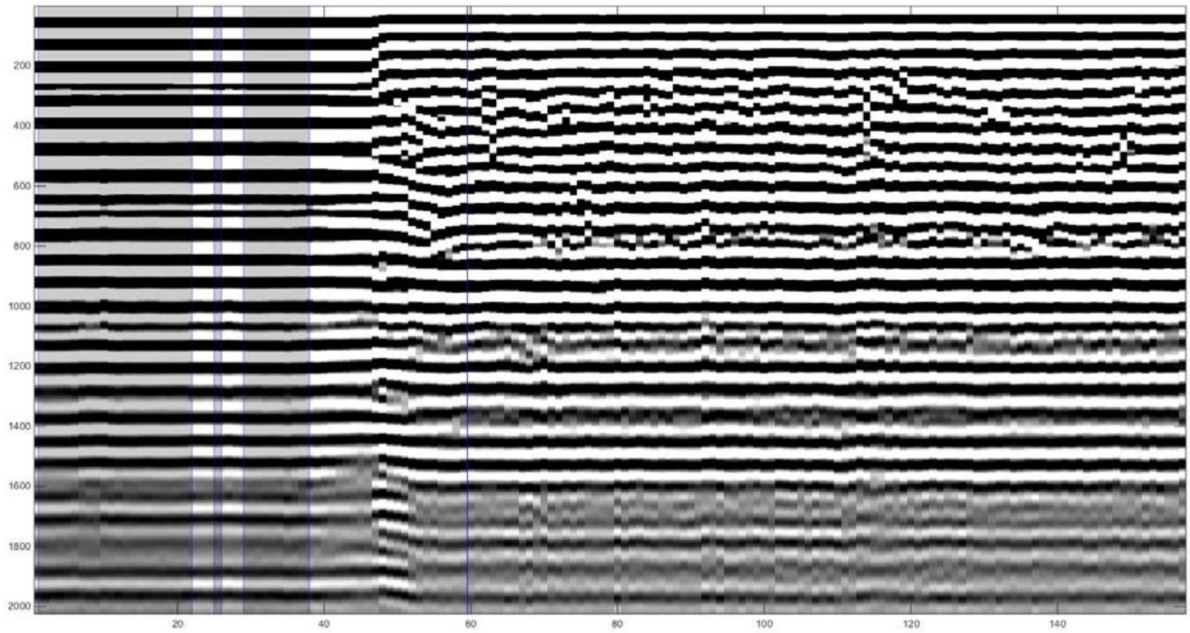
Appendix 2 consists of figures that appeared when running the different scripts in MATLAB.



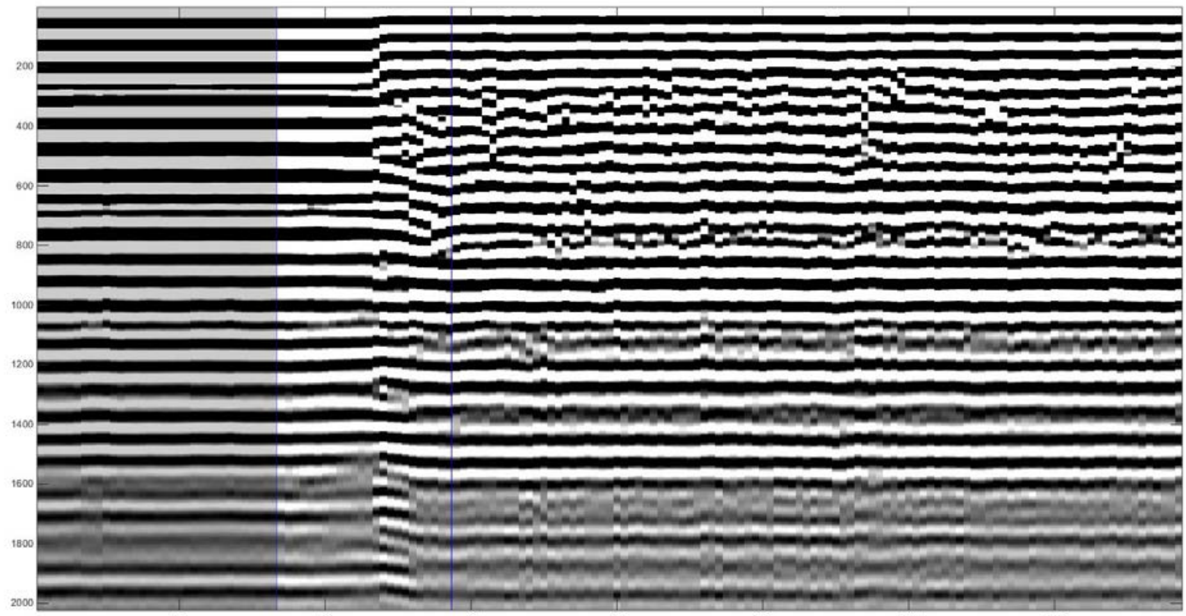
Appendix 2.1: Figure showing the variation of the data in X- and Y-direction. This figure appeared when running the MATLAB-script for editing of the raw radar data.



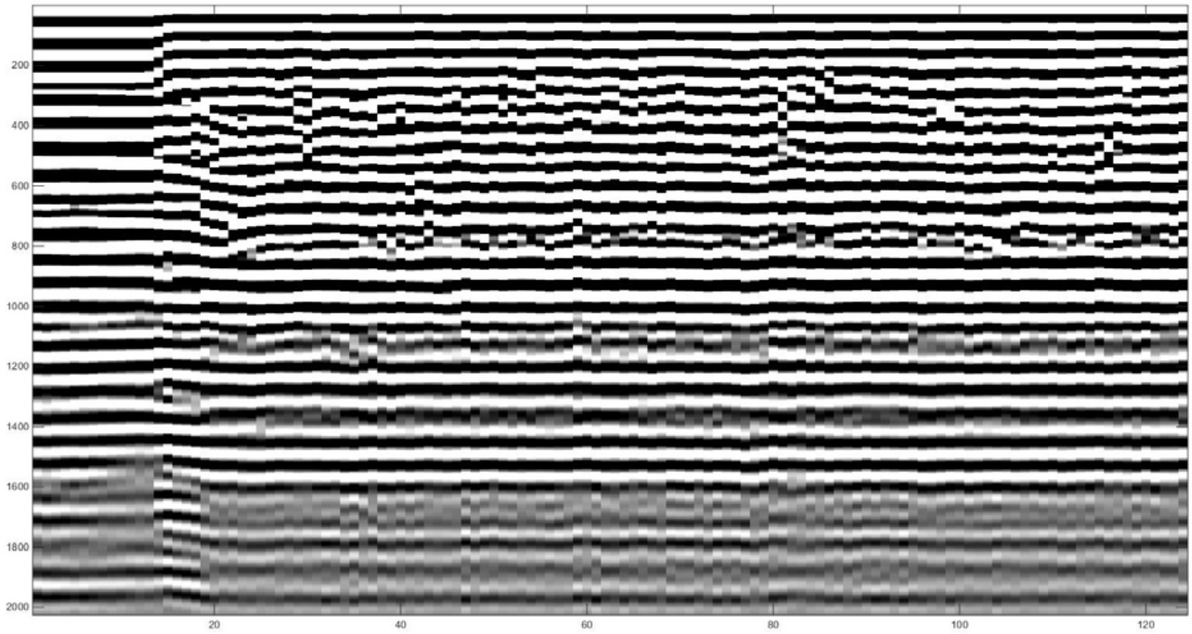
Appendix 2.2: Overview of the radar data in time and location, this figure appeared when running the MATLAB-script for editing of the raw radar data.



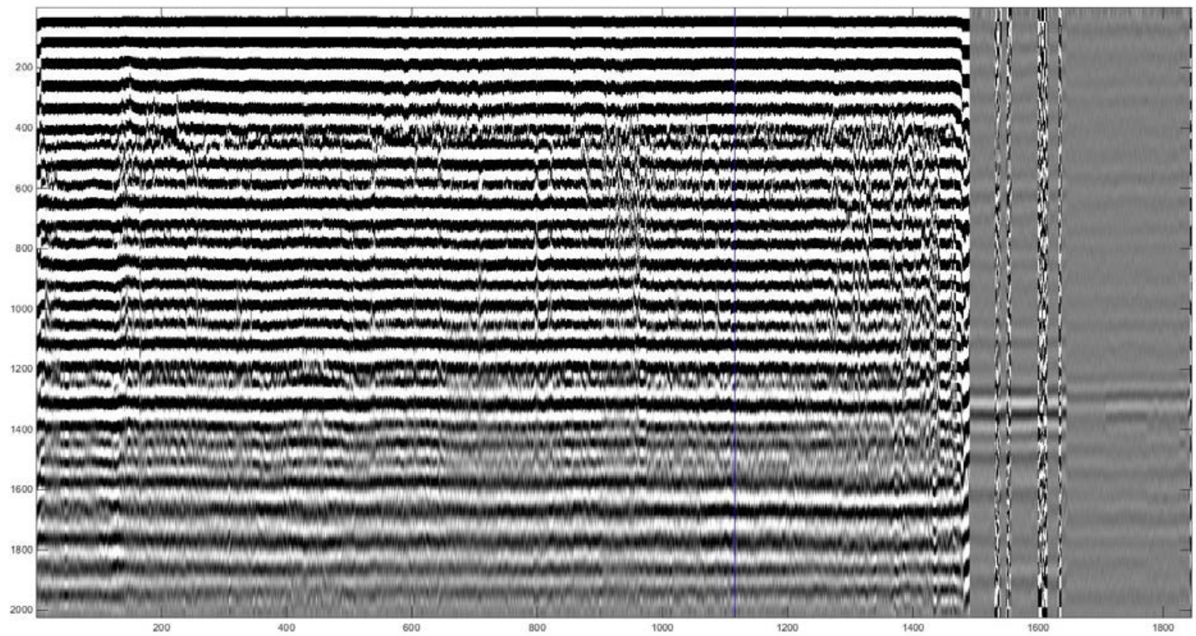
Appendix 2.3: Suggested parts for removal from the script for editing of the raw radar data in MATLAB.



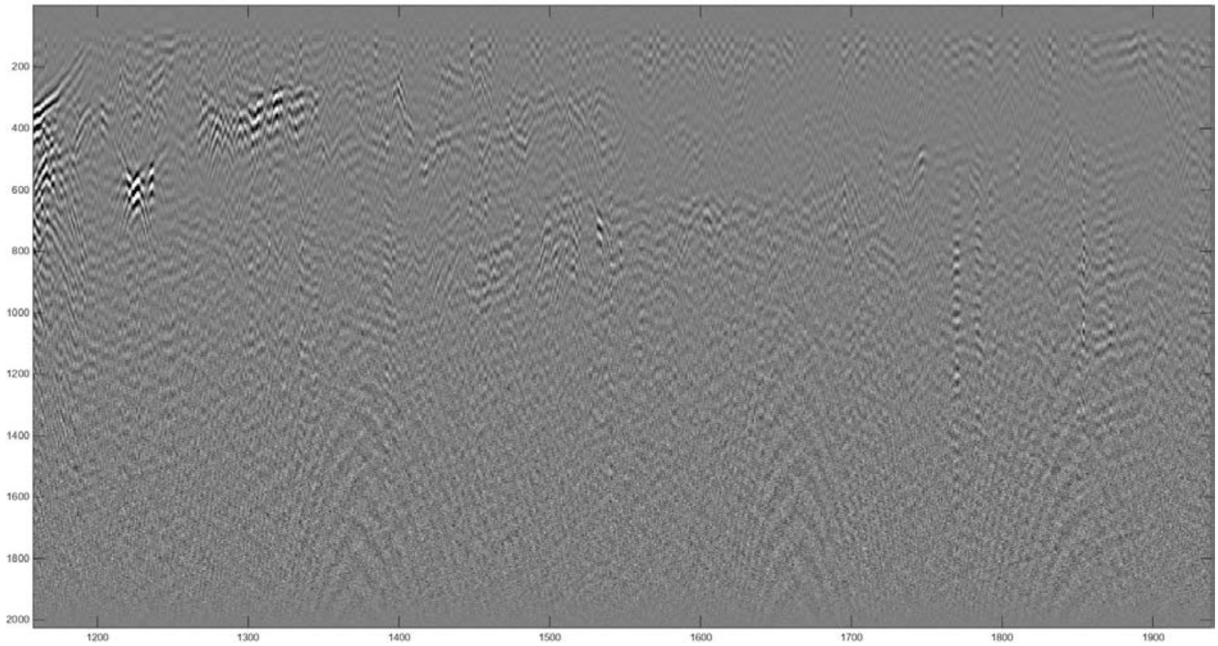
Appendix 2.4: Parts that were removed using the MATLAB-script for editing of the raw radar data.



Appendix 2.5: Result after removal of parts using the MATLAB-script for editing of the raw radar data.



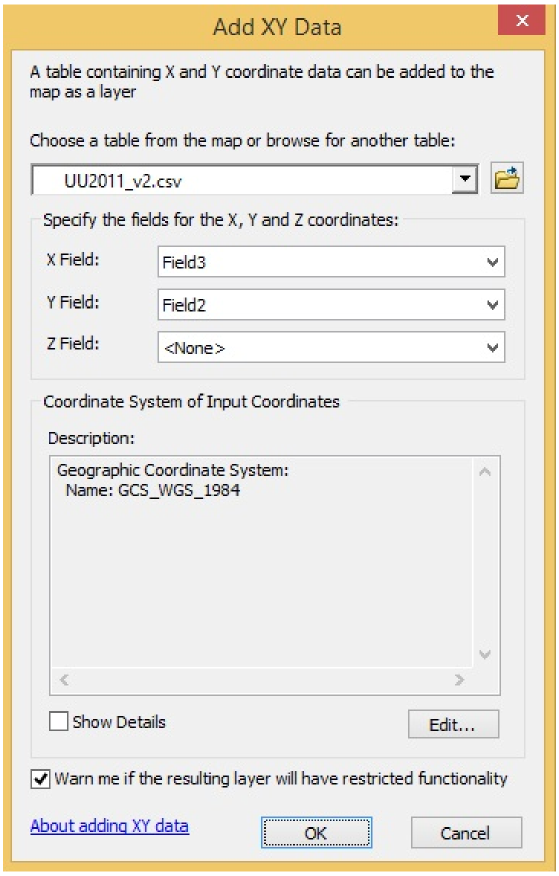
Appendix 2.6: Example of grey fields that could appear in the figure with suggested parts for removal when running the MATLAB-script for editing of the raw radar data.



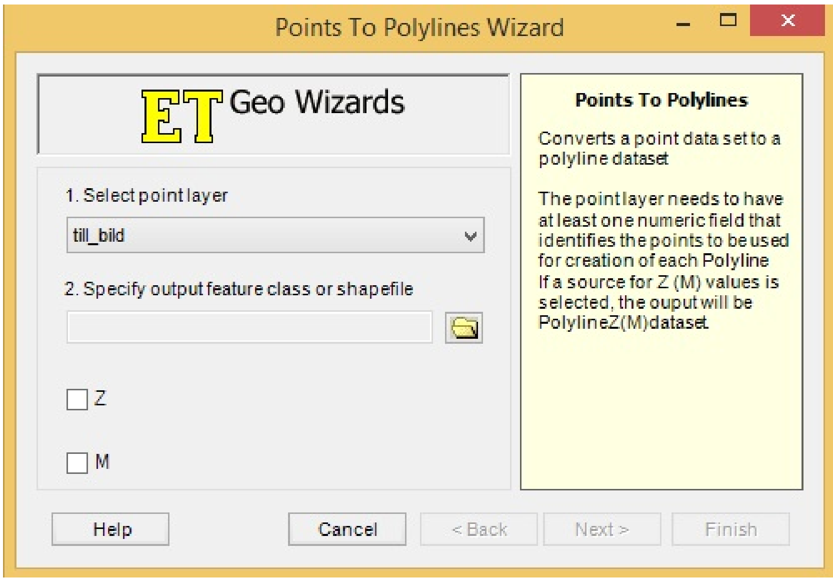
Appendix 2.7: Radar figure from the script for extraction of information of massive ground ice that showed grey areas.

10.3 Appendix 3

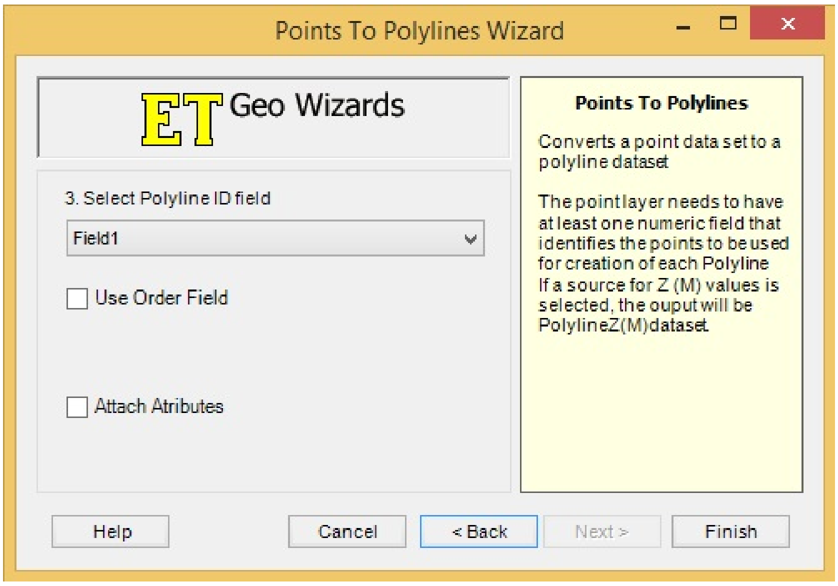
Appendix 3 consists of figures of the different commando-boxes that appeared when working with ArcGIS and the expansion ET GeoWizard.



Appendix 3.1: Different options when adding XY-data in ArcGIS**.**



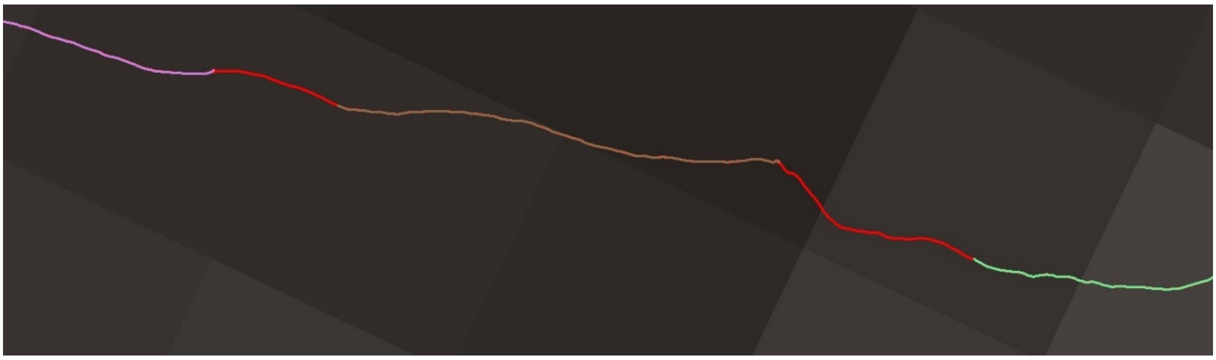
Appendix 3.2: Options from the ET GeoWizards expansion in ArcGIS for converting a point layer to polylines where the output shapefile was specified, the Z and M boxes were left unfilled.



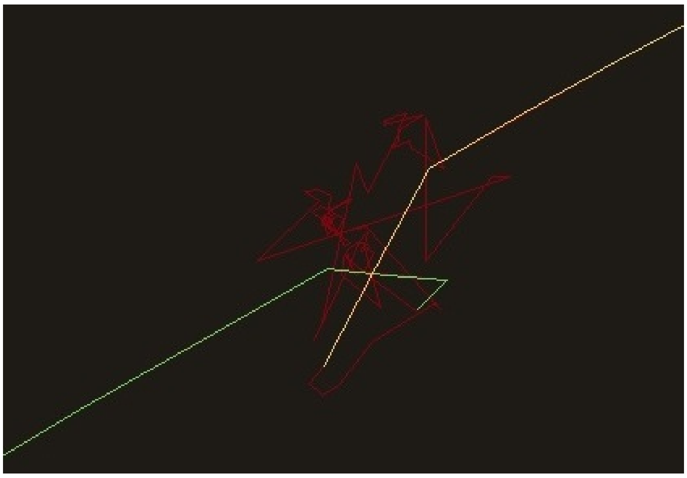
Appendix 3.3: Options from the ET GeoWizards expansion in ArcGIS for converting a point layer to polylines where the field used as ID field was selected.

10.4 Appendix 4

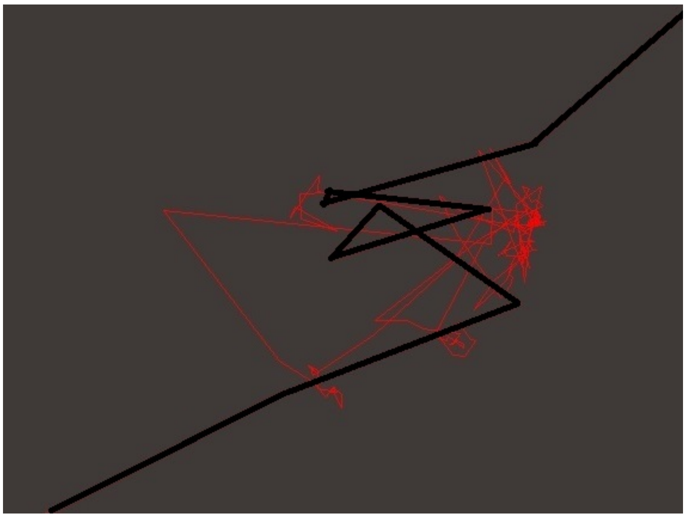
Appendix 4 consists of figures from ArcGIS that shows the result from the first editing that needed re-editing.



Appendix 4.1: Example of gaps between GPR profiles that occurred after the first editing of the raw radar data.



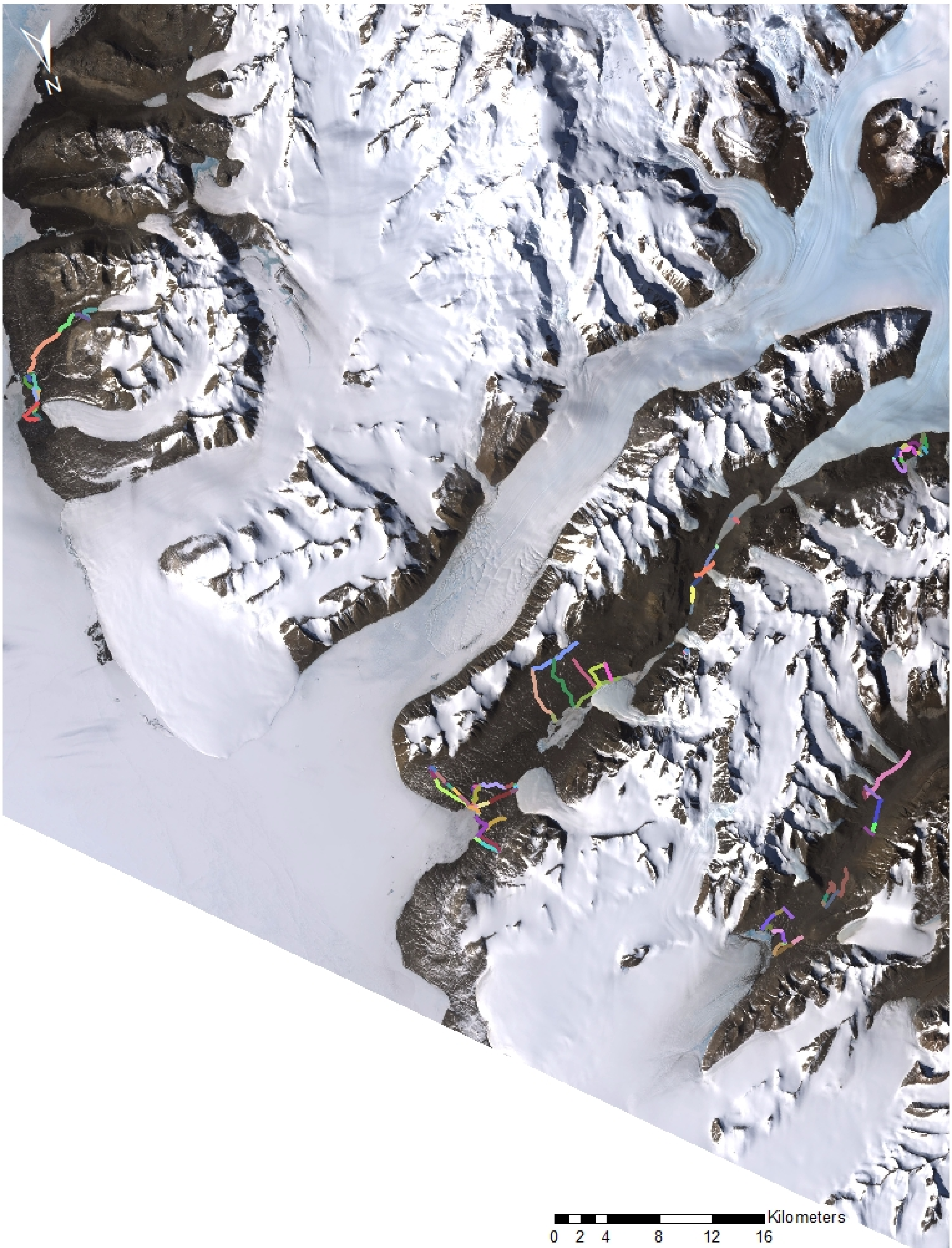
Appendix 4.2: Example of overlapping transition between two sections after the first editing of the raw radar data.



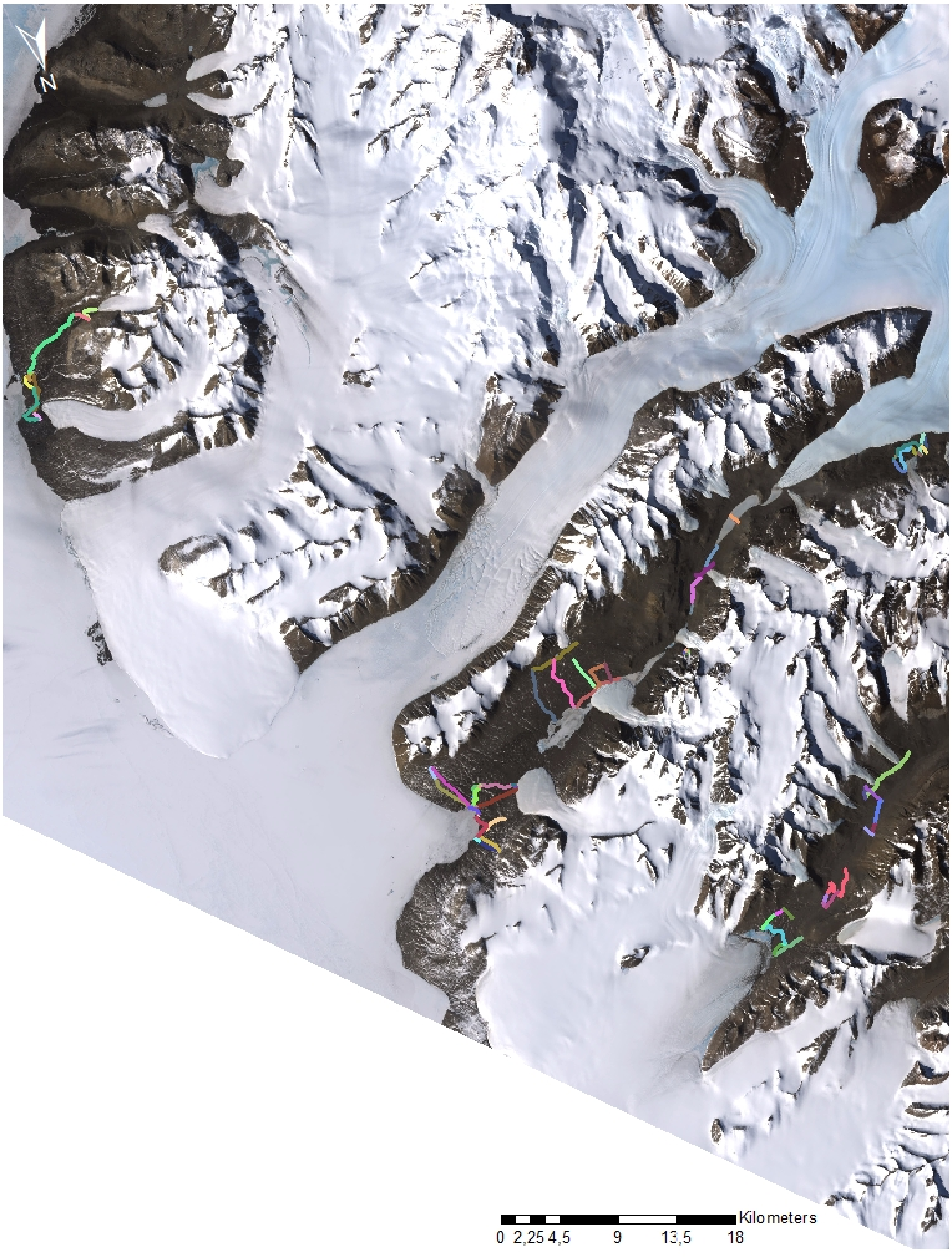
Appendix 4.3: Example of cluster of the background GPS in the middle of a section after the first editing of the raw radar data.

10.5 Appendix 5

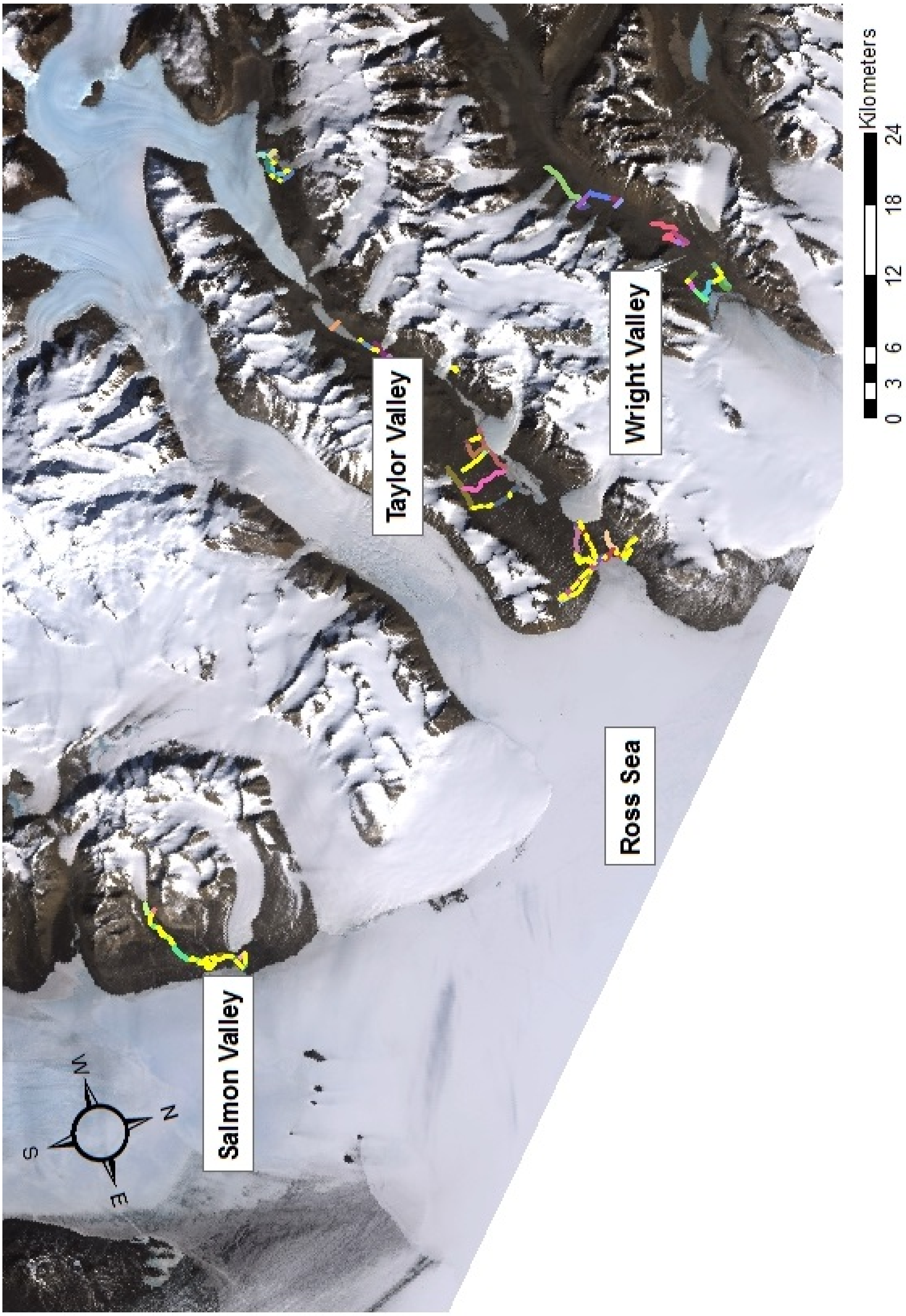
Appendix 5 consists of several maps that were created in ArcGIS during different steps in the workflow.



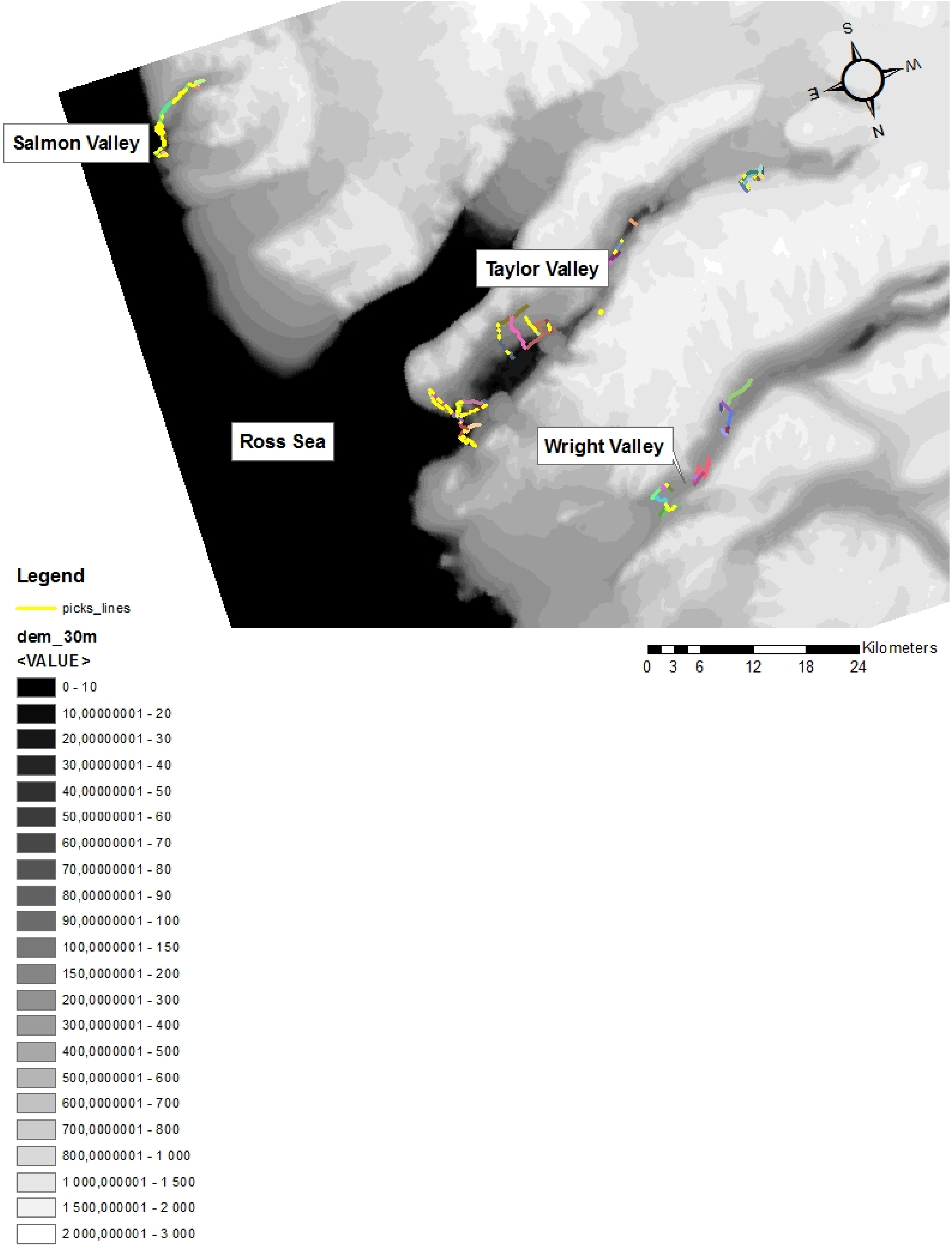
Appendix 5.1: The result from the second editing of radar data (GPR-profiles) in the whole area, the different colours of the lines in the map represents different edited profiles.



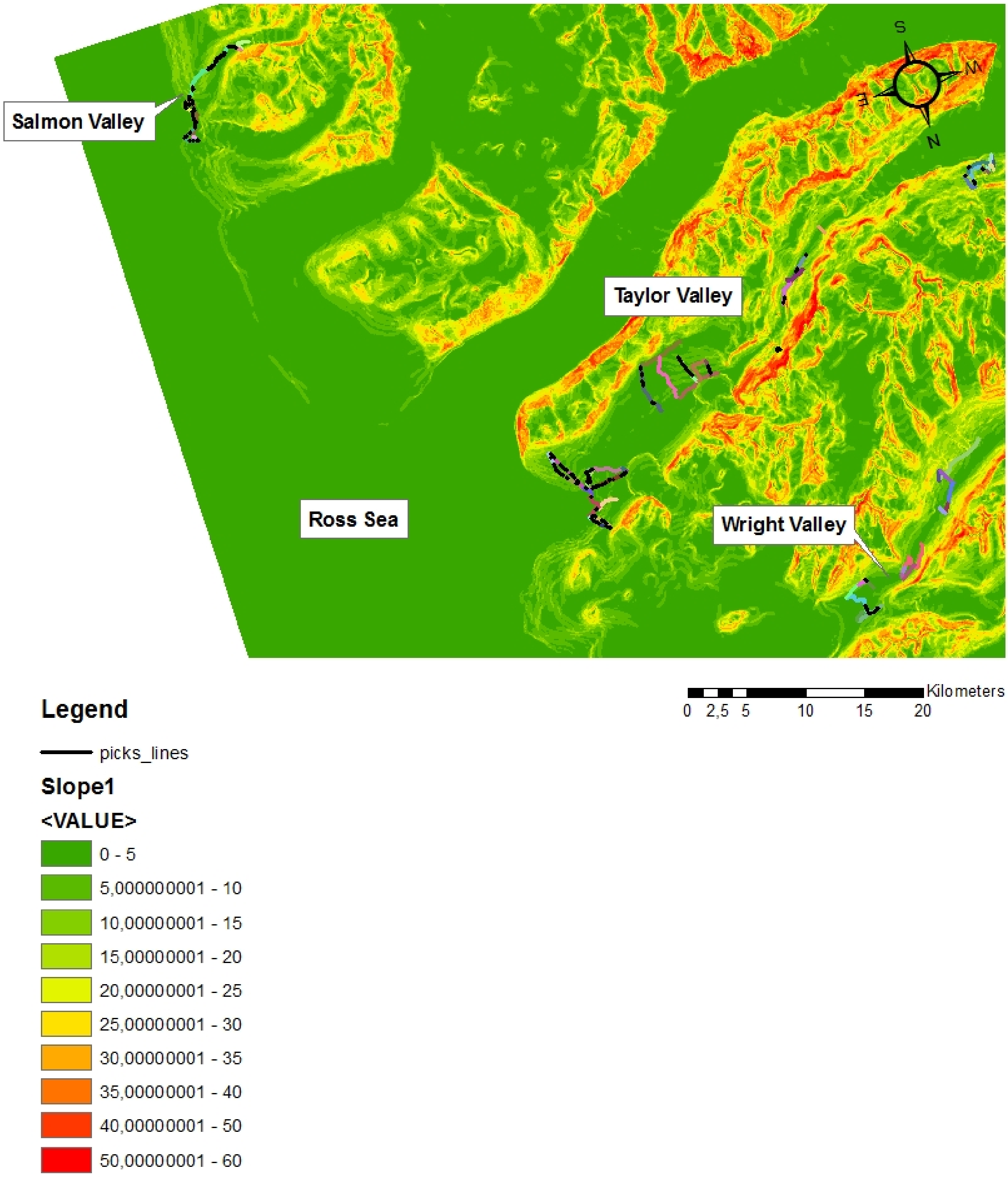
Appendix 5.2: The result from merging of appropriate profiles, showing all profiles in the whole area, both merged and single ones.



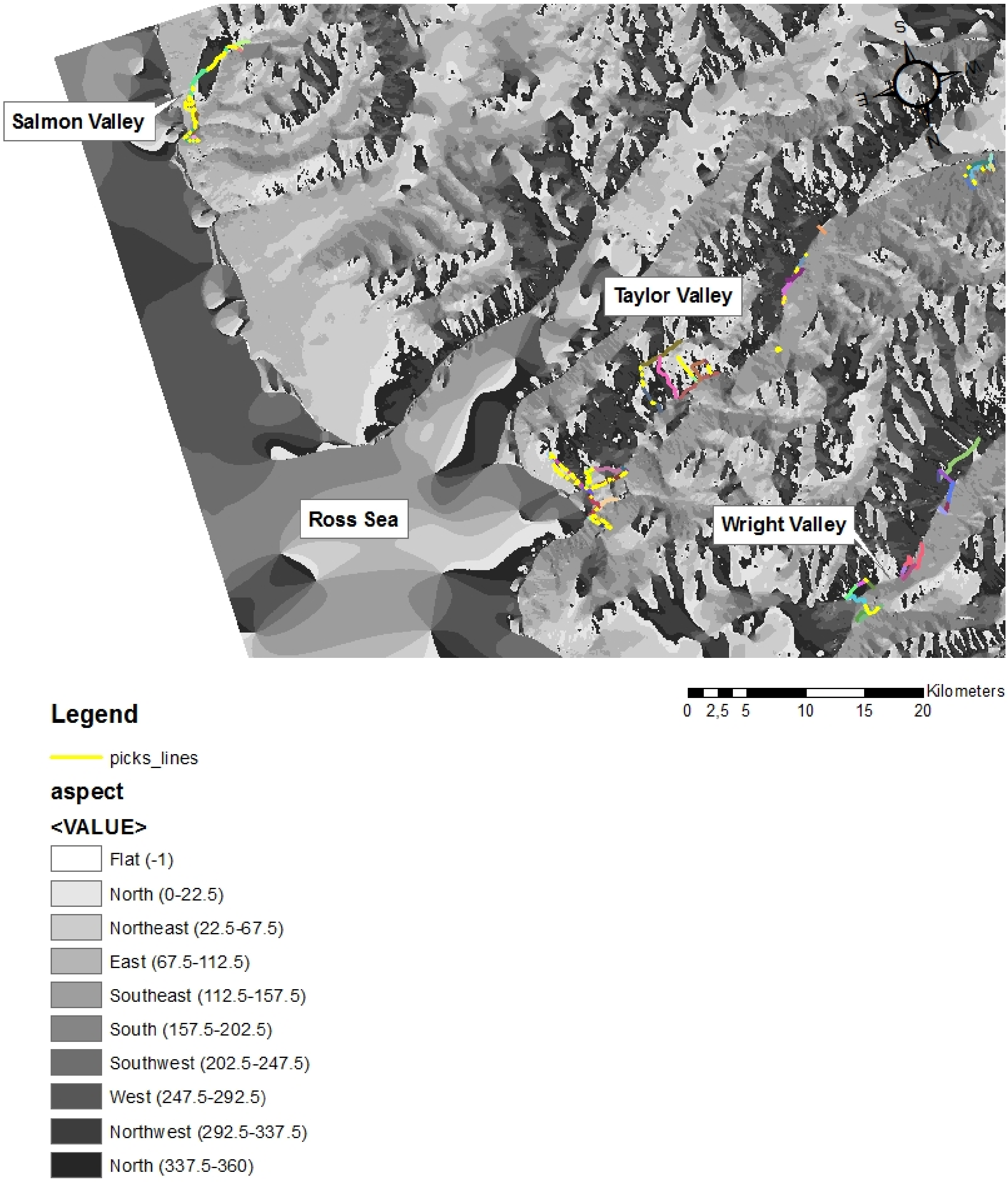
Appendix 5.3: Map showing the distribution of massive ground ice as yellow lines overlying all profiles as mixed colours.



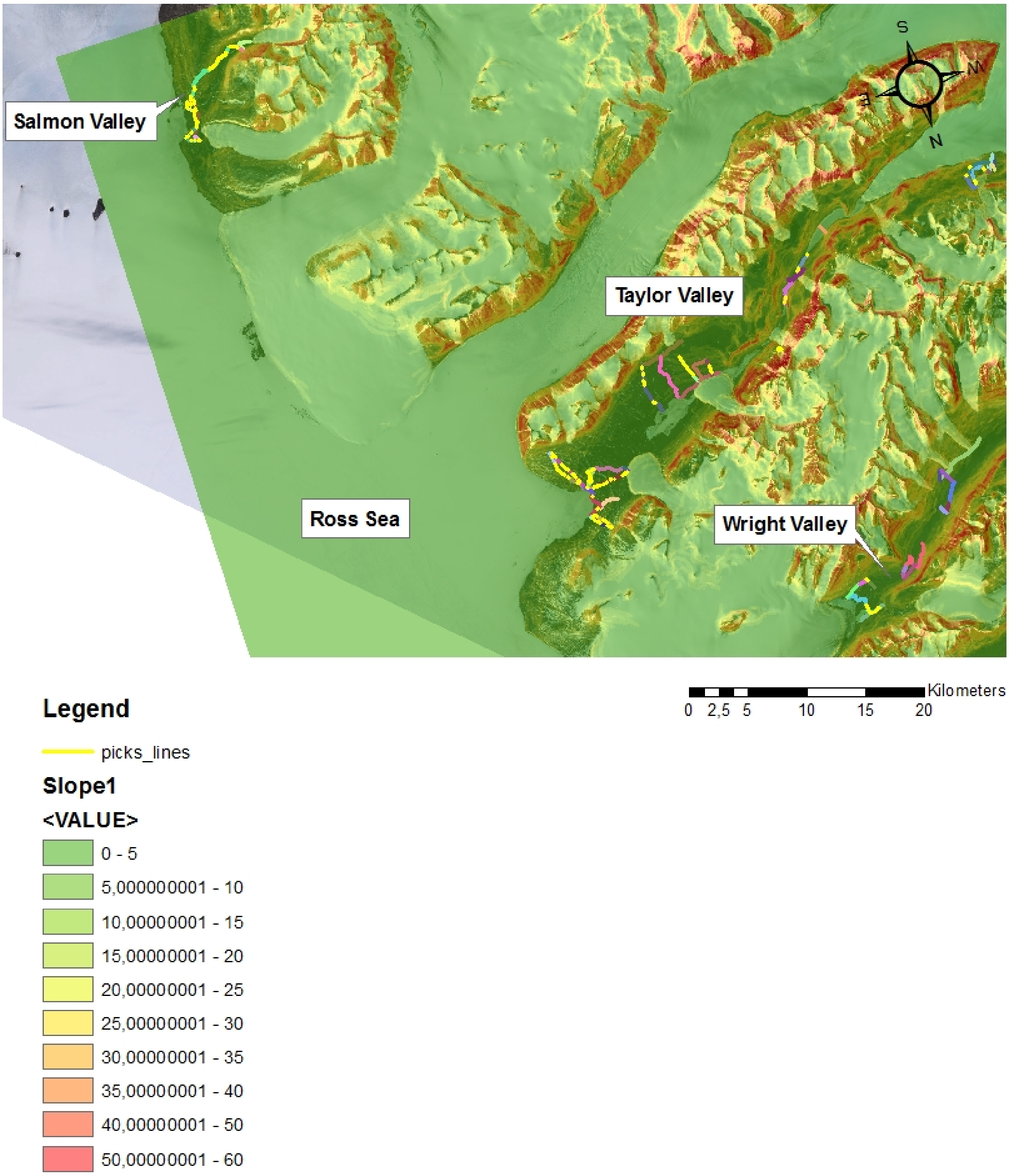
Appendix 5.4: The distribution of massive ground ice as yellow lines and all profiles as the mixed colours with the elevation raster as background.



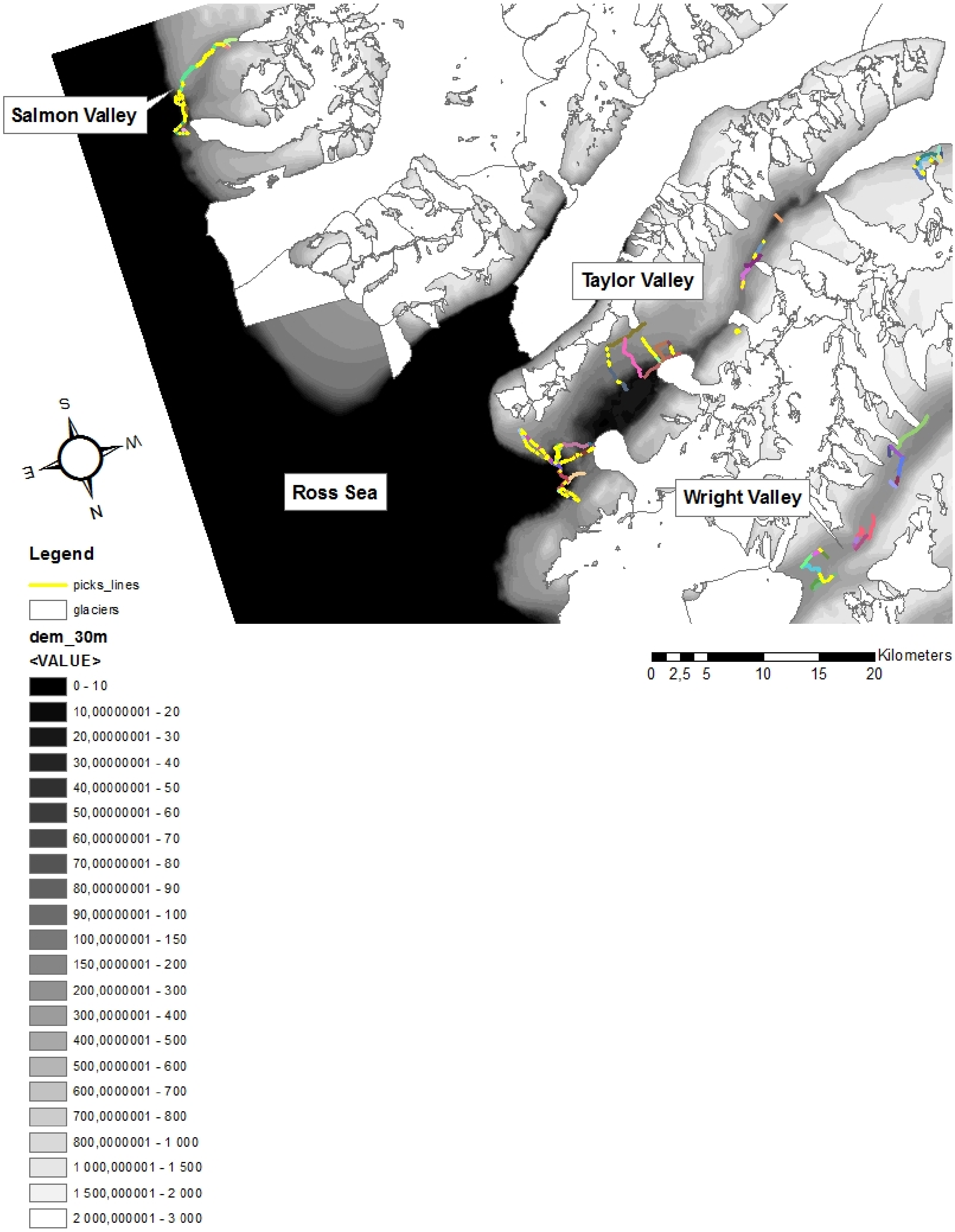
Appendix 5.5: The distribution of massive ground ice as black lines and all profiles as the mixed colours with the slope raster as background.



Appendix 5.6: The distribution of massive ground ice as yellow lines and all profiles as the mixed colours with the aspect raster as background.



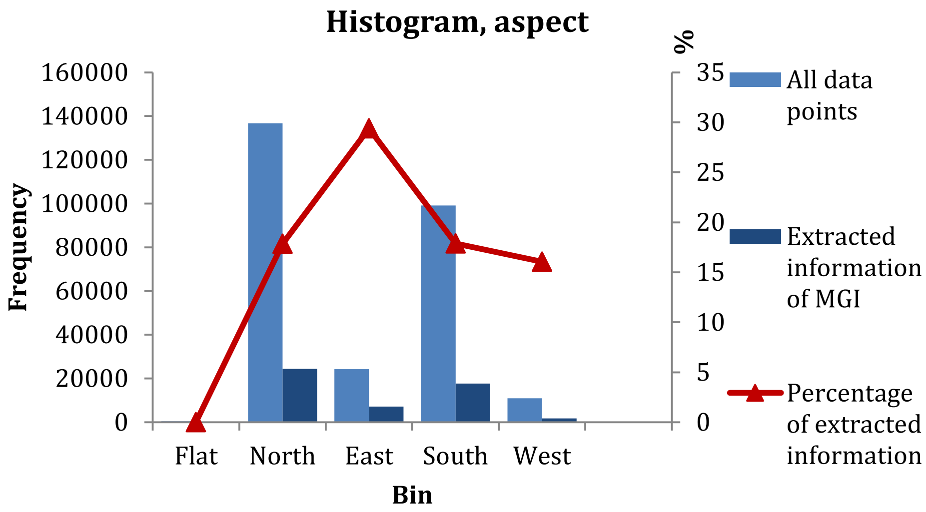
Appendix 5.7: The slope raster overlying the terrain raster, with the distribution of massive ground ice as black lines and all profiles as mixed colours.



Appendix 5.8: Glaciers in and around the McMurdo Dry Valleys, distribution of massive ground ice as yellow lines and all profiles as the lines with mixed colours.

10.6 Appendix 6

Appendix 6 consists of one histogram together with the bin and frequency data for the elevation, slope and aspect histograms.



Appendix 6.1: Summarized histogram showing the distribution of massive ground ice at the slope aspects flat, north, east, south and west.

All profiles		Digitations	
Bin	*Frequency*	*Bin*	*Frequency*
5	133124	5	25149
10	79282	10	19066
15	36547	15	4802
20	17655	20	1135
25	3962	25	707
30	859	30	145
35	0	35	0
40	0	40	0
50	0	50	0
60	0	60	0
More	0	More	0

Appendix 6.2: Tables showing the data received when creating the histogram for slope, showing the data frequency for different slope limits (bin, in degrees) for both all profiles and the extraction of information of massive ground ice made.

All profiles			Digitations	
Bin	*Frequency*		*Bin*	*Frequency*
10	18348		10	4104
20	6709		20	1253
30	8925		30	2824
40	8973		40	3249
50	16005		50	2948
60	10992		60	2281
70	5568		70	1334
80	5335		80	1180
90	7581		90	1945
100	13221		100	1899
150	25569		150	6337
200	19527		200	6650
300	62857		300	8460
400	25341		400	2384
500	7520		500	2271
600	5278		600	0
700	12841		700	733
800	5384		800	258
1000	5455		1000	894
1500	0		1500	0
2000	0		2000	0
3000	0		3000	0
More	0		More	0

Appendix 6.3: Tables showing the data received when creating the histogram for elevation, showing the data frequency for different elevation limits (bin, in meters) for both all profiles and the extraction of information of massive ground ice made.

All profiles			Digitations	
Bin	*Frequency*		*Bin*	*Frequency*
-1	375		-1	0
22,5	26483		22,5	6831
67,5	33371		67,5	7924
112,5	24288		112,5	7136
157,5	47466		157,5	8972
202,5	38239		202,5	6075
247,5	13460		247,5	2671
292,5	10938		292,5	1755
337,5	44575		337,5	5066
360	32234		360	4574
More	0		More	0

Appendix 6.4: Tables showing the data received when creating the histogram for aspect, showing the data frequency for different aspect limits (bin) for both all profiles and the extraction of information of massive ground ice made.

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