Periglacial landforms of the Ahlmannryggen and Jutulsessen areas of western Dronning Maud land, Antarctica

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Abstract

Periglacial landforms are a common occurrence in Ahlmannryggen and Jutulsessen areas of western Dronning Maud land (WDML). Classification and formation of these landforms were disputed in literature. In Antarctica information on periglacial landforms is limited or confined to a specific landform. Thus a holistic approach was taken when investigating the periglacial landforms found in WDML. An overview of the existing knowledge base on periglacial landforms in WDML was given which was coupled with the analysis of archival data. The landforms found in this area were patterned ground, openwork block deposits (OBD), rock glaciers, terraces, a pronival rampart and lake ice blisters. With patterned ground being the common periglacial landform in WDML, heave monitoring was used where time-lapse videos were used to investigate the formation processes in patterned ground. From consolidating existing knowledge as well as adding new knowledge on the formation of periglacial landforms, it is clear that the landforms in Antarctica should not be compared to other examples, especially examples from the northern hemisphere. Further research in the formation of periglacial landforms is needed and can be further enhanced with more extensive use of the heave monitoring method in future research.

Keywords: periglacial, periglacial landforms, periglacial environment, geomorphology, western Dronning Maud Land, freeze thaw cycles

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Table of Contents

Table of Figures

List of Tables

List of Abbreviations

µm	Micrometres
%	Percent/Percentage
°C	Degrees Celsius
3D	Three Dimensional
ARC	Antarctic Roadmap Challenges
cm	Centimetres
DGPS	Differential Global Positioning System
g	Grams
GIS	Geographic Information System
GPS	Global Positioning System
HD	High Definition
IPCC	Intergovernmental Panel on Climate Change
kg/m^3	Kilogram per meters cubed
km	Kilometres
m	Meters
mm	Milometers
NRF	National Research Foundation
OBD	Openwork Block deposit
SANAP	South African National Antarctic Programme
SCAR	Scientific Committee on Antarctic Research
UAV	Unmanned Aerial Vehicle
WDML	western Droning Maud Land

Chapter 1: Introduction

1.1. Background

Antarctica is the coldest, windiest and driest continent on the earth (Convey *et al.*, 2009). The lowest temperature recorded on the planet (-89,2°C) was at the Russian base (Vostok Station), which is on the Polar Plateau on Antarctica (Turner *et al.*, 2009). Antarctica is located south of the Antarctic Circle, with the exception of the northern region of the Antarctic peninsula and small parts of East Antarctica in Wilkes Land and Enderby Land (Convey *et al.*, 2009). Latitudes south of the Antarctic Circle (66°33′39″S) experience 24 hours of daylight at the summer solstice in December and then the opposite in June during the winter solstice (Convey *et al.*, 2009). There are few ice-free areas in Antarctica (less than 1%), which makes it globally unique and an important place to study landforms covered by ice (Bockheim and Hall, 2002). Antarctica contains 90% of the world's ice and is, therefore, influential on the world's atmosphere as the heat generated at the equator moves to the poles (Bockheim and Hall, 2002; Convey *et al.*, 2009; Vieira *et al.*, 2010; Kennicutt *et al.*, 2014). Thus, the continent acts as a heat sink and has an influence on the cryospheric system and atmosphere on Earth (Bockheim & Hall 2002; Vieira *et al*. 2010).

One of the reasons for doing research in Antarctica is that it is key to understanding climate change, as changes in climate are first manifested in the polar regions before anywhere else on the planet (Convey *et al.*, 2009; Guglielmin and Cannone, 2012). Antarctica is one of the few places on the earth that has little anthropogenic influence (Guglielmin, 2012; Guglielmin and Cannone, 2012; Terauds *et al.*, 2012), which means that scientific evidence for climate change with minimal human impact can be recorded (Kennicutt *et al*. 2014).

The Scientific Committee on Antarctic Research (SCAR) commissioned a study where involved scientists envisioned present and future research priorities for the continent (Kennicutt *et al*. 2014; Kennicutt *et al*. 2015). By conducting a horizon scan, a list of questions were developed and are seen as important to answer in the next two decades for the Antarctic region (Kennicutt *et al*. 2014; Kennicutt *et al*. 2015). A list of 80 key questions that are put into seven different categories (Kennicutt *et al*. 2014; Kennicutt *et al*. 2015). The research in this dissertation contributes to answering two of the questions:

> 39. "What are and have been the rates of geomorphic change in different Antarctic regions, and what are the ages of preserved landscapes?" (Kennicutt *et al*. 2015: 9).

42. How will permafrost, the active layer and water availability in Antarctic soils and marine sediments change in a warming climate, and what are the effects on ecosystems and biogeochemical cycles?" (Kennicutt *et al.* 2015: 9).

By using new ways of investigating the landscape and the history of the processes on the surface, the rationale behind question 39 will bring about new understanding of the landscape (Kennicutt *et al.* 2015). The landforms discussed in this research will contribute to the understanding of the landscape of Antarctica, especially in WDML as little is known about this region and research in this area is scarce.

Permafrost is a processes that influences landforms and a clear understanding of the role permafrost is vital to answer question 42. An accepted definition of permafrost is that it is ground that remains below a temperature of 0°C for two years consecutively, or longer (Summerfield, 1991; Bockheim and Hall, 2002; Burn, 2007). Permafrost varies in thickness from centimetres to kilometres (Burn, 2007). The layer can be found between the active (surface) layer and the depth of unfrozen ground (Burn, 2007). The active layer is that part of the ground above the permafrost that melts in the summer (Embleton and King, 1968). Published literature indicates that it can take up to a millennia for permafrost to form and can take just as long to degrade (e.g. Burn 2007). Climate has an influence on whether permafrost can form or not, the temperature of the air and the occurrence of snowfall in winter is needed for permafrost to develop (Burn, 2007). Moisture can be present in the form of ice or water, but it is not required for its formation (Bockheim and Hall, 2002). Permafrost degradation is an indication of climate change and the consequences have been discussed at length in an IPCC assessment (Fischlin *et al.*, 2007), which stated that it is vital to study the change in temperature of permafrost (Guglielmin and Cannone, 2012). Investigating permafrost can contribute to the understanding of water and its availability in ecosystems, especially under warming climates (Bockheim *et al.* 2013; Kennicutt *et al.* 2014).

Antarctica holds about 37% of the earth's permafrost (Bockheim and Hall, 2002), making it even more evident that research needs to be conducted in this area. Ice cemented permafrost is present in most areas of Antarctica, with the exception of the MacMurdo Dry Valleys (Bockheim and Hall, 2002). However, little is known about the permafrost in Antarctica (Bockheim, 2002; Fischlin *et al.*, 2007; Convey *et al.*, 2009; Vieira *et al.*, 2010; Guglielmin, 2012). Therefore, it is important to examine some of the confusion in the literature and also improve the understanding of permafrost. Thus, this research will contribute to answering the questions 39 and 42 as posed by Kennicutt *et al.* (2014). They are vital to add to the knowledge pool and provide the impetus for further studies.

Antarctica is seen as a wilderness that has not yet been fully explored or researched (Terauds *et al.*, 2012). Vieira et al (2010) identified areas that need further investigation, while it has been recognised as a specific and unique biogeographic region (Figure 1) (Terauds *et al.*, 2012). The biogeographic regions were assembled by comparing the groups that were created from an analysis of environmental domains and the areas which experts classified as defined bioregions (Terauds *et al.*, 2012). This dissertation focusses on an area of Antarctica, namely the western parts of Dronning Maud Land (WDML), which has been highlighted as one of the biogeographic regions (Figure 1) (Terauds *et al.*, 2012). Investigating periglacial landforms in this area will give indication of the habitat the landforms provide. There are many types of landforms but for the purpose of this research, periglacial landforms found at selected nunataks[1] in WDML were investigated and are discussed in detail in the literature review below.

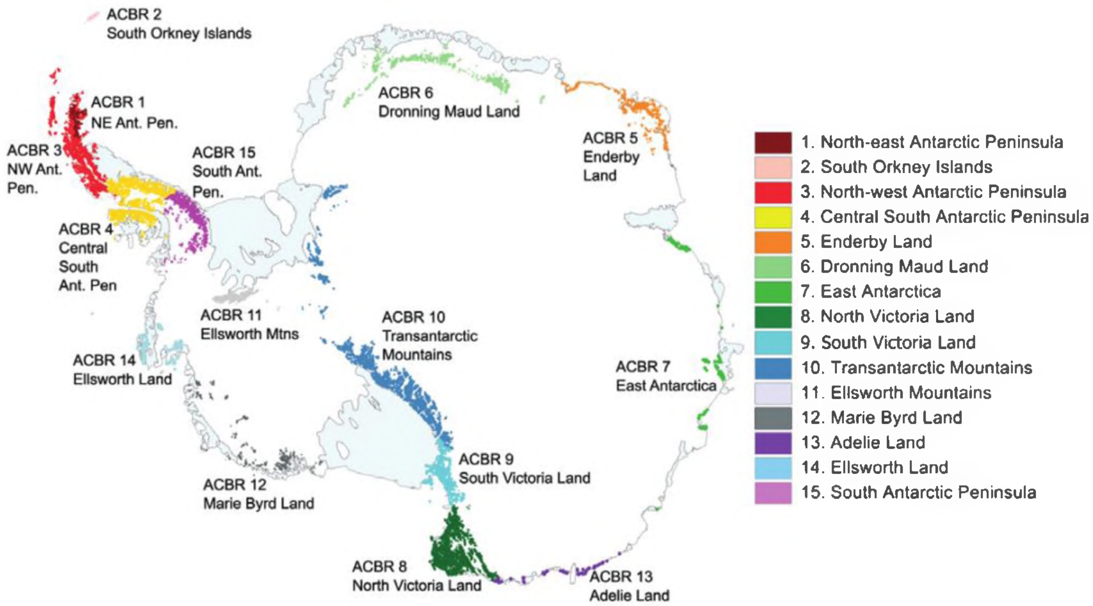

Figure 1: The fifteen Antarctic conservation biogeographic regions (Terauds *et al*. 2012: 734).

[1] Areas of exposed rock that is not covered in snow or ice.

1.2. Academic Problem

Literature on periglacial landforms is often contested and can become confusing and difficult to understand. Many studies highlight the importance of looking at the periglacial processes and landforms, for example; the periglacial landforms in the Antarctic Peninsula (López-Martínez *et al.*, 2012), sub-Antarctic region (Hall, 2002) and on the continent itself but mainly in the dry valleys (Hallet, Sletten and Whilden, 2011). There have, however, been previous studies on selected periglacial landforms in WDML where specific landforms are investigated, such as rock glaciers (Rudolph, 2015), blockfields (Hansen, 2014) and other landforms such terraces, polygons and patterned ground have been linked to the active layer (Scott, 2014; Kotzé, 2015). Considering the above, available information has been constituted and expanded upon for WDML in this dissertation. Furthermore, landforms that have not been mentioned in this area will be documented. Thus this dissertation looks at giving an overview of all the landforms found in WDML.

1.3. Aim and Objectives

Aim: Investigate the periglacial landforms on selected nunataks part of western Dronning Maud Land (WDML).

Objectives:

1. Consolidate the existing knowledge base regarding the periglacial landforms
2. Update on the periglacial landforms
3. Identify potential processes leading to patterned ground formation.

1.4. Structure of Dissertation

A review of the literature is presented to provide an understanding of the different types of periglacial landforms. The setting of the area is discussed to give an idea on what type of environment the landforms are found in. Methods chapter deals with how the data was collected and analysed. An overview of the archival data is presented and is followed by an update on periglacial landforms with 2016/17 data. Processes that lead to the formation of patterned ground is discussed. Limitations of the study and recommendations for the future are presented before the conclusion, which highlights how the aims and objectives are achieved.

Chapter 2: Literature Review

Literature relating to periglacial landforms is highly contested, which means that some of the landforms and the processes involved are not fully understood or explained (Boelhouwers and Meiklejohn, 2002). For example, the term periglacial and its definition is constantly changing (Berthling, Schomacker and Benediktsson, 2013). Concepts of periglacial geomorphology are discussed in order to get an overview on the environment and the processes involved with periglacial landforms. The different landforms that are found in the WDML area, are discussed in depth, as is the ongoing debate found in the literature.

2.1. Periglacial Environment

Periglacial Geomorphology which is a sub-discipline of Geomorphology that focuses on the processes and the landforms found in areas that are non-glacial but are still in cold regions (Clark, 1988; French, 2011). Periglacial environments cover approximately 20% of the land globally (French, 2011). It is important to consider the role of periglacial environments as they are significant in terms of the cryosphere (consisting of glacier, snow, river and lake ice, sea ice and frozen ground) and the impact they have on global change (Clark, 1988; French, 2011).

According to French (2011), Walery von Lozinski was the first person to use the term “periglacial” when investigating disintegration mechanisms of sandstone, where frost action was deemed to have been present. Furthermore, the term ‘periglacial’ is used where the climate and mechanisms influenced by climate are linked to Pleistocene ice sheets (Washburn, 1980). Today, the original definition is limited because frost action can be present over vast areas (both in Pleistocene and present day ice margins) and the term is used to describe processes that are active in cold-dominated areas (French, 2011). The word periglacial is linked to the idea of “inherited landscapes”, a concept by Migoñ and Goudie (2001), where the landscape could have been formed in a specific way in the past but it has been altered over time (Goodfellow, 2008). The term “periglacial” has been extended into considering non-glacial processes and landforms that are found in cold regions, without considering their age and how close they are in relation to glaciers (Washburn, 1980). Periglacial, as a term, has no quantitative measurements that have been recognised globally, but there is a rough measurement of the temperature limit (-15° C to - 1° C) for what would be considered periglacial (Washburn, 1980). Permafrost is a characteristic of the periglacial sphere, although it has been debated over time whether it is part of the definition of periglacial or not (Washburn, 1980). To consider the permafrost environment as a synonym for the periglacial environment is problematic as it restricts the definition

(Washburn, 1980). For example features such as patterned ground are periglacial landforms that are not necessarily related to permafrost (Washburn, 1980).

A periglacial environment is considered to be a non-glacial surface that is relict with clear boundaries from glacial areas (Goodfellow, 2008), yet there is no definition that has been accepted universally for what constitutes a periglacial environment (Goudie, 2004; Wilmot, 2015). This lack of a common frame of reference is problematic when trying to document and analyse periglacial landforms. The periglacial environment is influenced by many factors and these factors range from general to more localised factors (Washburn, 1980). They can also influence the processes involved in the formation of periglacial landforms (Washburn, 1980), especially when environmental conditions differ.

The independent environmental factors that are considered to influence the periglacial environment are climate, rock material and topography (Washburn, 1980). Washburn (1980) suggests climate be defined in three measurements. First, the zonal measurement considers effects such as the latitude and altitude (e.g. highland areas) (Washburn, 1980), which is vital when considering past climates and climatic changes in the environment (Washburn, 1980). Local climate (the second measurement) is a combination of the zonal climate and local topography influence (Washburn, 1980). The last measure is the microclimate. This is at a small scale which includes ground-surface characteristics (Washburn, 1980). The microclimate can change over short distances between areas and these changes can be lateral and/or vertical (Washburn, 1980). Microclimate is important in Antarctica as it can determine, or explain, some of the processes found there (Washburn, 1980). Temperature, wind, seasonal distribution and precipitation are important aspects of climate that control periglacial processes (Washburn, 1980).

Topography is another environmental factor and it determines the climate to some extent (Washburn, 1980). The altitude of an area determines the climate which impacts the processes that take place (Washburn, 1980). Factors such as aspect and slope explain the spatial and temporal changes in terms of climate and moisture availability (Washburn, 1980).

Rock material, which includes texture, structure, mineral composition, bedrock and colour, also has an influence on the periglacial processes (Washburn, 1980). The composition of the parent rock will affect the time it takes and the way in which it will be weathered (Rea, 2007; Hansen, 2014). Bedrock, however, is not part of the periglacial processes as it would be an older feature and existing before the processes began (Washburn, 1980). Soil formation is independent, as well as being dependant on climate (Washburn, 1980). Soil forms from a number of processes, especially how it influences the bedrock (Washburn, 1980). However, climate can influence the bedrock which impacts soil formation (Washburn, 1980). The structure of rock is the result of many different processes, for example joints and fissures are due to moisture, which cause erosion (Washburn, 1980). The mineral make up of rocks influences how the rock reacts to abrasion and weathering (Washburn, 1980). The texture of the rocks determines how the rock responds to processes; for example, coarse rock is more susceptible to erosion than fine grained material (Washburn, 1980). The porosity of the rock and the amount of moisture absorption that occurs contributes to the weathering of the rock (Briggs, 1977; Hansen, 2014). The colour and the dimensions of the rock material are also important as they can affect the temperature (Washburn, 1980; Poesen and Lavee, 1994). For example, rocks that are dark coloured, tend to absorb more radiant heat as well as warm areas that are close to or touching them compared to lighter coloured rocks (Washburn, 1980). Thus, thawing can take place in low temperatures due to the rock being warmer than the air temperature causing the snow to melt off the rocks (Washburn, 1980). Rocks with a darker colour will tend to affect water availability (Ayres, 2016). The angle and altitude of the sun influences the temperature of the rock (Ayres, 2016). Rock surface temperature depends on rock properties and climatic controls (Jenkins and Smith, 1990; Ayres, 2016).

Time is a vital factor as the more time there is, the more processes and influences can take place, especially in the case of periglacial research (Washburn, 1980). Some features such as fossil frozen ground are identified through a timeline, rather than looking at the present climatic conditions (Washburn, 1980). In addition, many of the processes that form periglacial landforms take a long time to develop, especially patterned ground.

Snow and ice cover are determined by the topography and the climatic conditions (Washburn, 1980). Snow is a good insulator due its high porosity (Washburn, 1980). Ice, however, is a poor insulator but it can prevent a lake from completely freezing vertically as well as promoting permafrost development, depending on the prevailing conditions (Washburn, 1980). Influenced by snow and ice, liquid moisture is dependent on climatic conditions, the rock material and topography (Washburn, 1980). The rock material influences the amount of liquid moisture that can be found in the ground and the texture of the rock can promote frost action (Washburn, 1980). Liquid found in soils is important as the solutes in the soil can alter the freezing point to be lower than usual (Washburn, 1980). In the Antarctic dry valleys this is true as the salinity in the soils, determined by solutes, lowers the freezing point to the point where freezing cannot take place thus allowing movement of the pore fluids (Washburn, 1980).

The frost action process is important when considering the process of freezing in that takes place in Antarctic soils. According to Washburn (1980), freeze thaw activity occurs, when water that is present in the particles of the soil thaws and freezes below zero degrees Celsius. Freezing changes the volume of the soil and ice (Washburn, 1980). The freezing of the soil is complex and not well understood, especially in the detail about the process and the movement of moisture (Washburn, 1980). Frost action relies on moisture to be present (Washburn, 1980). The amount of moisture present can determine the type of patterned ground that develops (Washburn, 1980). Temperature is important as the establishment of the ice lenses as well as the heaving action rely on temperature (Washburn, 1980). If freezing is rapid, then the moisture will freeze *in situ* (Washburn, 1980). Freeze thaw cycles can vary diurnally, creating differential frost heave (Matsuoka, Abe and Ijiri, 2003). Differential frost heave is the difference between each heave cycle and differs between coarse and fine material (Matsuoka, Abe and Ijiri, 2003). Cryoturbation is a term that is utilised to explain the process of patterned ground formation. This term can be confusing as two meanings have been identified (French, 1996). While cryoturbation can be used as a term to define frost action that affects all soil movements, it can also be used to explain the structures that form due to frost related processes such as frost action (French, 1996). Many periglacial landforms are linked to the processes of freeze thaw (Summerfield, 1991), and will be discussed further in the Periglacial Landforms section.

2.2. Nivation and Cryoplanation

Nivation and cryoplanation are presented as processes active in Antarctica but in the manner that one cannot separate the one from the other (Bockheim and Hall, 2002). Nivation is active in cirque-like structures in the Queen Maud Land mountains and is specifically related to warmer climatic periods (Bockheim and Hall, 2002). In order to understand the complex issues with nivation and cryoplanation, they both need to be explained separately and the issues will be highlighted subsequently.

2.2.1. Nivation

Nivation is defined as "combined action of frost shattering, gelifluction and slopewash processes thought to operate in the vicinity of snowbanks" (French, 1996: 159). Nivation is, thus, used as a noun to describe a suite of processes (the above three processes), as well as an adjective to identify the landform that is a product of the processes (Hall 1998; Thorn 1988). One of the dilemmas with nivation is the question as to whether the nivation happens after a hollow or landform is formed or if it creates the landform. (Hall 1998). If it is the former, then it means that other different processes created the landform, and nivation merely enhanced it (Hall 1998).

2.2.2. Cryoplanation

The term cryoplanation was first used by Bryan (1946) but the use of the term has confused rather than contributed to understanding it (Hall & André 2010). The term cryoplanation is defined as a "cryogenic process promoting the low angled slopes and level bedrock surfaces typical of many periglacial regions" (French, 1996: 181). Cryoplanation processes are what develop cryoplanation terraces which may be related, or not related, to the nivation process (Hall 1998). There is a discrepancy in literature due to some authors claiming that cryoplanation and nivation are different, but they are seen to be linked or to be similar. Snow impact in the two processes is what differentiates them (Hall 1998).

2.2.3. Confusion between the two terms

The two terms, nivation and cryoplanation are seen as being terms for separate landforms (Hall 1998). However, both terms use the same process to classify different landforms (Hall 1998). Literature contributes to the confusion and asks the question whether these terms are separate or if there is a link between them (Thorn, 1988; Hall, 1998). Both terms are used in two ways; one being as an adjective where it describes the landform as a product of a suite of processes (Thorn, 1988; Hall, 1998). The terms can also be used as a collective noun where they describe a process that falls within the suite of processes (Thorn, 1988; Hall, 1998). Furthermore, according to literature, nivation is something that contributes to the formation of hollows that are found in rock for example, but in the cryoplanation literature, nivation is seen to cause or start the processes of terraces (Thorn, 1988; Hall, 1998). Nivation and cryoplanation are part of the same "process-landform suite" but from different sections or sides of this 'suite'(Hall, 1998; Hall and Andre, 2010).

Climatic differences between the two terms have been identified (Hall 1998). In the cryoplanation literature, it is said that permafrost indicates the climatic difference, and a cryoplanation terrace means that permafrost is present, whereas in the nivation literature, there is no evidence that permafrost has an influence (Hall 1998).

Hall (1998) suggested a new model in which cryoplanation and nivation are seen not to be separate, but rather part of the same suite of processes. This new model is related to moisture where the nivation process is wetter and snow derived, and cryoplanation is a dry environment that is predominantly permafrost based (Hall 1998). It is, therefore, important to note the presence of moisture as it influences whether the process will be cryoplanation or nivation (Hall, 1998). They are part of the same suite of processes but considered independent from each other (Hall 1998).

2.2.4. A new term proposed

A problem with the term cryoplanation is that it has synonyms that are used to describe a landform; and to make it more confusing, the word cryoplanation was used along with the synonyms in the same paper (Hall 1998). In some instances, cryoplanation and nivation are used as synonyms in literature (Hall 1998).

The difficulty between cryoplanation and nivation is the discrepancy existing in their formation. To resolve the issue and not confuse the reader, a single term is proposed by Hall (1998). The end result of the landform is viewed as one entity which is formed by many variables and processes and thus creates 'one landform' (Hall 1998). Hall (1998) suggests the term 'periglacial mountain bench' which is a landform found in mountainous and cold regions and is seen to possibly have a periglacial origin (Hall 1998). Periglacial mountain bench suggests that the processes involved to create the end product are not specified (Hall 1998), therefore, a periglacial mountain bench is created by a suite of processes that would vary through time (Hall 1998).

2.3. Periglacial landforms

The landforms discussed below all have literature that is contested. The terms used to describe some of these landforms are used in a manner where the explanation of the landform does not relate or link to the term, which creates confusion of what term defines what landform (Bockheim and Hall, 2002). The landforms deliberated below are landforms that have been identified in WDML.

2.3.1. Patterned Ground

According to Embleton and King (1968), patterned ground is one of the most visible ,or obvious, group of landforms in a periglacial environment. Washburn (1980), proposed terminology (Table 1) to explain and describe patterned ground, which has been widely accepted due to its simplicity (Krantz, 1990; French, 1996). Patterned ground describes the surface of ground that has patterning which can be regular or irregular and may comprise of sorted or non-sorted material (Ballantyne, 2007; French, 2007). Common forms of patterned ground include: polygons, circles, stripes, irregular networks, lobes, garland patterns, oval and step-like patterns (French, 1996; Grab, 2002; Ballantyne, 2007; Warburton, 2013). There are many forms of patterned ground, which has led to the development of numerous definitions to explain or define them (Washburn, 1980). A patterned ground feature is identified through the description of the feature which may involve a number of ways to describe the same feature (Washburn, 1979).

Table 1: The classification of patterned ground (adapted from Washburn 1956).

Form		Sorting	Types included (Washburn 1956)
Circles	Flat	Non-sorted	Peat rings, tussock rings
	↓	Sorted	Debris islands
Polygons		Non-sorted	Frost-crack, ice-wedge, desiccation
		Sorted	
Nets		Non-sorted	Earth hummocks
		Sorted	
Steps		Non-sorted	
		Sorted	
Stripes		Non-sorted	
	Steep	Sorted	

Patterned ground is found in many different environments, however, most patterned ground is linked to periglacial or cold environments (Embleton and King, 1968; Washburn, 1980; Ballantyne, 2007; Warburton, 2013). While patterned ground can occur in environments that are not periglacial, a different suite of processes can cause the sorting (Ahnert, 1994; Warburton, 2013). The regions in which one would find patterned ground are heavily influenced by cryogenic processes or frost action, and these processes are normally linked to permafrost (Warburton, 2013). Patterned ground is normally located in the active layer, and can be found in a relict or active state (Embleton and King, 1968). These landforms can be used as evidence for past climates (Embleton and King, 1968). In periglacial environments, thawing and freezing are evident in the soil and, thus, cold climate and permafrost does not have to be present for the development of certain types of patterned ground (Krantz, 1990; Ballantyne, 2007). The formation of ground ice and frost are vital in determining the origin of patterned ground (Embleton and King, 1968). From a periglacial perspective, two processes have an impact on the formation of patterned ground (French, 1996). The first process involves cracking as a crucial contributor, and the second where cracking does not necessarily have to have taken place (French, 1996).

Literature recognises that there is a difference between how non-sorted and sorted patterned ground forms (Ballantyne, 2007). It is important to look at the how the sorting has occurred as well as the shape of the landform in order to determine what type of pattern ground exists (Embleton and King, 1968). Sorted patterned ground comprises alternating coarse and fine sediment on the ground surface (Ballantyne, 2007). The width of the patterned ground is related to the size of the clasts that form the margins of the pattern (Goldthwait, 1976; Ballantyne, 2007). Non-sorted patterned ground is influenced by the constant change between depression and mounds or, furrows and ridges, as well as vegetation cover; where it changes from vegetated to unvegetated (Ballantyne, 2007). There are various landforms that fall under these two descriptions (Table 1). The landforms, however, can morph or flow into one another (Embleton and King, 1968).

2.3.1.1. Polygons

Polygonal patterned ground is distinctive and found in the polar regions (Hallet and Prestrud, 1986; French, 2007; Hallet, Sletten and Whilden, 2011). Polygons have a general pattern of fines in the middle with a stony border-like crack surrounding it (Washburn, 1980) with thermal contraction being the primary mechanism to create the feature (Hallet, Sletten and Whilden, 2011). Polygons are one of the most well-known types of patterned ground landforms and there are many terms that have taken shape under the polygon landform (Embleton and King, 1968). The formation of this landform is influenced by the diurnal and annual changes in temperature and the rate at which frost penetrates the soil (Embleton and King, 1968). Polygons in general can form in environments that have permafrost or even seasonal frost (Embleton and King, 1968). These landforms are important in terms of climate and paleoclimate because cracking requires the presence of permafrost (French, 2007). The angle of intersection in a polygon net tends towards a right angled pattern, but angular junctions of hexagonal patterns have been observed (French, 2007). Polygons that are in different stages of development have been identified in Antarctica (French, 2007). Their cracks, are produced by the cooling of the ground surface when the tensile strength of frozen soil in the subsurface is exceeded (Sletten, Hallet and Fletcher, 2003; Hallet, Sletten and Whilden, 2011). These thermal contraction cracks open up in cold periods at the ground surface level (Hallet, Sletten and Whilden, 2011). Large thermal-contraction-crack polygons are observed to be the most common landforms found in the Northern Foothills of Antarctica (French and Guglielmin, 2000). They are surrounded by troughs and interpolygon furrows, however, there are similar landforms that have been noted in the Dry Valley Antarctica (French and Guglielmin, 2000). It is, therefore, important to consider whether they are the same landform and whether they are also found in other areas of Antarctica, otherwise they could be considered as unique landforms. Polygons found in Antarctica were identified to have a hexagonal pattern or a random orthogonal pattern (French and Guglielmin, 2000). Scott (2014) creates a 3D (Three dimensional) model of the polygons in WDML and Kotze (2015) discusses and maps polygons features relating to the active layer. The McMurdo Dry Valleys have been identified as areas where all types of polygons are recorded (Bockheim, 2002). There are certain types of polygons (ice-wedged polygons) that can only form in an area where permafrost is present and these landforms are vital for research into palaeoclimatic studies (Embleton and King, 1968).

Ice-wedge polygons are thermal contraction polygons, but differ in their characteristics such that melt water fills the cracks and creates a wedge when the water freezes and the borders of the polygon can be lower or raised depending on the centre materials (Embleton and King, 1968; Washburn, 1979; Hallet, Sletten and Whilden, 2011). A raised bordered ice wedged polygon has a furrow in which a bulge of ice on either side forms due to the underlying ice wedge and growth of permafrost (Washburn, 1980). A depressed border develops when thawing occurs and the centre of the polygon then heaves upwards (Washburn, 1980). They do need permafrost to exist (French, 2007). There is very little sorting that takes place in the formation of ice wedge polygons (Embleton and King, 1968). In Antarctica, ice-wedges are not as well developed as ice-wedges found in other parts of the world due to the fact that there is a lack of moisture (French, 2007). According to Péwé (1962), there are certain conditions that have to be present in order for ice wedge polygons to form (Embleton and King, 1968). Ice-wedge polygons have, therefore, been separated into three groups by Embleton & King (1968). The first group represents active ice-wedges, where permafrost is permanent and the temperature is between -6°C to -12°C (Embleton and King, 1968). Where temperatures are between -2°C and -8°C and permafrost is not continuous, more ice is not added to the wedge and frost cracking does not frequently occur in the formation of inactive ice-wedge polygons (Embleton and King, 1968; Washburn, 1980). Fossil ice-wedges, the third group, occur when the ice is melted and sediment takes its place (Embleton and King, 1968).

Sand-wedge polygons, also known to occur in Antarctica, are similar to ice-wedge polygons but differ in that they have sand-wedges instead of ice (Washburn, 1980). Sand-wedge polygons are associated with permafrost and formed through the process of frost cracking being repeated over time, filling cracks with sand rather than ice (Washburn, 1980; Summerfield, 1991). Sand-wedge polygons tend to occur in areas where the soil is dry (Washburn, 1980).

There are also non-sorted polygons that do not have a distinct border of larger stones but the pattern forming a polygonal shape, with or without a furrow (Washburn, 1980; French, 1996). The small non-sorted polygons form a mesh or net over a larger area of land (French, 1996). As stated above, permafrost presence is not required for the formation of non-sorted polygons (Embleton & King 1968). They are located in flat areas but have been documented on slopes (Washburn, 1980). The material found in the mesh area ranges from fine sand to gravel (Washburn, 1980). Larger non-sorted polygons do occur, but they are usually linked to ice-wedges as they are found at the edge of the polygon (French, 1996). Non-sorted polygons are found at Beacon Valley (Antarctica) where they are located on the valley floor and slopes (Linkletter, Bockheim and Ugolini, 1973). Some of the them were active, while others had contraction cracks and they ranged from being well developed to still forming (Linkletter, Bockheim and Ugolini, 1973).

Sorting does occur amongst polygon landforms and there are three mechanisms proposed by Embleton and King (1968). The first is sorting by frost heaving or uplift, which happens in action of thawing and freezing from the top of the soil (Embleton and King, 1968). Second, is sorting by the process of migration located in front of the freezing plane, and this happens when thawing and freezing occurs on the side or top of the polygon (Embleton and King, 1968). Lastly, mechanical sorting occurs when freezing takes place from below and thawing occurs from above leading to mound formation (Embleton and King, 1968). Vertical sorting takes place when the thawing or freezing initiates at the ground surface and the finer sediment moves toward the bottom, resulting in coarse sediment at the top (Embleton and King, 1968). Lateral sorting occurs due to thawing or freezing taking place on the sides of the polygon and the fine particles move away from the side whereas the coarse particles stay near the thawing side (Embleton and King, 1968).

Stripes are other features that are linked or formed from an original polygon and become more distinct as the gradient increases (Embleton and King, 1968). These landforms are more likely to form as a continuation of sorted polygons, due to similar processes being active (Embleton and King, 1968). Stripes that are sorted comprise alternating coarse and fine sediments (Embleton and King, 1968). Unsorted stripes have vegetation present were it alternated between vegetation and sediment (Embleton and King, 1968), but this landform is not found in WDML. It is rare to find stripes in Antarctica but non-sorted stripes are recorded in the Dry Valleys (Antarctica) by McCraw (1967).

2.3.1.2. Circles

Circles are found in an area where there little to no vegetation and where the coarse clasts are surrounded by finer material (Ballantyne, 2007). They are identified as having a border of stones as well as a circular mesh of fines (Washburn, 1956, 1980; Embleton and King, 1968; Holness, 2003). The clasts increase in size as one moves away from the centre of the circle (Washburn, 1980). This landform is characteristic of the polar regions, being well developed in areas where permafrost is present (Washburn, 1980), however, various mechanisms drive these formations.

The sediment present also plays a role when it comes to the development of the sorting process (Embleton and King, 1968). Sorted circles can comprise of cells or circular shapes, that have larger clasts surrounding finer sediments, an example is sorted circles (Washburn, 1956; Ballantyne, 2007). An example of a type of sorted circle (debris islands) is where fine material can be found amongst boulders on slopes (French, 1996). They can arise in groups or by themselves, and permafrost does not need to be present in order for these landforms to form (Embleton and King, 1968). Typically, the size of sorted circles is influenced by two factors: first, the deeper the frost action in the fine sediment the larger the circle and second, the circles are generally smaller if there is a small layer of fine sediment (Washburn, 1980). Non-sorted circles do exist, but they generally do not have a defined border of stones, their mesh is circular and they can be surrounded by vegetation (Washburn, 1980; French, 1996). The landform can reach a stage where it is not active anymore (Washburn, 1980). A good indicator of this is the presence of lichen and the development of stones (Washburn, 1980). The evolution of the circle must be taken into account when considering if a sorted circle is active or not (Washburn, 1980). Research on the morphology of the pattern and processes involved limits our knowledge on this, making it difficult to determine its activity (Holness, 2003).

Sorted circles have been documented in WDML where they are used in assessing the active layer (Meiklejohn, 2012; Kotzé, 2015). Kotzé (2015) identifies sorted circles and half circles to be active in WDML and maps them according to the areas that were investigated. Sorted and half circles are found in an OBD (Open Block Deposit) in WDML by (Hansen, 2014). Imbrication of sorted circles are found in the Beacon Valley, Victoria Land (Antarctica) (Linkletter, Bockheim and Ugolini, 1973). Well-developed sorted circles are investigated at King George Island, West Antarctica (Zhu, Cui and Zhang, 1996; Jeong, 2006; Michel *et al.*, 2014) and on the slopes of McMurdo Sound, there are sorted circles present (McCraw, 1967).

2.3.1.3. Steps

A step-like patterned ground has been documented on steep slopes (Embleton and King, 1968; Washburn, 1980). In the sorted formation, steps have wall-like borders with larger stones compared to the rest of the material found in the middle (Embleton and King, 1968). The steps can form parallel to the contours of the slope, but they can develop into a lobate form depending on the degree of the slope (Embleton and King, 1968). Steps do not develop on their own but are rather derived from other landforms such as polygons, circles and nets (Washburn, 1980).

There are many terms associated with steps, especially since they can morph into lobate-like forms, such as stone garlands and stone banked terraces (Embleton and King, 1968). Sorted steps can form groups but can also occur as a singular feature (Embleton and King, 1968). Unsorted steps can be smaller in size and have vegetation present on the on the raised border (Embleton and King, 1968). Thus, other terms such as “turf garlands” and “turf-banked terrace” are associated with unsorted steps (Embleton and King, 1968); this questions whether these are related to terraces in terms of their development. Furthermore, if the steps are irregular in shape, then they can become stripes if the slope angle increases (Embleton and King, 1968).

2.3.1.4. Development of Patterned ground

There are many features that are part of the patterned ground category. The processes involved in the formation of the different features are the same to some extent. Sorted patterned ground can either be relict (where there are many ways of identifying them, such as whether lichen that is present on the clasts) or active (where there is movement in the fine sediment as well as the clasts) (Ballantyne, 2007). Secondary sorting can occur where a smaller pattern is developed by clasts in the centre of the polygon (Ballantyne, 2007). During the thaw period, the outer larger clasts may be either raised above the finer sediment or appear below it (Ballantyne, 2007). Active sorted patterns have finer sediment that will heave and rise above the level of the larger clasts, especially in winter (Ballantyne, 2007). The process of the heaving of finer materials is something that needs attention, especially in Antarctica, as it can lead to formations that are not yet fully understood.

Numerous assumptions have been made on how sediment moves to form sorted patterned ground and three main theories exist on how they develop, namely (Ballantyne, 2007):

1. Differential frost heave occurs when sediment moves in a lateral direction, where the fine sediments move to the centre and the larger clasts move to the outside of the formation, which means that the freezing plane leads to frost heave due to its uneven angle (Nicholson, 1976; Ballantyne, 2007). Differential frost heave is a mechanism that develops sorted circles as well as polygonal forms (Holness, 2003).
2. Soil circulation occurs where patterns form due to "buoyancy-driven convection cells" that are found in freezing and thawing soils (Ballantyne, 2007: 2186). Hallet & Prestrud (1986) created a model for the displacements of sediments within sorted circles (Figure 2) (Ballantyne, 2007; Warburton, 2013). The sediment in the fine domain moves in a convection motion (Hallet and Prestrud, 1986). Contact between the fines and coarse material leads to subduction which then leads to a rolling action in the coarse border area (Hallet and Prestrud, 1986).

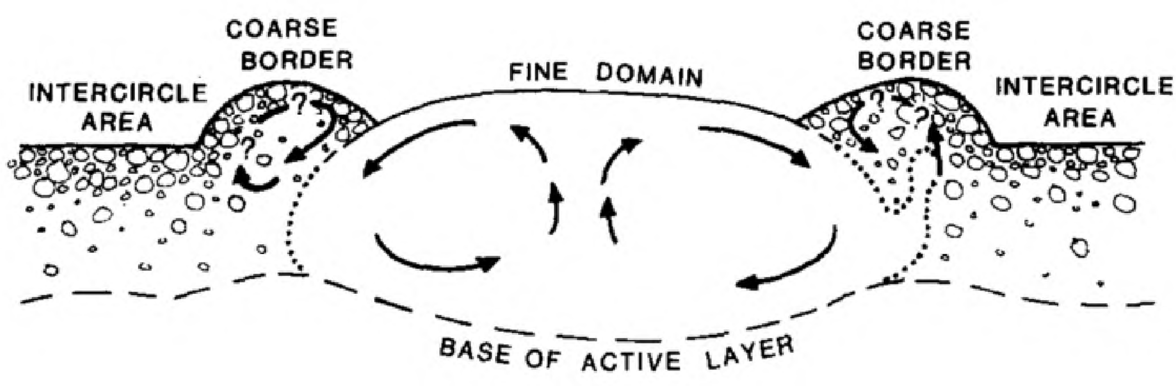

Figure 2: The simplest model for the displacements of sediments (Adopted from Hallet & Prestrud, 1986: 90).

3. “Free convection of pore-water” occurs when convection cells are produced during the thaw period, where warm dense water descends, causes melting; and cooler water ascends, leading to cooling at the surface (Figure 3) (Ballantyne 2007: 2187; Warburton 2013; Krantz 1990).

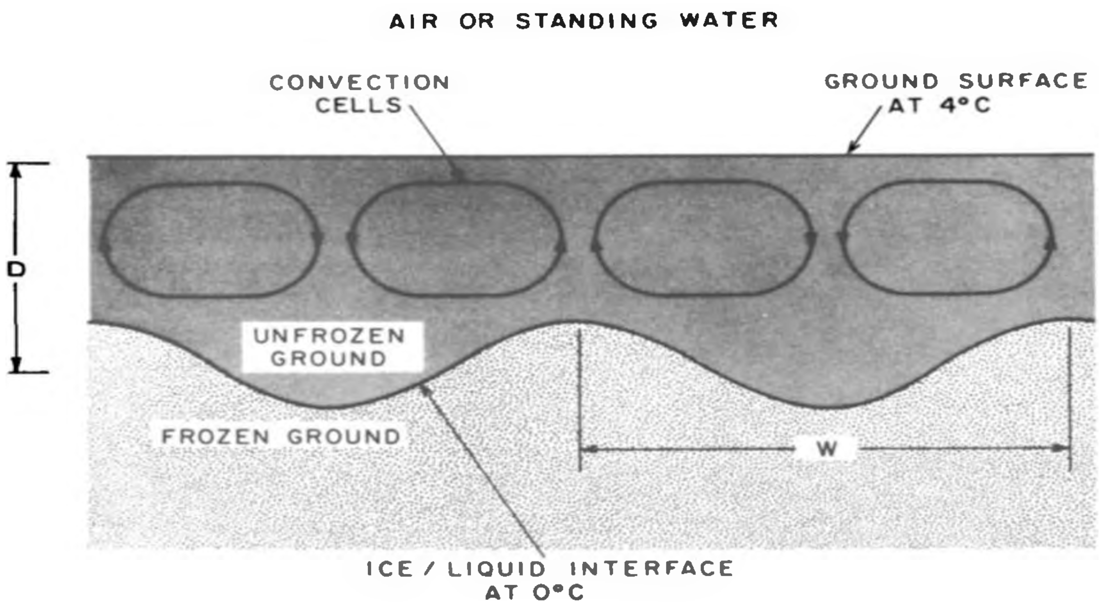

Figure 3: A cross section of free convection cells which are formed due to the freezing and thawing of the soil (Adopted from Krantz, 1990: 122).

The literature that covers patterned ground broadly considers the influential processes. However, a fundamental flaw exists. The mechanisms responsible for the sorting of different patterned ground is confusing and inconsistent (Warburton, 2013). Disjointed literature is evidence to this. The best way to understand patterned ground and its relevant processes is through Washburn's (1979) Venn diagram, which is purely descriptive (Figure 4) (Warburton, 2013). The diagram shows how patterned ground features are all linked by some processes but there are aspects which are unique to the feature.

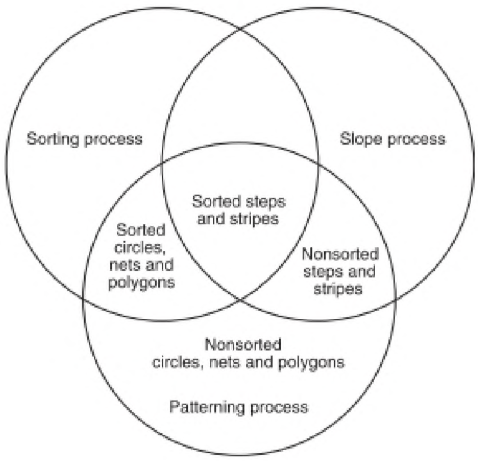

Figure 4: A Venn diagram showing how patterned ground, slope processes and sorting processes are interlinked (Adopted from Warburton 2013; Washburn 1980).

2.3.2. Openwork Block deposits (OBDs)

There are many terms that authors use to describe OBDs as well as processes involved in their formation (Wilmot, 2015). OBDs are an important landform in periglacial research (Boelhouwers, 2004). OBDs are periglacial landforms found in areas between mid-latitudes or high latitudes, but they have been documented in lower latitudes areas (Rea, 2007). They are generally described as areas where the surface is covered with blocky material, without an interstitial matrix, which "flows" from a rock headwall or where the profile is matrix supported (Rea, 2007). There are many terms used to describe this type of landform: blockmeer, boulder fields, mountain top debris, felsenmeer and stone fields (Rea, 2007). These differences depend on their age and origin, as well as the environment in which they occur (Rea, 2007). Some literature suggests that openwork block deposits specifically result from frost weathering, other weathering processes, or a combination of the two (Sumner and De Villiers, 2002; Rea, 2007). OBDs are found and investigated worldwide; for example the Drakensberg area (Grab, 1999; Boelhouwers *et al.*, 2002; Boelhouwers, 2003), Marion Island (Sumner and Meiklejohn, 2004) and Antarctica (Putkonen, Morgan and Balco, 2012; Hansen *et al.*, 2013; Hansen, 2014).

Slope and slope angle determine the existence and characteristics of OBDs (Rea, 2007). If there is a steep slope, more shear stress exists on the particles, and more movement takes place down the slope, which prevents blockfield formation (Rea, 2007). OBDs have been linked to tors, and tor-like formations in much of the literature (Rea, 2007). It has been observed that the material found on the surface of blockfields can have sizes ranging from small pebbles to large rocks or boulders, and the surface can also contain a fine matrix (Rea, 2007). The surface of openwork block deposits can display sorted patterns and imbrication (Rea, 2007). Developed sorting in openwork block deposits tends to have a finer matrix present but the steeper the slope, the lower the proportion of fines (Rea, 2007). OBDs represent three types of possible features: blockstreams, blockfields, or block slopes (Wilmot, 2015). Blockfields are explained to be areas where boulders with no fine material between them cover the slope (Ballantyne and Harris, 1994; Fjellanger *et al.*, 2006). Blockfields are a vital landform as they indicate relict surface areas and thus it is important to understand the rate at which these landforms are formed, their age, and their origin (Goodfellow, 2008).

According to Ballantyne (1998), there are three types of blockfield profiles. Depth is important in a blockfield profile which is influenced by many control factors such as: age, history of how the erosion has taken place, lithology, and the angle of the slope (Rea, 2007). Type one is an openwork block deposit, which has no fines present at the surface, but instead a matrix at depth (Figure 5) (Ballantyne, 1998). In type two, the blocks are set in a cohensionless sand matrix that can be found throughout the depth of the profile, as well as supported by a matrix (Figure 6) (Ballantyne, 1998). Type three has surface blocks set in a silt or clay matrix and it can have vertical frost sorting (Figure 7) (Ballantyne, 1998). These types of OBDs were based on blockfields observed in Scotland and thus the classification may not be applicable in other areas (Rea, 2007). Ballantyne's (1998), classification does however, provide a basis on which to build when looking at the surface of blockfields (Rea, 2007).

Figure 5: Type 1 blockfield, developed on fine-grained cambrian quartzite (Rea, 2007: 2228).

Figure 6: Type 2 blockfield developed on torridon sandstone (Rea, 2007: 2228).

Figure 7: A mixed blockfield surface, with type 3 showing well developed patterned ground and type 1 (in the bottom centre/left) showing crude sorting (Rea, 2007: 2227).

Blockfields have been associated with two terms that explain their different formative processes (Van Steijn *et al.*, 2002). The first term, allochthonous, is the formation of blockfields by the breaking down of bedrock and then movement downslope (Van Steijn *et al.*, 2002; Boelhouwers, 2004; Fjellanger *et al.*, 2006). The second, autochthonous, are blockfields that form by azonal processes, which are chemically weathered *in situ* (Van Steijn *et al.*, 2002; Boelhouwers, 2004; Fjellanger *et al.*, 2006; Goodfellow, 2008). Autochthonous blockfields have been identified in the WDML area (Boelhouwers, 2004; Hansen, 2014). Early explanations of blockfields detailed them as coarse blocky material found in cold regions (Boelhouwers, 2004).

Block streams are often mistaken for blockfields, rock glaciers, talus, and especially landforms that can morph into each other (Wilson, 2007). Andersson (1906, 1907) identified development of block stones as a result of the mechanism involved in the production of blocks; mass wasting (including a downslope movement); vertical sorting and frost heave of the blocks in transportation; and the removal of fined grained material leading to immobilisation of blocks (Wilmot, 2015). The origins of block streams can be ascribed to frost weathering by examining the surface and angles of the rocks (Boelhouwers, 1999). Certain fabric features are used to identified block streams (André *et al.*, 2008). They can be imbricated with rocks dipping upslope, or packed up next to each other on the edge, or there can be a parallel orientation of the rocks to the slope (Aldiss and Edwards, 1999; André *et al.*, 2008). Many interpretations exist as to how the stone runs formed (André *et al.*, 2008). Such interpretations include earthquakes, differential weathering and more relevant interpretation (André *et al.*, 2008). However, the question is whether their development is due to periglacial conditions, or not (André *et al.*, 2008).

Block slopes are similar to blockstreams and, thus, these landforms can be misinterpreted (Van Steijn *et al.*, 2002). They may be weathered by frost action and can be located below a cliff face (Van Steijn *et al.*, 2002). For a block slope to exist, the environment must be non-glaciated and have a dry, cold climate (Van Steijn *et al.*, 2002). Block slopes can convert into blockfields, especially on a flat surface which may be cause of confusion around the term (Van Steijn *et al.*, 2002).

Stone runs are another term that has been used to describe landforms that are blockfields or similar to openwork block deposits. The term describes, boulders that accumulated over time, there are no fines present and there is no vegetation present (Aldiss and Edwards, 1999; André *et al.*, 2008). Stone runs are also seen to be related to extensive blockfields (André *et al.*, 2008). Thus the question arises: are all the terms that used for openwork bock deposits the same or are they actually different? According to Aldiss & Edwards (1999), stone runs are part of the blockfield family but they are a unique landform as they provide evidence of lateral movement that takes place (André *et al.*, 2008). There are still questions that have not been answered on how such large areas on land are covered in rocks (stone runs) (André *et al.*, 2008).

2.3.2.1. Openwork Block Deposit formation

There are two general models that explain the formation of OBDs. The Neogene model suggests that a lengthy time period in which chemical weathering occurs, is needed for the formation of the regolith (Boelhouwers, 2004; Ballantyne, 2010; Hansen, 2014). During the Quaternary period, a lowering of the OBD mantle took place and over time a tor was formed, contributing to the new regolith (Hansen, 2014). Frost action during these stages of formation only influences the sorting of the OBD and is not the main influence in the formation of the landform (Ballantyne, 2010; Hansen, 2014). Tors can be associated with the tertiary age as the uplift of the blockfield occurs in that time period (Ballantyne, 2010). It has been argued that blockfields are not a product of post glacial frost action, where the bedrock shows little evidence of frost wedging (André 2002; Ballantyne 2010). Having high clay content indicates that there is evidence of chemical weathering which supports the Neogene model (Whalley, Rea and Rainey, 2004; Ballantyne, 2010; Hansen, 2014). Opposing evidence suggests that clay minerals cannot be an indication of a certain climate as clay can indicate there have been warmer periods over time (Ballantyne, 2010; Hansen, 2014).

The periglacial model illustrates that OBDs formed during Quaternary period along with frost sorting, weathering and frost wedging as the agents (Ballantyne, 2010; Hansen, 2014). Frost wedging is where water freezes in existing joints in the rocks, causing them to widen or break off (Washburn, 1979; Boelhouwers, 2004; Ballantyne, 2010; Hansen, 2014). The processes of freeze thaw, frost wedging, chemical weathering and the joints in the bedrock have been argued as the secondary mechanism for formation of OBDs (Boelhouwers, 2004; Ballantyne, 2010; Hansen, 2014). Clast angularity is said to be an indication of the influence of frost action on ODBs development (Boelhouwers, 2004; Hansen, 2014). However, there is little actual evidence that supports the link between frost action and blockfield development (Dredge, 2000; Boelhouwers, 2004).

Ballantyne (2010) suggests a new model for blockfield development that is a combination of the two models that occurs over four stages (Figure 8). Stage one is the chemical weathering of the rocks during pre-pleistocence time period (Ballantyne, 2010; Hansen, 2014). The regolith is stripped during the cold periods of the Pleistocene by ice (in stage two), resulting in tor emergence (Ballantyne, 2010; Hansen, 2014). The development of the blockfields starts to occur in stage three, through frost wedging of the tor formations (Ballantyne, 2010). By stage four the blockfield has developed and there are fines present due to erosion of clasts (Ballantyne, 2010). Two questions are raised when looking at this model: within the blockfield, what processes influence the clasts to break off from the bedrock (Ballantyne, 2010)? And how did the lowering of the bedrock happen during the Quaternary period (Ballantyne, 2010)?

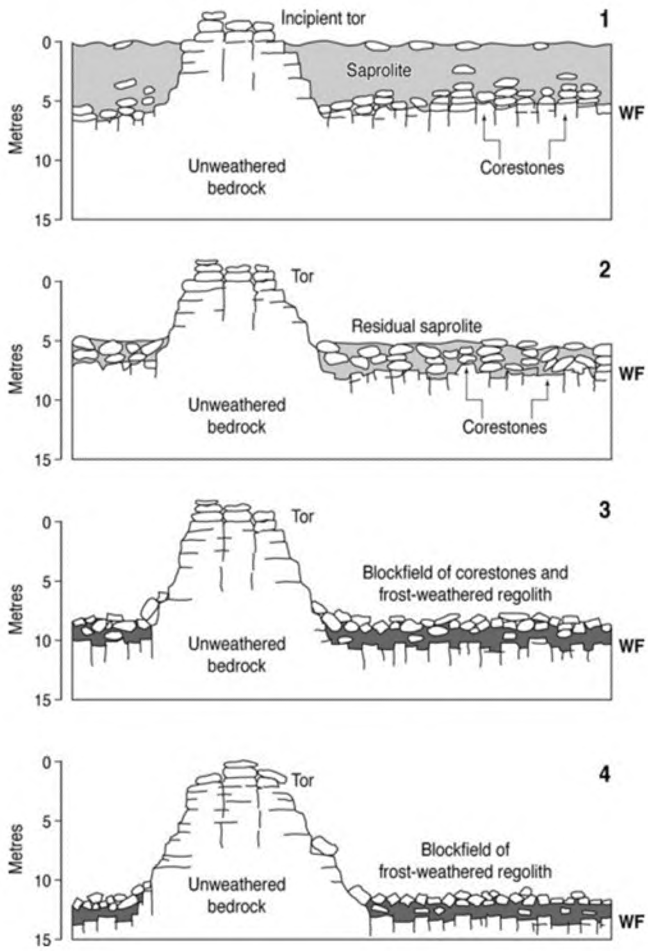

Figure 8: The general model of blockfield formation (Ballantyne 2010).

2.4. Rock Glaciers

Originally rock glaciers were interpreted as glaciers that were covered in debris (Kääb, 2007). Rock glaciers can be described as a system that has a down slope movement that contains ice, water and debris (Janke *et al.*, 2013). Since, rock glaciers have been given many other names and descriptions (Janke *et al.*, 2013). It is difficult to have one clear definition as these landforms are transitional, dynamic and commonly found in an alpine landscapes (Barsch, 1988; Janke *et al.*, 2013). The shape of rock glaciers can be a tongue-shape or lobate form and they are formed through glacial, periglacial and non-glacial processes (Barsch, 1988; Janke *et al.*, 2013). Rudolph (2015) suggests that the definition of a rock glacier is to break it down into three components, namely movement, mass and moisture, and ice. Rudolph (2015) highlighted that some landforms have been misidentified as rock glaciers, when they could instead be another type of landform. This is due to the fact that the definition is based on observations (Rudolph, 2015). There are numerous factors that one could use to classify a rock glacier. Some of the factors are rate of movement, size of the rock glacier and the type of environment they are found in, amongst others (Janke *et al.*, 2013). Influential factors include the topography and their movement, which is not fully understood (Barsch, 1988). Barsch (1988), however, does not agree with the interpretation of rock glaciers being glaciers that are covered in debris due to evidence found from geomorphological resistivity and seismic data.

Morphologically, rock glaciers can be described as comparing subsystems that are linked to create one entity (Figure 9) (Janke *et al.*, 2013). These include a talus and cliff, a surface and subsurface and then its outflow (Janke *et al.*, 2013). The outputs from one of the subsystems are linked to another subsystem as are also inputs (Janke *et al.*, 2013). A rock glacier may act as a storage unit for debris which is released during periods of melt in the form of solutes (Janke *et al.*, 2013). This type of system, however, is not seen to be a closed system but is a system where factors such as aeolian material could be introduced (Janke *et al.*, 2013). Typically rock glaciers are several hundred metres in length, range between 100-200m in width and are generally wider than 50m (Barsch, 1988). The volume of rock in a glacier can reach $10^{6}m^{3}$, where 40-50 percent is made up of ice and the other 40-50 percent contains clastic debris from talus or moraines (Barsch, 1988). Rock glaciers can be found worldwide often in areas of glaciers, however, a colder environment promotes their development more so than the development of glaciers (Kääb, 2007).

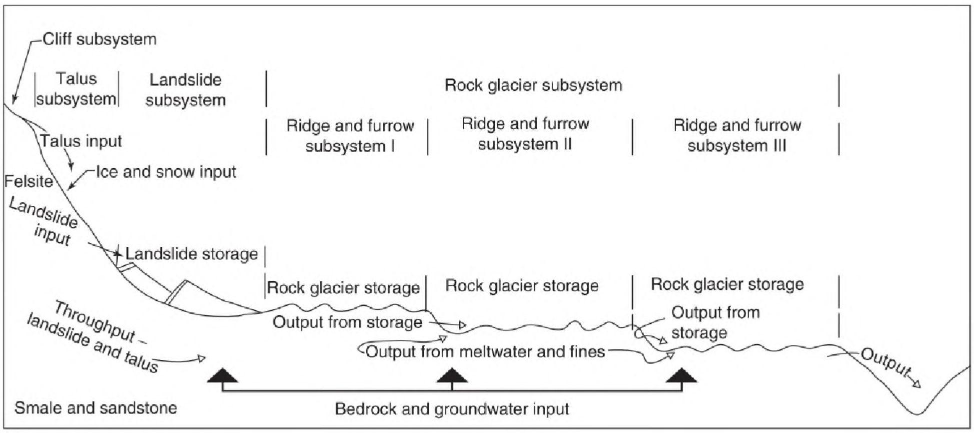

Figure 9: The rock glacier system (Janke *et al.* 2013: 243).

Issues arise when investigating the origin of rock glaciers. In simple terms, there are two ideologies of how rock glaciers originated (Janke *et al.*, 2013; Rudolph, 2015). Rock glaciers either have a periglacial origin where there is an ice-cemented structure or rock glaciers have an ice-cored structure and a glacial origin (Janke *et al.*, 2013; Rudolph, 2015). The mode of formation of rock glaciers has been categorised into three models by Whalley & Martin (1992) (Whalley and Azizi, 2003). There is the permafrost model, which considers the rock glacier to have a permafrost origin (Whalley and Azizi, 2003). Then there is the glacial model, which is a layer of thin ice that covers a layer of debris (Whalley and Azizi, 2003). The last model, the landslide model, suggests that rock glaciers are formed by massive landslides (Whalley and Azizi, 2003). Furthermore, Barsch (1988) proposed two locations for rock glaciers is below a talus slope (Figure 10) or below a glacier (Figure 11). These types are controlled by the topography, as topography determines the debris that enters the glacier (Barsch, 1988).

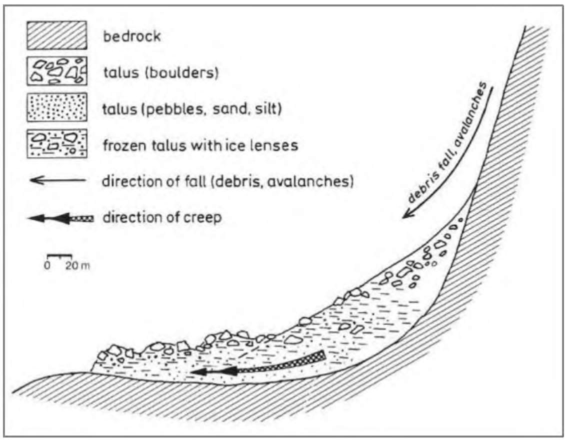

Figure 10: Rock glaciers below a talus slope (Barsch 1988: 80).

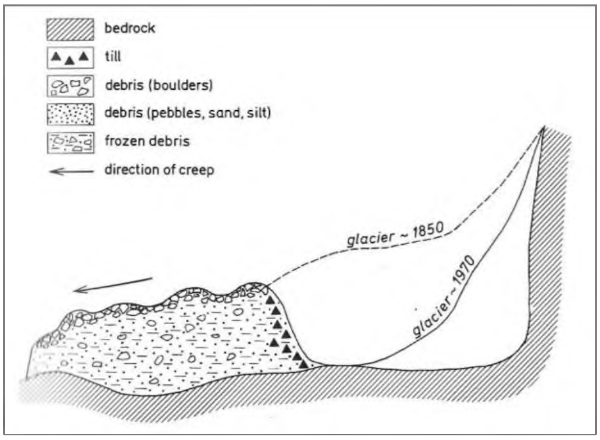

Figure 11: Rock glaciers below a glacier (Barsch 1988: 81).

Various characteristics need to be considered when investigating a rock glacier. One of the most important characteristics is the thermal state of its environment, which involves the presence of permafrost (Kääb, 2007). According to Kääb (2013), a rock glacier consists of ice, debris and permafrost. The rock debris ranges in size and forms as it depends on the environment, climate and composition of the rock (Kääb, 2007). Permafrost is needed to help distinguish the difference between a rock glacier, a glacier, and a glacier that is covered by a layer of debris, and thus the thermal state of the environment will determine the difference (Kääb, 2007). Debris from a rock glacier can form from glacial or periglacial processes and ice from the rock glacier can be sourced from melt water, rain, other glaciers or a combination of sources (Kääb, 2007). Rock glaciers do show the existence of permafrost but topography can determine whether permafrost is present during or after the formation of the rock glacier (Kääb, 2007). Displacement in the rock glacier system also influences its form (Kääb, 2007). A rock glacier deforms over time due to gravity, and thus depending on the topography, the movement of the landform can be vast over a year (Kääb, 2007). It is evident from the literature, that issues of the movement of glaciers needs to be resolved as there are many questions that are still being raised (Barsch, 1988).

A tongue rock glacier was identified in the Dry Valleys of Antarctica where the surface has parallel ridges (McCraw, 1967) and according to Mayewski and Hassinger (1980) and Hassinger and Mayewski (1983) the formation of rock glaciers in this area is influenced by the local climate and environment. Rock glaciers were investigated on King George Island (Michel *et al.*, 2014) and James Ross Island (Strelin and Sone, 1998). Rudolph (2015) investigates rock glaciers in detail in the WDML area as well as analysis of the surface characteristics of them.

2.5. Terraces

As with all the landforms that have been discussed so far, terraces have been described in many different ways. Terms such as goletz terraces, nivation terraces, equiplanation terraces, altiplanation terraces, and cryoplanation terraces exist for this landform (French, 1996). The size of terraces vary depending on the lithological and environmental conditions in the geomorphology of the system (French, 1996; Hall and André, 2010). Terraces take on elongated, narrow or a sickle like forms (French, 1996). Some are seen to be linked to solifluction (Hall, 2002), such as those in Victoria Land of Antarctica (Selby, 1971). There is, however, little evidence of the origin of these terraces (Selby, 1971).

Some literature classifies all forms as cryoplanation terraces, but other literature indicates that various terrace types exist. Cryoplanation is also discussed above in the context of its association with nivation. Many terms are used to describe what is considered as a cryoplanation terrace due to the variety of processes that are involved in the formation of the landform (Hall, 1998). Confusion is created as different terms are used interchangeably in papers, rather than sticking to a single term (Hall, 1998). The study of cryoplanation terraces has not passed a descriptive stage in 80 years (Nelson, 1989), which leads one to question if such a landform exists. Cryoplanation terraces are defined as terraces that comprise of bedrock and in terms of characteristics; display a tred and a riser on the slope of a mountain (Hall and André, 2010). They are generally found in cold environments where permafrost is present and there is evidence of mass movement (Nelson, 1989; Hall and André, 2010). They seem to not cover a whole mountain top but rather a portion where it consists of a series of alternating flat and steep areas as well as a flat area for the summit (Nelson, 1989). The process that is involved in making these landforms, is argued to be nivation (Nelson, 1989; French, 2007). Nivation, in this case, is linked to the climate as it determines how and where the cryoplanation terraces are formed (Nelson, 1989).

No data on the rate of development of cryoplanation terraces exists, which is seen as a contentious issue (Demek, 1969; French, 1996). Speculation as to why there are no data, is due to the disagreement on the perceived conditions required for cryoplanation terraces and the environment in which they develop (Nelson, 1989). The biggest question of all, is whether they actually exist (Nelson, 1989). French (1996, 2007) questions whether cryoplanation terraces have any significance, however, he does not question their existence.

The development of cryoplanation terraces is suggested to occur in four stages by Demek (1969) (Figure 12) (French, 1996). The first stage involves the removal of debris by gelifluction and sheet wash (French, 1996). The second stage is the development of a freeface and flat area (French, 1996). Frost action is suggested to lead to a steeper formation of the freeface and the action of wash and solifluction removes sediment (French, 1996). The third stage is the development of the flat surface, and the last stage is the process of down-wearing accompanied by frost action, which leads to sorting (French, 1996). The flat area of the terraces can become large like huge steps that are horizontal and have larger clasts (French, 1996).

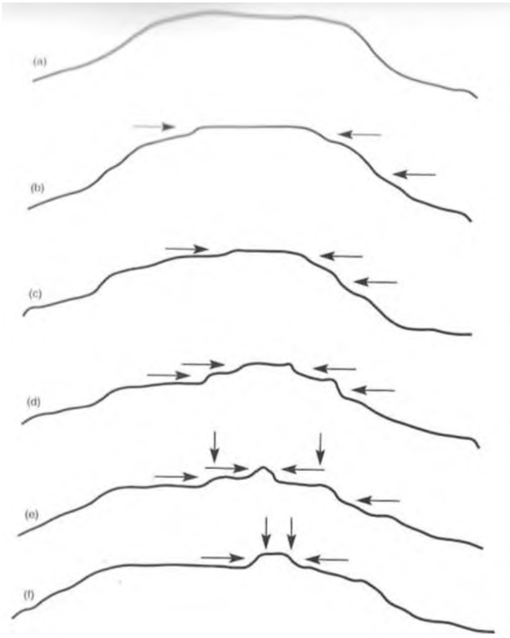

Figure 12: The stages of cryoplanation development (French 1996: 179).

Debates exist in published literature on whether permafrost must be present for the formation of terraces (Nelson, 1989; French, 1996). However, cryoplanation terraces are a result of a permafrost system being present (Bockheim, 2002; Scott, 2014). Terraces are important to study as they are large landforms that contribute to the understanding of slope developments in cold, non-glaciated areas (Nelson, 1989). Antarctic terraces have not been referred to as cryoplanation terraces (Scott, 2014). In Antarctica there is a lack of literature on cryoplanation terraces, which is a surprising as the stability of the climate in Antarctica would be the perfect environment for cryoplanation terraces to exist (Hall and Andre, 2010). Well-developed solifluction terraces are researched in the Dry Valleys of Antarctica by McCraw (1967). Terraces have been located on King George Island (Zhu, Cui and Zhang, 1996). Arguments that cryoplanation terraces are similar or the same as a nivation bench, as morphologically, the history of the landforms are composite (Hall, 1998). What is important about the cryoplanation terraces, is that they are seen to be the only landform that is active of the two landforms (Hall, 1998).

It is, therefore, important to further the research on these landforms in order to fully understand them in their environment.

2.6. Lake ice blisters and frost mounds

Ice blisters are one of three types of frost mounds (Guglielmin *et al.*, 2009). They can be found on slopes where there is discontinuous permafrost and high relief, they have also been determined in areas of continuous permafrost (Guglielmin *et al.*, 2009). This indicates a discrepancy in how their formation is viewed. According to Guglielmin *et al* (2009) lake ice blisters in Antarctica are similar to ice blisters, which raises the question of whether they are the same landform or not.

Lake ice blisters have been recorded in northern Victoria Land of Antarctica and they occur on small ice-covered perennial lakes (Guglielmin *et al.*, 2009). Other observations document similar landforms such as ice mounds or ice domes on frozen perennial lakes (French and Guglielmin, 2000; Guglielmin *et al.*, 2009). Permafrost is considered to be a condition important in the development of ice blisters, especially in Antarctica (Guglielmin *et al.*, 2009). The possibility that lake ice blisters are linked or related to ice mounds exists, as some lakes contain both features (Guglielmin *et al.*, 2009). According to Washburn (1979), cryostatic pressure can cause an ice blister or mound to form. Cryostatic pressure is hydrostatic pressure whereby water is trapped in the processes of downward freezing of the active layer (Washburn, 1980).

According to French (1996) there are different types of frost mounds, which is determined by the ice type and source of uplift (Figure 13).

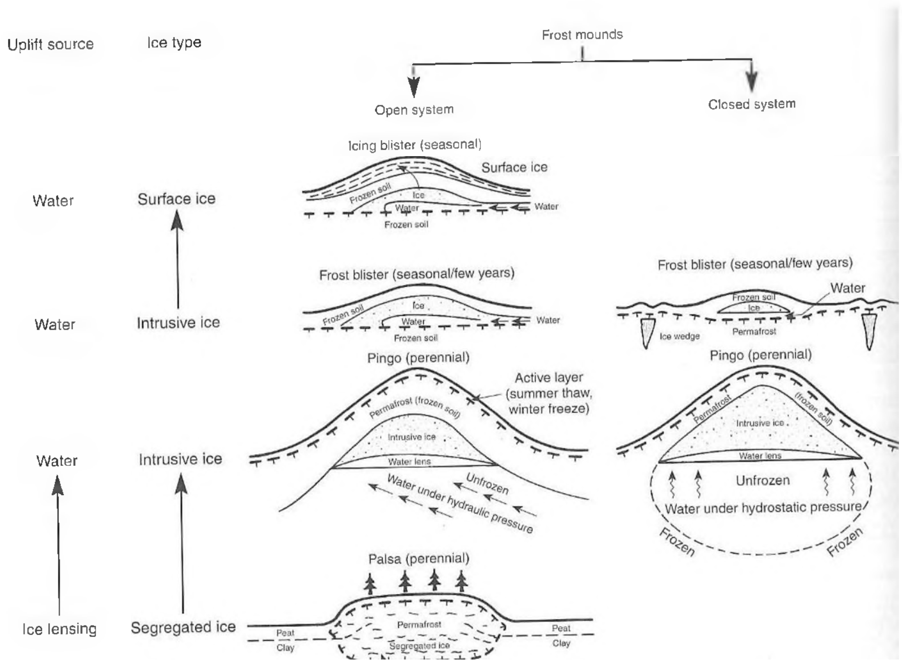

Figure 13: Different types of frost mounds (French 1996: 102).

Lake ice blisters contain gravel boulder debris and feature a conical or elliptical shape (French and Guglielmin, 2000). Small mounds, identified by McCraw (1967), contain a combination of ice and loose debris where the loose debris is the same as the debris found on the ground next to the frost mound. Terminology issues arise in the literature as classification of frost mounds and ice blisters/mounds are inconsistent and unclear. For the purpose of this dissertation, definitions for the terms are as follows:

Lake ice blisters are mounds that form on or near an edge of a frozen lake (Figure 14), whereas frost mounds are seen to have sediments and ice present (Figure 15). A study by Hansen *et al* (2016), observed frost mounds and lake ice blisters in WDML.

Figure 14: Lake Ice blister (photo provided by Ian Meiklejohn).

Figure 15: A frost mound (photo provided by Ian Meiklejohn).

2.7. Pronival Rampart

According to Shakesby (1997), a pronival rampart is defined as a ramp or ridge of debris, which is formed at the edge of the snowbed where the slope of the border meets the snowbed (Shakesby, Matthews and McCarroll, 1995; Hedding *et al.*, 2010; Brook and Williams, 2013; Hall, 2013; Hedding and Sumner, 2013; Hedding, 2014). According to Clark (1988) and Hedding (2014), pronival ramparts are located by the base of a steep cliff face. The term 'pronival' is used as it is more applicable universally than 'protalus' (Hedding *et al.*, 2010), yet there is a difference between the two. The word pronival is more accepted as it describes a fan like shape of debris which collects, regardless of the position of the slope (Hedding *et al.*, 2010). Pronival in simple terms, indicates that there is a snowbed in between the cliff and a bed of rocks (Brook and Williams, 2013). A protalus rampart has debris that has accumulated but the position of the slope is not important (Brook and Williams, 2013). Furthermore there are other terms that have been used to describe this type of landform, such as snowbank accumulations, nivation ridges, snowbank deposits, and winter talus ridges (Shakesby, Matthews and McCarroll, 1995). The term, 'nivation ridge' was questioned by Bryan (1934), as it linked the term nivation to erosion rather than depositional processes (Shakesby, Matthews and McCarroll, 1995; Hedding, 2014). The term 'winter talus ridge' is also questionable, as debris accumulation takes place in summer rather in the winter months (Ballantyne, 1987; Shakesby, Matthews and McCarroll, 1995). However, the term 'protalus rampart' has become accepted in literature as it is a universal term for the landform (Porter, 1987; Shakesby, Matthews and McCarroll, 1995).

For a landform to be considered a pronival rampart, it must have identical rock to the backwall (Shakesby, 1997; Hedding, 2014). It must be influenced by the transport of debris and the crest of the rampart and the backwall must have a distance less than 30-70m (Hedding *et al.*, 2010). The clasts found at a pronival rampart are generally angular (Hedding and Sumner, 2013; Hedding, 2014). Subnival processes are thought to influence the way in which a rampart develops (Shakesby, Matthews and McCarroll, 1995; Shakesby *et al.*, 1999). Supranival transport, however, is considered the primary source of depositional material (Shakesby, 1997; Hedding, 2014). Furthermore, continuous research has indicated that the processes of supranival and subnival transport contribute to pronival ramparts formation (Hedding, 2014).

Research conducted on active pronival ramparts is limited (Anderson *et al*. 2001). However, research exists on relict pronival ramparts (Curry, Walden and Cheshire, 2001; Brook and Williams, 2013). Similarly to most landforms, discrepancies in the identification of the landforms exists due to the lack of information on active pronival ramparts. This makes it difficult to distinguish a rampart from a moraine, rock glacier and landslide (Curry, Walden and Cheshire, 2001; Hedding, 2014). A number of relict pronival ramparts have been classified incorrectly (Hedding and Sumner, 2013). Limited criteria and little knowledge on how to identify a pronival rampart highlights the issue of identification (Hedding and Sumner, 2013; Scotti *et al.*, 2013; Hedding, 2014). A detailed list of criteria can only be drawn up once there has been more research done on these landforms, especially those that are active (Shakesby, 1997; Hedding and Sumner, 2013).

Various models have been proposed in an attempt to elucidate the development of ramparts. One model suggests that a rampart is developed gradually over time where debris is accumulated down slope of a firn field (Ballantyne and Kirkbride, 1986; Hedding *et al.*, 2010; Hedding, 2014). A model by Sissons (1979) states that during the formation of the rampart, the snowbed is stable (Hedding *et al.*, 2010; Hedding, 2014). Other theories, however, indicate that the snowbed is not necessarily stable but rather the volume of the snowbed varies (Hedding *et al.*, 2010; Hedding, 2014). According to Hedding et al (2007), a new model occurs where the development of the rampart fluctuates: due to decreases in the volume of the snowbed, especially if the rampart is relict (Brook and Williams, 2013).

The problem lies in the fact that there are various working theories on the origin and the formation of pronival ramparts (Curry, Walden and Cheshire, 2001; Hedding, 2014). Thus, it makes it difficult to understand how this landform originates. The table below shows the differentiation between ramparts, moraines and glaciers in terms of the different criteria each landform has (Table 2) (Hedding and Sumner, 2013). The list of criteria is still a work in progress, especially looking at the origins of the landform (Hedding and Sumner, 2013).

In Antarctica, there has been little research conducted on pronival ramparts but there is some literature in the sub-Antarctic areas (Hedding *et al*., 2010). A protalus rampart was investigated on Ross Island, Antarctica by Strelin & Sone (1998). Hedding et al. (2010) details one of the first documentations of an active pronival rampart in an area called the Grunehogna Peaks.

Table 2: The different criteria needed for pronival ramparts, glacial moraines, rock slopes and rock glaciers (adapted from Hedding & Sumner 2013).

Criteria	Reference
Pronival (Protalus) Rampart	
Ridge crest to cliff-foot distance <-30-70m	Ballantyne and Benn (1994)
Insufficient cross-section depth for snow to glacier ice transformation	Watson (1996); Shakesby and Matthews (1993); Ballantyne and Benn (1994); Bower (1998)
Underlying slope gradient that will facilitate snow/firn bed angle >20°	Ballantyne and Benn (1994)
No glacial erosional forms or evidence of overdeepening of the associated backwall area through sapping and subglacial erosion	Bower (1998)
Openwork fabric; absence of fines (<2mm)	Hedding et al. (2007); brook (2009); Hedding et al. (2010)
Backwall and ridge same lithology (no erratics)	Unwin (1975)
Absence of striated clasts	Shakesby and Matthews (1993); Curry et al. (2001)
Glacial Moraine	
Glacial erosion forms	Benn and Evans (2007)
Striated clasts	Shakesby and Matthews (1993); Curry et al. (2001)
Broadly arcuate in plan-form but in detail are often irregular and winding	Benn and Evans (2007)
Ridge crest to talus-foot distance >-30-70m	Ballantyne and Benn (1994)
Presence of times (<2mm)	Brook (2009)
Rock-slope Failure	
Recognizable source cavity or distinct scar of comparable volume, linked to the deposit by a feasible trajectory	Curry et al. (2001); Jarman et al. (2013)
Debris aprons beyond the feature	Curry et al. (2001)
Debris much larger than adjacent talus accumulations	Curry et al. (2001)
Large masses of displaced hillside within or above the area of debris accumulation	Curry et al. (2001)
Minimum size thresholds: 0.02km^2 in areal extent (source and deposits): 0.1Mm^3 in gross volume; and 5m depth of formerly intact bedrock	Jarman et al. (2013)
Protalus Rock Glacier	
Greater in length (down slope) than in width (across slope)	Curry et al. (2001)
Convex distal slope	Curry et al. (2001)
Typically terminate >70m from the talus slope	Curry et al. (2001)
Lobate or crenulated of the outer margin in plan form	White (1981); Wilson (1990)
Meandering and closed depressions, downslope ridges and furrows, and transverse ridges and depressions	White (1987); Curry et al. (2001)

2.8. Summary

The above review of literature reflects the discussions on landforms that have been identified as existing in WDML which fulfils objective one. However, some of the landforms mentioned in the literature have be investigated at length by other researchers and thus supplementary data will be given where appropriate. Following is the detail on the study area and its broader environmental and spatial contexts.

Chapter 3: Setting

The Ahlmannrggen (Ahlmann Ridge) is a major landscape feature in western Dronning Maud Land (WDML), a region of Antarctica (Figure 16) (Dwight, 2014). It is an, as yet, undefined part of Dronning Maud Land (DML), which is the Norwegian name for Queen Maud Land (ATS, 1959; Stewart, 2011; Dwight, 2014). It was claimed by Norway in 1939 but the claim is held in abeyance following the signing of the Antarctic treaty in 1959 (Stewart, 2011; Dwight, 2014). The mountain range that runs through WDML comprises doleritic nunataks that are approximately 10-30km apart (Von Brunn, 1964; Näslund, 2001). The dolerites in this area are of a tholeiitic composition and they are medium grained (Von Brunn, 1964). An expansive ice sheet drops in altitude downstream from the nunataks, which indicates the change from the Antarctic Polar Plateau (which is in the south) to the northern part of the coastal areas (Näslund, 2001).

WDML is not as well documented as some of the other regions of Antarctica, which means information on the nunataks is limited (Figure 16). To improve our understanding of the area research was conducted on a number of nunataks that are discussed below:

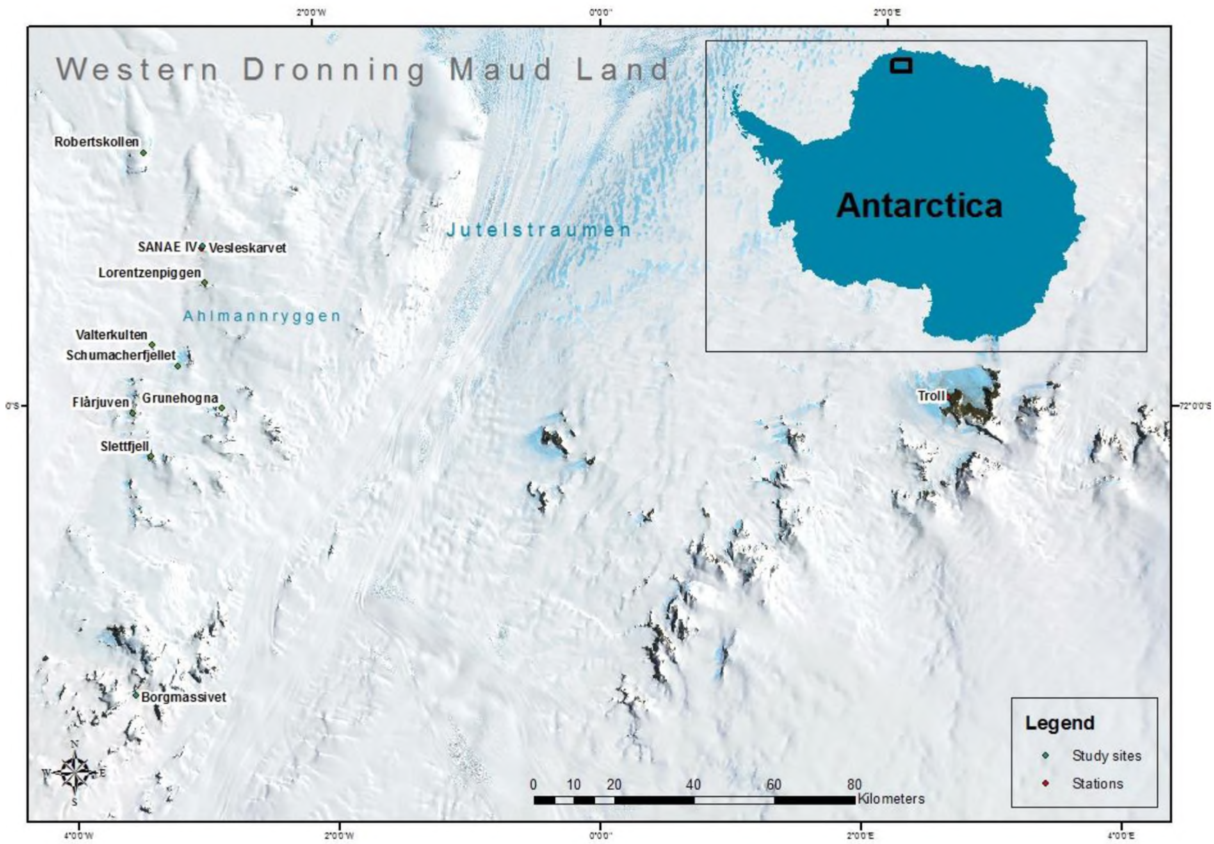

Figure 16: Study sites in WDML, Antarctica.

3.1. Geography

Although most of the nunataks are part of the Ahlmannryggen area, they all have a unique geography. Some similarities are that Veleskarvet and Flårjuven are located on top of a mountainous area where the top is fairly flat (Table 3). Robertskollen, Grunehogna and Schumacherfjellet comprise of mountainous peaks (Table 3). The nunatak with a flatter area is Slettfjell and Valterkulten has a basin area that is surrounded by slopes of rocks (Table 3). Troll is part of the coastal mountain range (Dallmann *et al.*, 1990) (Table 3). There are going to be some discrepancies when comparing periglacial landforms between the different nunataks as the geography of the nunataks are not the same.

Table 3: The geography of the nunataks in WDML

Nunatak	Geography
Veleskarvet	This nunatak is 160km from the edge of the ice shelf (Steele *et al.*, 1994; Dwight, 2014). Vesleskarvet has two components: the Northern Buttress and the Southern Buttress (Steele *et al.*, 1994; Dwight, 2014). In total, the flat topped exposed area comprises 22.5ha (Steele *et al.*, 1994; Dwight, 2014). The Southern Buttress is where the South African Base (SANAE IV) is located.
Robertskollen	Robertskollen (Roberts Knoll) is located on the northern part of Ahlmannryggen (Ryan *et al.*, 1989; Dwight, 2014), and comprises five large nunataks as well as some smaller ones (Tibbles and Harris, 1996). The nunataks are situated between 200 - 500m above sea level (Ryan *et al.*, 1989; Dwight, 2014)
Slettfjell	It is located 53km south of SANAE IV (Scott, 2014). The area appears to be fairly flat with a gentle gradient. There are large patches of snow between the exposed areas of rock.
Flårjuven	The mountain has a flat top and is located about 44km south west of Veleskarvet (Scott, 2014; Kotzé, 2015).
Troll	Troll comprises of many outcrops. Nonshøga (part of Troll) is located about 190km from Veleskarvet across the Jutulstraumen glacier (Scott, 2014; Kotzé, 2015). It is 200km away from the edge of the ice shelf and is part of the coastal mountain range (Dallmann *et al.*, 1990). Nonshøga is part of the Jutulsessen which is the same greater area as where the Norwegian base station (Troll) is (Dallmann *et al.*, 1990).
Valterkulten	This nunatak is 28km south west of SANAE IV (Scott, 2014). The slopes of the nunatak drain into a basin area where the one section of the slope is steeper than the other.
Grunehogna	Grunehogna comprises of peaks with steep cliffs. There are areas with gentle slopes of exposed rock surrounded by snow.
Schumacherfjellet	It is a narrow ridge with pinnacles that have sharp edges (Neethling, 1963). The area displays evidence of past active alpine erosion (Neethling, 1963). In the upper section of the sill rock there is jointing present (Neethling, 1963).

3.2. Geology

All of the nunataks are located in the Ahlmannryggen area which has Borgmassivet intrusions (Roots, 1969) (Table 4). These intrusions are comprised of diorite and gabbro and they are more resistant to erosion (Roots, 1969). Thus the erosion rate of the intrusions will be similar at the different nunataks, meaning that the rate at which the landforms have developed on the nunataks could be similar. However, there are differences between some of the geology of the nunataks. For example, Robertskollen has intrusions that are part of the Robertskollen complex (Roots, 1969) (Table 4). Slettfjell and Schumacherfjellet have geology part of the Schumacherfjellet formation (Roots, 1969) (Table 4). Troll is located across the Jutelstraumen glacier and has granitic geology which is different to the other nunataks (Dallmann *et al.*, 1990; Kotzé, 2015). Thus there will be a contrast in the periglacial landforms found here and could prove a problem to compare the landforms with other nunataks.

Table 4: The geology of the nuntaks in WDML

Nunatak	Geology
Veleskarvet	Homogenous, mafic rocks, which form part of the Borgmassivet intrusions (Steele *et al.*, 1994; Dwight, 2014; Hansen, 2014).
Robertskollen	Geology in this area is ultramafic (part of the intrusive Robertskollen complex) and is made up of mela-olivine gabbronorite, which is overlain with mafic lava comprised of gabbronorite and gabbro (Von Brunn, 1964; Roots, 1969; Krynauw, 1986; Dwight, 2014; Kotzé, 2015).
Slettfjell	The geology is part of the Borgmassivet intrusion where there are dykes of diorite and gabbro (Roots, 1969). Some areas of Slettfjell are part of Schumacherfjellet Formation, containing arkoses and quartzites which are entwined with siliceous siltstone (Meiklejohn, 2012; Kotzé, 2015).
Flårjuven	It is part of the Ahlmannryggen Group containing un-differentiated clastic rocks; made up of quartzite, greywacke, siltstone and conglomerate (Roots, 1969). Borgmassivet intrusions do cut through this area and they contain dikes and sills of diorite and gabbro that are highly differentiated (Roots, 1969).
Troll	The bedrock geology of this area is granitic augen gneiss and mafic zones in granitic gneiss (Dallmann *et al.*, 1990).
Valterkulten	This area is part of the Borgmassivet intrusion (Roots, 1969).
Grunehogna	The geology in this area comprises Borgmassivet intrusions of Precambrian age and have undergone metamorphosis (Hedding, 2014).
Schumacherfjellet	The geology of this area is part of the Ahlmannryggen Group which consists of clastic, quartzite, siltstone, continental rocks and conglomerates (Roots, 1969). Borgmassivet intrusions cut through the rock, where they comprise sills and dykes that contain diorite and gabbro (Roots, 1969).

3.3. Climate

Loggers were placed at the different nunataks and some have been recording since 2009. The temperature of the air and ground surface are the averages from 2009-2016 (Table 5). The air temperature for all the nunataks are between -13°C and -21°C. The minimum and maximum air temperatures vary between the nunataks. Valterkulten and Schumacherfjellet have similar air temperatures which is due to their promixomity in location. Thus the landforms found at these two nunataks can be compared. The ground temperature data relates to the active layer, which plays a significant role in the formation of periglacial landforms. The lowest ground temperature average is for Slettjfell (-20.1°C) and Grunehogna (-18.4°C) (Table 5). The periglacial landforms found at these two nunataks could be less active or even dormant. The more active sites are Vesleskarvet (-16°C) and Schumacherfjellet (-16.8°C) as they have warmer average ground temperatures (Table 5). However, in terms of temperature it will prove difficult to compare the landforms that are the same on different nunataks as the temperatures vary for all the nunataks.

Table 5: The air and ground surface temperature of the nuntaks in WDML (2009-2016)

		Air Temperature	**Ground Surface Temperature**
Veleskarvet	Maximum	6,8	20,1
	Minimum	-40,8	-39,7
	Average	-15,9	-16
Robertskollen	Maximum	6,4	15,9
	Minimum	-35,4	-35
	Average	-13,8	-13,2
Slettfjell	Maximum	0,4	9,3
	Minimum	-41,8	-40,1
	Average	-20	-20,1
Flårjuven	Maximum	2,7	23
	Minimum	-38,2	-37,1
	Average	-18,6	-17,9
Troll	Maximum	8,8	7,3
	Minimum	-50	-36,1
	Average	-17,6	-17,2
Valterkulten	Maximum	4,2	21,3
	Minimum	-36,7	-38,8
	Average	-16,5	-15,4
Grunehogna	Maximum	2	19
	Minimum	-39,5	-36,6
	Average	-19,2	-18,4
Schumacherfjellet	Maximum	4,6	14,8
	Minimum	-39,1	-37,1
	Average	-16,8	-16,8

3.4. Geomorphology

There various different periglacial landforms found in WDML, but not all the landforms are found at each nunatak. Patterned ground, in various forms, is found at each nuntak and is the most common landform in WDML (Table 6). Thus, an in-depth comparison of the patterned ground is possible between all the nunataks. In contrast, each nunatak has a unique environment which could prove challenging when comparing the landforms. Terraces are found at Flårjuven and Valterkulten and blockfields are at Veleskarvet (Table 6). Grunehogna has a pronival rampart and lake ice blisters (Table 6). Thus there are landforms that are only found in one or two of the nunataks which can prove difficult to compare but the landforms could be critiqued with other examples found in Antarctica.

Table 6: The geomorphology of the nunataks of WDML

Study site	Geomorphology
Veleskarvet	Landforms documented on the nunatak include blockfields and patterned ground, especially on the northern buttress (Hansen, 2014; Scott, 2014).
Robertskollen	The western part of Robertskollen has boulder slopes with a gentle gradient but comprises of some screes (Ryan *et al.*, 1989; Dwight, 2014). Landforms noted here are sorted patterned ground (e.g.: sorted circles), lobes and unsorted patterned ground (Scott, 2014; Kotzé, 2015).
Slettfjell	Sorted and non-sorted patterned round (such as stripe and polygons) have been recorded here (Scott, 2014).
Flårjuven	Landforms such as terraces and polygons are documented here (Scott, 2014).
Troll	Non-sorted polygons are found in this area, due to the ground freezing and contracting, which leads to cracks being present in the permafrost (Lee *et al.*, 2013; Kotzé, 2015). Sand-wedge polygons have been recorded, where cracks can become larger and deeper due to infilling by sand (Bockheim *et al.*, 2013; Kotzé, 2015). The polygon diameters have been measured between 5m to 30m, while the cracks average a width of 0.1m (Lee *et al.*, 2013; Kotzé, 2015). Limited sorted patterned ground has also been identified here, where the gradient of the slope 15° degrees or below and stone pit features are found here (Dallmann *et al.*, 1990; Kotzé, 2015). Landforms such as glaciers, pronival ramparts and moraines have been identified (Dallmann *et al.*, 1990).
Valterkulten	The lake is a brine lake which an important feature to study as it is linked to chemical weathering and geochemistry (Marshall *et al.*, 1995). The landforms identified here are thermal contraction cracks and terraces (Scott, 2014).
Grunehogna	Located here, is a pronival rampart (72°03'13''S; 2°42'47''W) which is still considered to be active (Hedding 2014; pers. obs.). It is found on the north-eastern edge of the Grunehogna peaks (Hedding, 2014). The study site is 200km inland from the ice shelf and at the end of the Ahlmannryggen (Hedding, 2014). Other landforms found here are sorted and unsorted patterned ground as well as lake ice blisters.
Schumacherfjellet	Patterned ground such as circles have been noted here.

Chapter 4: Methods

Field work was conducted in Antarctica during the 2016/2017 Austral Summer. Access to the continent involved travelling on the SA Agulhas II, which departed from Cape Town. From the ship, helicopters were used as transport to the South African base (SANAE IV). Data collected between December 2016 and January 2017 was verified and augmented during visits to all documented sites (see Table 7). This dissertation combines the archival and new data (2016/17) to give a comprehensive outlook on the periglacial landforms of WDML. Emphasis was placed on patterned ground because it is the most common and visible periglacial landform found in the study areas.

Objective one involves investigating the literature as well as consolidating the archival data which was conducted by others that fall under the same overall research project. Objective two was achieved by investigating landforms that had not yet been documented. Furthermore, additional research was conducted on the recommendations of the previous researchers for certain landforms. Objective three was achieved by heave mentoring techniques for the most common and influence landform which is patterned ground. The table below indicates the dates in which the different study sites in WDML were visited and what was collected at each site (Table 7). Valterkulten and Schumacherfjellet where the only placed where data was not collected for 2016/17 (Table 7). The daily visits to Vesleskarvet where checking on the heave monitoring equipment (Table 7). There are differences in what methods where used at each site, which due to the nature of research and the time available at each site[2]. However, for the 2016/17 data, soil samples were collected using a trowel and put into sample bags. GPS locations as well as pictures where taken for all 2016/17 samples. A summary of the analyses conducted for each landform is also given (Table 8). The blocks that are not highlighted in blue is the archival data collected from previous researchers (Table 8). The blocks that are coloured in blue is what was conducted in 2016/17 and what this thesis will focus on in Chapter Six and Seven (Table 8).

[2] See Chapter 8 :Limitations and recommendations

Table 7: Table showing the dates at which study sites where visited.

Date Visited	Study site	Investigations at each site
16/12/2016	Slettfjell	• Soil samples • GPS[3] co-ordinates • Orientation • Length of short and long axis • Pictures were taken
17/12/2016	Robertskollen	• Soil samples • GPS co-ordinates • Pictures were taken
24/12/2016	Valterkulten	• No new documentation • Previous work verified
26/12/2016	Grunehogna	• Soil Sample • GPS co-ordinates • Orientation • Length of short and long axis • Pictures were taken
26/12/2016	Schumacherfjellet	• No new documentation • Previous work verified
05/01/2017	Flårjuven	• Soil samples • Length of long and short axis • Pictures where taken • GPS co-ordinates
12/01/2017	Troll	• Took soil samples • GPS co-ordinates • Pictures were taken • Orientation and dip were measured • Length of long and short axis
Daily	Vesleskarvet (Northern Buttress)	• Heave monitoring (checking cameras and downloading results) • Soil sample • Pictures were taken • GPS co-ordinates

[3] GPS (Global Positioning System)

Table 8: A summary of previous analyses on periglacial landforms.

Landform	Methods						
	Particle Size Analysis	*Shape Analysis*	*Fabric Analysis*	*Soil Profile*	*Heave Monitoring*	*Morphology Measurements*	*Expanding on past research recommendations*
Blockfields (Hansen, 2014)	✓	✓	✓	X	X	✓	✓
Patterned ground (Scott, 2014; Kotzé, 2015)	✓	X	✓	✓	✓	✓	X
Rock glaciers (Rudolph, 2015)	✓	✓	✓	X	X	✓	X
Terraces (Scott, 2014)	✓	X	✓	X	X	✓	X
Lake ice blisters	X	X	X	X	X	✓	X
Pronival Rampart (Hedding, 2014)	X	X	X	X	X	✓	✓

4.1. Mapping

Due to the lack of spatial data existing in Antarctica, GIS (Geographic Information System) information is limited. For this reason, a variety of sources have been used to make the maps for Antarctica. The Antarctic Digital Database (ADD) was used and provides a compiled database of the entire Antarctic continent (SCAR, 2017). Quantarctica®, another spatial database compiled and managed by Norwegian Polar Institute (2017), was also used. The latter resource contains data categorised into geophysics, glaciology and geography (Norwegian Polar Institute, 2017). Therefore, all the data has been used collectively to create maps of each nunatak and what periglacial landforms are found there. The maps are part of fulfilling objective two, where the maps are an update as to where the landforms are located on the different nunataks.

ArcMap® was used to create the study area map and display different locations of the periglacial landforms WDML. A geodatabase was created with all the data and layers linked to periglacial landforms, for use in future research. The creation of a spatial database will provide the platform for further development and analysis.

4.2. Material Characteristics

The following discussion presents the methods that were utilised in the field and in the laboratory to determine the characteristics of the substrate where periglacial landforms were found and also of the material comprising the landform itself. Shape analysis was a method that was executed by previous researchers (archival data). Particle size and fabric analysis was completed in this dissertation for the 2016/17 and by the previous researches for the archival data.

4.2.1. Shape Analysis

Shape is a reflection of the depositional or slope environment (Briggs, 1977). The Zingg's Classification is used for calculating particle shape, where the three axes are used to determine the measurement (Briggs, 1977). A axis (long), b axis (intermediate) and the c axis (the shortest) were recorded. By measuring the axes, one can classify the shape into one of the four categories (Table 9).

Table 9: Zingg's four categories for classification (unit: cm) (Briggs 1977).

Form	b/a	c/b
Spheres	> 0,67	> 0,67
Discs	> 0,67	<0,67
Rods	< 0,67	>0,67
Blades	<0,67	<0,67

Krumbein's Sphericity Index:

The sphericity index has values that range between 0 and 1, where a true sphere has a value of 1 (Briggs, 1977). Using the Zingg and Krubein Index, the difference in sphericity and form has been identified (Briggs, 1977). Using the three axes (a, b and c), the sphericity index was calculated by using the following formula [1] (Briggs, 1977):

$$\psi = \sqrt[3]{\frac{bc}{a^2}} \qquad [1]$$

Cailleux's Flatness Index:

Ranging from 100 to infinity, the flatness of a clast was determined using Cailleux's flatness index. The flatter the clast, the higher the index value (Briggs, 1977). The formula uses three main axes (a, b and c) (Briggs, 1977) [2]:

$$F = \frac{a+b}{2c} \times 100 \quad [2]$$

4.2.2. Particle Size Analysis

Particle size analysis is important in understanding the processes that take place during transport and deposition of sediments (Briggs, 1977). It is important to use this method as it brings understanding of the past and present processes that have taken place, especially in the palaeo-environment (Briggs, 1977). The method adopted was helpful in identifying the types of deposits that were in the sample (Briggs, 1977), while the moisture content was assessed and recorded and the particle sizes was determined in each sample.

Particle sizes can be classified from clay, to cobbles and boulders (Briggs, 1977). In order to identify the sizes of the particles, a size grade or scale was used (Table 10) (Briggs, 1977). Soil samples were weighed before and after being placed in the oven for 24 hours at 105°C, to determine the loss of moisture (Briggs, 1977), and hence allow calculation of the proportion of moisture in the field. A pestle and mortar was used to break the soil aggregates (Briggs, 1977)[4]. The soil samples were sieved for 10 minutes in the Endecott test sieve shaker (Figure 17) and then the different sized sieves were weighed, emptied and cleaned (Briggs, 1977). Each sieve was weighed beforehand to calculate the difference in weight of the sediment found in each sieve (Briggs, 1977). The aperture sizes of the sieves used were 4000µm, 2000µm, 1000µm, 500µm, 250µm, 125µm, 63µm and the fines (bottom sieve), which was <63µm. The sieve stack was arranged in this order so that the sample can be analysed according to the particle sizes. The results have been plotted into a cumulative percentage frequency curve, as suggested by Briggs (1977).

Figure 17: Endecott test sieve shaker.

[4] Issues with breaking up the sediment is that particles could be broken down further or become damaged (Briggs, 1977).

If significant fine material was present in a sample (Figure 18), then the Malvern Mastersizer 3000 was used to further size the particles (Figures 19 and 20). The Malvern Mastersizer 3000 was an efficient, easy and accurate way to determine the particle size distribution of the sample (Blott and Pye, 2006; Malvern Instruments, 2017).

Figure 18: Fines found in the bottom of the sieve stack.

Figure 19: Malvern Mastersizer

Figure 20: Malvern Mastersizer.

Table 10: Size grades of sedimentary Particles. Adapted from (Briggs 1977).

Phi Size (ϕ)	Millimetres (mm)	Micrometres (µm)	Wentworth Grade	
-6,0	64	64000	Cobbles	60,0mm
-5,5	44,8	44800	Coarse gravel	20,0mm
-5	32	32000		
-4,5	22,4	22400		
-4	16	16000	Medium Gravel	6,0mm
-3,5	11,2	11200		
-30	8	8000		
-2,5	5,6	5600	Fine Gravel	2,0mm
-2	4	4000		
-1,5	2,8	2800		
-1	2	2000		
-0,5	1,4	1400	Coarse Sand	0,6mm
0	1	1000		
0,5	0,71	710		
1	0,5	500	Medium Sand	0,2mm
1,5	0,3565	355		
2	0,25	250		
2,5	0,118	180	Fine Sand	0,06mm
3	0,125	125		
3,5	0,09	90		
4	0,063	63		
4,5	0,045	45	Coarse Silt	0,02mm
5	0,032	32		
5,5	0,023	23		
6	0,016	16	Medium Silt	0,006mm
6,5	0,011	11		
7	0,0055	5,5		
7,5	0,0055	5,5	Fine Silt	0,002mm
8	0,004	4		
8,5	0,00275	2,75		
9	0,002	2	Clay	
9,5	0,00138	1,38		
10	0,001	1		

Cumulative frequency curves were used in further statistical analyses of the particle size analyses. The percentile value on cumulative frequency graph was used to calculate the Phi mean, skewness, Kurtosis and sorting (see Table 11)(Briggs, 1977). Percentile value was read off the graph where the y is the percentile and the x axis is the corresponding value (Briggs, 1977).

Table 11: Formulas used for particle size analysis.

Name	Formula	Explanation	Values
Phi mean	$$D_{\bar{x}} = \frac{\emptyset 25 + \emptyset 50 + \emptyset 75}{3}$$ [3]	To calculate the phi mean the 25th, 50th and 75th percentile are read off the graph and added together and divided by 3 [3] (Briggs, 1977).	
Phi skewness	$$Sk = \frac{\emptyset 84 - \emptyset 50}{\emptyset 84 - \emptyset 16} - \frac{\emptyset 50 - \emptyset 10}{\emptyset 90 - \emptyset 10}$$ [4]	The phi skewness is calculated by reading off the percentiles on the graph and using the formula [4] (Briggs, 1977). Phi skewness indicates the deviation away from the norm, hence the term "skewness" (Briggs, 1977).	
Phi sorting	$$So = \frac{\emptyset 90 + \emptyset 80 + \emptyset 70 - \emptyset 30 - \emptyset 20 - \emptyset 10}{5.3}$$ [5]	The formula is used to determine the standard deviation of the distribution in the particle size [5] (Briggs, 1977)	
Phi kurtosis	$$Kg = \frac{\emptyset 90 - \emptyset 10}{1.9(\emptyset 75 - \emptyset 25)}$$ [6]	Phi Kurtosis is linked to sorting and non-normality, as it measures the peak of the size of particle distribution [6] (Briggs, 1977).	
Kolmogorov-Smirnov Test	$$D_a = c(a)\sqrt{\frac{n_1 + n_2}{n_1\, n_2}}$$ [7]	This test indicates whether there is a difference or not between two samples that [7] (Till, 1974). If the samples are the same then they are considered to be part of the same population (Till, 1974).	*D_a = the critical D value* *c(a)= significance coefficient (see table 16)* *n_1 and n_1 = size of the sample 1 and 2*

Table 12: Level of significance of the coefficient c(a) (Adapted from Till 1974).

Level of significance (a)	0.10	0.05	0.025	0.01	0.005	0.0001
c(a)	1.22	1.36	1.48	1.63	1.73	1.95
H_0 states: There is no significant difference between the distributions. H_a states: The two distributions are so different that they must be considered to represent different populations.						

When utilising the Kolmogrorov-Smirov test, the largest difference between the two samples (that is read off the cumulative frequency graph) was the D value (Till, 1974). If the D value was greater than the critical D value, then H_0 was not accepted but if it was less than the critical D value then H_0 was accepted(Till, 1974).

4.2.3. Fabric Analysis

Fabric analysis indicates the preferred orientation of the long axis of clasts and provides an indication of the direction and velocity of movement (Briggs, 1977). Three-dimensional aspect of the clasts which are measured for orientation and dip to determine this (Briggs, 1977). The plane dip was measured by looking at the maximum angle of the dip on the clast using a clinometer (Briggs, 1977). The orientation is the direction in which the ab plane is angled and this was measured by using a Brunton® compass. Data was captured and transferred into Microsoft Excel ® and then into Grapher 7 ® to make the relevant graphs.

4.3. Heave monitoring

To observe the development of sorted circles and the fine material found in patterned ground, a method by Borg (2017) was applied. This method was conducted in this thesis for the 2016/17 data. Heave monitoring method was to fulfil objective three, by investigating the process of how pattern ground is formed or is forming. The basic outline of this method is that Bushnell Trophy Cam HD® cameras are used to capture the heave that takes place in soils (Borg, 2017). The method used by Borg (2017) to set up the cameras was altered to capture heaving in the Antarctic soils. The cameras were set to take a picture every minute so that even the smallest movement can be captured and recorded. These pictures were used to create a time-lapse so that one can view changes. The programmes used to make the time-lapse was Adobe Premiere® and Timelapse® which is an Apple Software program.

The camera was placed with its rear-end to the prevailing wind and to avoid sun directly shining into the lens, and also to avoid shadows present (Borg, 2017)[5]. In this instance, the cameras were placed on the ground and wedged between rocks to prevent the wind moving them (Figure 21). To analyse the time-lapse, a reference for scale was placed in the form of a long tent peg (Figure 22). A scale bar of 2,5cm notches made it possible to indicate the movement. This was hammered sufficiently far into the ground to avoid the heave of the soil displacing the peg. The red tape represented five cm while white tape represented every 2,5cm.

Figure 21: Placement of the Bushnell cameras.

Figure 22: The Scale Bar.

[5] The limitation is that it was difficult in Antarctica to avoid the sunlight shining directly into the lens because there is 24h hours of sunlight.

4.4 Morphological measurements

The morphological measurements for the specific landforms were completed over a number of Austral summer seasons. The measurement for sorted circles and half circles was completed by previous researches (for the archival data) and in this thesis for the 2016/17 data. Majority of the polygon data was collected by previous researches (archival data) but data was collected for this thesis (2016/17). Supplementary data was collected for blockfields and pronival ramprt in this thesis. The ice blister data is from this thesis (2016/17 data). The following methodology was applied to previous documentation: transects were completed across the landforms, using a DGPS (Differential Global Positioning System). A handheld GPS was used to mark the position of the landform centre and the position of where samples were taken from. A photo was taken of the landform with an item for scale reference (e.g.: a geopick).

4.4.1. Sorted circle and half circle

Using a trowel, a sample from the middle (fines) and from the outside area were collected, as indicated by the blue arrows (Figure 23). The length of the longest and shortest axis was measured with a measuring tape. The dip was measured using a clinometer (or Brunton® compass), and the orientation was measured by using a Brunton® compass. In previous summer seasons, transects were conducted across the sorted circles. Every one or two cm the clast a-axis length was measured. This allows the change in clast movement to be identified, as they taking move from the centre of the patterned ground in an outwards direction.

Figure 23: Sorted circle.

4.4.2. Polygons

A measuring tape was used to measure the length of the long and short axes of polygons (Scott, 2014; Rudolph, 2015). A soil sample was taken from the centre of the polygon and another in the crack of the polygon (Scott, 2014). The width of the crack of polygon was measured (Scott, 2014). The orientation and dip was taken for both the crack and the centre of the polygon. All measurements taken were used to contributed to the 3D modelling conducted by Scott (2014).

4.4.3. Blockfields

Blockfields was the topic of an investigation by Hansen (2014) and to supplement her study photographs are taken to contribute to the knowledge pool.

4.4.4. Pronival Rampart

The landform identified by Hedding (2014) was visited and snow/ice samples were collected at the snowbank above the rampart (Figure 24). Three samples were taken using a bulk density square (Figure 25) at the right side, in the centre and left side of the snowbank. This was to determine whether the ‘snowbank’ is actually snow or firn[6]. The snow samples were weighed and the density of the material was calculated using the dimensions of the bulk density square; i.e.:

Figure 24: Collecting ice samples on the snowbank.

Length: 8cm

Width:6cm

Height: 5cm

Therefore, the volume of the bulk density square is 240cm^3. With this, the density of the snow was calculated using the formula:

$$D = \frac{m}{v}$$

Where D = density, M= mass(weight) and v= volume.

The set of criteria that was adapted from Hedding *et al* (2007) and Shakesby (1997) was considered when investigating the pronival rampart. It was used as a checklist when discussing and analysing the landform (Table 13).

Figure 25: Bulk density square.

[6] Firn is the transition stage between snow and glacial ice as it is snow that has not been compacted into ice yet (Paterson, 1994).

Table 13: Diagnostics criteria for defining a pronival rampart from other similar landforms (Adapted from Shakesby 1997).

Criteria		Additional Comments
Glacier		
Talus-foot location	✓	
Glacial erosional forms	x	
Striated clasts	x	
Erratics	x	
Linear plan form	✓	Simuous
Asymmetrical cross-profile	✓	
Symmetrical cross-profile	x	
Class dip away from backwall	x	
Landslide		
Talus-foot location	✓	
Hillslope scar	x	
Debris apron beyond the feature	x	
Large masses of displaced hillside within or above the debris accumulation	x	
Protalus Rock Glacier		
Talus foot location	✓	
Multiple accurate ridges	x	Step on proximal slope
Greater in length (down-slope) than in width (across-slope)	x	
Crenulate or lobate plan form of the outer margins	x	
Convex distal slope	x	Rectilinear
Meandering and closed	x	
Depressions, downslope ridges and furrows, and transverse ridges and depression		
Pronival (Protalus) Rampart		
Talus-foot location	✓	
Large ridge to backwall summit inclination	✓	
Small ridge to backwall distance	✓	
Ridge crest to talus-foot distance	✓	
< *c.* 30-70m		
Restricted potential snow accumulation depth	✓	
Length < 300m	✓	
Openwork fabric with/without infilling fines	✓	
Single ridge	✓	Step on proximal slope
Ridge side increase with distance from talus foo	✓	
Backwall and ridge same lithology	✓	
Angular clasts	✓	

4.4.5. Ice blister

The location of lake-ice blisters was recorded and noted using a hand-held GPS. The crack widths of the ice blister were measured. The height of the ice blister could not be measured as the ice blister was deflated. Pictures were taken for documentation and compared to earlier photographs.

4.5 Summary

Past data collected each Austral Summer was augmented with new observations made during the 2016/2017 season and compiled in a database. The results are discussed over three Chapters, where Chapter 5 is the archival data, Chapter 6 and 7 is 2016/17 data.

Chapter 5: Overview of archival data

The archival data was collected over numerous Austral summers, however, the data is analysed in this thesis for the first time. The only landforms that feature here are two types of patterned ground. Due to the environment in WDML the most frequent periglacial landform that develops is patterned ground. Each type of patterned ground has an overview on what has been investigated by other researches that were part of the broader project. The results of the archival data are presented, followed by a discussion which will provide an opportunity to compare to the 2016/17 data in Chapter Six.

5.1. Patterned ground

The most frequent landform found in Antarctica is patterned ground (Hallet, Sletten and Whilden, 2011), which is evident on the nunataks in WDML and reflects in the archival data. Below the archival data for polygons and circles is examined.

5.1.1. Polygons

Polygons have been documented in many areas of WDML. Rudolph's (2015) research on the polygons at Vassdalen supports the contention that polygon formation is influenced by gravity, but it is also linked to the flow of past glacial movement rather than the movement of the slope. Polygons were mapped and digitized using a UAV (Unmanned Aerial Vehicle), 3D modelling and Digital Elevation models (DEM) (Scott, 2014). Kotzé (2015) mapped and discussed how the active layer processes form part of the formation of polygons. Discussed below, is the archival data that was collected by previous researchers during past Austral summers.

5.1.1.1 Results

Distribution:

The distribution of different types of polygons that are displayed in Figure 26 are from 2006-2008 archival data. The different types of polygons were grouped together for each nunatak (Figure 26). The polygons were also grouped by type of polygon, which due to the processes involved in the formation of each type (Figure 26). The polygons found at Troll are clearly the largest in size whereas the polygons found at Veleskarvet are the smallest (Figure 26). It is clear that the type of polygon influences the size of the polygon (Figure 26).

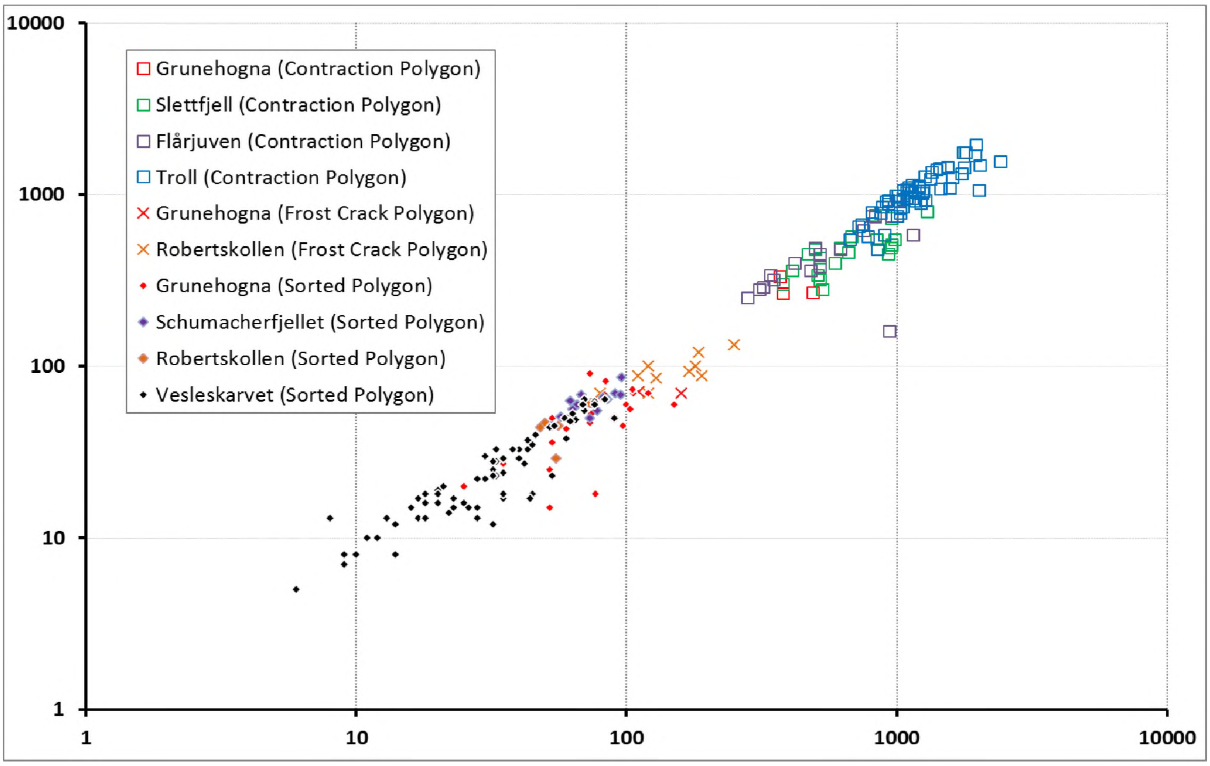

Figure 26: The distribution of different types of patterned ground in WDML (data from 2006-08). Where the x-axis is the long axis of the polygon and y-axis is the short axis of the polygon in cm.

Slope and orientation:

Slope and orientation are two of the many factors that can play a role in polygon formation. Figures 27, 28 and 29 display the orientation of the contraction polygons a-axis and the slope orientation. Figures 27 and 29 have been mirrored to give a clear indication of orientation. Figure 28 is not mirrored because the shape of the polygon is elongated parallel to the slope. Thus, the slope has an influence on the shape and size of the polygons at Flårjuven. The shape of the polygons at Troll are elongated perpendicular to the orientation of the slope, which indicates that the polygons are not influence by the slope (Figure 27). Polygons at Grunehogna have an elongated shape that is sub-parallel to the slope orientation (Figure 29). Therefore, the gradient of the slope does not affect the shape of the polygons to elongate at Grunehogna. Thus gravity can have an impact on the polygons' shape (Rudolph, 2015) but there are many other factors that can influence their formation such as freeze and thaw processes.

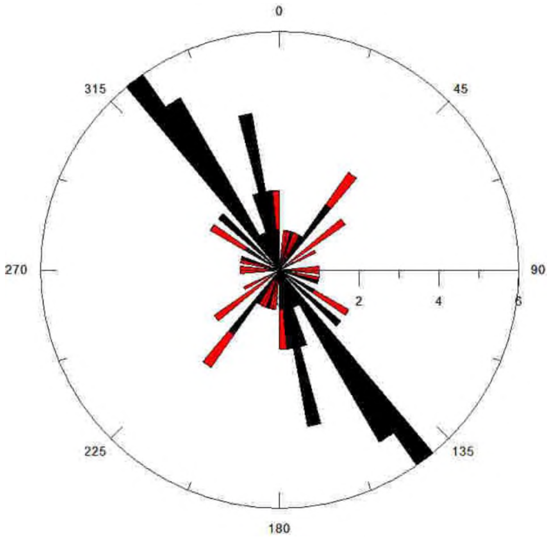

Figure 27: Orientation of Mimelia (Troll) contraction polygons. The red is the orientation of the a-axis and the black is the slope orientation (data from 2013/14).

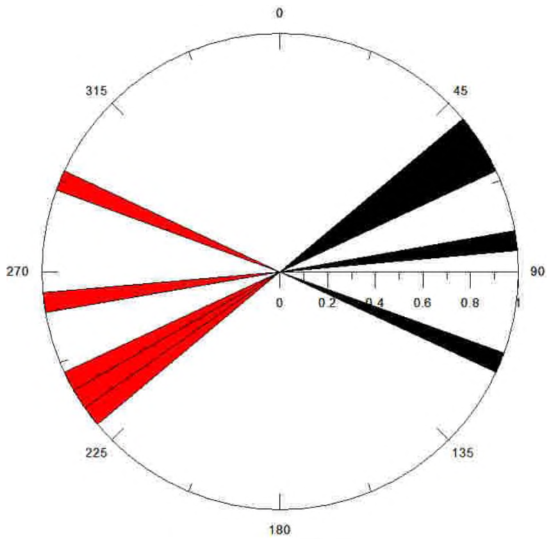

Figure 28: Orientation of Flårjuven contraction polygons. The red is the orientation of the a-axis and the black is the slope orientation (data from 2013/14).

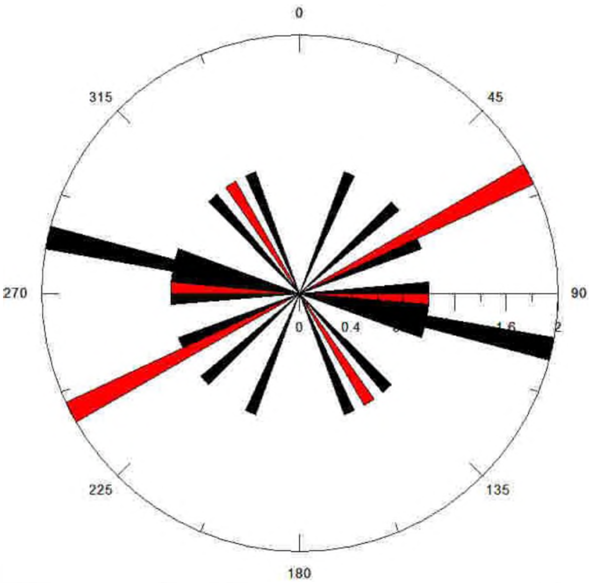

Figure 29: Orientation of Grunehogna contraction polygons. The red is the orientation of the a-axis and the black is the slope orientation (data from 2013/14).

Sediment analysis:

Freeze thaw processes are what drive the formation of polygons in periglacial environments (Washburn, 1980). Sediment analysis is an aspect that can give insight into how polygons form or develop over time. Thus the relationship between the centre and crack of the polygon is examined. The sediment analysis attempts to show the difference between the type of polygons and well as the interaction between the crack and centre in relation to the environment. Presented in Figure 30 is data analysed in the 2013/2014 Austral Summer, where samples were taken from the centre and the crack of the contraction polygons found in WDML. Due to multiple samples taken using a variety of methods, an average was used to interpret the data. Graphically, the different sites have a fairly similar graph curve, except for Troll (Figure 30), largely due to a different underlying lithology. The breakdown of the particle size shows that there is a similar distribution in all the samples (Figure 31). Troll (13.9%) has the highest presence of medium gravel (-3 phi) where as Flårjuven has the lowest (16.2%) (Figure 31). Fine silt and clay (8 phi) are present in all the samples where Flårjuven has the highest percentage (9%) and Grunehogna has the lowest (7.4 %).

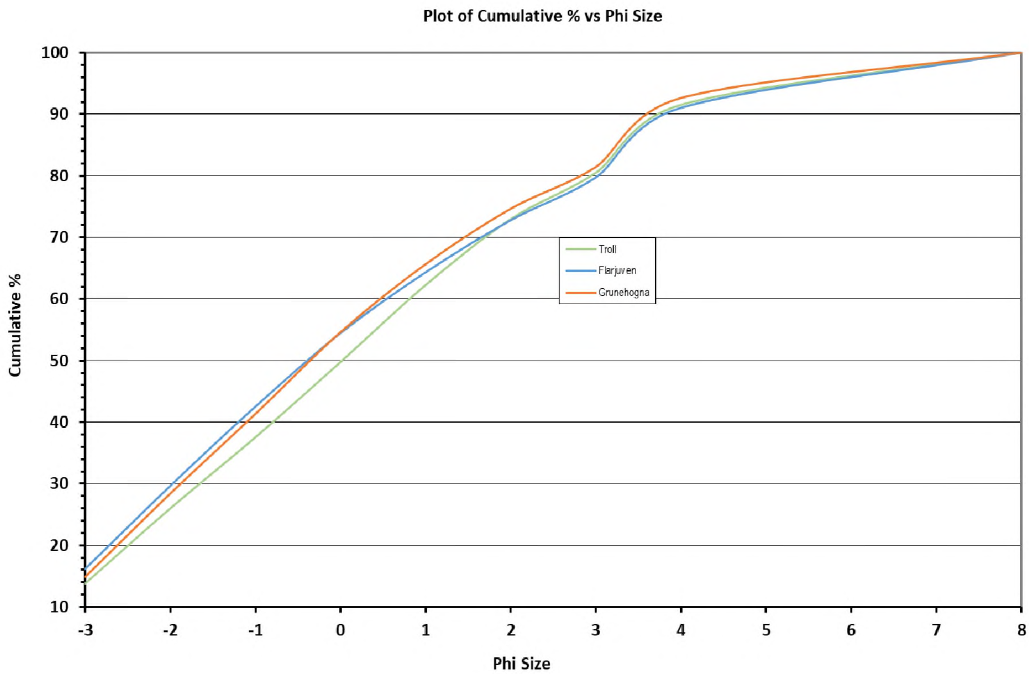

Figure 30: Plot of cumulative % vs phi size for the centre of the polygon data from 2013/14.

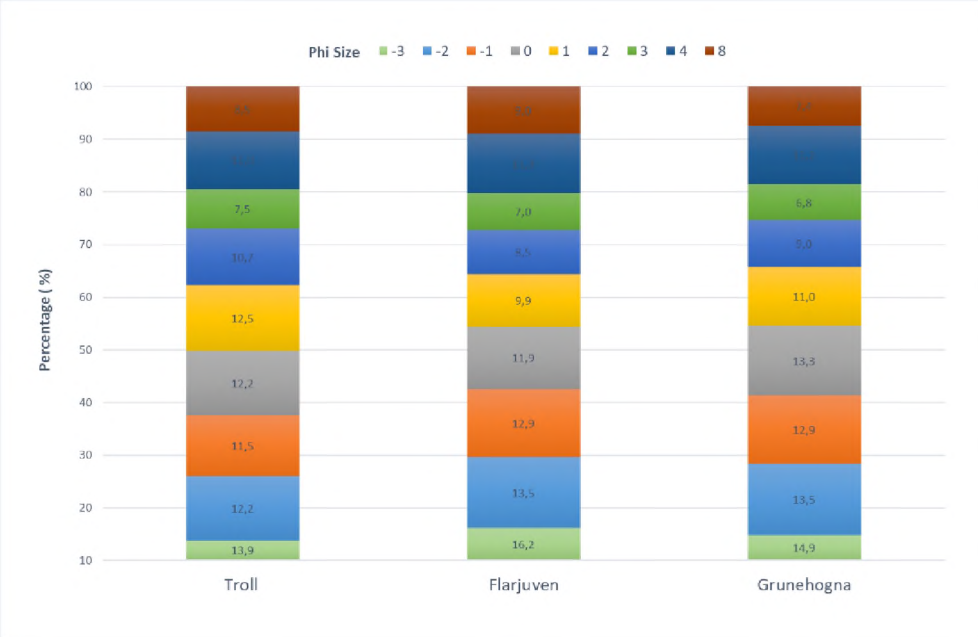

Figure 31: A breakdown of phi particle sizes for the centre of the polygons (2013/14).

The analyses of the ground texture shows a mixture of particle sizes in all the samples[7]. The phi mean particle size for Flårjuven (-0.20) and Grunehogna (-0.22) is coarse sand, whereas the particle size for Troll (0.05) is fine gravel (see Figure 32 and Table 17). Observations confirm that Flårjuven and Grunehogna had mixed material whereas Troll either had large clasts or fine sediment. Flårjuven has a phi skewness of 0.22 and Grunehogna has a phi skewness of 0.20 which indicates that they are positively skewed (see Figure 32 and Table 17). This shows that there are few fines present in the samples, but rather more coarse material (Briggs, 1977). Troll, however, is symmetrical, as the phi skewness result is 0.10 (see Figure 32 and Table 17) which indicates that there is equal presence of fine material and larger clasts (Briggs, 1977). Sorting is related to the size distribution according to the energy used to move the particles (Briggs, 1977). Phi sorting values for all study sites (Troll: 2.94, Flårjuven: 3.07 and Grunehogna: 2.91) indicated that they are very poorly sorted (see Figure 32 and Table 17). Flårjuven (1.30) and Grunehogna (1.41) are leptokurtic (see Figure 32 and Table 18). Thus, there are more fine particles present there (Briggs, 1977). Troll (1.58) is very leptokurtic (see Figure 32 and Table 17), meaning particles sizes are very well sorted (Briggs, 1977).

[7] For skewness, sorting and kurtosis analysis: Tables 14, 15 and 16 give the range of values for the different descriptive terms.

Table 14: The descriptive terms for skewness (Briggs 1977: 80).

Skewness			
Very negatively skewed	-1,00	-	-0,3
Negatively skewed	-0,3	-	-0,1
Symmertrical	-0,1	-	0,1
Positively skewed	0,1	-	0,3
Very postively skewed	0,3	-	1

Table 15: The descriptive terms for sorting (Briggs 1977: 80).

Sorting	
Very well sorted	<0,35
Well sorted	0,35-0,50
Moderately well sorted	0,50-0,70
Moderately sorted	0,70-1,00
Poorly sorted	1,00-2,00
Very poorly sorted	2,00-4,00
Extremely poorly sorted	>4,00

Table 16: The descriptive terms for kurtosis (Briggs 1977: 80).

Kurtosis	
Very platykurtic	<0,67
Playkurtic	0,67-0,90
Mesokurtic	0,90-1,11
Leptokurtic	1,11-1,50
Very leptokurtic	1,50-3,00
Extremely leptokurtic	>3,00

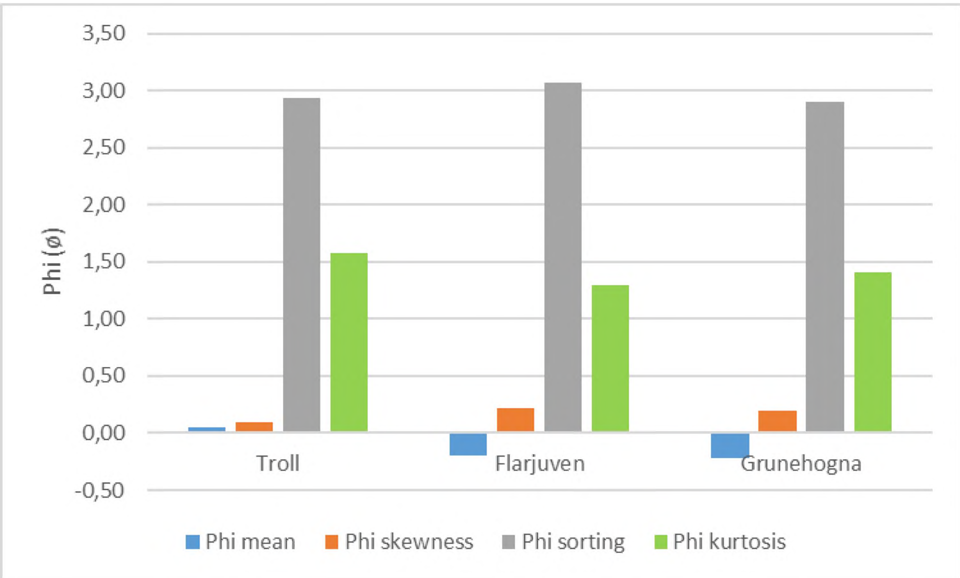

Figure 32: The phi mean, skewness, sorting and kurtosis values for the centre of the polygons (2013/14).

Table 17: Table showing phi mean, skewness, sorting and kurtosis descriptive terms for the centre of the polygons.

Polygon centre samples from 2013/14 data				
Samples	**Phi mean**	**Phi skewness**	**Phi sorting**	**Phi kurtosis**
Troll	Fine gravel	Symmertrical	Very poorly sorted	Very leptokurtic
Flarjuven	Coarse sand	Positively skewed	Very poorly sorted	Leptokurtic
Grunehogna	Coarse sand	Positively skewed	Very poorly sorted	Leptokurtic

The plot of cumulative % vs phi size graph for the polygon cracks (Figure 33) shows that the curves for the study sites are similar, except for one area in the Troll graph. There is a mixture of particle sizes for the samples (Figure 34). All sites have a large proportion of fine gravel present (-2 phi) (Figure 34), as well as fine silt and clay, with Grunehogna having the highest percentage (9%). The observed particle size distribution is further explained in the analysis below.

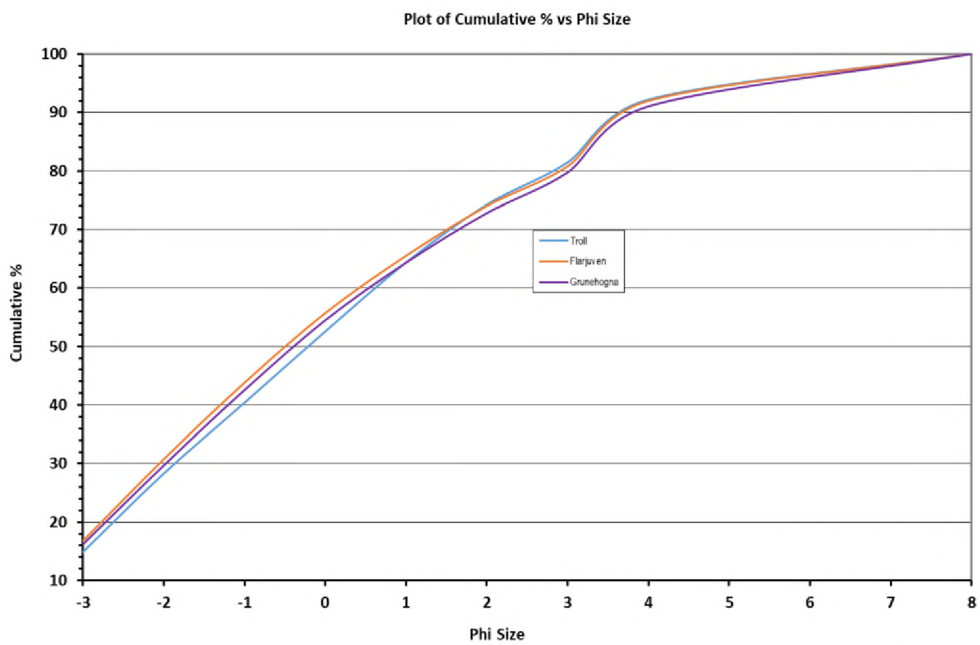

Figure 33: Plot of cumulative % vs phi size for the crack of the polygon from 2013/14 data.

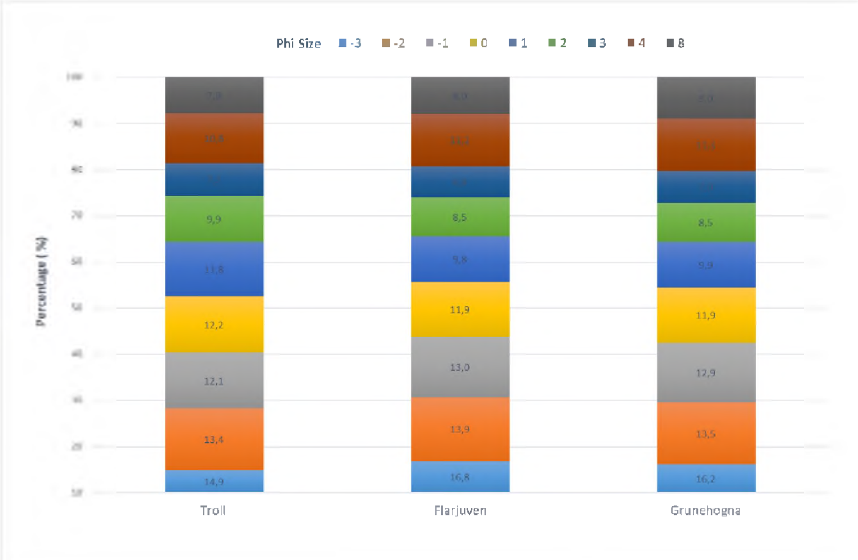

Figure 34: A breakdown of phi particle sizes for the crack of the polygons (2013/14).

The phi mean, skewness, sorting and kurtosis values were determined for the polygon cracks at three study sites. The phi mean for all three study sites indicates that the average particle size is coarse sand (see Figure 35 and Table 18). All three sites had particle size distributions that were positively skewed (Troll: 0.10, Flårjuven: 0.22 and Grunehogna: 0.20), which indicates that there are relatively high proportions of fine particles (see Figure 35 and Table 18) (Briggs, 1977). All samples were very poorly sorted (Troll: 2.93, Flårjuven: 3.09, Grunehogna: 3.04), indicating a mixture of particle sizes in the crack of the polygon (see Figure 35 and Table 18). All samples (Troll: 1.48, Flårjuven: 1.29 and Grunehogna: 1.30) have fines present and are sorted as the phi kurtosis is leptokurtic (see Figure 35 and Table 18).

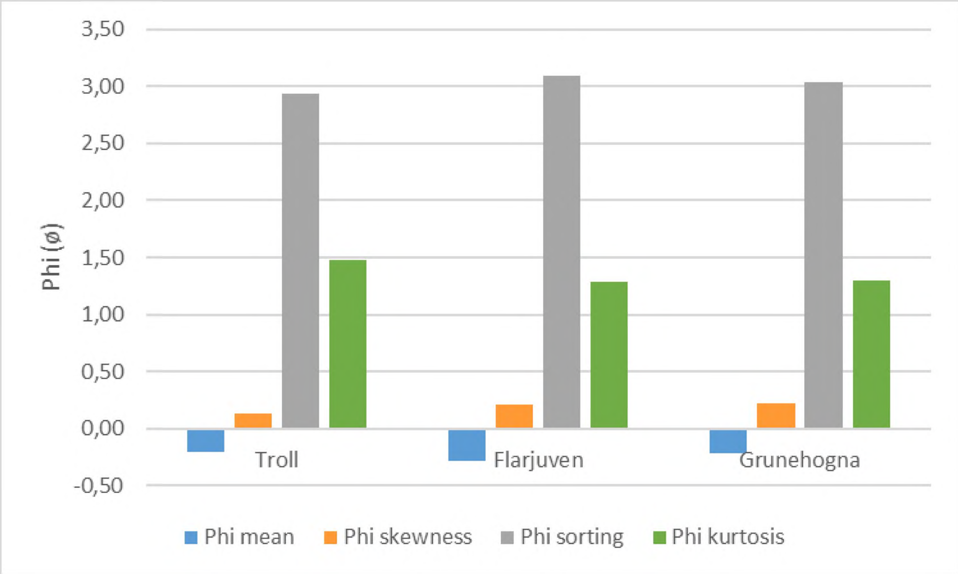

Figure 35: The phi mean, skewness, sorting and kurtosis values for the crack of the polygons (2013/14).

Table 18: Table showing the phi mean, skewness, sorting and kurtosis descriptive terms for the crack of the polygons.

Polygon crack samples from 2013/14 data				
Samples	**Phi mean**	**Phi skewness**	**Phi sorting**	**Phi kurtosis**
Troll	Coarse sand	Positively skewed	Very poorly sorted	Leptokurtic
Flarjuven	Coarse sand	Positively skewed	Very poorly sorted	Leptokurtic
Grunehogna	Coarse sand	Positively skewed	Very poorly sorted	Leptokurtic

Sediment and particle size play a role in the formation of polygons but another factor is moisture in the sediment. Moisture combined with temperature can cause sediment to heave and move (Brady, 1974). Troll had no moisture present in the crack of the polygon (0%) whereas the centre of the polygon had little moisture present (1%) (Table 19). Flårjuven had moisture present with the crack (0.71%) having less moisture than the centre (1.13%) (Table 20). The centre (2.10%) of the Grunehogna polygon has a higher soil moisture content compared to the crack (1.52%) of the polygon (Table 21).

Table 19: Soil moisture content (%) for the centre and crack of the Troll samples.

	Field mass (g)	**Dry mass (g)**	**Mass difference (g)**	**Moisture (%)**
Centre	648,89	645,96	2,93	0
Crack	684,26	679,89	4,38	1

Table 20: Soil moisture content (%) for the centre and crack of the Flårjuven samples.

	Field mass (g)	Dry mass (g)	Mass difference (g)	Moisture (%)
Centre	495,1	489,53	5,57	1,13
Crack	492,02	488,55	3,47	0,71

Table 21: Soil moisture content (%) for the centre and crack of the Grunehogna samples.

	Field mass (g)	Dry mass (g)	Mass difference (g)	Moisture (%)
Centre	472,3	462,3	9,93	2,10
Crack	435,4	428,7	6,63	1,52

5.1.1.2. Discussion

Freeze thaw processes are what drive the formation of polygons (Warburton, 2013). The difference between different types of polygons, is the processes that occur after the freeze thaw process (Levy *et al.*, 2008). These other processes are displayed in Table 22. Sorted polygons are polygonal in shape and have a distinct border of stones that surround a centre with finer material (Washburn, 1980). Frost crack polygons are not necessarily sorted but they are influenced by freeze thaw processes in the active layer as well as permafrost influences on the top layer (Washburn, 1980). Contraction polygons are formed by freeze thaw cycles where the tensile strength becomes too great for the frozen ground and thus creating a crack in the ground (Warburton, 2013).

Table 22: The factors that influences the formation of polygons (adapted from Ulrich et al. 2011).

Indicator	Control Factors	Effects	Reference
Polygon formation	Air and soil temperature, grain size	In silt, clay, and peat: <-3°C in sand and gravel: -8°C to -10°C	Washburn (1979); Romanovskii (1985); Yershov (2004)
	Insulation	Limiting the continuous frost cracking	Washburn (1979); French (2007)
Polygon diameter	Temperature gradient	Large gradient → harsher climate → smaller polygons	Yershov (2004); French (2007)
	Rheology of frozen ground	Heat conductivity (grain size, ice content) → fine-grained, high ice content → smaller poylgons	Lachenbruch (1962, 1966)
Polygon form	Stress free zones	Orthogonal → near the cooling surface hexagonal → in larger distance	Romanovskii (1977)
	Ground homogeneity	Hexagonal patterns- stress balance	Lachenbruch (1962); French (2007)
	Stage of development	Secondary cracking → polygon subdivision → more regular and orthogonal	Lachenbruch (1962); French (2007)
Polygon orientation	Stress relief	Orientated if stress-free vertical surfaces exist (i.e., anisotropy of strength)	Lachenbruch (1962)
Polygon nets	Drainage	Small nets → <27° slope Large nets → 31° slope	Washburn (1979)
Ice or sand-wedge formation	Atmospheric and ground humidity	High aridity → sand-wedge polygons	Péwé (1959); Black (1976); French (2007)
Ice-wedge polygon formation	Soil temperature, grain size	In clay → <-2°C, in gravels → <-6°C	Romanovskii (1985)

The polygons at Flårjuven and Grunehogna (Figure 36) are contraction crack polygons that are likely still being developed, due to the presence of permafrost and it is likely that these nunataks have only recently been deglaciated. The latter observation is based on the close proximity of the ice sheet and the low altitude differential between the ground surface and the ice. The polygons at Troll (Figure 37) are contraction sand-wedge polygons which is a type of contraction polygon. The polygons in this area are considered to be reaching maturity due to their shape and size (Kotzé, 2015) . However, there are secondary processes that do influence the polygons which indicates that they could be past maturity (Kotzé, 2015). The Dry Valley area of Antarctica has sand-wedge polygon features where some are active and some are relict (Marchant and Denton, 1996; Marchant *et al.*, 2002). The active polygons are found at a particular dry area of the Dry Valley (Marchant and Denton, 1996).

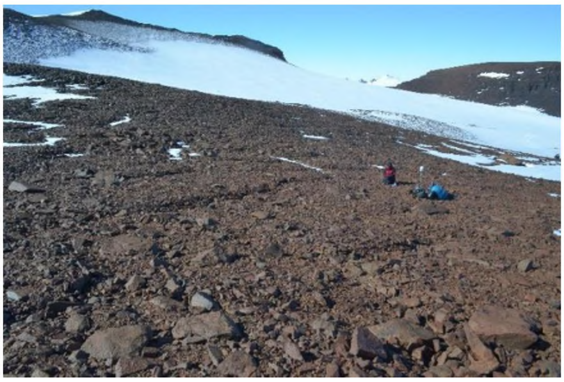

Figure 36: Polygons at Grunehogna.

Figure 37: Polygons at Troll.

Each nunatak has unique environmental conditions that produce slight variations in the formation processes, which, in turn, results in specific sizes, shapes and types of the polygons. The results indicate that the size of the polygon influences what type of polygon it is. It also highlights that the polygons are environmentally and nunatak specific. Thus, the grouping of the different polygon sizes (Figure 26) in WMDL can be accounted for. Scott (2014) shows that while the polygons in WDML might be the same type, the morphological measurements vary between each nunatak, indicating that each nunatak has its own environmental conditions that alter the polygon formations. Morphological measures such as shape, size and orientation of the polygons are explained below.

Polygons have developed with the influence of the gradient which elongates the shape of the polygon (Goldthwait, 1976; Rudolph, 2015). The orientation also supports the contention that the first cracks can determine the direction of elongation (Ulrich *et al.*, 2011). For the polygons examined in the results, it is suggested that the first cracks would have developed parallel to the slope orientation rather than on the transverse. This is similar to the polygons found in Norway where the polygons' orientation is subparallel to the slope orientation (Ulrich *et al.*, 2011). However, the polygons at Troll are perpendicular to the orientation of the slope which supports Rudolph's (2015) theory. The theory is that where the polygons follow the direction of the glacial flow (Rudolph, 2015). Rudolph (2015) further explains how the polygon shape looks compressed as it has followed the direction of the glacier rather than elongate due to gravity. If gradient has an effect on the elongation of the polygon, then it also affects the crack formation as primary cracking is formed along the a-axis orientation and then secondary cracking occurs along the contour (Ulrich *et al.*, 2011).

Polygons found in the Beacon Valley in Antarctica vary from inactive stages to active stages (Linkletter, Bockheim and Ugolini, 1973). Polygons here, have raise centres (Linkletter, Bockheim and Ugolini, 1973). The polygons investigated by Ulrich *et al.* (2011) in Norway were contraction polygons that have a raised centre. Therefore, the polygons in WDML are similar to both examples mentioned above, as the shape is convex where the centre of the polygon is raised above the cracks. The depressed cracks are a product of centre of the polygon freezing and thawing (Washburn, 1979). The contraction polygons at Grunehogna and Flårjuven have a mixed presence of sand and gravel in the crack. This differs, in the Beacon Valley, where the polygons contain only sand in the crack of the polygon (Linkletter, Bockheim and Ugolini, 1973). Polygons at Grunehogna are not sorted as there are still large clasts in the centre (Figure 41).

It is accepted that developed polygons have fine material in the centre and larger clasts present in the crack (Embleton and King, 1968; Washburn, 1979; Grab, 1997). The average particle size for centre and crack of polygons, found at Flårjuven and Grunehogna are similar, indicating that the polygons are still active and developing, as the sorting is visibly poor. The sediment in the cracks was poorly sorted, which was visible with both large clasts and fines being present. The moisture content in the cracks was lower than the centre, which manifested itself in a heaving central portion. Therefore if there is less moisture then there will be less sorting taking place (Embleton and King, 1968). Lower moisture contents at the particular site were counterintuitive, and likely to be the result of water draining in the cracks on a relatively steep slope. The centre of the two polygons had a mixture of particle sizes as the heaving process moved the larger clasts towards the cracks.

Troll had more fine material in the centre of the polygon, compared to Grunehogna and Flårjuven. In the crack, both fine and coarse material were visible (Figure 37). There was a mixture of particle sizes present in the centre and crack of the polygon. Which differs to the sand-wedge polygon at the Dry Valleys, as there was a layering of gravel and sand (Marchant and Denton, 1996). Sand-wedge polygons found in Hungary have fine to grained sediments in the crack of the polygon with some larger stones at the surface (Kovacs *et al.*, 2007). However, these polygons are relict and are speculated to have formed during the Pleistocene period in a similar environment to in Antarctica (Kovacs *et al.*, 2007). Sand-wedges found in Canada are thought to have formed in former Aeolian environment (Fisher, 1996). Currently the polygons have no vegetation present in crack but it occurs in the centre of the polygons (Fisher, 1996). The northern hemisphere examples are not appropriate for comparison to the Antarctic examples due the fact there is vexation and an increase of moisture present.

5.1.2. Sorted circles

Another type of patterned ground that is common in WDML is sorted circles. Sorted circles are common in WDML and they are found in different stages of development. Kotze (2015) analysed sorted circles at Robertskollen, Flårjuven, and Slettfjell using Gamma Spectroscopy, specifically aimed at tracing ^{137}Cs. The analysis showed that the sorted circles are still active (Kotzé, 2015). Mapping of circles was undertaken for selected nunataks by Kotze (2015). Below is the analysis of clast size in relation to shape and how this can be used to determine whether the development of sorted circles is still progressing. In addition, sediment analysis was undertaken to compare the centre and border of the circle to investigate potential sorting mechanisms.

5.1.2.1. Results

Shape analysis:

Environmental conditions influence the shape and size of the clasts and can further impact the formation process of periglacial landforms. A Zingg diagram was used to show that the clast at the edge of sorted circles are a spread of discs, blades and spheres[8] (Figure 38). By analysing the correlation of flatness and roundness it was possible to determine whether the sediments in sorted circles have a consistent shape (Figure 39). The relationship was poor between the flatness and rounds which emphasises that there is a mixed presence of clast shapes (Figure 39).

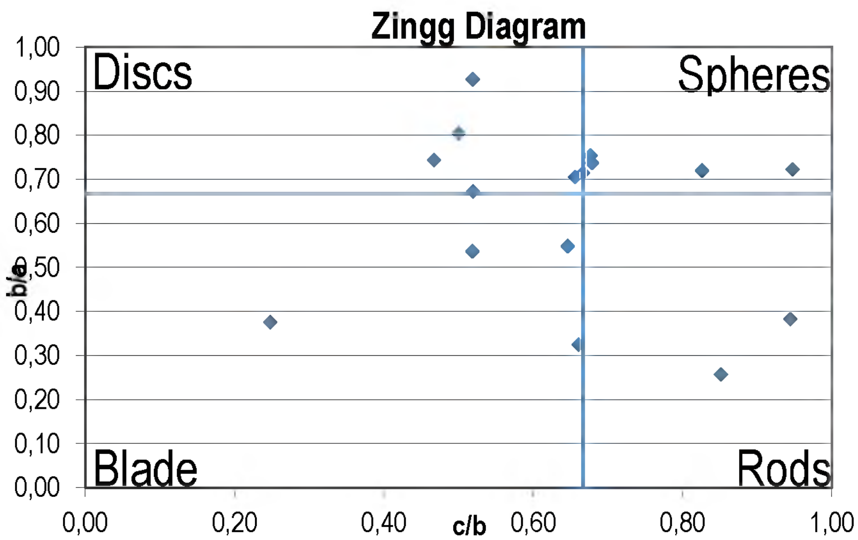

Figure 38: Zingg diagram of the coarse sediment at the edge of a sorted circle (data from 2006-2008).

[8] There is no shape analysis for the centre of the sorted circles as the archival data is not uniform and complete. See Chapter Eight: Limitations.

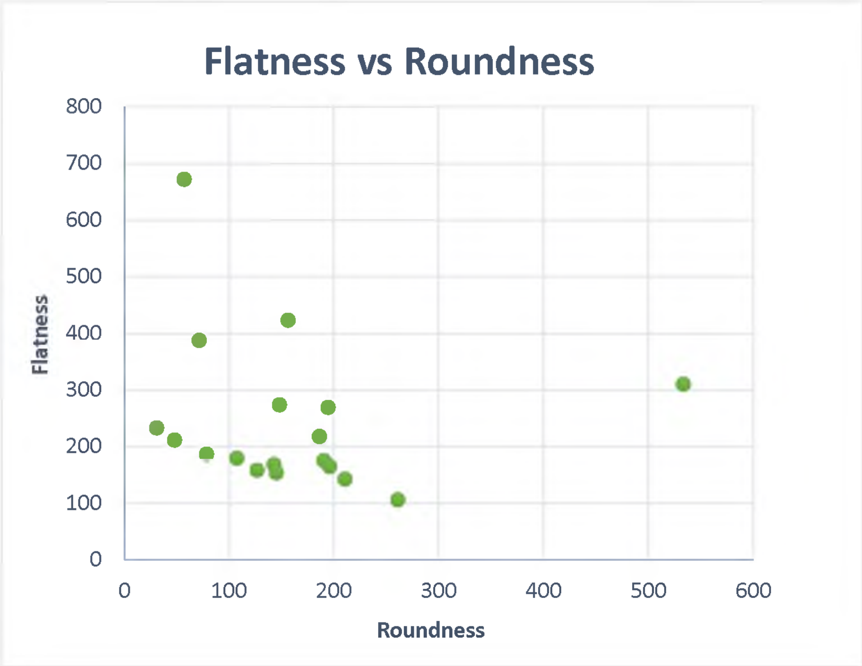

Figure 39: Flatness vs roundness for coarse sediment of the edge of sorted circles at Grunehogna (data from 2006-2008).

Clast size:

Clast size is important when analysing sorted circles as it can display the general shape of a sorted circle as well as show the variation across a sorted circle. Archival data (data from 2008/09) was graphically processed to show clast sizes across sorted circles (Figures 40, 41, 42 and 43). The shape of sorted circles and completeness of their formation is evident from larger clasts being found at the edge and as one moves towards the centre the clasts are smaller and fine material is often present (Washburn, 1980). The graphs shown below represent a cross section of the sorted circle showing the clast sizes (i.e. the longest, or a-axis) that were measured along that transect. Some of the graphs (Figure 40 and 41) display the "shape" of the sorted circles clearly, with coarse boundaries and finer centres, indicating that they were well developed. On the other hand, developing sorted circles have mixed clast lengths (Figures 42 and 43). Figure 48 displays the circles that are not well sorted as the clast sizes are mixed and they are imbricated[9]. Half circles[10] also develop in WDML and are frequent on the Northern Buttress of Vesleskarvet. The shape of a half circle consists of small clast sizes in the middle and as one moves away from the middle, the clast sizes increase (Figure 44 and 45). To

[9] Imbricated means that the clasts are stacked on top of each other.
[10] This patterned ground shape forms next to or in the overhang of a larger clast or bolder and develops outward where the sediment or clast size increases.

understand how sorted circles form, sediment analysis of the centre and border of the circles was undertaken in the 2016/17 Austral Summer season (see Chapter Six).

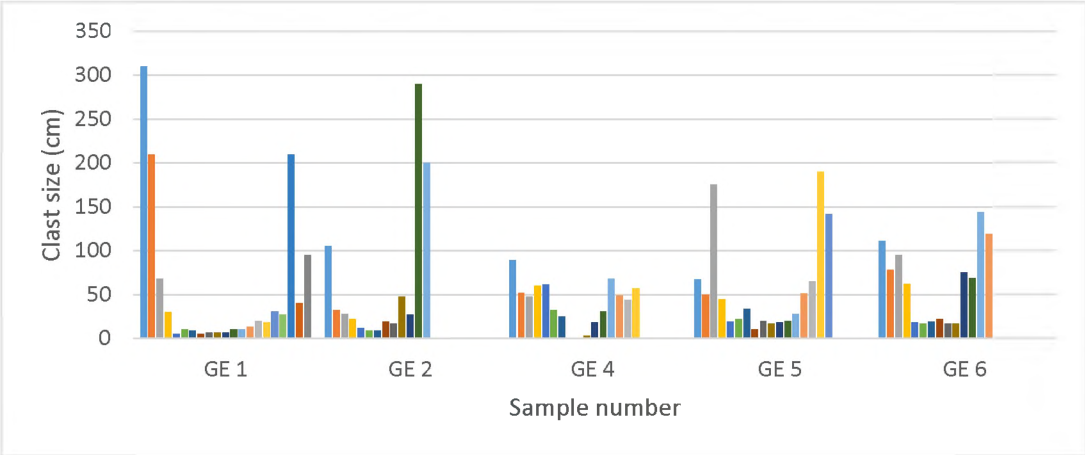

Figure 40: The length of clast a-axes for sample GE in the Grunehogna wind scoop (data from 2008/09).

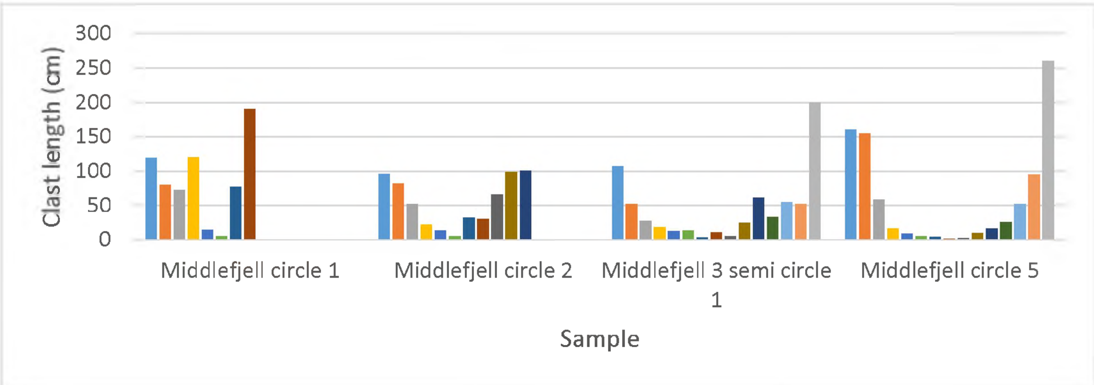

Figure 41: The length of clast a-axes at Robertskollen (data from 2008/09).

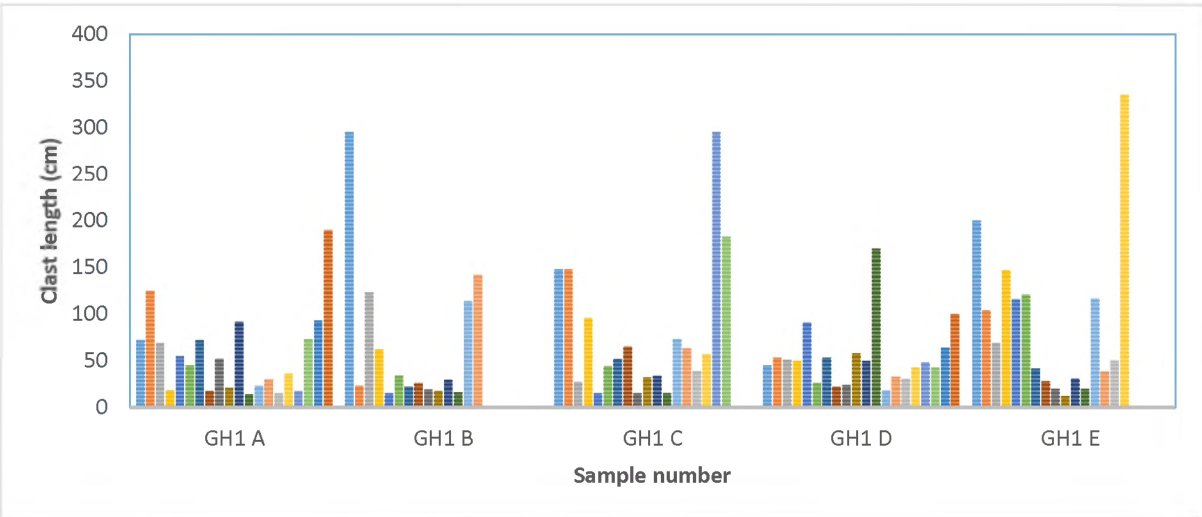

Figure 42: The pattern of sorted circles displayed using the clast a-axis length across "developing" sorted circles at Grunehogna (data from 2008/09).

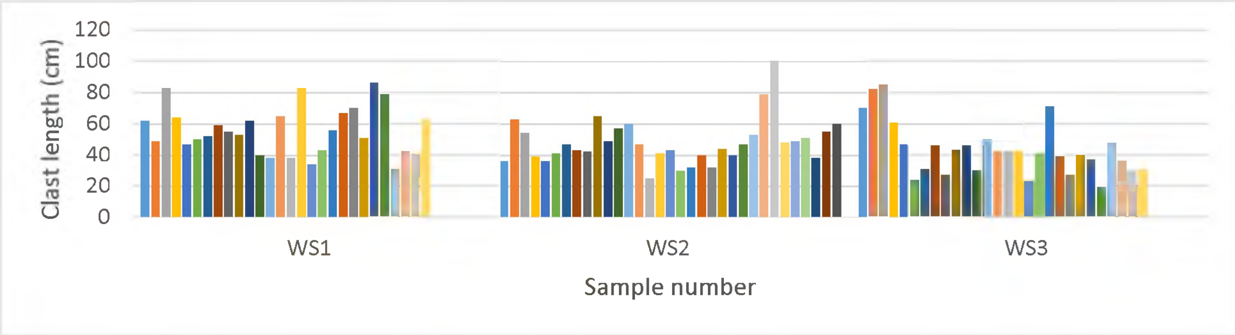

Figure 43: The length of clast a-axes of imbricated circles at Grunehogna wind scoop (data from 200/09).

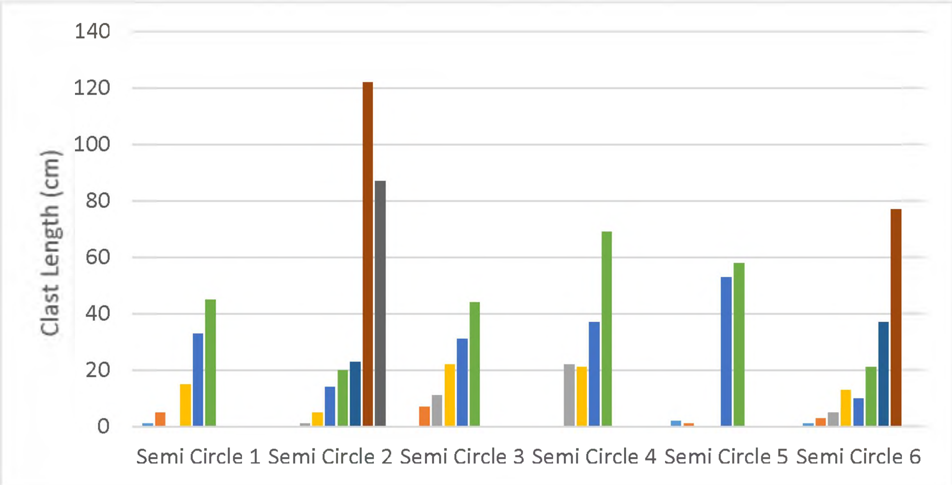

Figure 44: Clast a-axis measurements for half circles on the Northern Buttress of Vesleskarvet (data from 200/09).

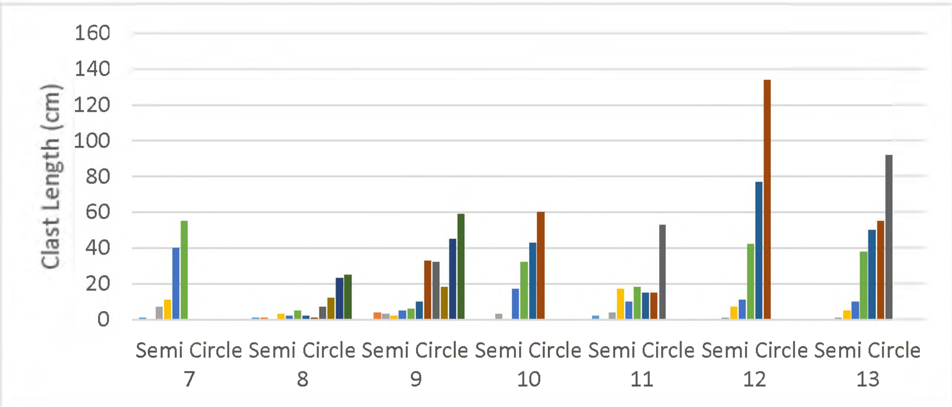

Figure 45: Additional clast a-axis measurements for half circles on the Northern Buttress of Vesleskarvet (data from 200/09).

5.1.2.2. Discussion

Periglacial conditions are often argued to produce sediments that are relatively coarse and clasts that are angular in shape, unless erosive glaciers have been active previously, which would lead to more rounded material (Briggs, 1977). In Antarctica, the harsh elements are thought to result in physical processes being active and it is argued that the angular clast shapes in Figures 43 and 44 reflect this. The glacial and slope influences have produced clasts that are angular/sub-angular where the roundness of clasts in low and the flatness varies (Briggs, 1977). Roundness will increase with transport of the clasts (Briggs, 1977). Additionally, the cold-based Antarctic glaciers are unlikely to have been erosive. Aeolian processes may additionally influence process and produce clasts that are slightly rounded with a sandblasted polish (i.e. ventifacts) (Briggs, 1977). Sorted circles examined in the Drakensburg Plateau (Lesotho, South Africa) display more rounding in the clasts on the border of the sorted circle (Grab, 2002), which is different to the sorted circles found at Grunehogna. This is due to the fact the Drakensberg environment is different and that the sorted circles are relict, which affects the erosion of the clasts (Grab, 2002).

The shape and size of larger clasts depends on the environment at the nunatak as well as the movement taking place. Most clasts analysed from sorted circles were a mixture of platy, sub-angular and angular. Slope, wind and past glaciers are the influences that alter the shape of the clasts (Briggs, 1977). Measurements of the clast a-axis lengths (Figures 45-50) across the sorted circles indicated that sorting had occurred. These figures emphasise the theory of freeze thaw as the formation of patterned ground in general which will be further explain in Chapter Eight. The general pattern was that large clasts were found in the border and as one moves across the circle towards the centre, the clasts decrease in size. Some centres even had fine sediment present. Although the Drakensburg Plateau (Lesotho) have different environmental conditions, the relict sorted circles do display the pattern of the sorted circles through clast sizes where the larger sizes are in borders of the sorted circles and the smaller clasts are in the centre (Figure 46) (Grab, 2002). This similarity between the Drakensburg Plateau examples and WDML are reiterated in Chapter Eight.

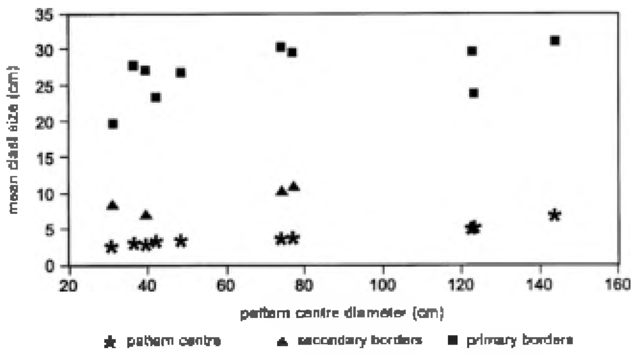

Figure 46: Plot of the mean clasts sizes against the diameter (Grab, 2002: 1734).

Chapter 6: Update on periglacial landforms WDML

To complement the research completed by past researchers', data from 2016/17 Astral summer is presented below, which fulfils objective two. Soil samples are investigated for patterned ground. Supplementary data is examined for blockfields and the pronival rampart. Documentation of lake ice blisters allows for the beginning of future research on these landforms in WDML. To consolidate the archival and 2017/18 data, maps are presented with locations of all landforms documented in WDML[11].

6.1. Patterned ground

As mentioned in Chapter Five, it is evident that patterned ground appears to be the most common periglacial landform on the nunataks in WDML. This is due to the environment in Antarctica, where freeze thaw processes and permafrost take place and allowing for the formation of patterned ground (Washburn, 1980; Warburton, 2013). The formation processes are further explored in Chapter Seven. By examining soil samples from patterned ground in WDML, it gives insight into the sorting that occurs in the freeze thaw events. The soil samples for polygons and circles are presented and discussed below.

6.1.1. Polygons

During the 2016/17 season, further samples were retrieved from the polygons near Troll station. These are the only polygon samples due the nature of the research, time only allowed for polygon soil samples within one nunatak. However, it does bring opportunity to compare with the archival results of polygons located at Troll. The results below compare the crack and centre of the polygon soil samples, to give an indication of how the freeze thaw events impact soil movement.

[11] The locations of these landforms is a combination of archival GPS points and 2017/18 GPS points.

6.1.1.1. Results

Clear differences emerged when comparing the crack and centre samples of the polygon at Troll (Figure 47). The difference is seen in the respective proportions of particle sizes present in the crack and centre (Figure 48). The crack has more fine gravel (-2 phi) than the centre (30.8%). Medium sand (-1 phi) is present in similar proportions in the crack (26.1%) and centre (30.8%). The smallest particles present were fine sand (4 phi) (Figure 48), and here the crack had none and the centre had 1.1 %. The particle size of the samples is further discussed below with statistical analysis.

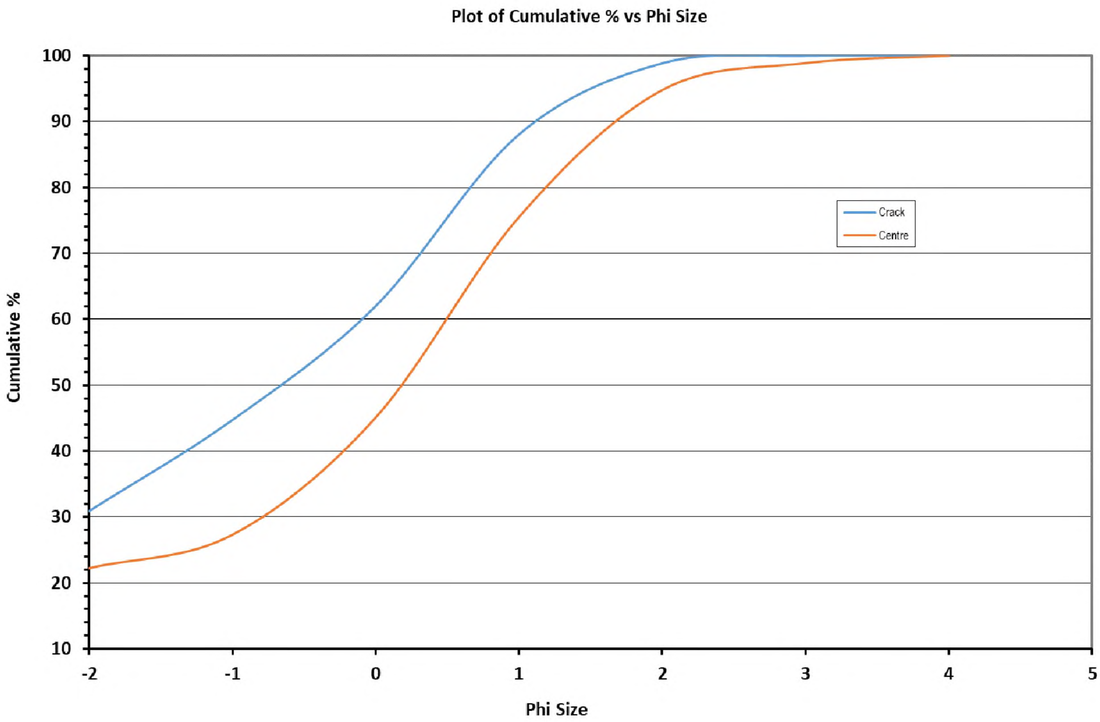

Figure 47: Plot of cumulative % vs phi size of the polygon sample taken in 2016/17 from Nonshøga (Troll).

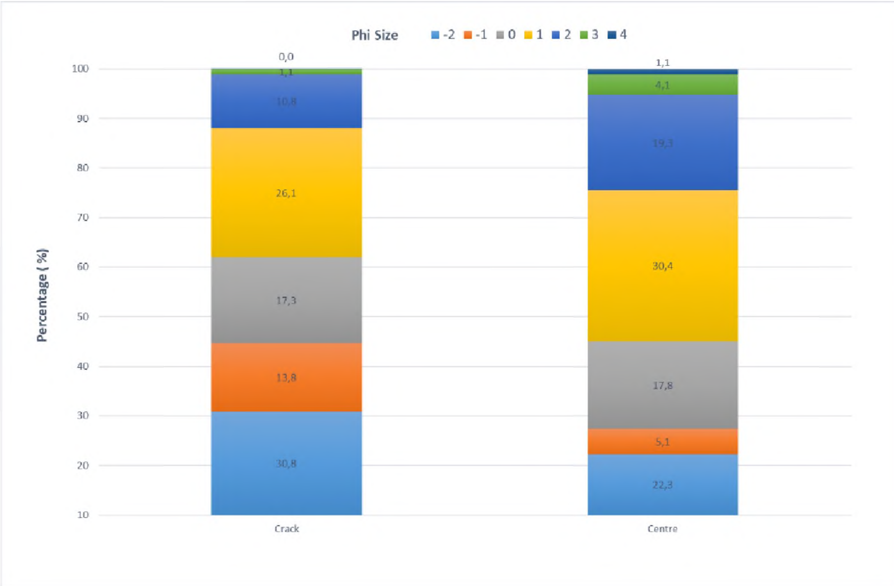

Figure 48: A breakdown of phi particle sizes for the polygon at Troll.

To further understand the particle size distribution differences between the crack and centre of the polygon, the phi mean, skewness, sorting and kurtosis are analysed. The phi mean (see Table 23) indicates the average particle size for the sample group. The crack phi mean (-0.72) shows that the particle size is between fine gravel and coarse sand whereas the centre of the polygon (-0.05) is coarse sand. The phi skewness gives an indication whether the material found in a sample has a finer or larger particle bias (Briggs, 1977). In the crack of the polygon, skewness (0.05) is symmetrical (see table 14 and 23), which means there are equal proportions of fine and coarse material. This could be due the fact there were large clasts as well as finer material present in the cracks of the polygons (Figure 49). The phi skewness for the centre of the polygon (-0.26) indicates that it is very negatively skewed, meaning that there is little fine material present (Figure 51 and Table 23) (Briggs, 1977). The

Figure 49: Fine and coarse material present in the crack of the polygon.

Figure 50: Fine and coarse material present in the centre of the polygon.

phi sorting explains the dispersion of the material in the sample (Briggs, 1977). For both the centre (1.59) and crack (1.53) samples were poorly sorted (see Figure 51 and Table 23) because of a mixture of fine material and larger clasts being present (Figure 50 and 51). Both the crack (1.55) and the centre (2.78) of the polygon are very leptokurtic (see Figure 51 and Table 23), which indicates that there is more fine material present (Briggs, 1977).

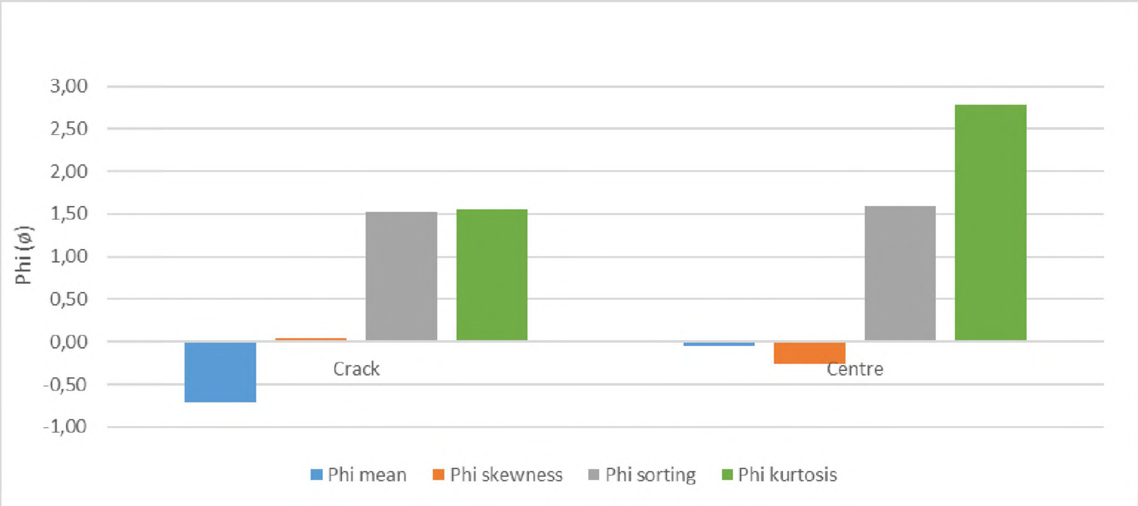

Figure 51: The phi mean, skewness, sorting and kurtosis values for a polygon at Troll.

Table 23: Table showing the phi mean, sorting, skewness and kurtosis for a polygon at troll.

Troll 2016/17 samples				
Samples	**Phi mean**	**Phi skewness**	**Phi sorting**	**Phi kurtosis**
Crack	Fine gravel/Coarse sand	Symmertrical	Poorly sorted	Very leptokurtic
Centre	Coarse sand	Negatively skewed	Poorly sorted	Very leptokurtic

Moisture in the sediment/substrate is an important factor in the development of polygons as well as the differences that may exist between the crack and the centre of a polygon. From observations at Troll it was clear that the sediment was dry. The soil moisture content for the crack and centre of the sample both indicate that there was little moisture. The crack of the polygon had the least amount of moisture (0.06%), compared to the centre of the polygon (0.08%) (Table 24).

Table 24: Table showing the soil moisture content (%) for the crack and centre of polygons found at Nonshøga (Troll).

	Field mass (g)	Dry mass (g)	Mass difference (g)	Moisture %
TN2 Centre	722,05	721,45	0,6	0,08
TN1 Crack	631,92	631,52	0,4	0,06

6.1.1.2. Discussion

The 2016/17 sample from Troll differs from the archival sample due to them being sourced from different locations in the area. The archival sample where taken form an area called Mimelia whereas the data from 2016/17 is from an area near the Troll Base called Nonshøgda[12]. At Nonshøgda it is possible that human activity from the base could have an impact on the polygons.

The mean particle size for the centre and crack of the polygon at Nonshøgda was coarse sand for both. Coarse sand allows for moisture to pass through easily as there are larger pore spaces (Brady, 1974). There was a relatively high moisture content in the centre of the polygon compared to the crack. The crack and centre of the polygons are poorly sorted, meaning the particle sizes are mixed. Sand-wedge polygons found in the dry valleys of Antarctica are described as having raised centres (Ulrich *et al.*, 2011) which is similar to those in the Troll region. For a fully developed sand-wedge polygon, there should only be sand particles in the crack and a mixed presence of particle sizes in the centre (Ugolini, Bockheim and Anderson, 1973). Further, the development of polygons relies on the soil development in the crack of the polygon (Ugolini, Bockheim and Anderson, 1973). The polygons at Troll can be referred to as poorly expressed sand-wedge polygons (Ugolini, Bockheim and Anderson, 1973). Developed polygons do have large centre diameters and large crack widths where the sand-wedge is well developed (Péwé, 1962). Other observations at Troll, such as the polygons being large in diameter (2016/17: 11.5m) and having large crack widths could be an indicator that the polygons in the area are well developed. The formation of the polygons is through heave in the centre where lateral sorting causes the gravels or larger clasts to move towards the cracks of the polygons (Grab, 1997). However, determining the age or how developed the polygons are in this area can only be achieved by further research.

The polygons at Troll were larger than other polygons in WDML and had lower moisture content. The polygon data from 2016/17 differs to the archival data, which attributed to the fact the archival polygon samples are from another area near the troll station. This limits the comparison between the two data sets. However, it is evident that the polygons from the data sets differ slightly. The centre of the archival polygons is fine gravel whereas the centre of 2016/17 polygons are coarse sand. The different location could be the reason for the difference but the time period that has passed could also have an impact on the conditional development of the polygons. Both sets of polygon data do indicate that the type of polygons that form in the Troll region are sand-wedge polygons due to the accumulation of sand in the crack of the polygons. The geology of the Troll region is different to the

[12] Due to the fact that the polygon data is from a different location near the Troll Base, it can be seen as a limitation. However, it does allow for comparison as the polygons are comprised of the same geology.

Grunehogna and Flårjuven nunataks which makes it challenging to analyse all the samples together. The erosion and weathering rate of the sediments and clasts thus will be different. It could explain why the Troll polygons are classified as sand-wedge polygons and that Grunehogna and Flårjuven are contraction polygons. Other differences found, is that the polygons at Troll in both the 2016/17 data and archival data are large in diameter and have little to no moisture present compared to the polygon at Grunehogna and Flårjuven. Therefore, in the future, the polygons at Troll should be examined as separate entities and rather compared to other sand-wedge polygons in the same region that has the same geological composition.

6.1.2. Sorted circles

Sorted circles is one of the common patterned ground types found in WDML. They can be found in areas where other periglacial landforms are located such as blockfields, glaciers and terraces. Particle size analysis is examined together and individually for each sorted circle. Further examination in the sorted circles was completed through the master sizer results and the presence of moisture in the sediment. The discussion looks at each circle separately, followed by a comparison between the sorted circles. Lastly sorted circles are compared to others from different places in the world.

6.1.2.1. Results

In the 2016/2017 season, data was collected to fill the gaps to contribute to and complement the data that had already been collected in previous seasons. Below, there are graphs showing the cumulative % vs phi size of the sediment taken from the centre and border of sorted circles (Figure 52 and 54 respectively). There was a clear difference in the sediment size distributions between the centre of the circles when compared to the borders (Figure 53 and 55).

The centre of the circle had a mixture of particle sizes (Figure 53). Grunehogna2 had the highest percentage of fine gravel (49.2 %) (-2 phi). Flårjuven 01 had the highest proportion (77.3 %) of -1phi (i.e. fine gravel). The Northern Buttress of Vesleskarvet had the lowest percentage (11.1 %) of -2phi but largest proportion of fine sand (11.1 %) (4 phi). Clays are present in the Northern Buttress sample as data from sieving indicates a large presence of finer sediment found in the bottom tray[13]. Robertskollen has the second highest percentage of fine sand (6.3%). Clays are present in this sample too, which is discussed further on.

[13] All samples with large amounts of sediment in the bottom tray are further analysed through the use of the MasterSizer

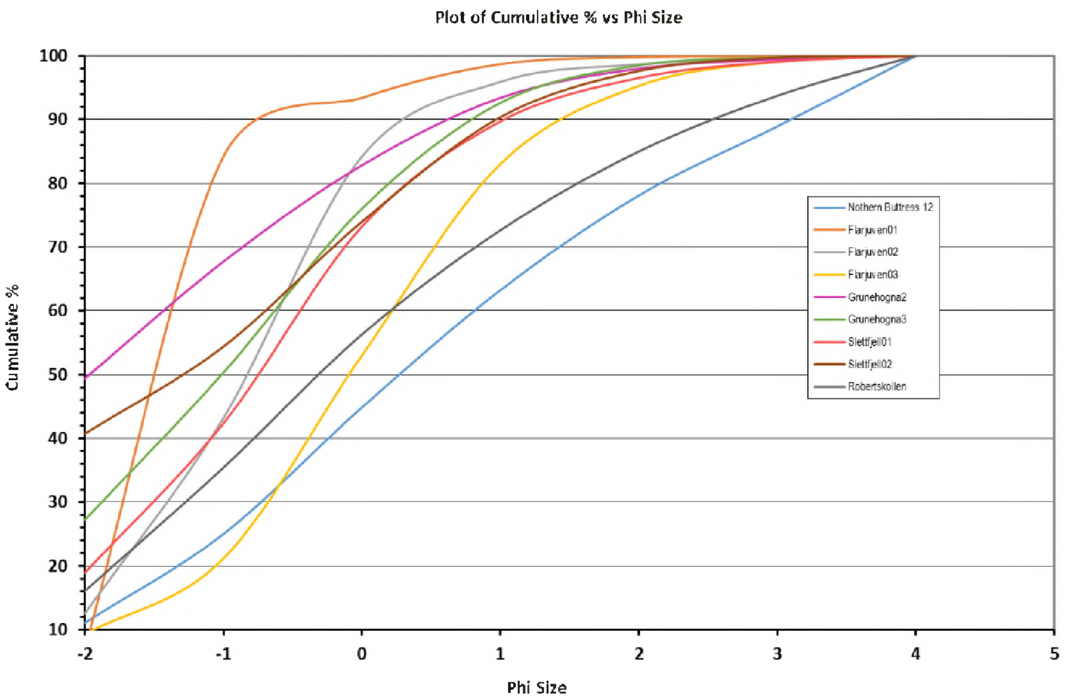

Figure 52: Plot of cumulative % vs Phi size for the centre of the sorted circles in WDML.

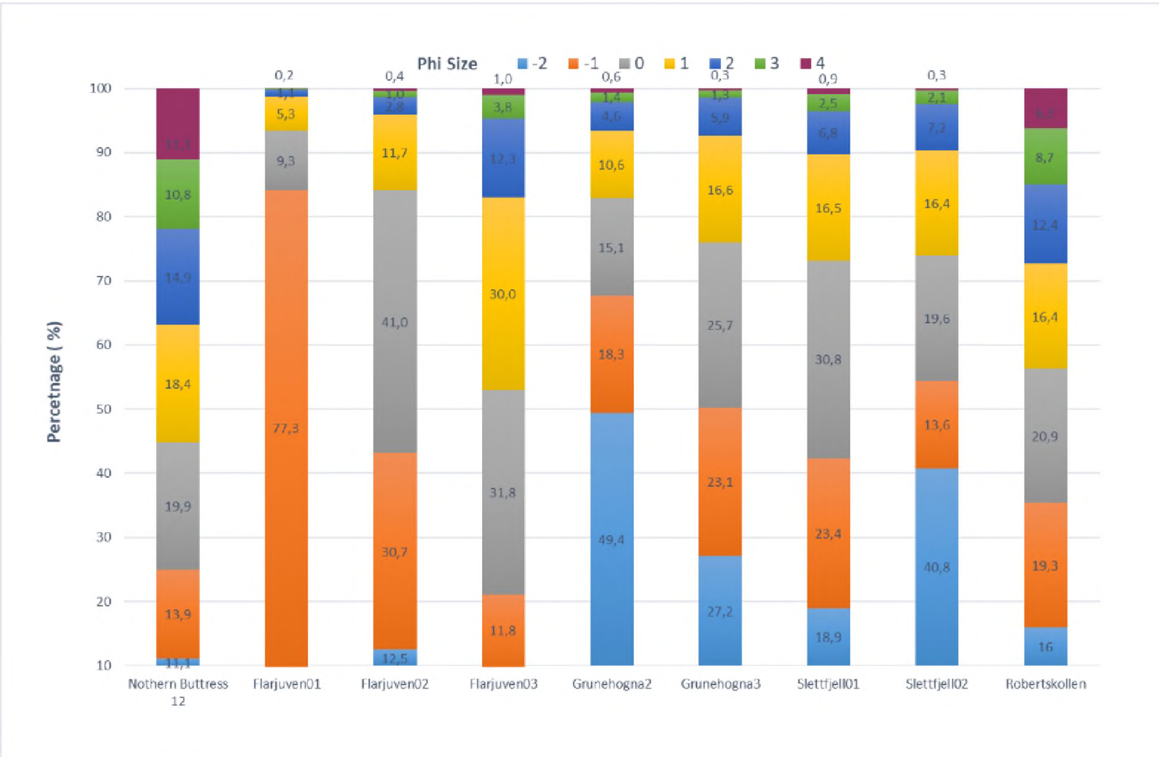

Figure 53: A breakdown of phi particle sizes for the centre of sorted circles in WDML.

The centre of the circles (Figure 52) comprise fine material and the boundaries larger particles (Figure 54). Figure 54 further discriminates the particle size distribution for the samples shown in Figure 55. The graphs show that the border of the circle had larger particle sizes than the centre (Figure 55 and 53). The highest percentage of fine gravel (-2 phi) was found at both the Grunehogna sites, with Grunehogna2 at 71.5% and Grunehogna3 at 63.7%. Flårjuven 01 has 71.3% of phi 1 particle size (fine gravel), which was the highest of all the samples. The Northern Buttress of Vesleskarvet did have fine material in the border, where 0.4% was fine sand (4 phi). Below is the statistical analysis for the sorted circles documented at the nunataks that were sampled.

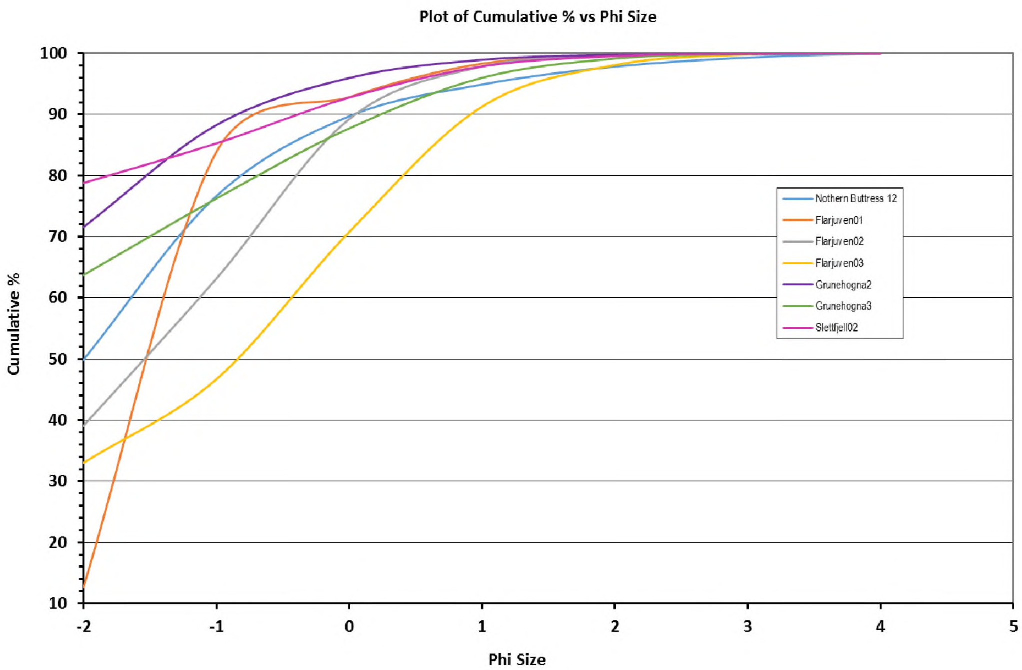

Figure 54: Plot of cumulative % vs Phi size for the border of the sorted circles in WDML.

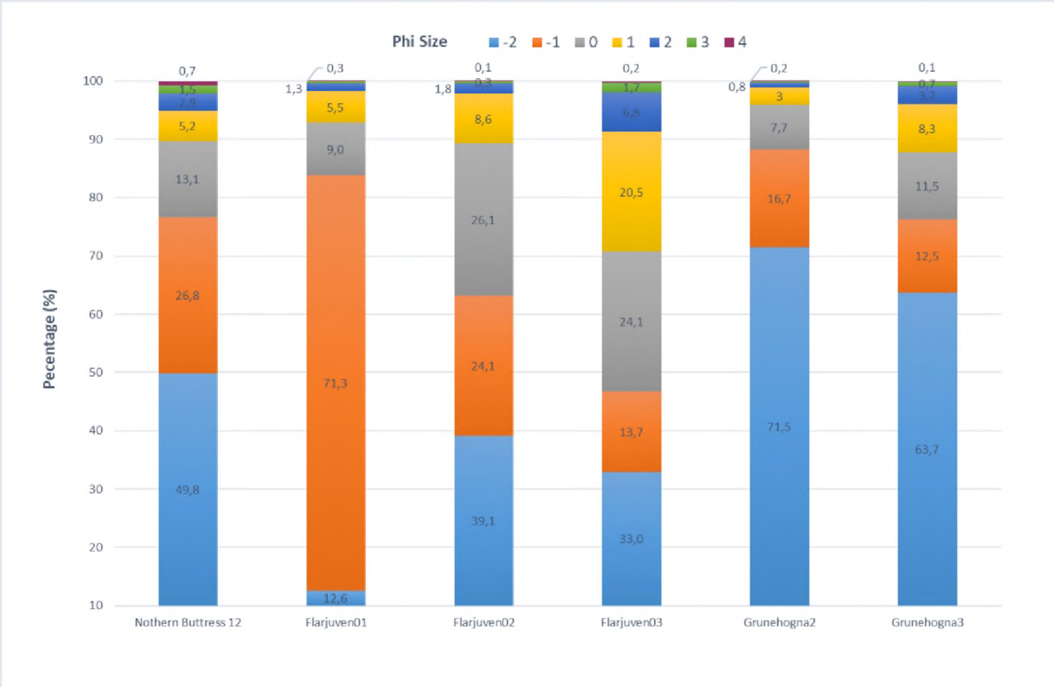

Figure 55: A breakdown of phi particle sizes for the border of sorted circles in WDML.

The results for the Northern Buttress sample showed that the centre of the circle had an average particle size of coarse sand (0.33) (see Figure 56 and Table 25), whereas on the border of the circle the average particle size was fine gravel (-1.70) (see Figure 57 and Table 26). The phi skewness indicates that the centre of the circle was positively skewed (0.11) (see Figure 56 and Table 25) and the border was very positively skewed (1) (see Figure 57 and Table 26). This shows that there were more fines in the border of the circle than in the centre (Briggs, 1977). The centre of the circle was very poorly sorted (2.13) (see Figure 56 and Table 25), whereas the border was moderately sorted (0.75) (see Figure 57 and Table 26). Phi kurtosis values show that the centre was very leptokurtic (1.79) (see Figure 56 and Table 25) and the border leptokurtic (1.20) (see Figure 57 and Table 26). Thus the centre had more fines present than the border.

Three samples were collected at Flårjuven. The Flårjuven 01 sample showed that the phi mean for centre (-1.47) (see Figure 56 and Table 25) and the border (-1.52) have similar particle sizes, which are fine gravels (see Figure 57 and Table 30). The centre of the circle had fines present as the phi skewness was positively skewed (0.25) (see Figure 56 and Table 25). The border of the circle had coarse material present as the phi skewness was very positively skewed (0.31) (see Figure 57 and Table 26). The sorting value in the centre was 0.54 meaning that it was moderately well sorted (see Figure 56 and Table 25), compared to the border which was 0.48 and this means that it was well sorted (see Figure 57 and Table 26). Phi kurtosis showed that the centre of the circle was very leptokurtic (1.58) (see Figure 56 and Table 25) and the border was leptokurtic (1.46) (see Figure 57 and Table 26), indicating that the centre had more fines present than the border.

Flårjuven 02 had a phi mean value of -0.88 for the centre and -1.43 for the border (see Figure 56 and 57). They both fell in the fine gravel particle size range (see Table 25 and 26). Skewness in the centre was symmetrical (-0.09) (see Figure 56 and Table 25) and the border was very positively skewed (0.68) (see Figure 57 and Table 26). Sorting for centre (092) (see Figure 56 and Table 25) and border (0.92) (see Figure 57 and Table 26) indicate that they were both moderately sorted. There was more fine material present in the centre as the phi kurtosis value indicated a very leptokurtic distribution (see Figure 56 and Table 25). The border of the circle had mixed particles sizes present as the phi kurtosis is mesokurtic (see Figure 57 and Table 26).

Flårjuven 03 had a phi mean of 0.17 in the centre and -0.85 for the border (see Figure 56 and 57). Meaning they both fall under the coarse sand particle size (see Table 25 and 26). Phi skewness for the centre was symmetrical (-0.01) indicating there are mixed particle sizes present (see Figure 56 and Table 25). Phi skewness for the border was positively skewed (0.12) meaning there are fines present rather than larger particle sizes (see Figure 57 and Table 26). The circle was poorly sorted as the centre of the circle was 1.08 (see Figure 56 and Table 25) and the border was 1.39 (see Figure 57 and Table 26). Phi kurtosis in the centre was very leptokurtic (1.99) (see Figure 56 and Table 25) and on the border it was leptokurtic (1.48) (see Figure 57 and Table 26).

The Grunehogna 2 circle had an average phi mean of -1.49 in the centre and -1.92 for the border (see Figure 56 and 57). This means that they both fell in the fine gravel particle size range (see Table 25 and 26). Both the centre (0.96) (see Figure 56 and Table 25) and the border (1) (see Figure 57 and Table 26) had a phi skewness value that is very positively skewed. The centre of the circle was poorly sorted (1.03) (see Figure 56 and Table 25) whereas the border (0.29) was very well sorted (see Figure 57 and Table 26). Phi kurtosis for the centre was mesokurtic (0.96) (see Figure 56 and Table 25) and the border was very leptokurtic (2.32) (see Figure 57 and Table 26).

The Grunehogna 3 sample had an average phi mean of -1.03 in the centre and -1.71 at the border (see Figure 56 and 57). Thus, both could be categorised as being fine gravel particle size range (see Table 25 and 26). The skewness value in the centre of the circle was positively skewed (0.23) (see Figure 56 and Table 25), whereas the border was very positively skewed (1) (see Figure 57 and Table 26). Phi sorting values for the centre of the circle showed it to be poorly sorted (1.25) (see Figure 56 and Table 25), compared to the border which was moderately sorted (0.78) (see Figure 57 and Table 26). Phi kurtosis was very leptokurtic (1.64) for the centre (see Figure 56 and Table 25) and the border was leptokurtic (1.35) (see Figure 57 and Table 26).

The sample from Slettfjell 1 had only produced results for the centre in terms of particle size analysis as the border sample had clasts that were too large to sieve. The phi mean for the centre was -1.05 which indicates that the average particle size was fine gravel (see Figure 56 and Table 25). Phi skewness was 0.46, meaning that it was very positively skewed (see Figure 56 and Table 25). The sorting value in the centre indicated that it was poorly sorted as the phi sorting was 1.32 (see Figure 56 and Table 25). Phi kurtosis was 1.19 meaning it is leptokurtic (see Figure 56 and Table 25).

Slettfjell 2 had an average phi mean size of -1.05 for the centre and -2 for the border of the circle (see Figure 56 and 57). This indicates that they both had an average particle size in the fine gravel range (see Table 25 and 26). Phi skewness for the centre was 0.45 (see Figure 56 and Table 25) and the border 1 (see Figure 57 and Table 26), meaning they were both very positively skewed. The centre of the circle was poorly sorted (1.38) (see Figure 56 and Table 25) but the border of the circle was well sorted (0.37) (see Figure 57 and Table 26). Phi kurtosis for the centre of the circle is 1.15, meaning that it was leptokurtic (see Figure 56 and Table 25)[14].

Only the centre of a circle was analysed from Robertskollen in the 2016/17 summer, as the border sample had clasts that were too large to sieve. The Phi mean value was -0.17 which indicates that the centre had an average particle size of fine gravel (see Figure 56 and Table 25). Phi skewness was 0.19, meaning that it was positively skewed (see Figure 56 and Table 25). The centre was poorly sorted as the phi sorting was 1.89 (see Figure 56 and Table 25). Phi kurtosis was 1.71, indicating that the centre was very leptokurtic (see Figure 56 and Table 25).

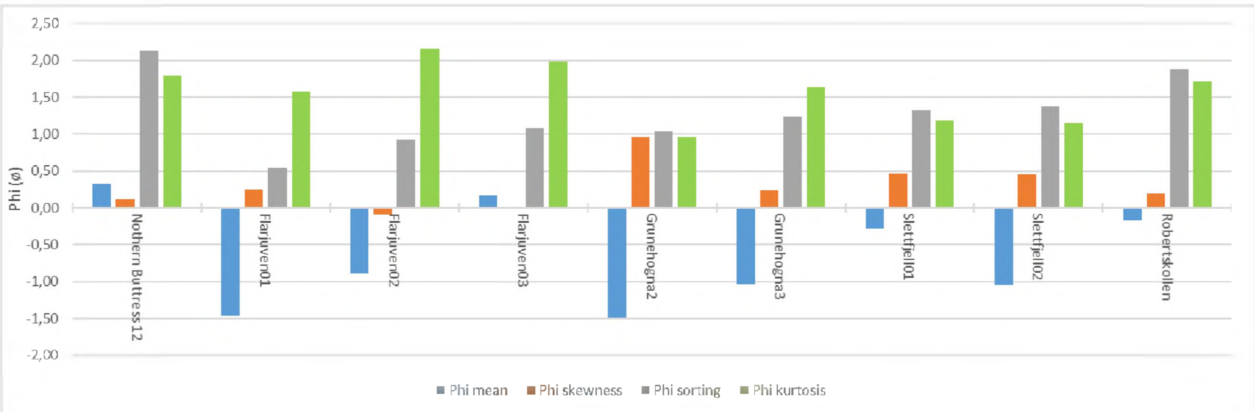

Figure 56: The phi mean, skewness, sorting and kurtosis values for the centre of sorted circles in WDML.

[14] The border of the circle had no phi kurtosis due to the fact that one cannot divide by a zero.

Table 25: Table showing the phi mean, skewness, sorting and kurtosis descriptive terms for the centre of the sorted circles sampled during the 2016/17 Austral Summer.

Samples	Phi mean	Phi skewness	Phi sorting	Phi kurtosis
Nothern Buttress 12	Coarse sand	Positively skewed	Very poorly sorted	Very leptokurtic
Flarjuven01	Fine gravel	Positively skewed	Moderately well sorted	Very leptokurtic
Flarjuven02	Fine gravel/Coarse sand	Symmertrical	Moderately sorted	Very leptokurtic
Flarjuven03	Coarse sand	Symmertrical	Poorly sorted	Very leptokurtic
Grunehogna2	Fine gravel	Very postively skewed	Poorly sorted	Mesokurtic
Grunehogna3	Fine gravel	Positively skewed	Poorly sorted	Very leptokurtic
Slettfjell01	Fine gravel/Coarse sand	Very postively skewed	Poorly sorted	Leptokurtic
Slettfjell02	Fine gravel	Very postively skewed	Poorly sorted	Leptokurtic
Robertskollen	Fine gravel	Positively skewed	Poorly sorted	Very leptokurtic

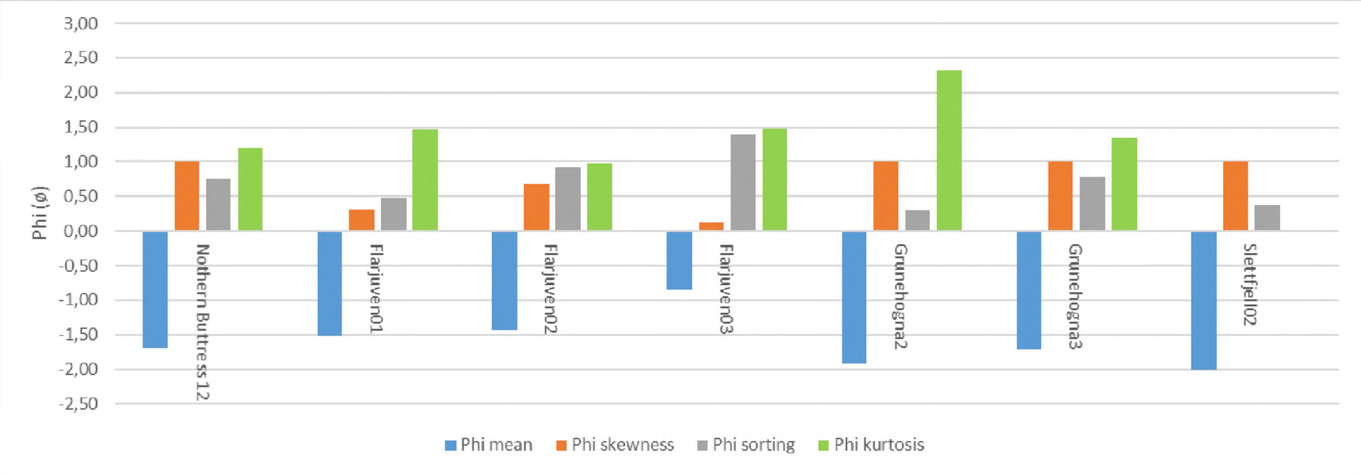

Figure 57: The phi mean, skewness, sorting and kurtosis values for the border of sorted circles in WDML, sampled during the 2016/17 Austral Summer.

Table 26: Table showing the phi mean, skewness, sorting and kurtosis descriptive terms for the border of the sorted circles, sampled during the 2016/17 Austral Summer.

Sorted circles outside				
Samples	Phi mean	Phi skewness	Phi sorting	Phi kurtosis
Nothern Buttress 12	Fine gravel	Very postively skewed	Moderately sorted	Leptokurtic
Flarjuven01	Fine gravel	Very postively skewed	Well sorted	Leptokurtic
Flarjuven02	Fine gravel	Very postively skewed	Moderately sorted	Mesokurtic
Flarjuven03	Fine gravel/Coarse sand	Positively skewed	Poorly sorted	Leptokurtic
Grunehogna2	Fine gravel	Very postively skewed	Very well sorted	Very leptokurtic
Grunehogna3	Fine gravel	Very postively skewed	Moderately sorted	Leptokurtic
Slettfjell02	Fine gravel	Very postively skewed	Well sorted	NA

Due to the similarity in the results between the border and the centre of the sorted circle, the Kolomogorov-Smirnov test was used to determine if there was a difference between the two. The D value calculated was 0.87. In order for there to be a difference between the centre and border of the sorted circles, the Calculated D value must be more than the D value (See table 27) (Till, 1974). However, the Calculated D value was not greater than the D value and thus the border and centre of the sorted circles had no significance between them (Table 27). A possible explanation for the similarity is that the centre and the border of the sorted circles all have the same lithology, which means clasts would weather or erode at the same rate. Thus similar particle size distributions within finer material would be found in both places even though there are bigger clasts present on the border, the finer particles are the same as the ones found in the centre of the sorted circles.

Table 27: Table showing the calculated D value and D value for the study sites.

	Calculated D value	D	>D
Nothern Buttress	0,52	0,87	N
Flarjuven 01	0,06	0,87	N
Flarjuven 02	0,27	0,87	N
Flarjuven 03	0,26	0,87	N
Grunehogna 2	0,22	0,87	N
Grunehogna 3	0,37	0,87	N
Slettfjell 2	0,38	0,87	N

For some of the samples there was a large amount of sediment found in the bottom tray of the sieve stack (<63µm) and the Malvern Mastersizer was, thus, used for further analysis. Only two samples were analysed from sorted circles, due to the lack fine material in the study area. Below is the frequency graph and the table from the report generated from the Malvern Master sizer for the Robertskollen sample (Figure 58 and Table 28). The highest particle size that the Malvern Master sizer recorded from the sample was 98.1µm, which is considered to be fine sand (Table 28). This suggests some particles got through the sieve to the bottom tray. The highest frequency for particle sizes in this sample was 31.1µm, (coarse silt) and this is indicated by the peak of the graph and the highlighted section in pink on the table (Figure 58 and Table 28). The smallest particle present is 0.594µm indicating that there was clay present (Table 28). Finer particles such as clay do hold moisture more than other particle sizes (Brady, 1974). Thus movement, through heave was possible. The Robertskollen study site did have more moisture present amongst its fines compared to other sites. This can be seen as the amount of moisture in this sample at Robertskollen is 8.12% (Table 30), which indicates that there a presence of heave taking place which causes sorting to occur.

Figure 58: Frequency graph of particle size for Robertskollen.

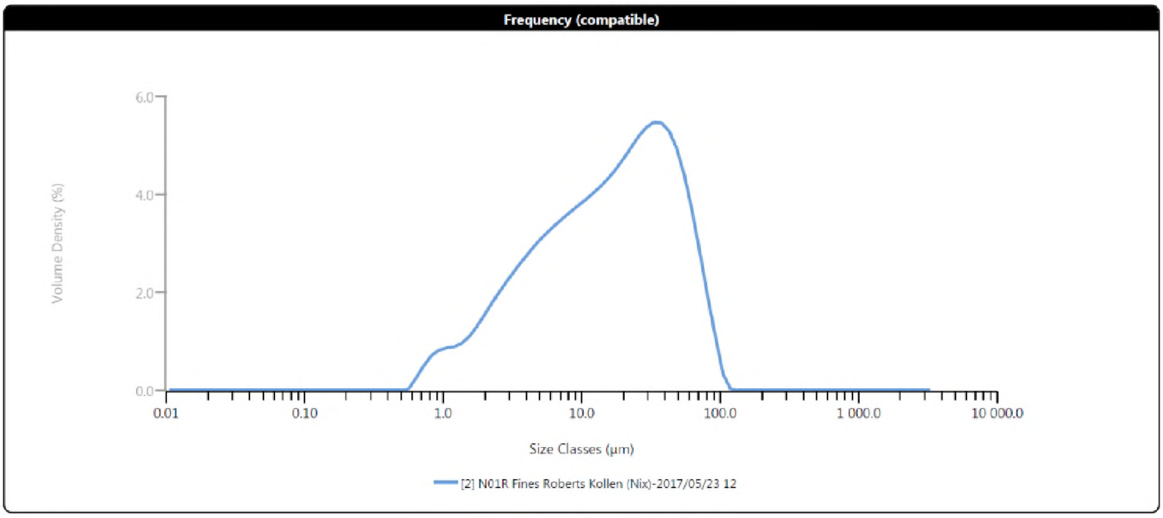

Table 28: Table showing particle size of the sample form Robertskollen (µm).

Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In
0.0100	0.00	0.0679	0.00	0.460	0.00	3.12	2.06	21.2	4.12	144	0.00	976	0.00
0.0114	0.00	0.0771	0.00	0.523	0.00	3.55	2.23	24.1	4.31	163	0.00	1110	0.00
0.0129	0.00	0.0876	0.00	0.594	0.20	4.03	2.39	27.4	4.47	186	0.00	1260	0.00
0.0147	0.00	0.0995	0.00	0.675	0.41	4.58	2.53	31.1	4.57	211	0.00	1430	0.00
0.0167	0.00	0.113	0.00	0.767	0.59	5.21	2.67	35.3	4.56	240	0.00	1630	0.00
0.0189	0.00	0.128	0.00	0.872	0.69	5.92	2.79	40.1	4.42	272	0.00	1850	0.00
0.0215	0.00	0.146	0.00	0.991	0.72	6.72	2.91	45.6	4.13	310	0.00	2100	0.00
0.0244	0.00	0.166	0.00	1.13	0.74	7.64	3.02	51.8	3.67	352	0.00	2390	0.00
0.0278	0.00	0.188	0.00	1.28	0.79	8.68	3.12	58.9	3.06	400	0.00	2710	0.00
0.0315	0.00	0.214	0.00	1.45	0.92	9.86	3.23	66.9	2.35	454	0.00	3080	0.00
0.0358	0.00	0.243	0.00	1.65	1.09	11.2	3.34	76.0	1.60	516	0.00	3500	
0.0407	0.00	0.276	0.00	1.88	1.30	12.7	3.46	86.4	0.93	586	0.00		
0.0463	0.00	0.314	0.00	2.13	1.50	14.5	3.59	98.1	0.25	666	0.00		
0.0526	0.00	0.357	0.00	2.42	1.70	16.4	3.75	111	0.00	756	0.00		
0.0597	0.00	0.405	0.00	2.75	1.88	18.7	3.93	127	0.00	859	0.00		

A sample from Northern Buttress, which is the nunatak that had the most moisture present in WDML, was also analysed through the Malvern Mastersizer. Results from the Malvern Mastersizer are depicted in the graph and table below (Figure 59 and Table 29). There was slight change in the gradient of the curve as the clast size reaches approximately 1µm (Figure 59). A dip in the frequency graph (Figure 59) indicates that there is a decline in the percentage of particles that are between 0.991µm - 1.28µm clast size (indicated by the blue circle in table 29). The smallest particle measured was 0.523µm (clay) indicated in yellow (Table 29), while the largest sized particle present in this sample is 98.1µm which is fine sand (indicated in red in Table 29). Medium silt comprised the largest proportion by volume of the sample is the particle size of 12.7µm (indicated in blue Table 29) which suggested that the circle is still developing. Clay was present in this sample, which is why a higher moisture content was recorded. Clay holds moisture in the fine materials as it has an increased capacity to hold water (Brady, 1974). The increased presence of moisture is reinforced by the moisture content for this sample, which is 10.10% (see Table 30). A high moisture presence in the sediment indicates that there is a considerable amount of movement taking place in the heave process[15].

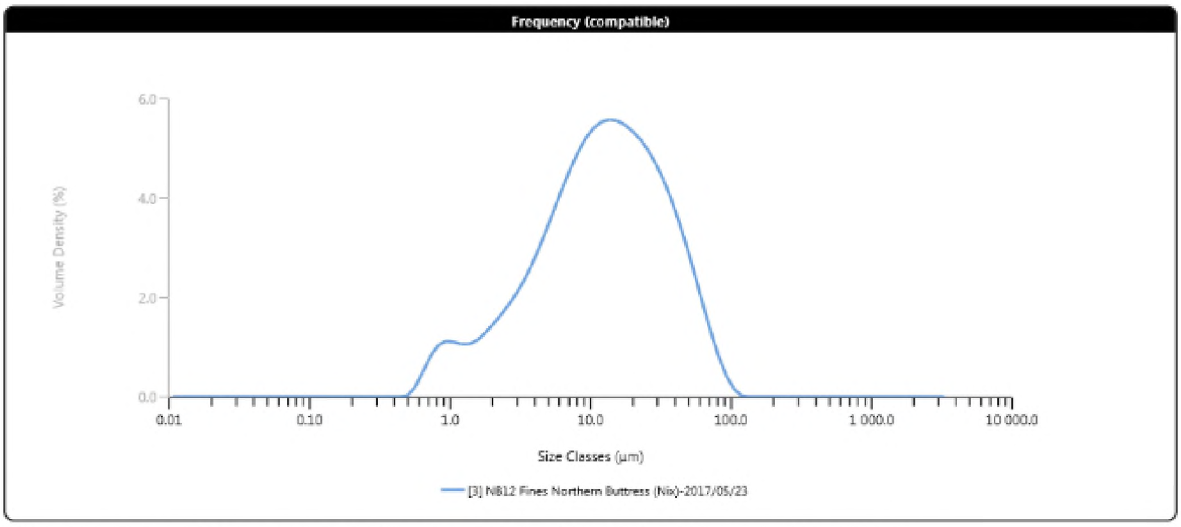

Figure 59: Frequency of the particle size present in the Northern Buttress sample.

Table 29: Table showing particle size of the sample form Northern Buttress (μm).

Size (μm)	% Volume In	Size (μm)	% Volume In	Size (μm)	% Volume In	Size (μm)	% Volume In	Size (μm)	% Volume In	Size (μm)	% Volume In	Size (μm)	% Volume In
0.0100	0.00	0.0679	0.00	0.460	0.00	3.12	1.94	21.2	4.32	144	0.00	976	0.00
0.0114	0.00	0.0771	0.00	0.523	0.14	3.55	2.20	24.1	4.14	163	0.00	1110	0.00
0.0129	0.00	0.0876	0.00	0.594	0.40	4.03	2.50	27.4	3.91	186	0.00	1260	0.00
0.0147	0.00	0.0995	0.00	0.675	0.68	4.58	2.83	31.1	3.63	211	0.00	1430	0.00
0.0167	0.00	0.113	0.00	0.767	0.87	5.21	3.17	35.3	3.31	240	0.00	1630	0.00
0.0189	0.00	0.128	0.00	0.872	0.94	5.92	3.51	40.1	2.92	272	0.00	1850	0.00
0.0215	0.00	0.146	0.00	0.991	0.92	6.72	3.83	45.6	2.50	310	0.00	2100	0.00
0.0244	0.00	0.166	0.00	1.13	0.88	7.64	4.11	51.8	2.04	352	0.00	2390	0.00
0.0278	0.00	0.188	0.00	1.28	0.88	8.68	4.35	58.9	1.56	400	0.00	2710	0.00
0.0315	0.00	0.214	0.00	1.45	0.94	9.86	4.52	66.9	1.10	454	0.00	3080	0.00
0.0358	0.00	0.243	0.00	1.65	1.06	11.2	4.62	76.0	0.68	516	0.00	3500	
0.0407	0.00	0.276	0.00	1.88	1.21	12.7	4.66	86.4	0.35	586	0.00		
0.0463	0.00	0.314	0.00	2.13	1.36	14.5	4.63	98.1	0.12	666	0.00		
0.0526	0.00	0.357	0.00	2.42	1.53	16.4	4.57	111	0.00	756	0.00		
0.0597	0.00	0.405	0.00	2.75	1.72	18.7	4.46	127	0.00	859	0.00		

Moisture found in the soil plays a role in the formation of sorted circles as well as the sorting process that occurs amongst the sediments. Soil moisture content was recorded for all the sorted circles sampled during the 2016/17 summer (Table 30). Northern Buttress had more moisture present in the centre of the circle (10.10%), when compared to the border (0.32%) (Table 30). The samples from Flårjuven all had more moisture present in the centre where FN01 had 0.29%, FN02 had 1.08% and FN03 had 3.21% (Table 30). However, the border of the circles for all Flårjuven samples had a soil moisture content that was below one percent (Table 30). Grunehogna samples had very little moisture

[15] This is further explored in Chapter Seven

present overall. G2N had 0.31% in the centre and 0.14% in the border of the circle (Table 30). G3N had 0.35% of soil moisture for the centre and 0.28% for the border of the circle. The centre of the circle analysed at Robertskollen had a soil moisture content of 8.12%. Thus all samples indicate that there is more moisture present in the centre of circles rather than on the border.

Table 30: Soil moisture content (%) for all sorted circle samples taken in 2016/17 season in WDML.

Study site	Sample name	Field mass (g)	Dry mass (g)	Mass difference (g)	Moisture %
Nothern Buttress	NB12 Centre	288,92	259,73	29,19	10,10
	NB12 Border	40,3	40,17	0,13	0,32
Flarjuven	FN01 Centre	349,82	348,82	1	0,29
	FN01 Border	15,27	15,24	0,03	0,20
Flarjuven	FN02 Centre	436,52	431,82	4,7	1,08
	FN02 Border	91,69	91,55	0,14	0,15
Flarjuven	FN03 Centre	451,05	436,55	14,5	3,21
	FN03 Border	99,23	99,19	0,04	0,04
Grunehogna	G2N Centre	458,65	457,25	1,4	0,31
	G2N Border	69,9	69,8	0,1	0,14
Grunehogna	G3N Centre	432,32	430,82	1,5	0,35
	G3N Border	53,09	52,94	0,15	0,28
Slettfjell	N01 Centre	251,96	250,38	1,58	0,63
	N01 Border	NA	NA	NA	NA
Slettfjell	NO2 Centre	152,86	148,42	4,44	2,90
	N02 Border	23,19	23,16	0,03	0,13
Roberts Kollen	NO1R Centre	174,82	160,63	14,19	8,12

6.1.2.2. Discussion

Individual discussion:

Figure 60: Circle found at Northern Buttress.

The circle at Northern Buttress is still developing but showed visible sorting (Figure 60). The particle size analysis supports that there are smaller particles in the centre and that the border of the circle is sorted. Moisture content in the centre of the circle was higher than in the border, which is where the movement takes places. From analyses, this nunatak had highest moisture values in WDML. The Master Sizer results indicate that clay is present in the centre of the circle. Clay particles tend to absorb more moisture (Brady, 1974), which is why a higher moisture level was recorded there. The presence of clay has been found in the centre of circles in the Drakensberg (Grab, 2002). This adds to the contention that the more fines present the higher the moisture content will be (Grab, 2002).

A sorted circle (FN01) at Flårjuven had fines that were surrounded by larger clasts (Figure 61). Potentially it could be classified as either a half circle or a circle. The particle size analysis indicates that in the centre of the circle there were small particles present with coarse particles and large clasts on the border. The centre was sorted whereas the border was poorly sorted. Little moisture was present in both the centre and the border. This indicates that the landform may not be active. However, there was snow present at the time especially in the centre which accounts for there being more moisture in the centre of the circle rather on the border. The snow melt does have impact on the movement that takes place in the centre (Grab, 2002).

Figure 61: Circle found at Flårjuven (FN01).

The second circle (FN02) at Flårjuven, is still active and developing (Figure 62). The particle size analysis showed mixed particles sizes present in the centre. This is visible in the adjacent image as the centre of the circle had mixed particle sizes as well as large clasts present (Figure 62). The border had larger clasts present. However, the particle size analysis shows that there are smaller particles present. The circle was moderately sorted which means that it may still be developing. Little moisture was present which was evident at the time the sample was taken. There was snow present within the circle and, thus, moisture from melting snow melt had not entered the substrate yet (Figure 62). Snow melt can have an impact on the development of sorted circles (Grab, 2002). Thus, once the snow melts, moisture will enter the sediment and add to the movement that is already taking place.

Figure 62: Circle found at Flårjuven (FN02).

A half circle was found at Flårjuven (FN03), where the centre of the circle was against a large clast and the sorting develops from the large clast outward (Figure 63). The centre of the half circle had a mixture of particle sizes, which is evident in the adjacent image (Figure 63). There was a larger clast on the border of the half circle. However, the particle size analysis did show that there were still smaller particles present. The analysis also showed that the centre and border are poorly sorted, which means that the half circle is still active and developing. There was little moisture present in the centre of the half circle, which will increase as the snow melts. Half circles develop by the heat transmission from the rock that melts the substrate beneath. Once the sediment under the large clasts has reached saturation, the weight of the large clast pushes or forces the sediment out and the sediment then collects on the edge (Figures 64 and 65)[16]. The sediment that collects at the edge of the clast contains moisture that is active under conditions that promote freeze thaw processes. The heaving leads to sorting occurring where the clast size increases as one moves away from the large clast.

Figure 63: Half circle found at Flårjuven.

Figure 64: Half circle at Northern Buttress.

Figure 65: Half circle at Northern Buttress.

[16] Figure 64 and 65 are half circle found at Northern Buttress. Photos where just taken for explanation to show what half circles look like.

A sorted circle (G2N) at Grunehogna, is well developed and has larger particle sizes for both centre and border (Figure 66). There were, however, smaller particles present both in the centre and on the border. This is an indication that the circle is still active and forming. The circle is a sorted circle as the particle size analysis shows that the centre of the circle is sorted and the border is very well sorted. There was little moisture present in the sorted circle which could mean that the circle was not active as it visibly appeared to be a well-developed sorted circle.

Figure 66: Sorted circle at Grunehogna (G2N).

G3N was a sorted circle at Grunehogna, that was visibly active and still developing (Figure 67). Both the centre and the border of the circle had small and large particles present, also evident in the adjacent image (Figure 67). The particle size analysis showed that the centre of the circle was poorly sorted due to there being large clasts amongst the sediment. Thus the circle was considered to be active and still forming. The border is moderately sorted. There was however little moisture present in the circle and thus the movement of the circle could be limited.

Figure 67: Sorted circle at Grunehogna (G3N).

N01 was the largest sorted circle that was found at Slettfjell in the 2016/2017 season (Figure 68). Its long axis was 3.21m and short axis is 2.29m. The particle size analysis revealed that the circle was poorly sorted in the centre and this is evident in the picture as there was sediment present, together with clasts varying in size (Figure 68). The border of the circle only had large clasts present (indicated in blue) (Figure 68). It could be argued that this sorted circle could be a sorted polygon. It is possible as there sorted polygons in this area (Scott, 2014). However, the sorting of the sediment in the circle does not fit the criteria for a sorted polygon. Thus, the circle is considered to be still active and developing as

Figure 68: Large sorted circle at Slettfjell (N01). Blue line indicates the border of the circle. The green circle indicates a secondary circle is developing.

the centre is not sorted and developed yet. Moisture was present in the centre which means that there was movement taking place, whereas the border had no moisture present. Large amounts of moisture are needed to develop large sorted circles (Grab, 2002) and, thus, the amount of moisture present in the centre was small; this indicates that the large sorted circle could be relict or less active. Large sorted circles, thus, do go through periods of being active, dormant, and finally decay (Grab, 2002). On the edge of the circle imbrication was evident, as plate-like clasts stood vertically against one another (Figure 68). Similar imbrication has also been identified in the Beacon Valley circles, Antarctica (Linkletter, Bockheim and Ugolini, 1973). The plate-like clasts are faced towards the centre of the circle which is the same as the circles in the Drakensberg (Grab, 2002). Lateral sorting could be the mechanism influencing the sorting that has taken place on the border of the circle (Grab, 2002). Also, the clasts facing inward, supporting the theory of the convection model for the development of the circle (Grab, 2002). Nelson (1982), discusses how clasts on the border of the circle have inclined b-axes. This happens by the fines expanding upwards, putting pressure on the border of the circle which cause the larger clast to be vertical (Nelson, 1982) (Figure 69).

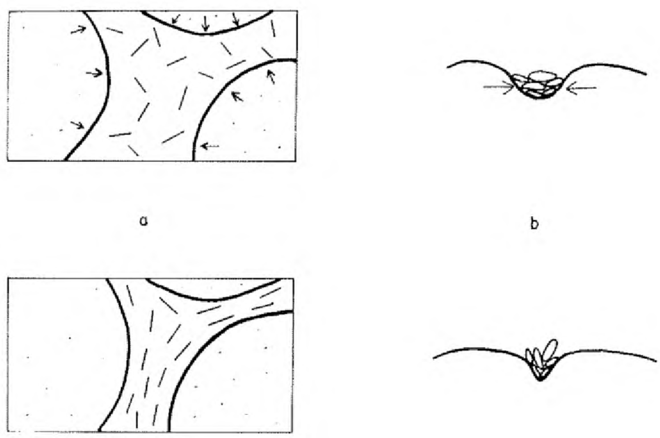

Figure 69: Shows the development of the border of some of sorted circles where the clasts in the border have a b axis that is vertical (Nelson 1982:52). a- is the bird eyes view. b- is the cross section view.

A second sorted circle (NO2) documented at Slettfjell was small and still developing (Figure 70). The particle size analysis indicated that the centre of the circle was poorly sorted as there was a mixture of small and large particles present. However, the border of the circle was moderately sorted which implies that there is movement and sorting taking place. Moisture was present in the centre which emphasises that there is heave taking place. Little moisture was found in the circle border.

Figure 70: Sorted circle at Slettfjell (NO2).

A sample taken at Robertskollen was not a sorted circle but a feature was that it had finer sediment surrounded by larger clasts (Figure 71). The particle size analysis for the fines indicated that it was poorly sorted as a mixture of particles sizes was present. The fines had large amounts of moisture present and this is evident in the adjacent image, where the fines are dark, indicating they are moist (Figure 71). To further analyse the sample, the Malvern MasterSizer results indicated that clay was present in the fines which explains the moisture presence. Clay particles can retain moisture (Brady, 1974). Thus the more moisture there is, then an increase in movement will occur due to heaving of the fines (Grab, 2002).

Figure 71: Fines at Robertskollen.

General discussion:

Overall, the general movement in the sorted circles analysed in WDML was similar across samples analysed. The gravels found in the centre of the circles did have fine material underneath which was potentially susceptible to frost heave (Grab, 2002). Thus the moisture in the fines in the centre of circle freezes, which leads to the expansion of the fines. The upward movement from expansion forces the larger clasts to the border of the circle. This sorting supports the convection model where the fines are drawn to the centre and larger clasts are pushed to the border (Ballantyne, 1996; Grab, 1997, 2002; Holness, 2003). Furthermore, the convection model implies that the centre of the circles would be up-domed and this is due to the presence of saturated soil (eg: circles at Marion Island; Holness 2003). This is not always the case within the sorted circles in WDML, and this could be due to thawing taking place causing the centre to collapse. Lateral sorting of the larger clasts takes place during the thaw period (Grab, 1997). However, there are difficulties in formulating how circles develop as the mechanisms that started the processes are not easy to determine (Grab, 2002). The increased size in circles is evidence that there are large amounts of water present, as well as frequent freeze thaw events taking place (Grab, 2002). A conceptual model by Kessler *et al*. (2001) also explains the formation of circles, where during the freezing process of the moisture in the soil, latent heat is released.

Sorted circles located at the Barton Peninsular, King George Island, have centres that are wet and the border is dry (Jeong, 2006). There are troughs which contain meltwater that separate the circles from one another (Jeong, 2006). However the environment here is humid and precipitation does occur (Jeong, 2006). The sorted circles found around WDML do not have a complete moist centre or dry border. Most samples have moisture present in both the centre and the border, indicating that the samples from WDML are possibly still developing.

A well-developed sorted circle will have no fines present in the centre or border of the circle but rather larger clasts will be present (Holness, 2003). An example of a well-defined sorted circle is found at Robertskollen (Figure 72). An example of a well-developed sorted circle is in the Drakensberg and is similar to the one at Robertskollen (Figure 73). These sorted circles have pebbles and gravel size clasts instead of sediment in the centre and clasts increasing in size moving away from the centre (Grab, 2002).

Figure 72: Well developed sorted circle at Robertskollen.

Figure 73: Well developed sorted circle in the Drakensberg (Grab 2002: 1732).

6.2. Ice suspension

The Northern Buttress of Veleskarvet in WDML has been classified by Hansen (2014) as an autochthonous blockfield as well as having patterned ground present. Ice suspension of the clast in this area was recommend by Hansen (2014) as future research. Thus this section is an addition to the research completed by Hansen (2014) and the concept is explored.

As mentioned by Hansen (2014) the freezing and thawing of the snow and ice (that is seasonal and diurnal) in the area can have an influence on the development of the blockfield. Thus, the evidence from the heave monitoring section displays the movement that takes place on a small scale. However, the ice suspended clasts in the blockfield experiences the same process on a larger scale (Figure 74). The melt water fills in the cracks and joints of the bedrock (Hansen, 2014). The process of the water freezing leads to the expansion of the cracks in the rock (Washburn, 1980; Boelhouwers *et al.*, 2002; Boelhouwers, 2004; Sumner and Meiklejohn, 2004; Hansen, 2014). Thermal cycles have been linked to the widening of cracks in rocks and bedrock by the moisture freezing and expanding (Matsuoka, 2001; Hall *et al.*, 2002). Over time clasts will break off the bedrock and become part of the block production for the blockfield (Figure 90) (Washburn, 1980; Boelhouwers *et al.*, 2002; Boelhouwers, 2004; Sumner and Meiklejohn, 2004; Hansen, 2014).

Figure 74: The bedrock being broken up into clasts that add to the block production for the blockfield. Once broken off the flatter bedrock that are heaved by the ice which thus changes their orientation. This can be seen in the background.

The clasts are then influenced by the ice, where the melt water moves underneath the clasts through the spaces which then freezes (Boelhouwers, 2004). The expansion of the ice during freezing, causes the clasts to heave vertically and horizontally (Boelhouwers, 2004). The ice present on the nunatak is a source of moisture (due to freeze thaw cycles daily), meaning that the heave will be great as there is a large amount of moisture present (Sumner and Meiklejohn, 2004; Hansen, 2014) compared to other nunataks in WDML. Due to the repeated heaving, a substrate portion (pers. obs.) of the clasts in the blockfield are now suspended in ice (Figure 75) (Hansen, 2014). From observations of the area, there are parts of the blockfield where all the clasts are suspended or are on top of the ice (Figures 76 and 77). Therefore, the movement that is taking place in the blockfield is a post weathering of ice.

Figure 75: Clasts suspended in ice.

Figure 76: Large areas of the blockfield where clasts are suspended in ice.

Figure 77: Clasts support by ice.

6.3. Lake Ice Blisters

In previous summer take over seasons, lake ice blisters were recorded in the Grunehogna area of WDML. During the 2016/2017 summer season, only one lake ice blister was observed and recorded. The blister is situated on the lake at Grunehogna (Figure 78). The blister was deflated which is due to the impact of the warm summer that Antarctica experienced in the 2016/1017 season. Thus, the warmer weather creates a decline in the presence of blisters as they have either melted or have not developed. There are however, larger forms of lake ice blisters found at Terra Nova Bay, Antarctica (Guglielmin *et al.*, 2009). Additionally, frost mounds have also been identified in the same vicinity (Guglielmin *et al.*, 2009). However, Grunehogna has no frost mounds due to the lack of fine sediment near the frozen lake but there are clasts that surround that lakes at Grunehogna (Figure 79 and 80). Guglielmin *et al*. (2009) found that lake ice blisters can reoccur in the same position as well as in new positions on the frozen lake. This is evident at Grunehogna, as the blister recorded has occurred in the same position in previous years.

Figure 78: Lake ice blister at Grunehogna.

Figure 79: Lake ice blister at Grunehogna.

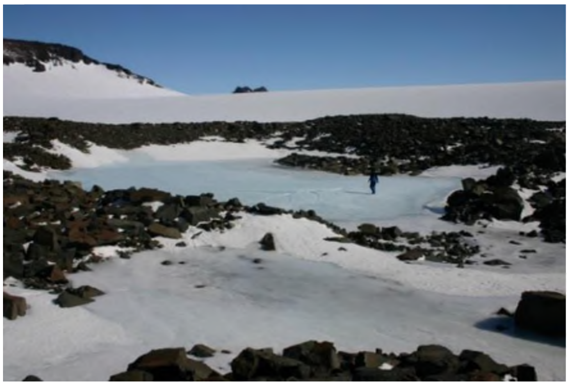

Figure 80: Lake ice blister and frozen lake surrounded by clasts (photo: Ian Meiklejohn).

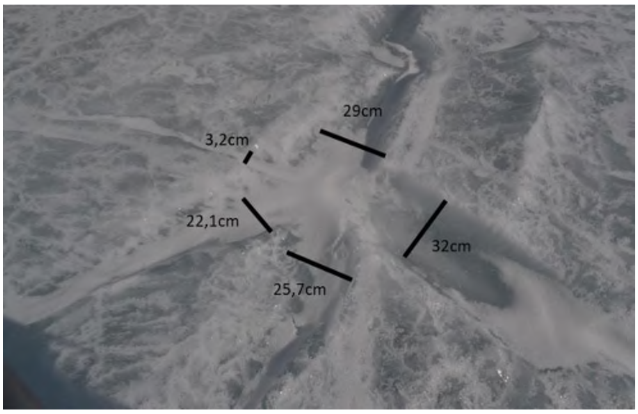

Figure 81: The lake ice blister documented in the 2016/2017 take over. A GPS point was taken as well as the widths of the cracks of the blister.

The lake ice blisters found at Grunehogna all generally have a low raised dome-like shape with three to four major cracks that go through the blister (Figure 81). The lake ice is smooth whereas the blister area is rough on the surface and this is a product of how they form. This lake ice blister is likely to have formed through an aggradational process. Aggradation is where there is a force of pressure that heaves ice (Guglielmin *et al.*, 2009). The heaving of ice is caused by either hydraulic or hydrostatic conditions (Guglielmin *et al.*, 2009). Hydraulic process requires water that flows or taliks to be present (Guglielmin *et al.*, 2009). A hydrostatic formation requires pressure to be present where the lake would freeze from the top downwards (Guglielmin *et al.*, 2009). Therefore, blisters found at Gruneohgna are formed by hydrostatic conditions as it is unknown if there is flowing water or liquid in the lake and there are no taliks present.

The way in which blisters form annually (Figure 82), is at the start of winter water found at the bottom of the lake freezes but this occurs in a closed system where there is a frozen layer on the top of the lake (Guglielmin *et al.*, 2009). The expanding that happens during the freezing of water causes hydrostatic pressure to build (Guglielmin *et al.*, 2009). The pressure is released by the blisters developing cracks on the top (Guglielmin *et al.*, 2009). During the spring and summer months, radiation from the sun hits the surfaces of the clear ice and causes melting to occur from below (Guglielmin *et al.*, 2009). This creates melt water or brine to collect at the bottom and thus leaving the frozen layer on top intact (Guglielmin *et al.*, 2009). Sublimation occurs, during this process, on the top of the blister which causes it to deflate (Guglielmin *et al.*, 2009). The recharge of moisture or liquid to the lake happens late in the summer where the melt occurs on the edge of the lake as well as the ice that is contact with the clasts (Figure 83, 84 and 85) (Guglielmin *et al.*, 2009).

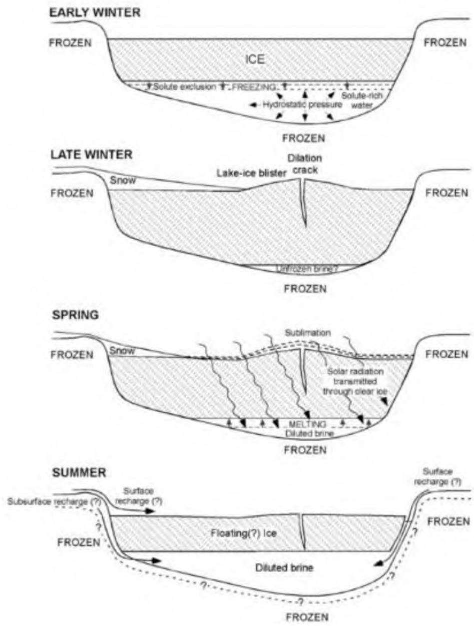

Figure 82: The hydrostatic hypothesis for the formation of lake ice blisters (Guglielmin et al. 2009: 108).

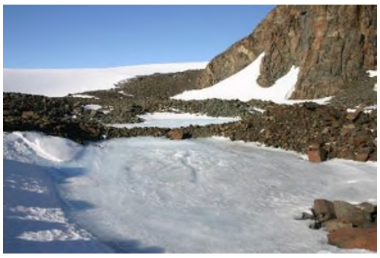

Figure 83: Lake ice blister where clasts present on the edge of the frozen lake (photo: Ian Meiklejohn).

Figure 84: Deflated lake ice blister (photo: Ian Meiklejohn).

Figure 85: Multiple lake ice blisters present on one lake at Robertskollen (photo: Ian Meiklejohn).

The above cycle is based on observations of the blisters found at Terra Nova Bay, Antarctica (Guglielmin *et al.*, 2009). From observations of the blisters at Grunehogna, there is visible evidence that they could be formed in the same manner[17]. A limitation for doing research on lake ice blisters in Antarctica is that, the end of the winter is when ice blisters generally start to deflate and degrade

[17] Further research is needed to be able to confirm that the blister from Terra Nova Bay and Grunehogna form in the same way.

(Guglielmin *et al.*, 2009), making it challenging to do research on how they form as access to these blisters is only possible in the summer period.

6.4. Pronival Rampart


Figure 86: Pronival Rampart at Grunehogna.

In order for a landform to be classified as a pronival rampart, there needs to be a snowbank above the debris accumulation (Figure 86). As mentioned above, in the literature, there is an ongoing debate on which terms to utilise for such landforms. The word protalus was replaced with pronival (Hedding *et al.*, 2010; Brook and Williams, 2013). This was due to the fact that pronival represents debris accumulations at a firn foot, regardless of the position on the slope (Hedding *et al.*, 2010; Brook and Williams, 2013). Whereas protalus originally describes ramparts that have debris accumulations below the backwall and above the snowbank (Hedding *et al.*, 2010).

Hedding *et al*. (2010) classified this landform as a pronival rampart as the geology of the rampart crest is the same as that in the backwall. The landform is affected by supranival process (Hedding *et al.*, 2007). Clasts from the backwall would fall and roll down the firn bank and rest at the ridge crest or further downslope (Hedding *et al.*, 2010). This is evident through the striations of the firn bank where clasts have rolled down the bank (Figure 87). The brown mark on the bank was a clast that fell while the firn samples were being collected (Figure 87). The landform is classified as small for the size of the backwall which indicates that the feature is young and still active or it can imply a slow production rate from the back wall (Hedding *et al.*, 2010). The origin of rampart and the continuous development is based on having a long lasting snow bed rather than one that fluctuates (Hedding, 2016). Thus if the snow does fluctuate in terms of thickness or formation then it is considered that the rampart landform is dormant (Hedding, 2016). The variation of the amount of snow or firn in a pronival rampart is seen as an indication that the landform is active (Colucci *et al.*, 2016; Hedding, 2016). The rampart could be small due to the fact that the snow push mechanisms are having less impact or only having an influence over a long period of time (Shakesby *et al.*, 1999).

Figure 87: Striations on firn bank made by clasts rolling down the bank.

Another reason why the rampart is not that large considering the size of the backwall, could be due to the fact that the snowbed is not snow but rather firn. Snow is seen as material that has not been altered since the time that it fell whereas firn is defined as snow that has been wetted that has not been transformed into ice (Paterson, 1994). Density of the snow samples were calculated (Table 32) and all the three sample densities fall under the firn category, but near the upper limit of the transition to glacial ice (Table 31). The firn is dense firn as it has melted and refrozen. Thus the clasts that come off the backwall will travel further as the dense firn creates a hard and slippery surface. The snowbank above the pronival rampart is not actually snow but rather firn. Resulting in the fact that this landform may be a pronival rampart, as the term pronival means having a snowbank in front (Hedding *et al.*, 2010).

Table 31: The different types of densities (Adapted from Paterson 1994: 8).

New snow (immediately after falling in calm)	50-70
Damp new snow	100-200
Settles snow	200-300
Depth hoar	100-300
Wind packed snow	350-400
Firn	400-830
Very wet snow and firn	700-800
Glacier ice	830-917

Table 32: Table showing the density of the snow samples from Grunehogna.

Left	682 kg/m^3
Right	660.8 kg/m^3
Middle	697.4 kg/m^3

Snow and firn has been used interchangeably when referring to the snowbed of the pronival rampart (for example: Hedding *et al.* 2007; Hedding *et al.* 2010; Hedding & Sumner 2013; Hedding 2014; Colucci *et al*. 2016; Hedding 2016). Whereas other literature it is only referred to as a snowbed (for example: Shakesby *et al.* 1995; Hall & Meiklejohn 1997; Shakesby *et al*. 1999; Matthews *et al.* 2011; Brook & Williams 2013). This causes confusion as to when a rampart should be classified as a pronival rampart. There are differences between firn and snow (Paterson, 1994). Thus the criteria list (refer to Table 2: page 30) created by Hedding & Sumner (2013) could be amended so that there are terms that distinguish between a rampart with a snowbank and rampart with a firnbank. The term pronival rampart should be used to define a rampart that has a snowbank and another term should be used to define a rampart that has a firnbank.

6.5. Mapped periglacial landforms

In WDML, periglacial landforms are found on many of the nunataks, however not all landforms are found on all of the nunataks. The environment at each nunatak is unique and, thus, some aspects or influences that produce the landform will be unique to that area. Presented below are the maps displaying all the different periglacial landforms found in on the nunataks in WDML. All the landforms documented during previous summer field seasons, were compiled together to create spatial database of periglacial landforms. There could, however, be landforms that have not been documented, or investigated, as access to all the nunataks is not always possible. The data available for GIS is limited for Antarctica. Thus, further research and data collection is needed in order to create a geodatabase. Satellite imagery with a greater resolution is needed in order to be able to digitize the landforms on the nunataks. This will provide a better understanding of the extent of the area the landforms cover over the nunatak area. The imagery would be useful to monitor landform development as well as snow accumulation or loss on the nunataks. Mapping the locations of the landforms does give an indication of what is present on the nunatak and what landforms could potentially influence each other. Following (Figures 88-94) are maps showing specific periglacial landforms documented above and mapped. The maps and database provide a baseline from which changes and responses to environmental changes can be documented.

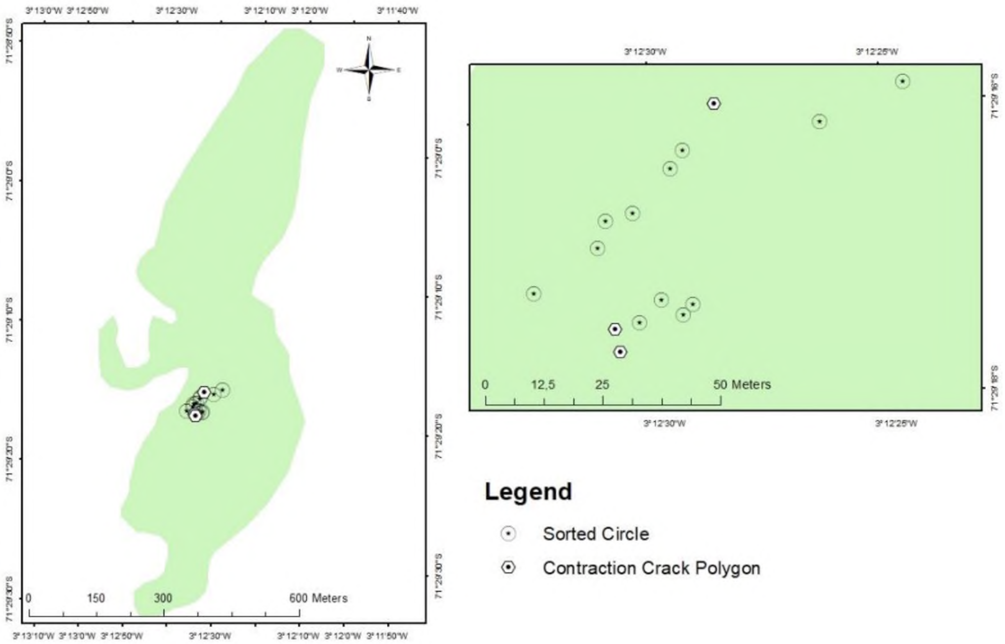

Figure 88: Periglacial landforms found at Robertskollen.

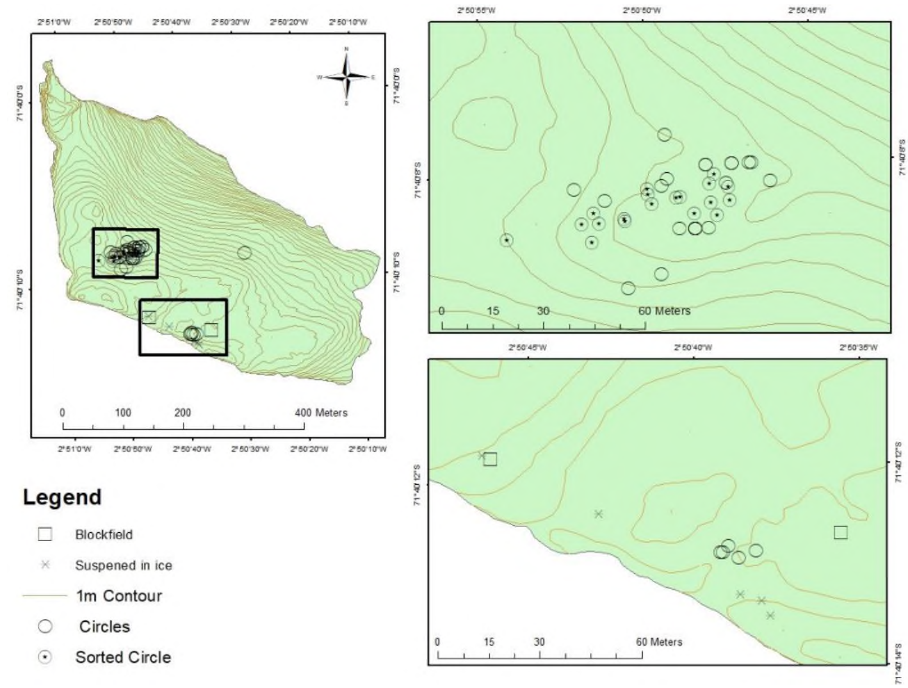

Figure 89: Periglacial landforms found at Northern Buttress.

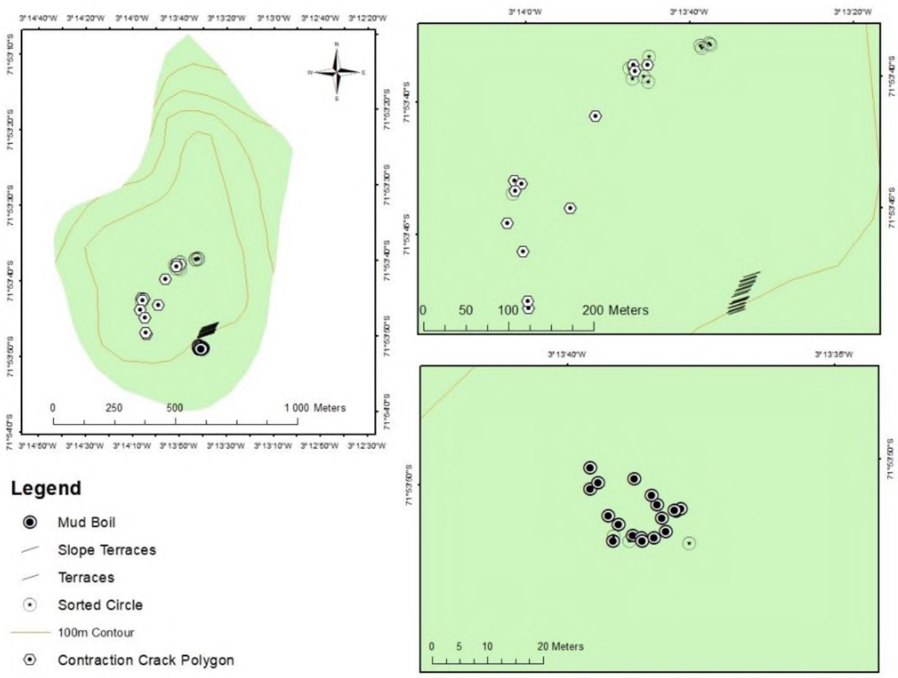

Figure 90: Periglacial landforms found at Valterkulten.

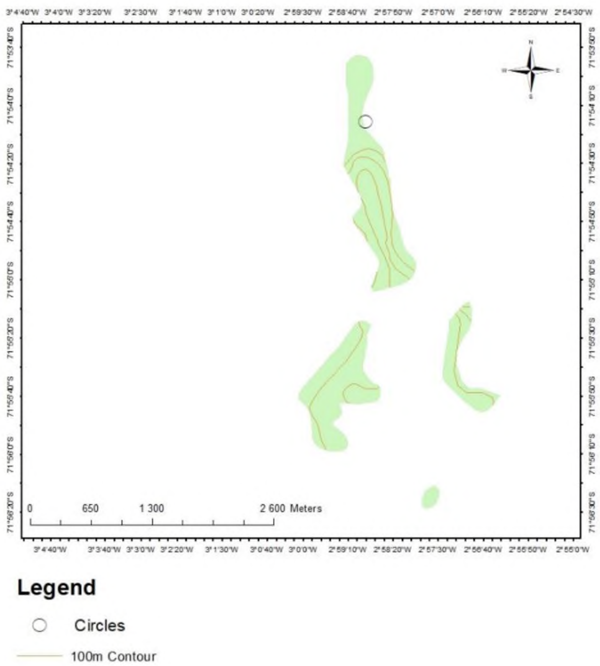

Figure 91: Periglacial landforms found at Schumacherfjellet.

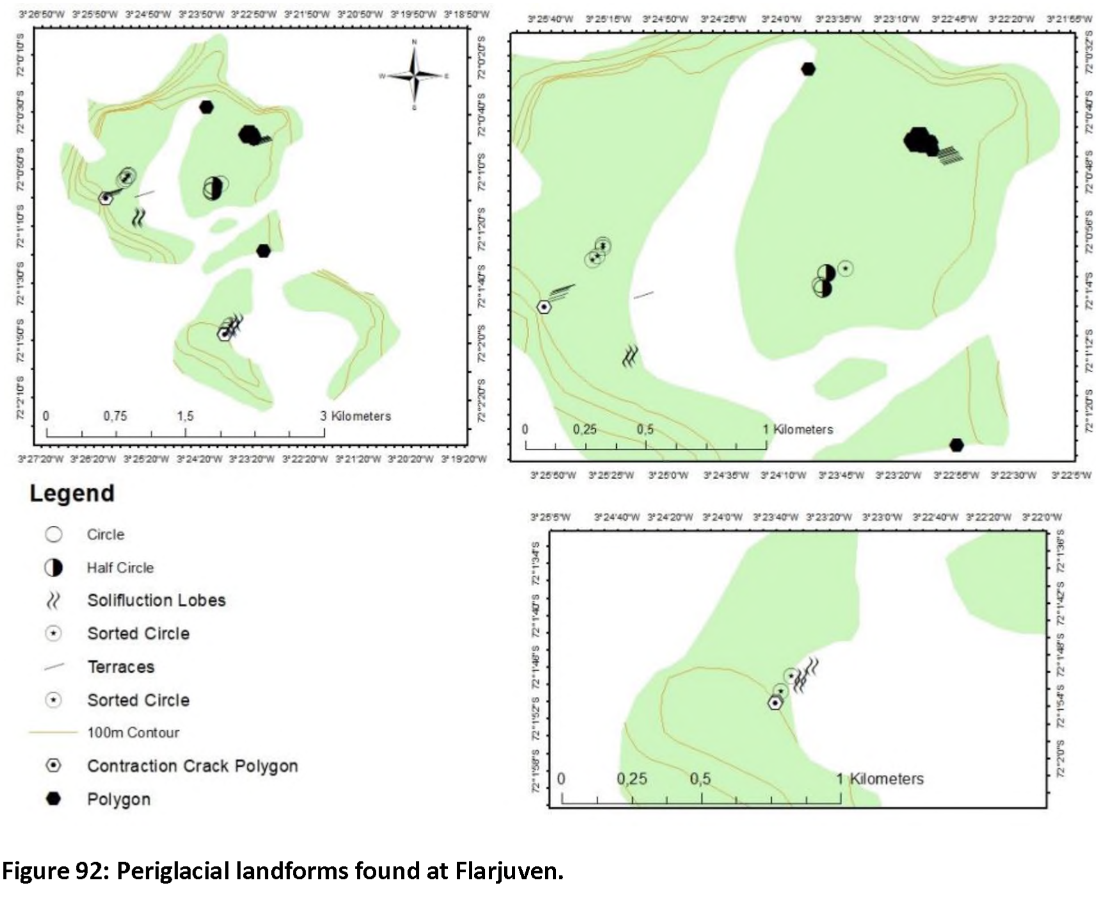

Figure 92: Periglacial landforms found at Flarjuven.

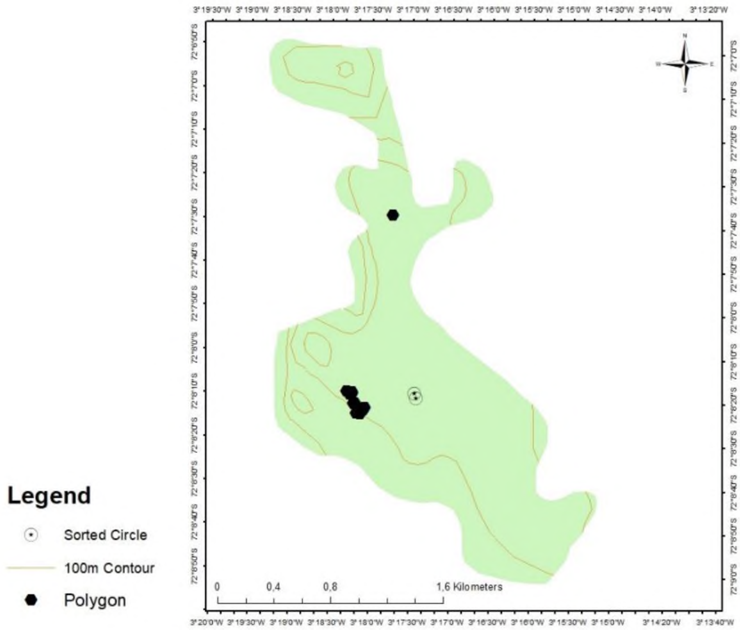

Figure 93: Periglacial landforms found at Slettfjell.

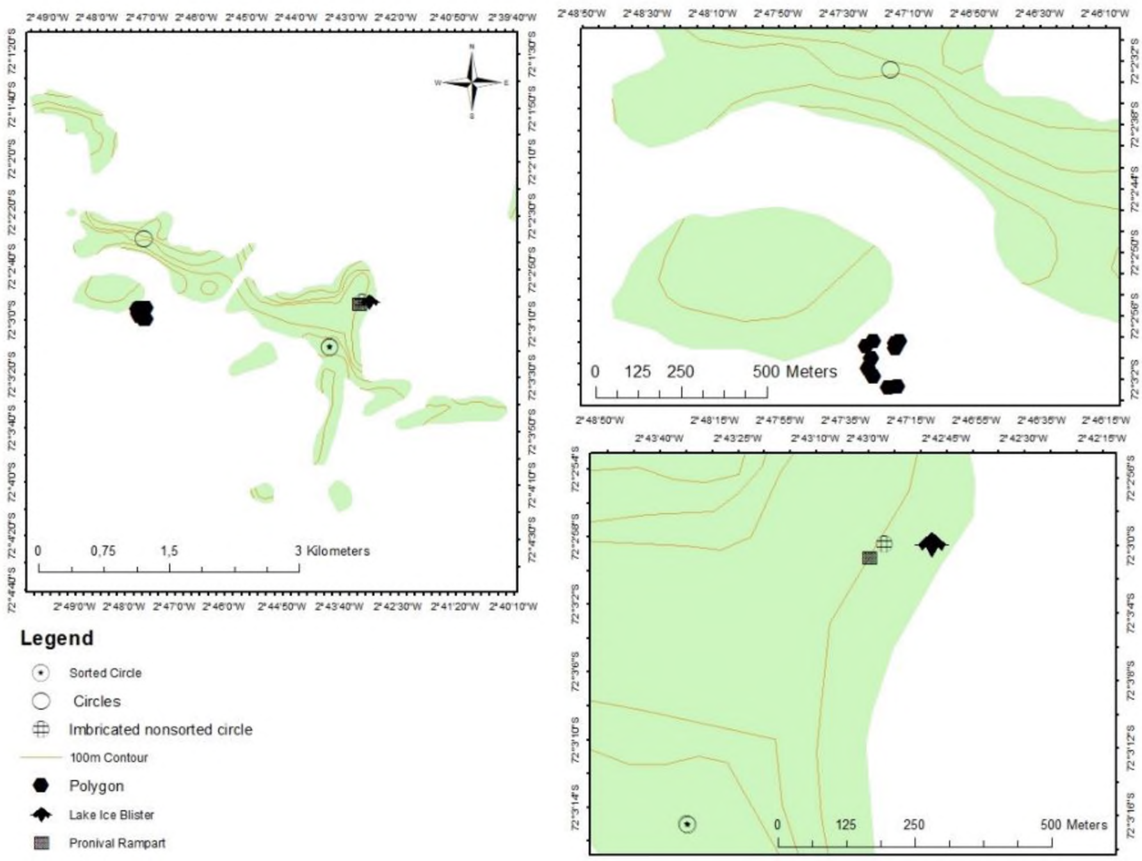

Figure 94: Periglacial landforms found at Grunehogna.

Chapter 7: Investigation into the processes that leads to the development of patterned ground

Patterned ground is the most common periglacial landform in WDML. Thus, this chapter shifts the focus from examining all the periglacial landforms, to an investigation of the processes that lead to the formation of patterned ground. By doing so, this fulfils objective three and showcases how to monitor the processes that create these landforms. Therefore, heave monitoring highlights the theory explained in the literature about freeze thaw events being the process that develops these landforms. Below, the results are presented in different time-lapses from 2016/17 data. Following the results is the discussion on the overall processes of freeze thaw and findings from the results

7.1. Heave monitoring results

Heave monitoring is another way to measure the movement that is taking place on the ground in Antarctica. Movement in Antarctica is seen to be slow due the climate but from the results below, it indicates that movement is happening daily. Thus, heave monitoring has captured the scale of the movement and what affects that movement has over longer periods of time. It also displays the movement that subsequently creates patterned ground. The results are spilt into time-lapses that occurred over one to a number of days, depending on weather. There is a line that is drawn over the 2,5cm mark for all the time-lapse images and then a rough outline of the area that is expanding to convey how the ground does heave. To see the time-lapse videos, please refer to Appendix B for camera one and two. The temperature records for the period of each time-lapse sequence are documented in Appendix C

7.1.1. Time-lapse Analysis - 27/12/2016

For a short period (two days), time-lapses sequences were recorded from two cameras placed at different angles. Camera one (Figure 95) had a more side profile view of the area that heaves whereas camera two (Figure 97) had a front profile shot.

Both time-lapse sequences display that the ground heaved. Camera one captured a side angle of the heave that took place. As the temperature decreased during the night, one can see the heave in the moist ground, when it froze (Figure 95: pictures A – E) and during this time, some of the larger clasts were pushed outward (Appendix B). This event can be identified in temperature data for the same period, where the logger temperature[18] (in red) decreased in the late afternoon and continued to decrease throughout the night. This is when the heave of the sediment took place (Figure 96). The logger and sensors recorded temperatures from measurements near the surface to a 10cm depth. The diurnal sensors showed a repetitive pattern, with differences between the air and ground temperatures (Figure 96). The reason for this is that the ground and rocks retain heat, while whereas air temperature changes more rapidly (Brady, 1974). In Figure 95 picture F (the next morning), the moist area had not decreased rapidly, as past cycles, as the temperature had not increased enough for melting to be drastic.

[18] The logger temperature is the Int temperature in red and this sensor is placed in pelican case. Thus it is not affected by the ground or rocks.

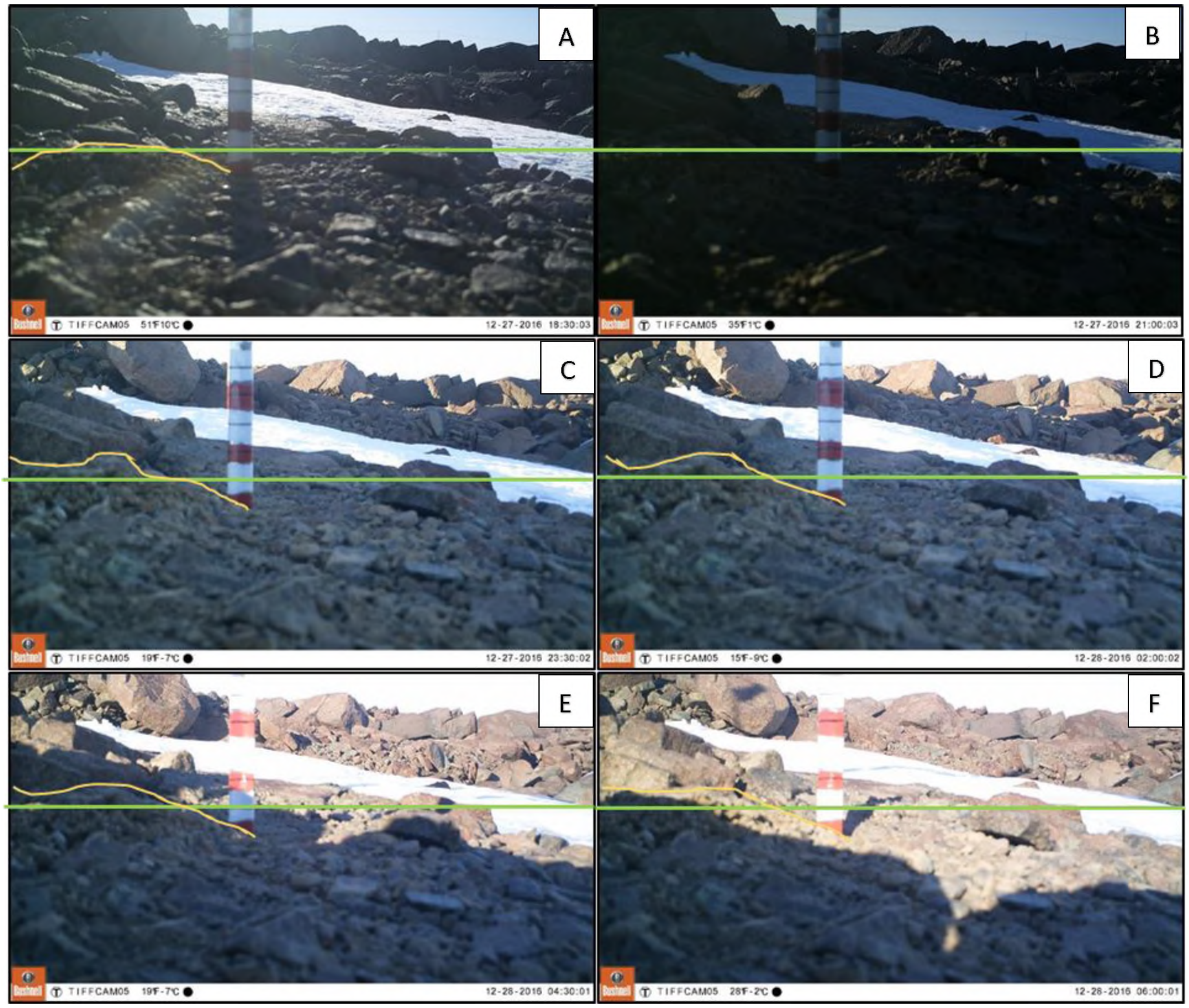

Figure 95: Camera one 27/12/2016 time-lapse pictures that extended over two days.

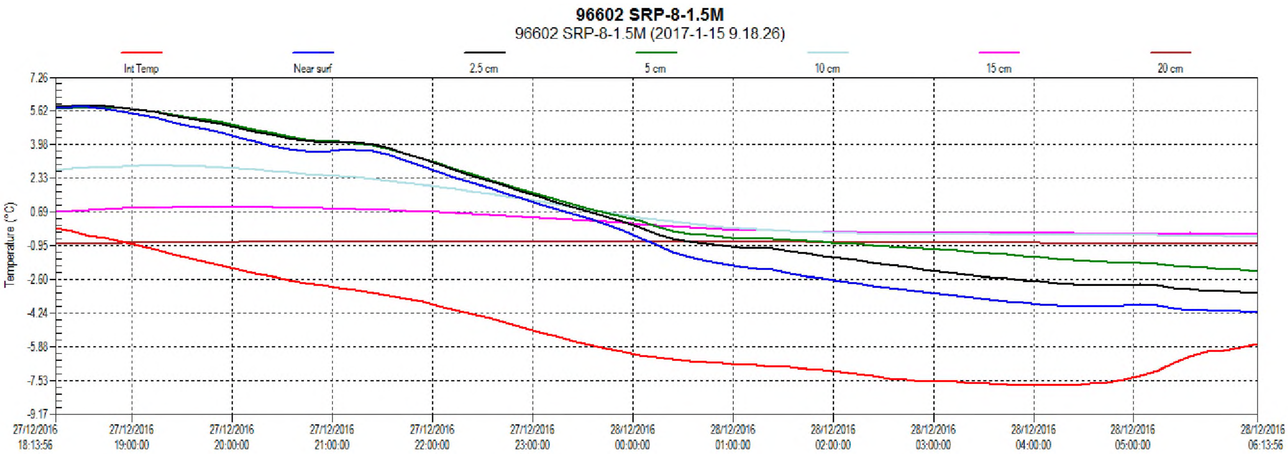

Figure 96: Temperature graph of loggers at different depths for same time-period as the time-lapse sequence from Camera one 27/12/2016.

Camera two (Figure 97) captures more evidence of the melt that occurs in the morning; unfortunately the camera stops taking photos before the completion of the melting process. Pictures A – F (Figure 97) show the freezing of the moisture and heave that took place, which was measured at around 1,25cm vertically. Picture G (Figure 97) shows the melting process. It was not just the fines moving but a large rock was heaved in the process (indicted by the blue circle) (see Appendix B). The movement in the time-lapse (appendix B) was linked to the temperature graph (Figure 98). As the temperature decreased, the moisture in the sediment started to freeze, causing heave to take place. This processes happened between 19:00 and 20:00 but at approximately 21:00 there was a flattening in the temperature graph, which is seen as being a reflection of the "zero curtain effect" (Kotzé, 2015) (Figure 98: indicated in orange). This indicates that latent heat is being released while the freezing is taking place, and it is when the ground is heaved. The melting processes starts at about 7:00, where the temperature increases. By 9:00 there is a decrease in temperature (Figure 98) during melting which is an indication of latent heat absorption.

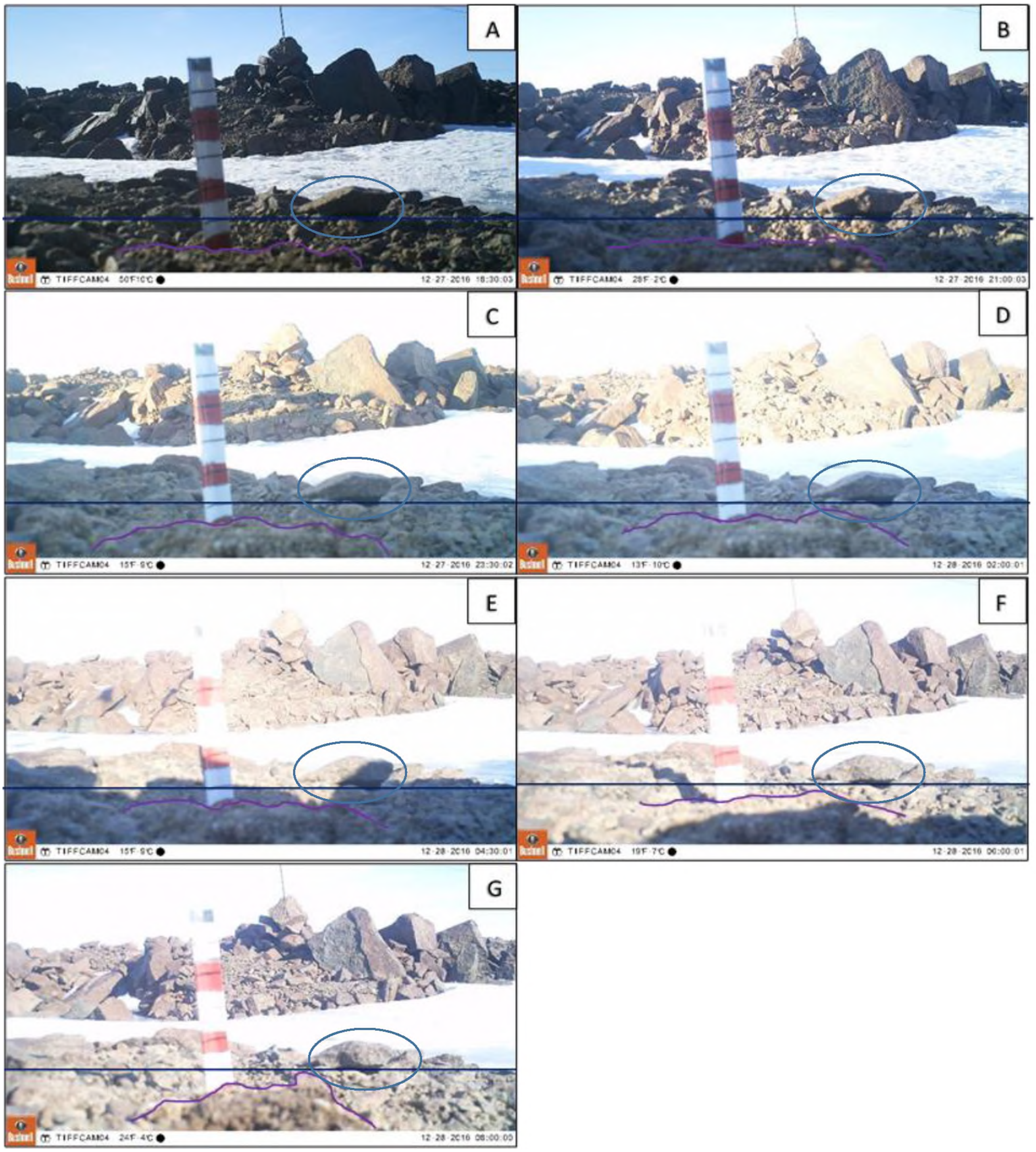

Figure 97: Camera two 27/12/2016 time-lapse pictures that expand over two days.

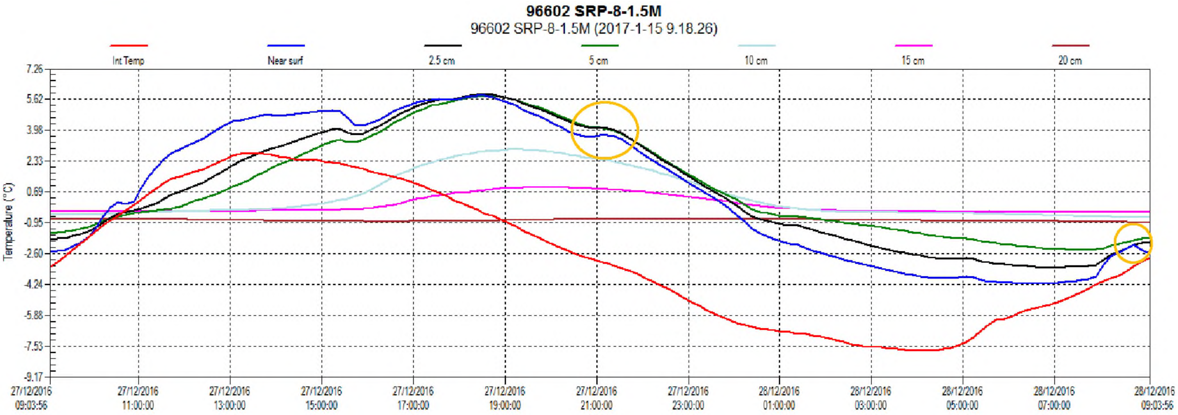

Figure 98: Temperature graph of loggers at different depths for the time period of the time-lapse Camera two 27/12/2016.

7.1.2. Time-lapse Analysis - 7-9/01/2017

The duration of this time-lapse was three days and it took place immediately after a storm. Please refer to Appendix B for the time-lapse video[19]. The temperatures recorded for the period of each time-lapse are in Appendix C. Picture A shows that there was still ice present and, thus, no moisture had yet entered the ground (Figure 99). Frames B to E show that the moisture content had increased due to the melting of surrounding ice and the area had also heaved up due to the moisture expanding on freezing (Figure 100). The moisture entering the sediment is evident in the temperature graph as there is a decrease in temperature during melting that reflects latent heat absorption (Figure 100: indicated in orange). Latent heat is absorbed again between 15:00 – 16:00 (Figure 100: indicated in purple). Latent heat release is evident between 19:30 -20:30, where the heave process takes place (Figure 100: indicated in yellow).

[19] Unfortunately, there is only one time lapse as the second camera failed to work.

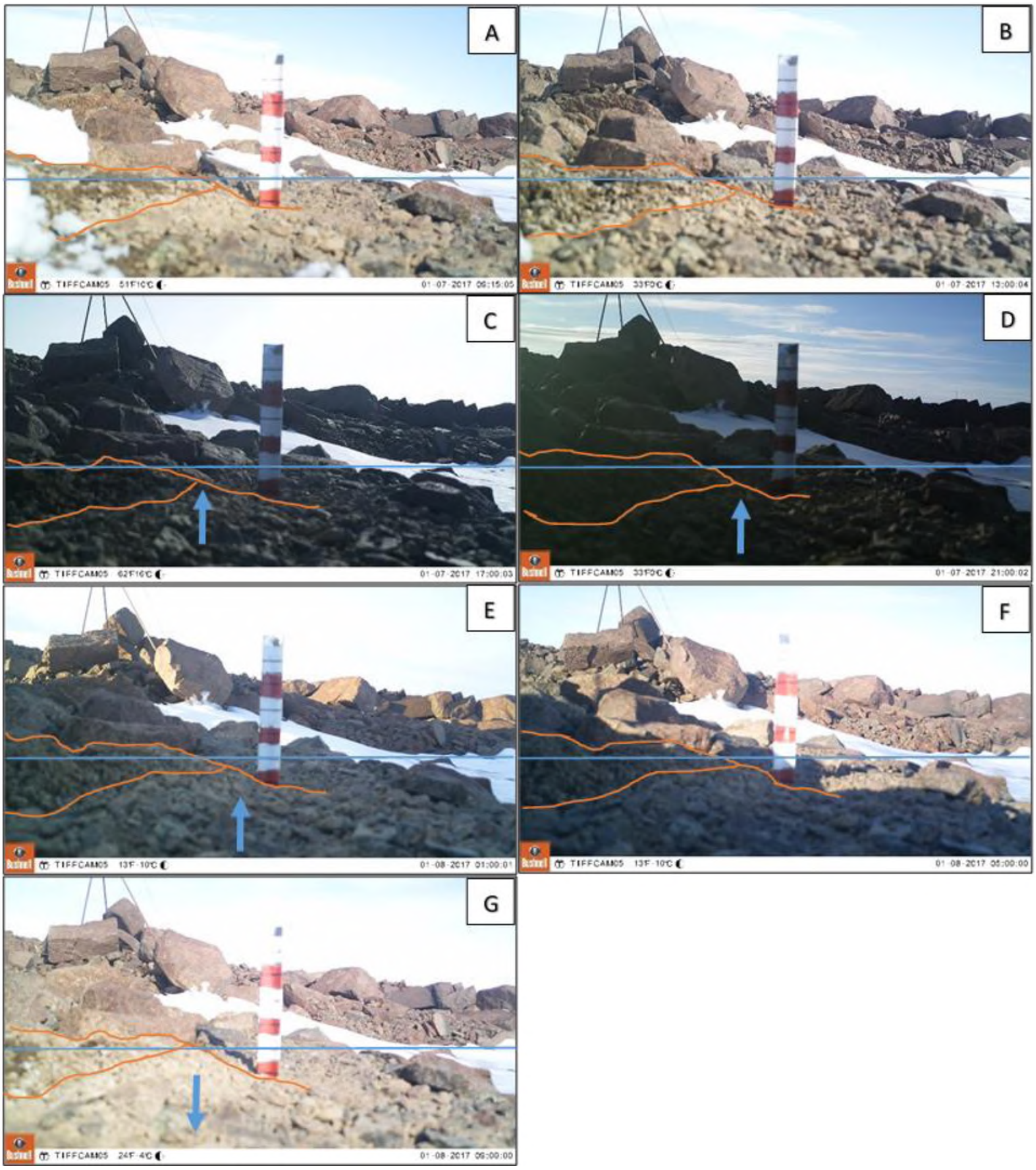

Figure 99: Camera 7-9/01/2017 time-lapse pictures that expand over three days.

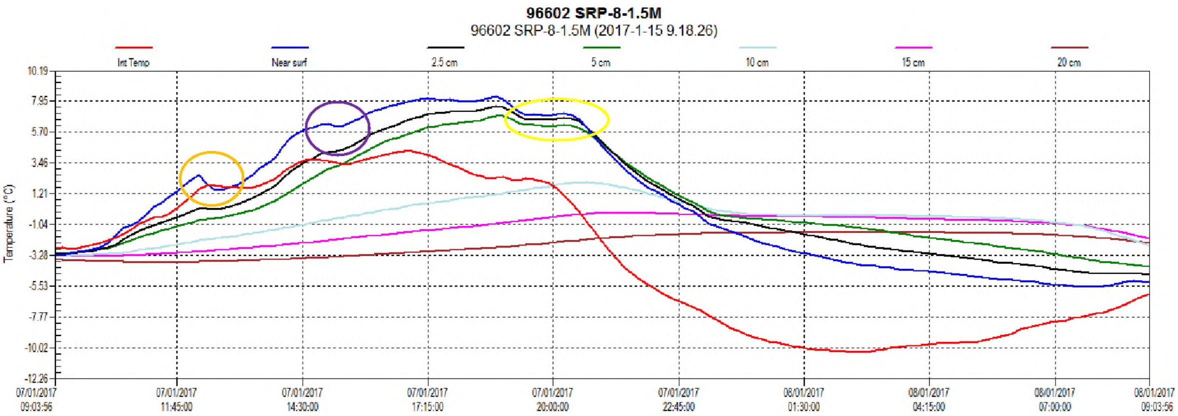

Figure 100: Temperature graph of loggers at different depths for the time period of the time-lapse 7-9/01/2017.

7.1.3. Time-lapse Analysis 12-15/01/2017

This was the longest period that the cameras were utilised for records. Camera 1 (Figure 101) recorded images for three days, while Camera 2 (Figure 103) was only operational for one day[20]. The cameras were again placed at different angles to get different perspective of the same area. Please refer to Appendix B for camera one and two when looking at the pictures and the temperature graphs. To see the temperatures recorded for the period of each time-lapse, refer to Appendix C.

Camera one (Figure 101) clearly displays the heave process that happens daily over three days (Appendix B). This time-lapse (Appendix B) gives a sense of the general time when the heave process takes place. Some of the time-lapse sequences only display one daily cycle or half of a cycle due to the limitations of the camera. The temperature data from the loggers provides evidence that there are cycles of heave happening daily. However, there is a time lag between what is seen on the time-lapse and the temperature data. The reason for this is that sediment and rocks retain heat and an inertia exists in the ground and rock temperatures (Brady, 1974). The observed time when freezing of the moisture and heaving took place during the period of monitoring was 18:00 – 04:00 (Appendix B).

A zero curtain effect occurred where latent heat was released, which provided the energy for the sediment and rocks to be heaved upwards (Figure 102: orange 1). As the temperature increased heat absorption took place during the melting process (Figure 102: orange 2). There were events of latent heat absorption as the temperature increased from about 8:30 to 16:30 on the second day (Figure

[20] See Chapter Eight: Limitations and Recommendations.

102). During the decrease of soil temperature, latent heat was released (Figure 102: orange 3). On the morning of the third day, the time-lapse showed sun rays moving over the heaved sediment (Appendix B). The energy increase from the solar radiation caused melting and latent heat absorption to occur (Figure 102: orange 4). As the temperature of the soil increased throughout the day there were further events of latent heat absorption observed during the melting period (Figure 102). At the climax of the melting there was another event of latent heat absorption (Figure 102: orange 5). Around 19:30 on the third day, a plateau effect occurs where it indicated a change from melting to freezing (Figure 102: orange 6). This could be due to the fact that rocks and sediments take longer to change temperature as they retain heat for longer than the air (Brady, 1974). Energy absorption took place on the last day during melting (Figure 102: orange 7). Over the four day period, the greatest displacement measured was 2,5cm[21]. Also, over the period monitored, there are four heave cycles that take place. The third melting period was the warmest and this impacted sediments and clasts that were at greater depths in the ground. The temperature graph showed this as the 10cm and 15cm depths also showed temperature changes (Figure 102).

[21] More movement is seen in the time-lapse but the scale bar moves as well which is a limitation

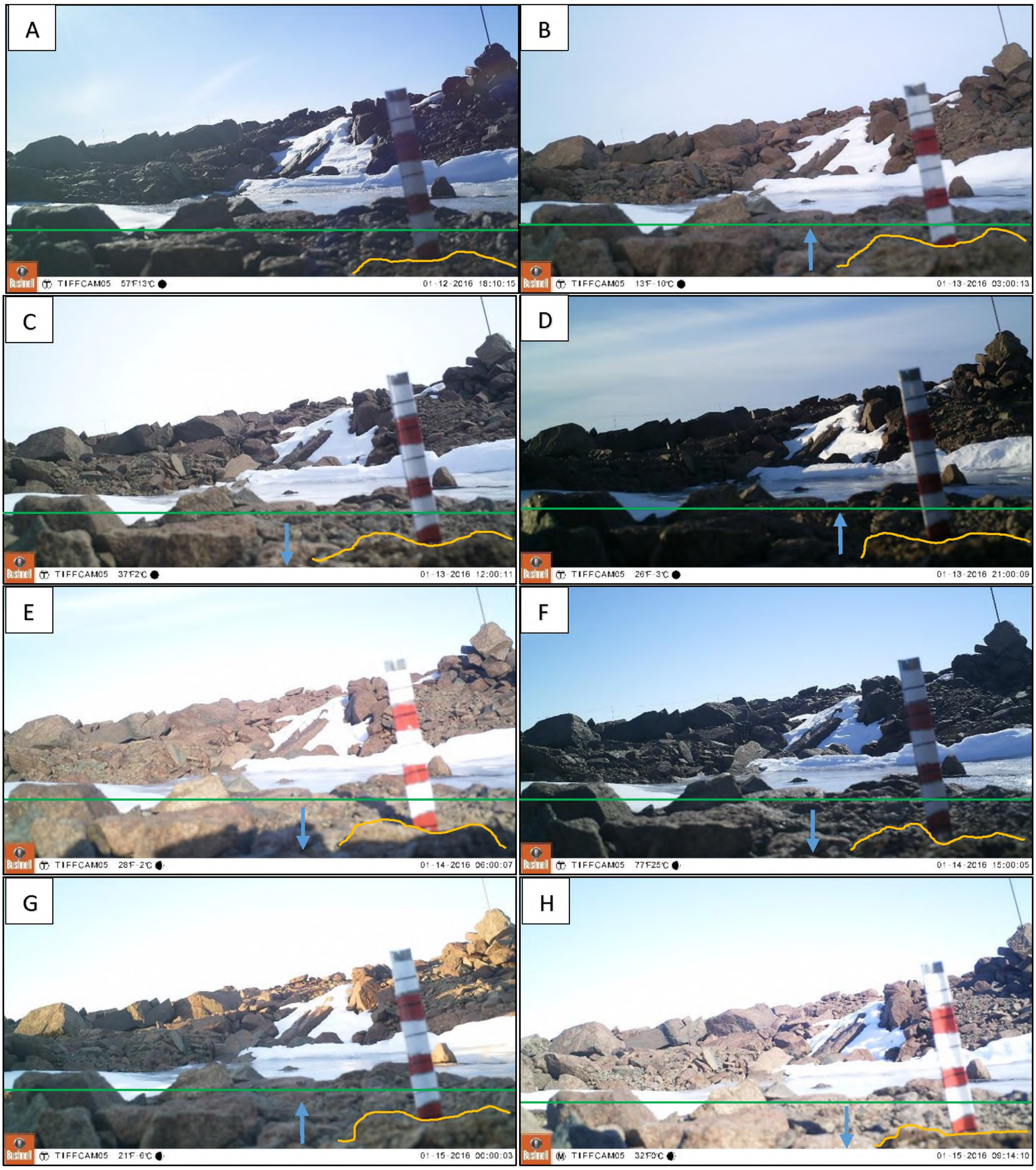

Figure 101: Camera one 12-15/01/2017 time-lapse pictures that expand over three days.

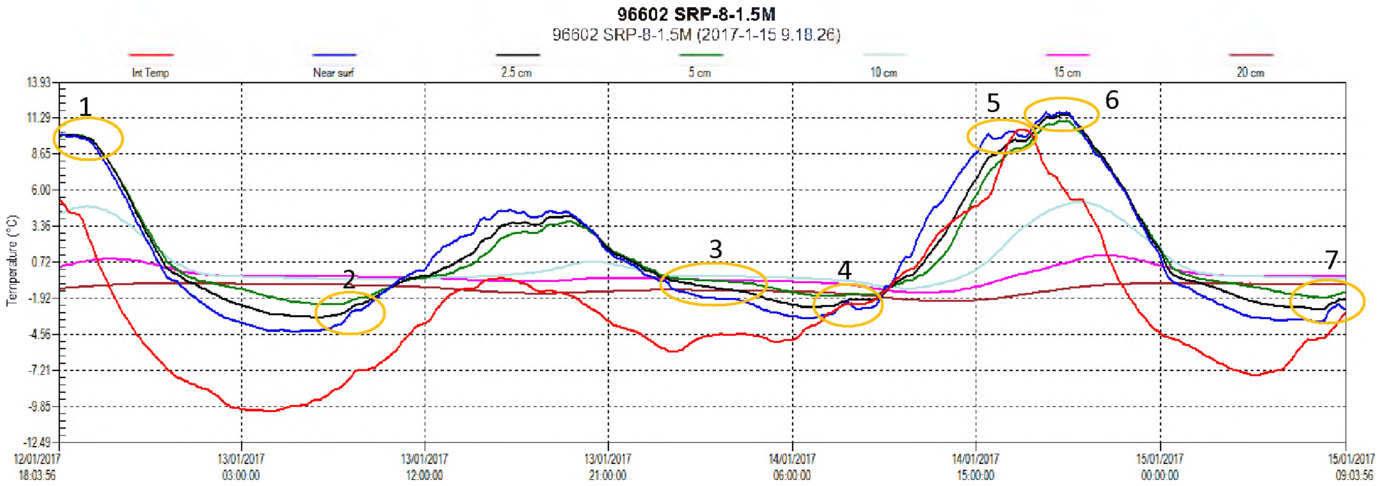

Figure 102: Temperature graph of loggers at different depths for the time period of the time-lapse camera one 12-15/01/2017.

Camera two (Figure 103) recorded for only one day (Appendix B) and had a side on view of the heave. In this time-lapse sequence the magnitude of the ground moisture increase is visible, as indicated by the orange outline throughout pictures A-H (Figure 103). Picture A was at the start of the freezing process and the area highlighted in orange was relatively small (Figure 103). During the process of heaving, latent heat was released. This is visible in the temperature graph (Figure 104: indicated in orange). As one goes through the images to F at 04:00, the height of the heave ground had achieved a maximum (Figure 104). The time-lapse sequence demonstrates that larger clasts were pushed away from the moist ground, which heaved on freezing (Appendix B). Thus, demonstrating the sorting process. Over all, the time-lapse also showed that the ground heave occurs over the entire area visible in the camera lens.

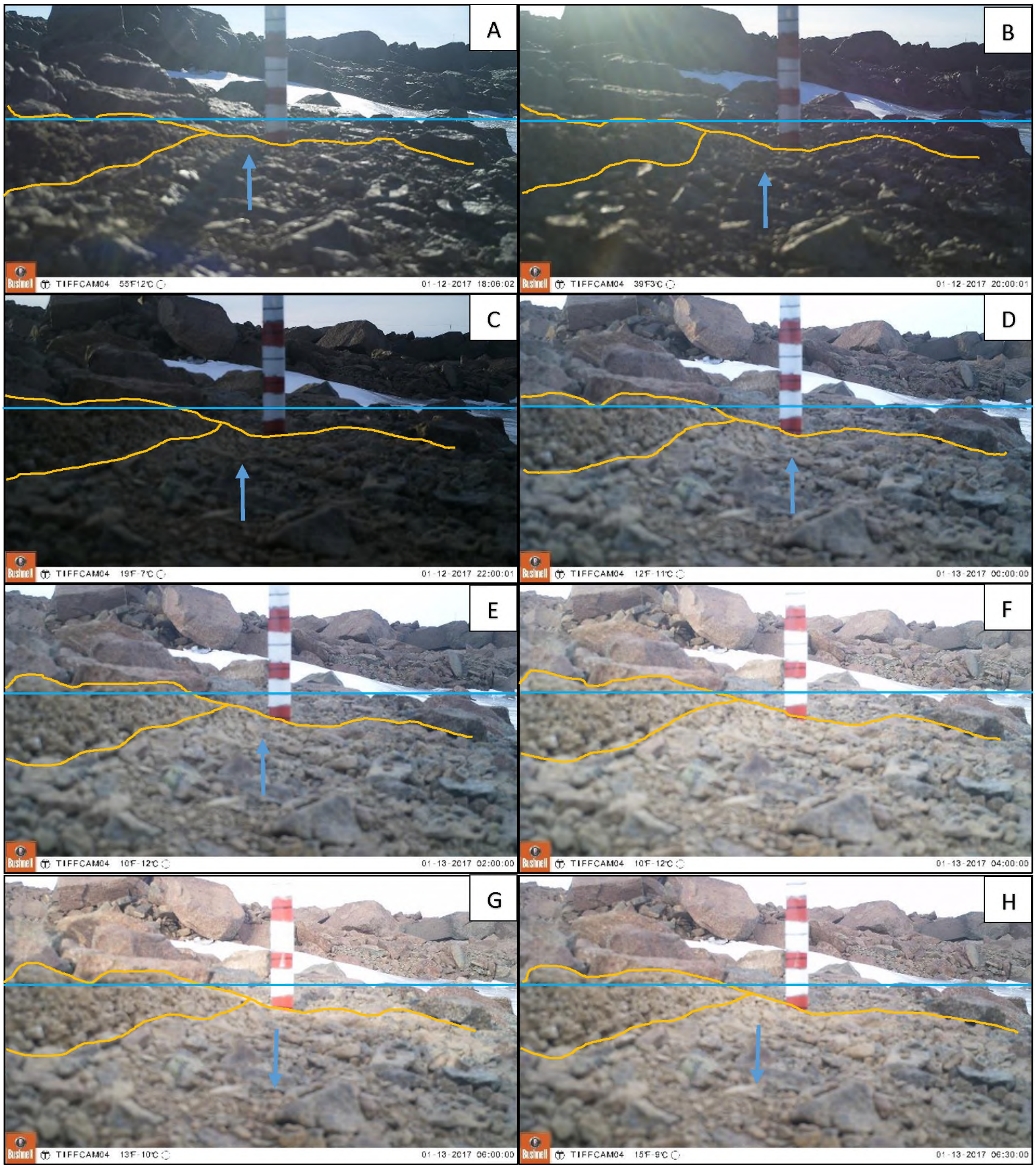

Figure 103: Camera two 12-15/01/2017 time-lapse sequences over one day.

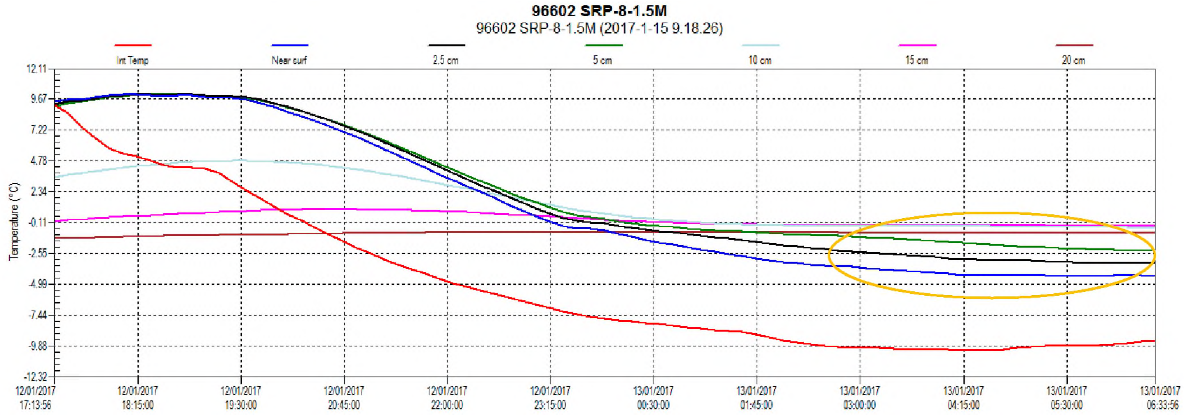

Figure 104: Temperatures from loggers at different depths for the time period of the time-lapse Camera two - 12-15/01/2017.

All the time-lapse sequences indicated diurnal cycles of movement, and that this heave is not limited to small, moist portions. The time-lapses of the heave that occurred on the Northern Buttress were complemented with particle size analyses. At the end of the season, two soil samples were taken. One in the area where a lot of moisture was visible and another from the drier border of that moist area.

7.2. Particle size analysis results

To fully understand the heave that is taking place, soil samples from the heave study site were taken, one where the moisture content was high (indicated in orange) and the other sample where the ground was visibly drier (indicated in blue) (Figure 105). The sample that had the highest moisture content will be referred to as the "wet" sample and the other as "dry" sample. The cumulative percentage vs phi size graph indicates that there is a difference in particle sizes between the wet and dry sample (Figure 106). The wet sample had smaller particle sizes than the dry one (Figure 106 and 107). The dry sample had the largest percentage of -2 phi with 70.3% (Figure 107). There was 3 phi-sized material in the dry sample, but there was 0.01% of 4 phi (fine sand). The wet sample had a high percentage of zero phi (18%), which is coarse sand. All

Figure 105: Two soil samples were taken from the area where the cameras took pictures of the heave.

particle sizes from zero phi to four phi had higher proportions in the wet sample. The wet sample had a percentage of 0.4% for 4 phi (i.e. fine sand). The "wet" area was where the highest displacement through heaving was observed, and where particle sizes were smaller. Below are the representations from particle size analyses that provide an insight into the sorting that is taking place during the heave process.

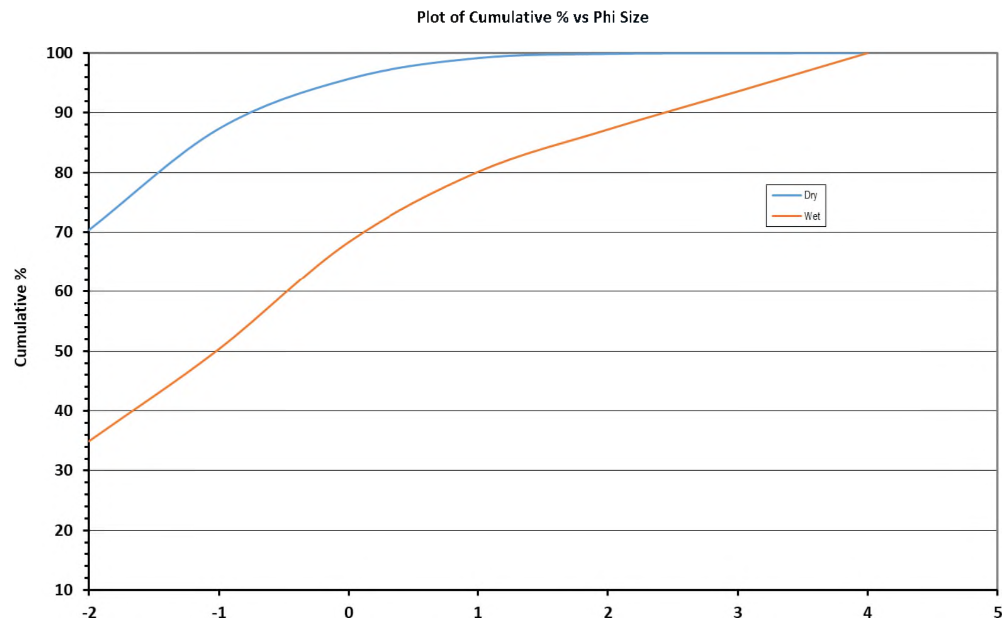

Figure 106: Plot of cumulative % vs phi size for the heave monitoring area.

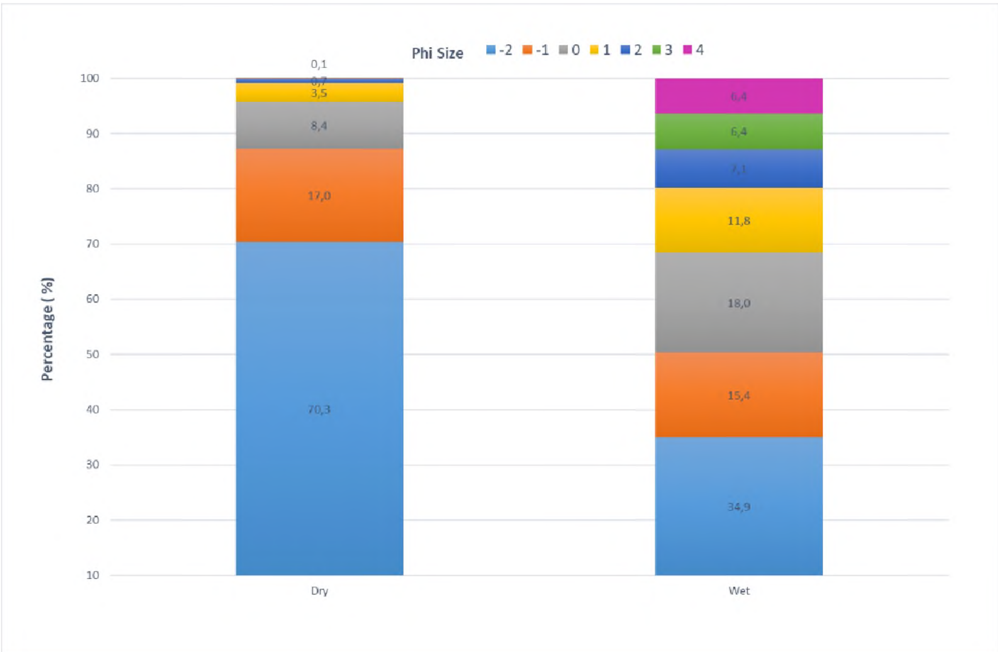

Figure 107: A breakdown of phi particle sizes for the heave monitoring.

To fully understand the data represented; phi mean, skewness, sorting and Kurtosis are discussed. For the phi mean, the dry sample had fine gravel particle size (-1.92) whereas the wet sample had a higher proportion of coarse sand particle sizes (-0.88) (see Figure 108 and Table 33). Both the wet (0.59) and dry (1) samples were very positively skewed (see Figure 108 and Table 33). Thus, they both had relatively high proportions of fine particles (Briggs, 1977). From observations, the area studied did have more fine material than the surrounds; i.e. there were no large clasts. However, despite the visual similarities in the samples analysed, phi sorting values were different for the dry and wet samples. The dry sample was very well sorted (0.34), while the wet sample is poorly sorted (1.80) (see Figure 108 and Table 33). Displacement of ground from the wet area toward the dry area is seen as contributing to the very well sorted values recorded there. The phi kurtosis value for the dry sample was very leptokurtic (2.63) whereas the wet sample was leptokurtic (1.34) (see Figure 108 and Table 33). Thus it indicates that there is a difference between the two samples, even though both were sorted and had fine particle sizes present. The difference is further emphasised from the analysis of soil moisture contents.

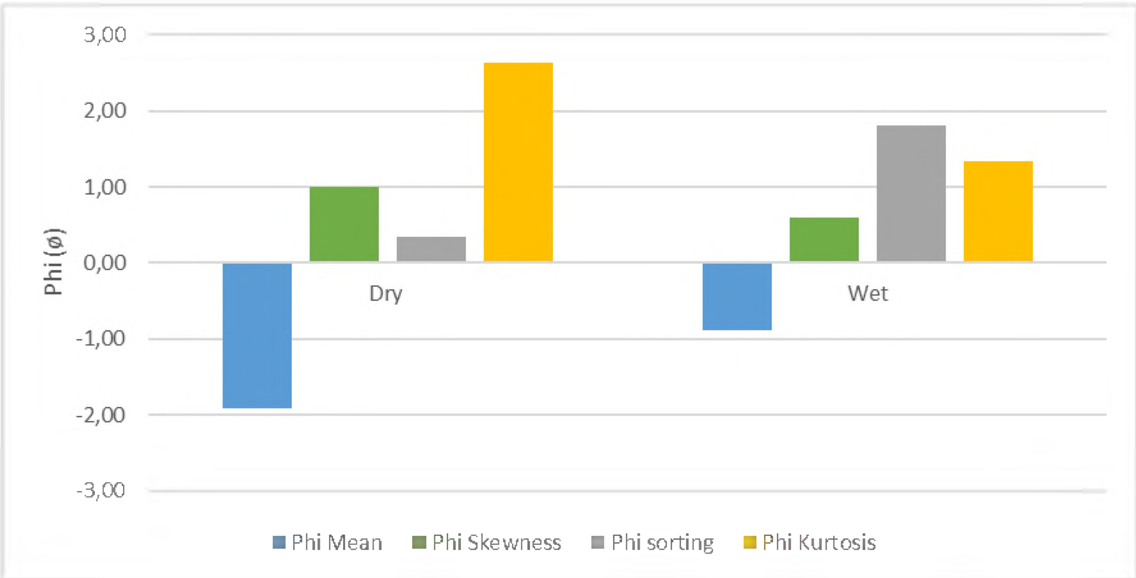

Figure 108: The phi mean, skewness, sorting and kurtosis values for the heave monitoring samples.

Table 33: Table showing the phi mean, skewness and kurtosis descriptive terms for heave monitoring samples.

Heave monitoring samples				
Samples	**Phi mean**	**Phi skewness**	**Phi sorting**	**Phi kurtosis**
Dry	Fine gravel	Very postively skewed	Very well sorted	Very leptokurtic
Wet	Fine gravel/Coarse sand	Very postively skewed	Moderately well sorted	Leptokurtic

Soil moisture content indicates that there was a different between the wet and dry samples. The wet sample had a soil moisture content of 9.38% which is a large amount of moisture (Table 34). The dry sample had only 0.78% of soil moisture content. The results showed that despite the second area being identified as dry, moisture was still present, and was subjected to heave upon freezing of the ground (Table 34). Results further showed that the more moisture there is, the more heaving will take place. From observations in the field, the Northern Buttress area had the highest moisture content of all the sites investigated in WDML and this nunatak, consequently, would be expected to have the highest heaving activity.

Table 34: Soil moisture content (%) for the wet and dry heave monitoring samples.

Sample name	Field mass (g)	Dry mass (g)	Mass difference (g)	Moisture %
Dry	642,09	637,09	5	0,78
Wet	592,82	537,22	55,6	9,38

The Malvern Mastersizer was used to analyse the "wet" sample to see if there was clay present as well as the fine particle distribution. There were not enough fines present from the dry sample to warrant analysis with the Malvern Mastersizer. The analysis of the Malvern Mastersizer results is presented below in the form of a frequency graph and a table that shows proportions of each particle size present (Figure 109 and table 35). The smallest particles (as shown in yellow) in this sample had a diameter 0.523µm (Table 35), which is smaller than the upper limit for clay particle. The largest particles retrieved had a diameter of 86.4µm (highlighted in purple) in the fine sand category (Table 35). The highest portion, in terms of particle size, was medium silt at 8.68µm (indicated in green; Table 35). From observations, there is a considerable amount of moisture present. It could mean that the clay present (indicated in the blue circle) was able to retain moisture in the fines (Table 35).

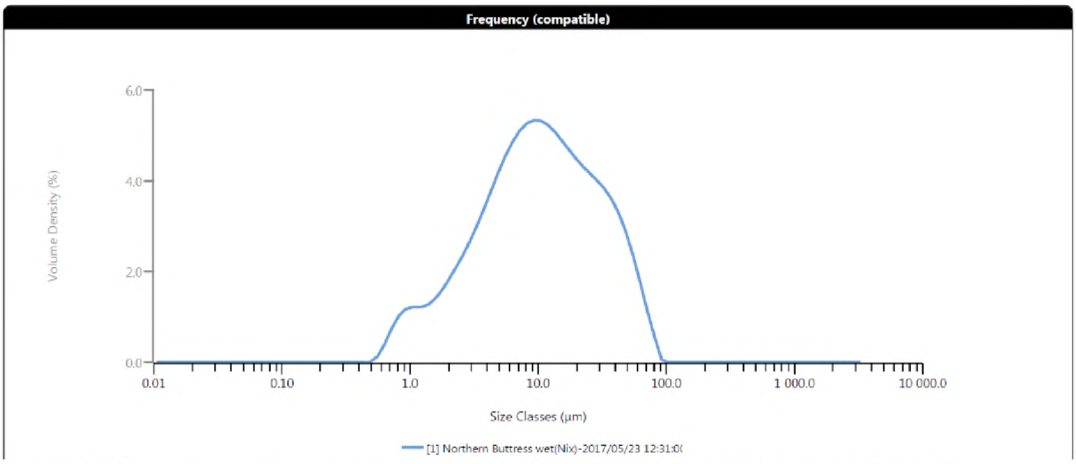

Figure 109: Frequency of the particle size present in the Northern Buttress "wet" sample.

Table 35: Table showing particle size of the sample form Northern Buttress "wet" sample (µm).

Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In	Size (µm)	% Volume In
0.0100	0.00	0.0679	0.00	0.460	0.00	3.12	2.51	21.2	3.58	144	0.00	976	0.00
0.0114	0.00	0.0771	0.00	0.523	0.10	3.55	2.83	24.1	3.46	163	0.00	1110	0.00
0.0129	0.00	0.0876	0.00	0.594	0.34	4.03	3.16	27.4	3.33	186	0.00	1260	0.00
0.0147	0.00	0.0995	0.00	0.675	0.63	4.58	3.49	31.1	3.18	211	0.00	1430	0.00
0.0167	0.00	0.113	0.00	0.767	0.87	5.21	3.79	35.3	2.99	240	0.00	1630	0.00
0.0189	0.00	0.128	0.00	0.872	0.99	5.92	4.05	40.1	2.73	272	0.00	1850	0.00
0.0215	0.00	0.146	0.00	0.991	1.01	6.72	4.26	45.6	2.39	310	0.00	2100	0.00
0.0244	0.00	0.166	0.00	1.13	1.01	7.64	4.39	51.8	1.95	352	0.00	2390	0.00
0.0278	0.00	0.188	0.00	1.28	1.04	8.68	4.45	58.9	1.45	400	0.00	2710	0.00
0.0315	0.00	0.214	0.00	1.45	1.15	9.86	4.44	66.9	0.93	454	0.00	3080	0.00
0.0358	0.00	0.243	0.00	1.65	1.31	11.2	4.36	76.0	0.47	516	0.00	3500	
0.0407	0.00	0.276	0.00	1.88	1.51	12.7	4.23	86.4	0.01	586	0.00		
0.0463	0.00	0.314	0.00	2.13	1.73	14.5	4.06	98.1	0.00	666	0.00		
0.0526	0.00	0.357	0.00	2.42	1.96	16.4	3.89	111	0.00	756	0.00		
0.0597	0.00	0.405	0.00	2.75	2.22	18.7	3.73	127	0.00	859	0.00		

7.3. Discussion

Overall, the time-lapse sequences showed that heave was a diurnal occurrence in summer and the magnitude of movement is larger than one would expect. Thus, research is starting to provide an indication of how important it is to investigate moisture in Antarctica, as moisture and soil conditions dictate how much heave and particle movement takes place (Wang and French, 1995). Washburn (1979) stresses the importance of the frequency of freeze thaw cycling as this, in turn, influences the amount of frost action that takes place.

The temperature analyses presented indicates that the soil does respond to the air temperature, in that it is synchronous. However, sediment and soils do retain heat longer, creating a lag time (Brady, 1974). Therefore there is a delay between the temperature cycle and the heave cycle at the Northern Buttress. The freeze thaw events that are examined in Valletta, Switzerland, by Matsuoka, Abe and Ijiri, (2003), also display a lag time between the temperature cycle and heave cycle. The graphs, discussed above, do indicate that the soil or sediment at depth is not as heavily influenced by the temperature, as the surface substrate is. The ground surface and subsurface represent different thermal regimes, as evidenced in the analyses presented above (Washburn, 1980; Kappen *et al.*, 1998). In some instances, the sensors at greater depths did indicate a variation in temperature but this happened with large magnitude changes in ambient temperature. The depth at which the moisture freeze could also have an impact on the vertical heave that takes place (Matsuoka, Abe and Ijiri, 2003). Thus, the depth of the moisture being frozen in Switzerland is less (Matsuoka, Abe and Ijiri, 2003), compared to the depth at which moisture freezes at Northern Buttress. Where the Switzerland example is similar to Northern Buttress as larger soil particles do have little movement and the temperature influence decreases with depth (Matsuoka, Abe and Ijiri, 2003).

Diurnal cycles of freeze thaw events are examined in Valletta, Switzerland, by (Matsuoka, Abe and Ijiri, 2003). However, vertical movement was only measured to a maximum 6mm (Matsuoka, Abe and Ijiri, 2003), whereas the vertical movement on Northern Buttress had a maximum of 2.5cm. There the movement is greater at Northern Buttress. Harsh environmental conditions could explain the vertical movement at Northern Buttress. The shape and size of larger clasts can impact how they are moved by the heave (Washburn, 1980). Freeze thaw cycles tend to influence the movement of soils and clasts on a vertical plane where the fines move downward and the larger clasts move upward (Embleton and King, 1968). Horizontal and vertical sorting always occur at the same time due to differential movement (Embleton and King, 1968).

The mineralogy of the fines does influence the process of freezing in the instance of heaving and movement of the moisture in the sediment (Washburn, 1980). Clay particles are able to retain water as their structure is expandable (Brady, 1974; Washburn, 1980). Particle size influences the formation and growth of ice in the soil in two ways (Washburn, 1980). One, the temperature at which freezing occurs of the "phase boundary water" and the water in the space of the soil and two, the way the water moves towards a freezing front (Washburn 1979: 67). The grain size and the space between the particles can influence at what temperature freezing takes place (Washburn, 1980; Summerfield, 1991). Thus, content of the particles, the moisture present and the climate all play a role in how the heaving processes take place.

As mentioned above the highest percentage of particle size was silt for the "wet" sample from Northern Buttress. Silt is susceptible to heaving as it allows movement between particles and it represents a relatively open system (Washburn, 1980; Summerfield, 1991). Open systems allow for moisture to be added into the environment and thus more heave takes place and it can be continuous, whereas in a closed system there is no additional moisture added, limiting the heaving process (Washburn, 1980). The entire WDML, according to the research analysed in this thesis, would comprise an open system. Storms do add more moisture into the system and this was evident in the heave monitoring as the moisture from the snow that melted did cause an increase in the observed magnitude of heaving.

Although change in temperature will influence heaving, there are factors such solar radiation and the energy absorbed by the rocks from this sunlight. The temperature of the rocks is influenced by the angle of the sun, altitude and the position of the rock (Ayres, 2016). The colour of the rock can influence the input of moisture into the heaving processes; darker rocks, under clear conditions, will be warmer as they absorb heat rather than reflect it (Ayres, 2016). All of these factors impact the temperature that the sediments at the surface and at depth will occur.

Furthermore, the temperature of the soil is influenced by the process of energy being absorbed and released (Brady, 1974). The temperature analyses presented show that latent heat absorption takes place during melting and latent heat release occurs during the freezing (i.e. during heave) (Washburn, 1980). The energy generated during the heave process creates a force that moves even the larger clasts and boulders (Washburn, 1980). During freeze thaw cycles and hence heave and collapse, clasts over time roll off the mound of frozen fine material, creating a sorting effect (Washburn, 1980). This process is clearly evident in all the time-lapse sequences and shows that freeze-thaw is an important process in the formation of sorted patterned ground. In some of the time-lapse images it was evident that even large clasts of several kilograms in mass moved during the heaving processes.

The heaving processes are responsible for the development of patterned ground such as polygons and circles as well as influencing how blockfields develop (Wang and French, 1995). The heaving process is part of the differential frost heave, where vertical and horizontal movement of the sediment occur simultaneously (Ballantyne, 2007). Therefore, the monitoring of the heave processes is important to understand further how patterned ground develops (Wang and French, 1995). Many factors play a role in the heaving process, and some of these have obviously not been considered due to an absence of relevant data. Thus, heave monitoring is critical to understanding how patterned ground develops to contribute to improved theoretical concepts.

Chapter 8: Limitations and recommendations

Limitations and recommendations are discussed in three sections. Any limitations that are not discussed here are mentioned in the relevant Chapters. The limitations are acknowledged and then followed by recommendations for future research. Due to the nature of the environment in Antarctica, issues did arise during data collection and data analysis. Even though there were limitations, these did not hinder achieving the aim and objectives of this thesis.

8.1. Antarctica

Doing research in Antarctica has its own limitations. The weather in Antarctica is unpredictable and can change at any moment in time, which can delay or shorten the time spent in the field to collect data. Due to the remote location of some of these nunataks, we also have to rely on helicopter transport. Getting to Antarctica is an expensive endeavour and we, thus, take full advantage of any good weather days we have to collect as much data as possible. This leads to opportunistic sampling where one samples anything that is seen as interesting as well as what one planned to do. This can be a limitation as due to the variety of samples, the data can look unfinished and not statistically sound.

8.2. Heave monitoring

There were five time lapses created and some were taken for longer periods of time and others were short due to weather constraints. The temperature displayed by the Bushnell HD cameras is incorrect which limits the time-lapses. However, the location where the cameras were placed was adjacent to the temperature logger for that nunatak. Thus the temperature data and the time-lapses are analysed together.

The Bushnell HD cameras are designed to track animal movement which makes it difficult to set up for the type of environment in Antarctica. Thus, by reprogramming, the cameras were forced to take a picture every minute. However, sometimes the cameras would still only take a picture when it sensed movement. The first attempts had results where it took picture when we moved the camera and walked away and when we came back to collect the data. After reprogramming the cameras, they did take photos every minute regardless of any movement taking place in the view of the lense.

For the time spent in WDML, the research was carried out under conditions of permanent daylight, which potentially limits access during periods that are conceivably more active as far as frost action is concerned, when there are definite day-night cycles. The permanent daylight also hindered the quality of the photo being taken as at times direct sunlight effected the camera lens. A solution for this would be to angle the cameras onto a stake which can be hammered into the ground. However, this was attempted, but due to the shallow ground and hard bedrock, was not possible. Consequently, the stake could not be hammered in far enough to be stable. Thus the cameras were placed on the ground, wedged between rocks in order to create stability in windy conditions. The pictures taken from this angle show the heave in the sediment was increased when moisture was present, however, heave was also noticeable in dryer areas. The time-lapses even showed that rocks weighing over 10kg were moving. However, with the cameras being placed on the ground, the time-lapses indicated that the cameras are also being heaved up and down. This is a finding in itself as it shows the power of the heave process that takes place. When trying to measure the heave off the scale bar, when the camera is moving, proves to inaccurate as the camera and the ground are both moving.

The accuracy of measuring the movement is hindered as the scale bar does move during the freeze-thaw cycles. Kotze (2015) stresses that nunataks with frequent freeze-thaw cycles will heave equipment that is placed in the ground. A recommendation is to add a heave meter that was used by Wang & French (1995). This includes an anchor rod where it is hammered past the permafrost table and then a cylinder pipe or rod is slid over it so that is can move with the heaving of the sediment (Figure 110) (Wang and French, 1995). Hammering any rod or stake into the ground in Antarctica has been proven to be difficult but the solution would be to drill into the bedrock itself to secure the rods or scale bars.

Figure 110: Heave meter (Wang & French 1995: 339).

Future heave monitoring should use a scale bar, the heave meter and the Bushnell HD cameras. To enhance the data monitoring it should be conducted near a logger to be able to couple the temperature with the time on the time-lapses. Freeze-thaw cycles can affect patterned ground and the formation of block fields. Thus heave monitoring needs to be used to capture the formation process of periglacial landforms.

8.3. Archival Data

This research in this thesis is a combination of archival data from previous seasons as well as data collected in the 2016/2017 take over season. The aim was to synthesise the data that has not been used with new data to give a holistic view of the periglacial landforms in WDML.

The way in which the archival data was captured sometimes differed from year to year. The data did not always have an explanation of how it was collected or what the units of measurement were. Some of the samples had GPS locations or other variables while other samples did not. This hindered how much of the data could be used and what could be analysed. Some data collected had explanations and pictures and information of where the samples were taken, the units they are measure in and more. However, other data sets are only numbers and thus becomes challenging trying to decipher what methods of data collection were used and what instruments where involved. The nature of the environment and location does render to incomplete looking data due to the opportunistic sampling style. However, all data that was collected from Antarctica is valuable as it is not a location that is easily accessible. To continue the analysis on the periglacial landforms in WDML, it is suggested that a standardised data collection system is implemented.

It should not matter who collects the data and when, if there are standard procedures that are put in place. A list of instructions should be created to guide the person who does the data collection as well as a list of standard equipment that will be needed. Some of the methods that could be used is mark the gps points of all samples, take the dip and orientation, note any observations and take pictures. Other instructions can be made per landforms for data collection. The data can be entered into template excel spreadsheets that can be used every time. This will help create uniformity to the continuous data collection that occurs every year. There is so much data that has been collected but cannot be used as due to necessary measurements being missing, which hinders the data and statistical analysis that can be done. Furthermore, some archival data could not be used at all as there were not enough measurements to warrant analysis. Dealing with archival data in this thesis, has created an unfished feel which while it took away from the aims and objectives, it further broadened the scope of the thesis. Therefore, by standardising data collection in the future, it will create research that can be more holistic, clear and to the point.

Chapter 9: Conclusion

The thesis is concluded with reference to the aim and objectives of the research conducted for periglacial landforms in WDML. It important to remember that this research does contribute to the research that attempts to answer two questions from the horizon scan. Question 39 looks at the rates of geomorphic change in different areas of Antarctica as well as investigation of the age of the preserved landscape (Kennicutt *et al.*, 2015). This thesis highlights that the rate of geomorphic change for patterned ground is more frequent than previously imagined. Change and movement of the patterned ground is a diurnal occurrence. However, the age of the preserved landforms is something that needs to be further investigated, and is not discussed in this thesis. Question 42 raises concerns about what changes will take place due to climate change on the permafrost processes, the active layer and the water availability in Antarctica (Kennicutt *et al.*, 2015). Question 42 is answered in conjunction with question 39 in this thesis in Chapter Seven. The 2016/17 summer in Antarctica was a warmer summer, thus the impact of the warmth is noticed in the heave monitoring. There was an increase of moisture in the soils especially where the heave monitoring station was located. The results so that the moist plays a major role is influencing the sorting and formation of patterned ground. The increased rate at which heave takes placed as mentioned earlier, will in time mean that patterned ground will be forming or changing at an increased rate. This can be linked to a warming climate where Antarctica, is not necessarily as dry as it used to be. However, further research is needed to be able to fully understand these horizon scan questions.

Periglacial landforms are not well documented, especially more so in WDML, Antarctica. This thesis aims to highlight the periglacial landforms found on selected nunataks in WDML. The aim was achieved by fulfilling the three objectives that are discussed below.

Objective one was to consolidate the existing knowledge base regarding the documented periglacial landforms in WDML. The literature review provided the relevant background information on the formation of the landforms and the processes involved. However, there were not many examples relating to Antarctica and how the processes differ from other examples of periglacial landforms found in other areas of the world. Chapter Five is part of objective one, where an overview of the archival data is examined. What this chapter highlights is that the environment of nunataks is unique and how the environment has an impact on the formation of periglacial landforms. Furthermore, particle size and moisture content is important when investigating periglacial landforms. Particle size and moisture content do influence the patterning and shape of periglacial landforms, especially patterned ground. Therefore, with the combination of the literature review and Chapter Five, this thesis attempts to give a holistic view on the existing knowledge base that is present at the time of writing.

Objective two is an update on the periglacial landforms in WDML. Fulfilment~~,~~ of this objective was achieved in Chapter Six by analysing the data collected in the 2016/17 Austral Summer. The findings of this chapter reiterate that particle size and moisture content are vital in the formation of patterned ground. Findings for pronival rampart exposes the issue of the inconsistency of naming conventions in the literature. Results for the lake ice blister prove that a warming climate is having an impact on the development of periglacial landforms. Discussion about ice suspension of blockfields is discussed and linked to freeze thaw events. A collaboration of all the GPS locations from archival and 2016/17 data of the periglacial landforms were mapped for each nunatak. The maps confirmed that patterned ground is the most common landform in WDML. Therefore, the formation processes of patterned ground are investigated in Chapter Seven.

Objective three is addressed and achieved in Chapter Seven, whereby research into the formation of patterned ground was developed using a new method of heave monitoring. Time-lapse photography was used to measure heave, while at the same time utilising ground temperature logging to identify the thermal conditions and energy exchanges that are involved in developing sorted patterned ground. Heave monitoring highlights that freeze thaw events do play a major role in the formation of patterned ground.

The research conducted not only provided the basis for future investigations into the Periglacial Geomorphology of part of western Droning Maud Land, but allowed an improved understanding of processes and problems with the existing literature that uses Northern Hemisphere examples as proxies for Antarctica. The Northern Hemisphere has a different environment to Antarctica and, thus, the formation of landforms in Antarctica is different to similar landforms found elsewhere. When investigating the formation of periglacial landforms in Antarctica, one must look at them separately from examples in the northern hemisphere, in order to ensure that their individual characteristics are fully understood. Further investigation is needed to explain the influence of the freeze thaw cycles on patterned ground. By fulfilling the objectives, it is evident that periglacial landforms in WDML do not always conform to the manner the literature explains their formation, and this could be due to the unique environmental conditions in Antarctica. Thus, periglacial landforms in Antarctica should be examined separately to landforms found in other parts of the world.

Therefore, this thesis aimed at investigating all the periglacial landforms found in WDML. Below is a table of what research has been achieved on periglacial landforms in WDML and future recommendations (Table 36). Therefore, the aim of this thesis has been achieved through the three objectives and the overall summary of what landforms have been investigated and Table 36 brings a holistic view of what research has been conducted on periglacial landforms and what future research is needed.

Table 36: The periglacial landforms in WDML. A summary of what has been achieved and what future research could be done.

Achieved	Future research
Patterned ground	
Polygons	
3D modelling and geo-referencing (Scott 2014) Formation influenced by the active layer (Kotze 2015 and Scott 2014) Slope influences on the shape of polygons (Rudolph 2015) Orientation of polygons Sediment analysis of the crack and the centre of the polygons Location mapped (Kotze 2015) - updated locations see Chapter 6	Heave monitoring - with regards to the formation of polygons
Sorted circles	
Sediment analysis Shape and formation analysis Location mapped (Kotze 2015) - updated locations see Chapter 6 Active layer dynamics (Kotze 2015)	Heave monitoring - with regards to the formation of circles
Half circles	
Sediment analysis Shape and formation analysis Theory on how they form Location mapped	Heave monitoring - with regards to the formation of half circles
Terraces	
Transect measurements (Scott 2014) Slope movement (Scott 2014) Location mapped (Kotze 2015)	Asses the slope movement
Openwork block deposits	
Classify the openwork block deposit (Hansen 2014) Measurements of morphology and clasts (Hansen 2014) Investigating aspect and weathering and their relantionship (Hansen 2014) Examine the temperature regimes and soil moisture (Hansen 2014) Investigating the eosrion and weathering on the openwork block deposit (Hansen 2014) Ice suspension in some areas of the deposit Mapped landform (Hansen 2014)	Full investigation into the ice suspension occuring in the deposit Research on the clasts in the deposit in terms of (Hansen 2014): → thermal porperties → rock mineralogy → climatic variblilty
Rock glaciers	
The landforms are mapped usings a DEM and gemorphic elements (Rudolph 2015) Physical characteristics of the landform such as (Rudolph 2015): → soil and clast properties → near surface temprature → active layer processes Classification of the rock glaciers (Rudolph 2015) Mapped the landforms (Rudolph 2015)	Increase research in processes and movement on the surface (Rudolph 2015) GIS anlysis of raster data to further the stduy on surface temprature (Rudolph 2015)
Pronival Rampart	
Formulated a definition of a pronival rampart (Hedding 2014) Investigate the oirgins of ramparts (Heddings 2014) Development of a criteria list for ramparts (Hedding 2014) → it has been suggest that this needs amending (see Results and Discussion) Morphological measurements (Hedding *et al* 2010) Assement into the depsotion and transport of clats from rampart debris field (Hedding et al 2010) Location mapped Density of snow bank investigated	Amend the cretieria list → to inlcuded density of the snow/firn bank
Lake ice blisters	
Mapped location Measurement of crack width of blister centre Description of the blister	Calculate blister volume (Guglielmin 2009) Investigate the formation of the blisters → see if they are simular to blisters found in other areas of Antarctica (Guglielmin 2009)

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Appendix A: Equipment list

Table 37: The equipment used in the field and laboratory analysis.

Equipment	Manufacturer	Model	Specifications
GPS	Garmin ®	60CSx	3-10m accuracy
DGPS	Spectra Precision®	Epoch ®	5-10m accuracy
GIS	ESRI	10.5	ArcGIS™
Microsoft® Excel	Microsoft®	2016	
Grapher 7	Golden Software		
Trend Reader®	ACR	2.50	
Sieve shaker	Endcott		8 Sieves
Drying overn	Gallenkamp™		
Clinometer	Clino Master		
Mastersizer	Malvern	3000	
Bushnell Trophy Cam	Bushnell ®		HD

Appendix B: Time-lapse videos

Refer to USB submitted with dissertation.

Appendix C: Temperature data for time-lapse

Presented below is the average temperature statistics for the heave monitoring. A log of the temperature at certain times that relate to the time-lapse stills presented.

Table 38: The temperature statistics for the whole time period that heave monitoring took place. Start time: 2016/12/18 7:43:56 PM. End time: 2017/01/15 11:13:56 AM.

Description	Maximum	Mean	Minimum	Range	Std Deviation
Int Temp	11,37	-2,95	-10,92	22,29	4,45
Near surf	13,07	0,3	-7,16	20,23	4,44
2.5 cm	11,8	0,3	-6,61	18,41	3,98
5 cm	11,46	0,36	-6,07	17,53	3,63
10 cm	6,37	-0,42	-5,11	11,49	2,22
15 cm	2,55	-1,11	-4,69	7,24	1,55
20 cm	-0,61	-2	-4,95	4,34	1,26

Table 39: The temperature statistics for 27-28/12/2016 camera 1. Start time: 2016/12/27 6:13:56 PM. End time: 2016/12/28 6:13:56 AM.

Description	Maximum	Mean	Minimum	Range	Std Deviation
Int Temp	-0,09	-5,14	-7,8	7,71	2,38
Near surf	5,81	0,02	-4,18	9,99	3,51
2.5 cm	5,89	0,7	-3,25	9,14	3,19
5 cm	5,83	1,18	-2,2	8,03	2,77
10 cm	2,94	0,89	-0,51	3,45	1,35
15 cm	0,94	0,19	-0,37	1,32	0,53
20 cm	-0,74	-0,8	-0,86	0,12	0,04

Table 40: The temperature for the time in the time-lapse pictures 27-28/12/2016 camera 1.

Timestamp	Int Temp (°C)	Near surf (°C)	2.5 cm (°C)	5 cm (°C)	10 cm (°C)	15 cm (°C)	20 cm (°C)
2016/12/27 18:33	-0,47	5,81	5,89	5,83	2,84	0,78	-0,84
2016/12/27 19:03	-0,95	5,44	5,68	5,68	2,94	0,88	-0,82
2016/12/27 19:33	-1,56	4,9	5,27	5,33	2,92	0,92	-0,8
2016/12/27 20:03	-2,11	4,33	4,8	4,88	2,82	0,94	-0,78
2016/12/27 20:33	-2,64	3,75	4,27	4,37	2,63	0,9	-0,78
2016/12/27 21:03	-3,01	3,68	4,1	4,12	2,43	0,84	-0,76
2016/12/27 21:33	-3,39	3,46	3,81	3,75	2,21	0,76	-0,76
2016/12/27 22:03	-3,91	2,63	2,98	3,04	1,92	0,69	-0,76
2016/12/27 22:33	-4,49	1,86	2,19	2,27	1,58	0,57	-0,74
2016/12/27 23:03	-5,18	1,08	1,44	1,54	1,22	0,43	-0,74
2016/12/27 23:33	-5,79	0,35	0,69	0,84	0,8	0,27	-0,76
2016/12/28 0:03	-6,31	-0,59	-0,04	0,27	0,43	0,09	-0,76
2016/12/28 0:33	-6,59	-1,5	-0,74	-0,39	0,11	-0,04	-0,76
2016/12/28 1:03	-6,78	-1,99	-1,03	-0,61	-0,1	-0,18	-0,78
2016/12/28 1:33	-6,91	-2,3	-1,23	-0,67	-0,24	-0,26	-0,78
2016/12/28 2:03	-7,13	-2,7	-1,55	-0,84	-0,34	-0,32	-0,8
2016/12/28 2:33	-7,45	-3,04	-1,9	-1	-0,37	-0,34	-0,8
2016/12/28 3:03	-7,58	-3,3	-2,2	-1,15	-0,39	-0,36	-0,82
2016/12/28 3:33	-7,7	-3,6	-2,49	-1,34	-0,39	-0,36	-0,82
2016/12/28 4:03	-7,8	-3,83	-2,72	-1,54	-0,41	-0,36	-0,82
2016/12/28 4:33	-7,7	-3,94	-2,87	-1,71	-0,43	-0,37	-0,84
2016/12/28 5:03	-7,32	-3,81	-2,85	-1,8	-0,45	-0,37	-0,84
2016/12/28 5:33	-6,37	-4,09	-3,09	-2,01	-0,47	-0,36	-0,86
2016/12/28 6:03	-5,94	-4,16	-3,23	-2,15	-0,51	-0,37	-0,86

Table 41: The temperature statistics for 27-28/12/2016 camera 2. Start time: 2016/12/27 9:03:56 AM. End time: 2016/12/28 9:03:56 AM.

Description	Maximum	Mean	Minimum	Range	Std Deviation
Int Temp	2,74	-2,72	-7,8	10,54	3,54
Near surf	5,81	0,79	-4,22	10,03	3,65
2.5 cm	5,89	0,84	-3,34	9,23	3,11
5 cm	5,83	0,99	-2,39	8,22	2,69
10 cm	2,94	0,47	-0,69	3,63	1,23
15 cm	0,94	-0,02	-0,39	1,34	0,47
20 cm	-0,74	-0,82	-0,94	0,19	0,05

Table 42: The temperature for the time in the time-lapse pictures 27-28/12/2016 camera 2.

Timestamp	Int Temp (°C)	Near surf (°C)	2.5 cm (°C)	5 cm (°C)	10 cm (°C)	15 cm (°C)	20 cm (°C)
2016/12/27 9:03	-3,33	-2,49	-1,86	-1,52	-0,53	-0,36	-0,74
2016/12/27 10:03	-1,42	-1,29	-1,25	-1,05	-0,51	-0,36	-0,76
2016/12/27 11:03	0,28	0,9	-0,22	-0,39	-0,41	-0,34	-0,78
2016/12/27 12:03	1,61	3,15	0,84	0,06	-0,36	-0,34	-0,78
2016/12/27 13:03	2,64	4,46	2,13	0,96	-0,28	-0,34	-0,82
2016/12/27 14:03	2,59	4,76	3,1	2,15	-0,18	-0,32	-0,84
2016/12/27 15:03	2,28	4,99	3,91	3,23	0,09	-0,28	-0,86
2016/12/27 16:03	1,79	4,35	4	3,66	0,8	-0,18	-0,9
2016/12/27 17:03	1,12	5,44	5,25	4,97	2	0,31	-0,88
2016/12/27 18:03	0,07	5,68	5,72	5,63	2,65	0,67	-0,86
2016/12/27 19:03	-0,95	5,44	5,68	5,68	2,94	0,88	-0,82
2016/12/27 20:03	-2,11	4,33	4,8	4,88	2,82	0,94	-0,78
2016/12/27 21:03	-3,01	3,68	4,1	4,12	2,43	0,84	-0,76
2016/12/27 22:03	-3,91	2,63	2,98	3,04	1,92	0,69	-0,76
2016/12/27 23:03	-5,18	1,08	1,44	1,54	1,22	0,43	-0,74
2016/12/28 0:03	-6,31	-0,59	-0,04	0,27	0,43	0,09	-0,76
2016/12/28 1:03	-6,78	-1,99	-1,03	-0,61	-0,1	-0,18	-0,78
2016/12/28 2:03	-7,13	-2,7	-1,55	-0,84	-0,34	-0,32	-0,8
2016/12/28 3:03	-7,58	-3,3	-2,2	-1,15	-0,39	-0,36	-0,82
2016/12/28 4:03	-7,8	-3,83	-2,72	-1,54	-0,41	-0,36	-0,82
2016/12/28 5:03	-7,32	-3,81	-2,85	-1,8	-0,45	-0,37	-0,84
2016/12/28 6:03	-5,94	-4,16	-3,23	-2,15	-0,51	-0,37	-0,86
2016/12/28 7:03	-5,21	-4,16	-3,34	-2,36	-0,57	-0,37	-0,88
2016/12/28 8:03	-4,08	-3,19	-2,94	-2,3	-0,65	-0,39	-0,92
2016/12/28 9:03	-2,84	-2,58	-2,05	-1,77	-0,69	-0,39	-0,94

Table 43: The temperature statistics for 07-08/01/2017. Start time: 2017/01/07 9:03:56 AM. End time: 2017/01/08 9:03:56 AM.

Description	Maximum	Mean	Minimum	Range	Std Deviation
Int Temp	4,28	-3,43	-10,39	14,68	5,32
Near surf	8,32	0,56	-5,59	13,91	4,87
2.5 cm	7,62	0,51	-4,7	12,32	4,04
5 cm	6,88	0,56	-4,11	10,99	3,43
10 cm	2,02	-0,54	-3,34	5,36	1,41
15 cm	-0,18	-1,37	-3,34	3,16	1,04
20 cm	-1,61	-2,51	-3,79	2,18	0,84

Table 44: The temperature for the time in the time-lapse pictures 07-08/01/2017

Timestamp	Int Temp (°C)	Near surf (°C)	2.5 cm (°C)	5 cm (°C)	10 cm (°C)	15 cm (°C)	20 cm (°C)
2017/01/07 9:03	-2,76	-3,25	-3,21	-3,15	-3,34	-3,3	-3,62
2017/01/07 11:03	-0,79	-0,32	-1,32	-1,8	-2,85	-3,25	-3,77
2017/01/07 13:03	1,64	1,86	0,43	-0,28	-1,84	-2,79	-3,7
2017/01/07 15:03	3,59	6,28	4,27	3	-0,71	-2,19	-3,43
2017/01/07 17:03	4,16	8,07	6,84	5,83	0,45	-1,52	-3,06
2017/01/07 19:03	2,26	7,66	7,24	6,66	1,34	-0,84	-2,62
2017/01/07 21:03	-2,31	4,65	4,93	4,84	1,94	-0,2	-2,05
2017/01/07 23:03	-7,1	-0,1	0,33	0,59	0,37	-0,32	-1,75
2017/01/08 1:03	-9,8	-2,81	-1,46	-0,8	-0,37	-0,45	-1,63
2017/01/08 3:03	-10,25	-4,09	-2,7	-1,44	-0,39	-0,55	-1,61
2017/01/08 5:03	-9,67	-4,8	-3,51	-2,36	-0,51	-0,71	-1,65
2017/01/08 7:03	-8,13	-5,48	-4,33	-3,25	-0,9	-0,98	-1,82
2017/01/08 9:03	-6,13	-5,3	-4,7	-4,11	-2,6	-2,05	-2,38

Table 45: The temperature statistics for 12-15/01/2017 camera 1. Start time: 2017/01/12 6:03:56 PM. End time: 2017/01/15 9:03:56 AM.

Description	Maximum	Mean	Minimum	Range	Std Deviation
Int Temp	10,44	-3,01	-10,29	20,73	4,78
Near surf	11,73	1,19	-4,41	16,14	4,75
2.5 cm	11,56	1,33	-3,34	14,9	4,26
5 cm	11,06	1,48	-2,41	13,48	3,86
10 cm	5,12	0,57	-1,25	6,36	1,77
15 cm	1,2	-0,32	-1,55	2,76	0,62
20 cm	-0,88	-1,27	-2,19	1,31	0,37

Table 46: The temperature for the time in the time-lapse pictures 12-15/01/2017 camera 1.

Timestamp	Int Temp (°C)	Near surf (°C)	2.5 cm (°C)	5 cm (°C)	10 cm (°C)	15 cm (°C)	20 cm (°C)
2017/01/12 18:03	5,33	10,03	9,98	9,91	4,25	0,35	-1,25
2017/01/12 19:33	2,43	9,62	9,81	9,76	4,78	0,82	-1,07
2017/01/12 21:03	-2,59	6,18	6,75	6,81	3,93	0,9	-0,96
2017/01/12 22:33	-5,79	1,84	2,39	2,74	2,15	0,61	-0,88
2017/01/13 0:03	-7,87	-1,02	-0,37	0	0,47	0,06	-0,88
2017/01/13 1:33	-8,79	-2,77	-1,52	-0,82	-0,26	-0,26	-0,9
2017/01/13 3:03	-10,08	-3,72	-2,47	-1,29	-0,37	-0,34	-0,92
2017/01/13 4:33	-10,25	-4,33	-3,11	-1,88	-0,41	-0,34	-0,92
2017/01/13 6:03	-9,77	-4,33	-3,3	-2,28	-0,47	-0,36	-0,94
2017/01/13 7:33	-8,69	-4	-3,21	-2,39	-0,55	-0,37	-0,96
2017/01/13 9:03	-7,19	-2,64	-2,26	-1,84	-0,59	-0,39	-1
2017/01/13 10:33	-5,79	-0,78	-0,94	-0,94	-0,55	-0,41	-1,05
2017/01/13 12:03	-3,73	0,27	-0,34	-0,43	-0,47	-0,47	-1,15
2017/01/13 13:33	-1,42	2,35	0,72	0,13	-0,41	-0,55	-1,3
2017/01/13 15:03	-0,57	3,79	2,45	1,4	-0,36	-0,67	-1,46
2017/01/13 16:33	-0,74	4,27	3,54	2,82	-0,18	-0,74	-1,57
2017/01/13 18:03	-1,36	4,42	3,98	3,41	0,13	-0,71	-1,59
2017/01/13 19:33	-2,11	3,79	3,7	3,46	0,65	-0,55	-1,52
2017/01/13 21:03	-3,67	1,4	1,62	1,7	0,61	-0,45	-1,44
2017/01/13 22:33	-4,58	0,06	0,37	0,53	0,13	-0,47	-1,36
2017/01/14 0:03	-5,85	-1,15	-0,63	-0,45	-0,32	-0,55	-1,34
2017/01/14 1:33	-4,79	-1,84	-1,05	-0,63	-0,36	-0,61	-1,36
2017/01/14 3:03	-4,64	-1,99	-1,34	-0,76	-0,37	-0,65	-1,38
2017/01/14 4:33	-4,82	-2,74	-1,88	-1,05	-0,39	-0,69	-1,4
2017/01/14 6:03	-4,97	-3,3	-2,43	-1,52	-0,45	-0,74	-1,46
2017/01/14 7:33	-3,33	-3,23	-2,57	-1,78	-0,57	-0,84	-1,54
2017/01/14 9:03	-2,36	-2,68	-2,09	-1,65	-0,72	-1,02	-1,67
2017/01/14 10:33	-1,36	-1,07	-1,48	-1,34	-1,09	-1,34	-1,9
2017/01/14 12:03	0,41	2,21	0,06	-0,41	-1,21	-1,54	-2,11
2017/01/14 13:33	3,39	5,76	3,1	1,58	-0,74	-1,46	-2,17
2017/01/14 15:03	4,92	8,85	6,97	5,81	0,23	-1,07	-2,09
2017/01/14 16:33	9,41	10,24	9,46	8,71	2,27	-0,43	-1,82
2017/01/14 18:03	8,83	11,11	10,8	10,29	4,06	0,11	-1,5
2017/01/14 19:33	5,43	11,61	11,48	11,01	5,05	0,74	-1,21
2017/01/14 21:03	2,81	8,41	8,69	8,5	4,78	1,18	-1
2017/01/14 22:33	-2,03	5,03	5,22	5,18	3,33	0,98	-0,9
2017/01/15 0:03	-4,55	0,9	1,4	1,66	1,48	0,43	-0,88
2017/01/15 1:33	-5,54	-1,32	-0,69	-0,34	0,13	-0,08	-0,88
2017/01/15 3:03	-6,81	-2,45	-1,38	-0,76	-0,32	-0,3	-0,9
2017/01/15 4:33	-7,61	-3,34	-2,19	-1,13	-0,37	-0,34	-0,92
2017/01/15 6:03	-7,06	-3,57	-2,57	-1,55	-0,39	-0,34	-0,92
2017/01/15 7:33	-5	-3,64	-2,74	-1,86	-0,45	-0,36	-0,94
2017/01/15 9:03	-2,98	-2,79	-2,07	-1,54	-0,47	-0,36	-0,96

Table 47: The temperature statistics for 12-13/01/2017 camera 2. Start time: 2017/01/12 17:13. End time: 2017/01/13 6:33:56 AM.

Description	Maximum	Mean	Minimum	Range	Std Deviation
Int Temp	9,18	-4,97	-10,29	19,47	5,8
Near surf	10,05	1,4	-4,41	14,46	5,58
2.5 cm	10,07	2,13	-3,34	13,41	5,16
5 cm	10,05	2,66	-2,38	12,42	4,72
10 cm	4,78	1,6	-0,51	5,29	2,1
15 cm	0,92	0,16	-0,36	1,28	0,49
20 cm	-0,88	-0,98	-1,4	0,52	0,13

Table 48: The temperature for the time in the time-lapse pictures 12-13/01/2017 camera 2.

Timestamp	Int Temp (°C)	Near surf (°C)	2.5 cm (°C)	5 cm (°C)	10 cm (°C)	15 cm (°C)	20 cm (°C)
2017/01/12 17:13	9,18	9,5	9,27	9,08	3,43	0	-1,4
2017/01/12 18:03	5,33	10,03	9,98	9,91	4,25	0,35	-1,25
2017/01/12 19:03	4,19	9,86	9,98	10	4,73	0,69	-1,13
2017/01/12 20:03	0,52	8,67	9,04	9,01	4,67	0,9	-1,03
2017/01/12 21:03	-2,59	6,18	6,75	6,81	3,93	0,9	-0,96
2017/01/12 22:03	-4,91	3,25	3,81	4,06	2,8	0,76	-0,9
2017/01/12 23:03	-6,59	0,39	1,02	1,48	1,5	0,43	-0,88
2017/01/13 0:03	-7,87	-1,02	-0,37	0	0,47	0,06	-0,88
2017/01/13 1:03	-8,52	-2,26	-1,15	-0,69	-0,12	-0,2	-0,9
2017/01/13 2:03	-9,46	-3,25	-1,9	-1	-0,34	-0,32	-0,9
2017/01/13 3:03	-10,08	-3,72	-2,47	-1,29	-0,37	-0,34	-0,92
2017/01/13 4:03	-10,22	-4,2	-2,94	-1,67	-0,39	-0,34	-0,92
2017/01/13 5:03	-10,01	-4,28	-3,15	-2,05	-0,43	-0,34	-0,94
2017/01/13 6:03	-9,77	-4,33	-3,3	-2,28	-0,47	-0,36	-0,94
2017/01/13 6:33	-9,46	-4,35	-3,34	-2,38	-0,51	-0,36	-0,96