

# Biogeomorphic aspects of lichen colonisation in part of western Dronning Maud Land, Antarctica.

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by

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## ABSTRACT

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Ice-free regions in Antarctica provide natural laboratories for investigating and modelling change in landscapes and ecosystems. The terrestrial ecosystems in western Dronning Maud Land are potentially critical to improve current understanding of polar ecosystems, however, they remain poorly represented and under-protected. Lichen habitats were used to elucidate geomorphic-biological feedbacks that shape the landscape's topography and biodiversity, which in turn promote environmental heterogeneity. Environmental parameters acting on two landforms were measured to determine the colonisation and growth of lichens in niche habitats. The habitats were identified and characterised, and topographic heterogeneity was found to control lichen colonisation. Micro-topographical niches provide the most stable environments for colonisation, and are preferred habitats. Lichen-habitat interactions were species specific, and closely related to insolation and moisture availability. The bidirectional relationships between rock weathering and lichen colonisation was ascertained. Results showed that lichens are good indicators of landform heterogeneity, but also promote landform heterogeneity. Given the habitat preferences of specific lichen species, they provide proxy to evaluating environmental responses, especially environmental change. The findings of this research are to be used as baseline data for future studies exploring ecosystem development in emerging landforms.

Keywords: lichens, heterogeneity, micro-topography, western Dronning Maud Land

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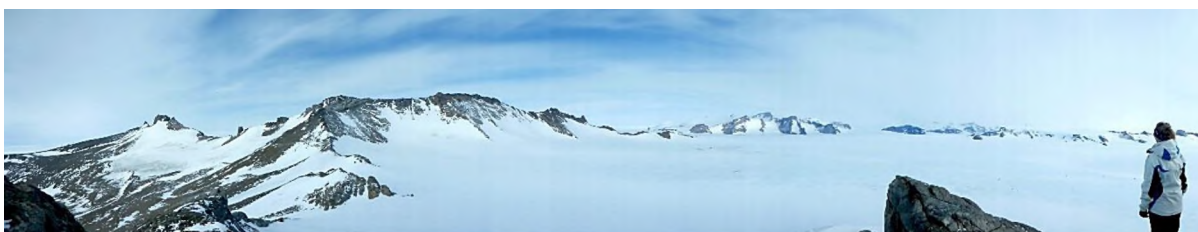
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## LIST OF ABBREVIATIONS

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<b>µm</b>	Micrometre
<b>3D</b>	Three Dimensional
<b>ACBR</b>	Antarctic Conservation Biogeographic Regions
<b>ALS</b>	Advanced Laboratory Solutions (South Africa)
<b>ASPA</b>	Antarctic Specially Protected Areas
<b>ATS</b>	Antarctic Treaty System
<b>BAS</b>	British Antarctic Survey
<b>BRT</b>	Boosted Regression Trees
<b>C</b>	Celsius
<b>cm</b>	Centimetre
<b>DEA</b>	Department of Environmental Affairs
<b>DEM</b>	Digital Elevation Model
<b>DGPS</b>	Differential Geographical Positioning System
<b>EIA</b>	Environmental Impact Assessment
<b>FLIR</b>	Forward Looking Infrared Radiometer
<b>gbm</b>	Generalised Boosted Regression Models
<b>GIS</b>	Geographical Information Systems
<b>GPS</b>	Global Positioning System
<b>km</b>	Kilometres
<b>m</b>	Metre
<b>m.a.s.l</b>	Metres Above Sea Level
<b>mm</b>	Millimetre
<b>PAR</b>	Photosynthetically Active Radiation
<b>RST</b>	Rock Surface Temperature
<b>SANAE</b>	South African National Antarctic Expedition
<b>SANAP</b>	South African National Antarctic Programme
<b>SCAR</b>	Scientific Committee for Antarctic Research
<b>SEM</b>	Scanning Electron Microscope
<b>SfM</b>	Structure From Motion
<b>UV</b>	Ultra Violet
<b>w.e</b>	Water Equivalent
<b>WDML</b>	western Dronning Maud Land

# CHAPTER 1: INTRODUCTION

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## Background

Antarctica's cold desert ecosystems have persisted through glacial cycles since the Oligocene, withstanding a variety of environmental conditions (Kappen 2000; Magalhães *et al.* 2012). Terrestrial ecosystems have been established in the ice-free regions of the continent's landscapes, which are uniquely controlled by glacial advances and retreats (Magalhães *et al.* 2012). These ice-free areas represent high-latitude, periglacial ecosystems and can be described as small, developed, 'island-like' environments separated by expansive areas of cold desert (Convey, 2010; Baroni, 2013; Hughes, *et al.* 2015). In light of changing climates, environments, and impacts, the biotic communities of these inland ice-free areas provide study sites for developing natural models for change. As lichens are the prominent biotic component in the Antarctic, they are a suitable measure for this prospect.

Lichens are composite organisms, meaning they have a symbiotic<sup>1</sup> relationship involving a mycobiont (or fungus) and a photobiont (an alga or/and cyanobacterium). Lichens are well adapted to environments that experience short, cold summers and extreme conditions, such as freeze thaw cycles, high salinity, freezing temperatures, aridity, high ultra-violet (UV) radiation, minimal nutrient availability, and prolonged periods of darkness (Melick and Seppelt 1992; Øvstedal and Smith 2001; de Vera *et al.* 2003; Magalhães *et al.* 2012). Their tolerance of abiotic stresses permits an opportunistic life strategy. Due to this, lichens colonise places that other vegetation would not, which is why they habituate ice-free areas in the Antarctic (Beckett *et al.*, 2013; Engelen *et al.*, 2016). Moreover, this marks lichen as a main component of terrestrial vegetation (Sancho *et al.*, 2007), successively acting as indicators for change in climate, geomorphology and biodiversity (e.g. Walker *et al.*, 2005; Sancho *et al.*, 2007; Favero-Longo *et al.*, 2015).

Existing knowledge of the vegetation of continental Antarctica is found within the findings of small studies at close proximity to major research stations (e.g. Kappen, 1985; Ryan *et al.*, 1989; Steele *et al.*, 1994; Seppelt *et al.*, 1995.), and intermittent surveys covering greater areas (e.g. Castello and Nimis, 2000; Øvstedal and Smith, 2001; Cannone and Seppelt, 2008; (Seppelt *et al.* 2010). Many authors maintain that development and functioning of lichen communities in Antarctica are controlled by physical processes, with this being the primary reason for the relatively simple and unique systems (Lindsay 1978; John and Dale 1990;

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<sup>1</sup> Symbiosis is an interaction and association of two or more dissimilar organisms where typically, a mutually beneficial relationship exists between the *bionts*.

Convey 2010; Magalhães *et al.*2012). In Antarctica, lichens are described as a pioneer species; colonising recently deglaciated rock or substrata quickly - particularly in the maritime Antarctic (Lindsay, 1978). However, information for continental lichen communities is limited, with few data suggesting conclusions about their colonisation and succession. Therefore, environmental factors that characterise lichen colonisation in these habitats are considered controlling factors in habitat preference. Knowledge of the nature and composition of lichens in their habitats will improve our understanding of community structure, development and the functioning of Antarctic ecosystems.

## **Rationale and Purpose**

Antarctica is now an imperative focus and component across research disciplines. The continent and its ice sheet contain valuable information about past climates, geology and biology (Turner *et al.*, 2009). Since the early Twentieth Century, anthropogenic activity has rapidly increased due to land based industries, such as science and tourism (Shaw *et al.*2014; Hughes *et al.*2015). Whilst there is life outside of ice-free areas, Antarctica's biodiversity is concentrated on terrestrial nunataks<sup>2</sup>, where human activity is subsequently concentrated (Shaw *et al.*2014). As a result of the growing interest, variety, intensity and frequency of human activity, in conjunction with changing climates and climate forecasts, the threats to the continent's ecology are materialising (Shaw *et al.*2014). Terauds *et al.*(2012) identified distinctly different ice-free areas across the continent and peninsula, using existing data. This led to the establishment of 15 Antarctic Conservation Biogeographic Regions (ACBRs), and a more formal structure of governance and conservation by the Antarctic Treaty System (ATS). Additionally, Antarctic Specially Protected Areas (ASPAs) and corresponding management plans were developed as a mechanism for protecting Antarctic habitats (Hughes *et al.*2015). Contrary to the idea that Antarctica is a natural laboratory for peace and science protected by the ATS, it has been revealed that the continent is in fact one of the least protected areas on Earth. Only 1.5% of ice-free areas are formally protected under the ASPA system, 0.2% of which fall within western Dronning Maud Land (WDML) (Shaw *et al.*2014; Hughes *et al.*2015). This is not due to a lack of ice-free areas in WDML, but rather a lack of data (Dwight 2014).

The Scientific Committee for Antarctic Research (SCAR) commissioned a horizon scan, which attained Antarctic science a high priority status (Kennicutt *et al.*2014; Kennicutt *et al.*2015). The outcome of the process is presented as a framework of 80 key scientific

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<sup>2</sup> Mountain peak exposed above a glacier or ice sheet.

questions to be considered for future Antarctic research; opening opportunity for both collaboration and science. Two questions are appropriate in this study:

Question 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?”*

Question 74: *“How can natural and human-induced environmental changes be distinguished, and how will this knowledge affect Antarctic governance?”*

Antarctica is susceptible to perturbations of climate change and/or human impact, giving researchers the opportunity to detect initial effects on the ecosystems abiotic and biotic components (Cannone 2004). Lichens, in particular, are sensitive to impacts on their environment, and it can be expected that their responses to such impacts are more localised (Sancho *et al.*2007). Threats to their systems have been well documented (Convey *et al.*2003; Bargagli 2008), generating concern for the monitoring and implementation of conservation strategies. Current concerns include species invasion, pollution (due to growing scientific activity), and biological homogenisation (Hughes and Convey 2010; Terauds *et al.*2012). Should these concerns not be addressed, the opportunity to use these areas as model systems will be less effective.

Given their ability to sustain key roles in successional processes within a region sensitive to environmental changes, lichens are ideal biomonitors for assessing the status of biodiversity in Antarctica, and provide ideal baseline data to assist in answering the questions identified in Kennicutt *et al.*(2015). Investigation into WDML, a poorly represented and under-protected area of the Antarctic, is therefore critical in order to improve our current understanding of polar ecosystems.

## Aim and Objectives

The aim of this project was to investigate habitat preference for epilithic<sup>3</sup> lichens on the Vesleskarvet and Robertskollen nunataks, via the identification of environmental parameters acting on landforms, in order to facilitate the establishment and existence of lichens in their niche<sup>4</sup>. Four key objectives for this study are set out below:

1. Investigate habitat heterogeneity
  - i. conduct a species analysis.
2. Determine the morphology and characteristics of lichen habitats
  - i. measure rock characteristics.
  - ii. measure sub-metre topographical features.
3. Investigate the relationship between clast surface temperature and lichen colonisation
  - i. monitor temperature of rocks.
  - ii. observe temperature differences in rocks and lichens.
4. Examine the biodeterioration of lichen-colonised rocks:
  - i. thin sections of lichen-rock interfaces.
  - ii. SEM analysis.

The project falls within the discipline of Physical Geography, in particular, the field of Geomorphology. Typically characterised as a system science that focusses on development and change in landscapes and landforms, the contemporary discipline follows an arrange of conceptual focus-points (Church 2010). This research addresses the intersection with life – a recent and under-considered direction of geomorphology (Church 2010). It is not hypothesis driven, but rather an explorative and investigative study that makes use of the deductive scientific method; interpretations have incorporated an empirical approach. In addition to this, the approach has, however, been adjusted to follow an objective and quantitative approach - involving mathematical and statistical analysis where possible. It must be emphasised that although this study takes a biological approach, it is not a biological investigation. Instead, lichens have been used as proxy for landscape characterisation and habitat development respectively. The results of this study, however, are of equal value across disciplines and the thesis is an important source of information for polar biologists, ecologists, geomorphologists and geologists.

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<sup>3</sup> Growing on the surface of a rock.

<sup>4</sup> In ecology, a niche is a well-defined concept that defines a species' position and roles within a community. For this study, it refers to the recess in which the lichen locates itself unless stipulated otherwise i.e elaborated as an 'ecological niche'.

## **Dissertation Structure**

This dissertation is comprised of eight chapters. The first chapter introduces the research, providing context and outlining its aim and four objectives. Following this is a literature review providing a background text relevant to the research topic, and giving it context in existing findings, contributions and knowledge. A brief description of the setting and study sites is then provided. Hereafter, the reader is presented with chapter four to seven, with each chapter focussing on a single objective. In each of these chapters, the reader will find an introduction to the objective, the methods used to achieve this objective, and the results and discussion thereof. The final section captures the main outcomes of the research by synthesising findings, identifying limitations and recommending future opportunities, approaches and research. Attached to this dissertation are appendices containing supplementary material referred to in-text.

## CHAPTER 2: LITERATURE REVIEW

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Regions characterised by extreme environmental stresses are typically limited in biodiversity, providing habitats only to biota capable of adapting to stressors ( Lindsay 1978; Kappen 2000; Øvstedal and Smith 2001). For instance, there are plant taxa that use heliotropism<sup>5</sup> as a mechanism to survive the Arctic, by maximising on a small heat budget - e.g. *Papaver radicum* (Kevan 1975). Compared to other global regions, the Antarctic presents harsh environmental conditions that ought to be resisted by its unique, terrestrial biota, which is constituted almost entirely of lower organisms (Øvstedal and Smith 2001; Lindsay 1978). Lichen, a plant that represents a symbiotic relationship, is the dominant life-form adapted to the continent's freezing temperatures, physiological drought and seasonal limitation of insolation ( Lindsay 1978; Kappen 2000; Øvstedal and Smith 2001). Studies have highlighted that lichens play a key role in the structure, development and functioning of Antarctic communities (eg. Lindsay 1978; Seppelt *et al.*2010). Scientific interest and exploration has increased since the 1980s due to the fact that the continent and its ecosystems are beginning to hold greater value in many research disciplines ( Block 1994; Øvstedal and Smith 2001). This growing interest in Antarctica has developed a need for active conservation, which requires baseline studies. Investigating the interactions between lichen - a key organism in its ecosystem - and the Antarctic landscape offers a baseline that contributes to a better understanding of the Antarctic biome.

### Understanding Lichens

#### Mutualistic Relationship

In nearly every climatic region, including extremely dry, cold and nutrient limited habitats, lichens are one of the first colonisers of bare rock and surfaces (Bargagli 1999). It is for this reason that lichens are pioneers of the Antarctic; constituting most of the continent's biomass (Bargagli 1999). Their succession is represented by their symbiotic relationship with two partners: 1) mycobiont – or fungal partner, and 2) photobiont – or photosynthetic partner, which in most cases (for the Antarctic) are green algae *Chlorophyta*, or cyanobacteria (especially *Nostoc spp.*) (Bohuslavová 2012). The mycobiont protects its partner from harmful UV radiation and desiccation, as well as providing nutrients to the symbiosis by means of mineral uptake from its substrate and air (Easton 1994; Bohuslavová 2012). The photobiont

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<sup>5</sup> Turning to and with the sun (Kevan 1975).

is involved in carbon fixation to assist in growth and development of the symbiosis (Easton 1994; Bohuslavová 2012).

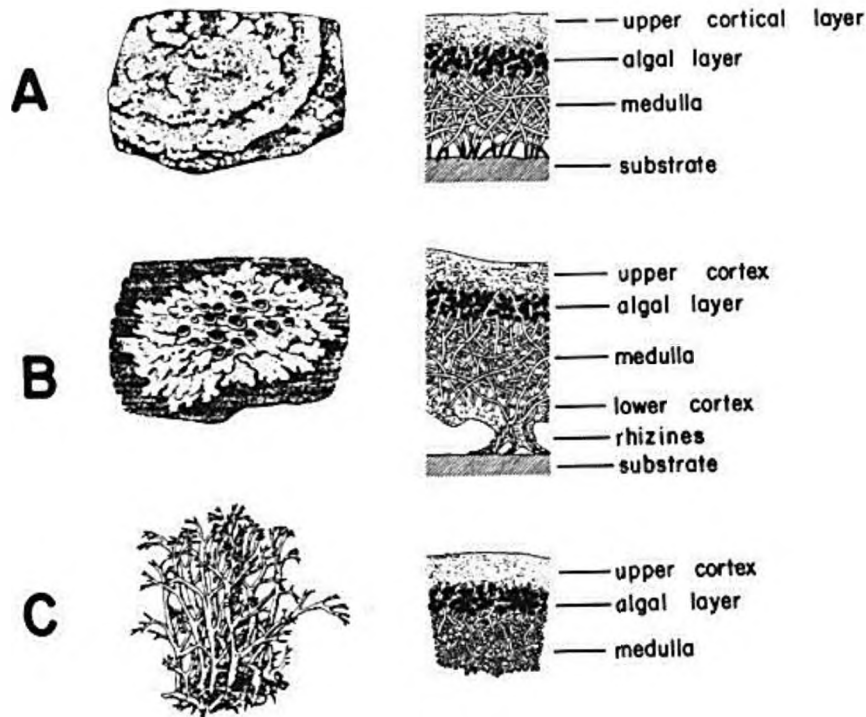


Figure 1: Cross sections of the three growth forms of lichens to show differences in tissue structure. (A) crustose (B) foliose (C) fruticose. Source: Easton (1994).

### Growth and Anatomy

Lichens are morphologically grouped according to the structure of their thallus<sup>6</sup>. These groups can, however, be misleading, as some lichens belonging to the same family have varying growth forms (Easton 1994). Three main growth forms or groups exist: crustose, foliose and fruticose (Figure 1). Foliose lichens have a leafy, dorsiventral appearance, and are attached to substrate by rhizines<sup>7</sup>, whereas crustose lichens grow on the substrate by tightly adhering at all points, which form a “crust” on the surface (Bohuslavová 2012). Crustose lichen borders can be diffuse or distinct (Easton 1994). Many crustose species have a fungus that precedes the thallus. More developed thalli appear areolate or centrally fissured (e.g. *Rhizocarpaceae*) (Easton 1994). The most specialised crustose species are squamulose: a discrete lobe-like structure that can be partly or wholly free from its substrate (Easton 1994). These crustose species are sometimes confused with foliose species, but can be distinguished by their lack of distinct lower cortex (Easton 1994). Fruticose lichens are hair-like or shrubby, attaching to

<sup>6</sup> The plant body of the lichen as an undifferentiated system of parts (stem, leaves and roots).

<sup>7</sup> Root-like filament or hair growing from the lichen.

a substrate at a solitary point and having a radially symmetric thallus (Easton, 1994; Bohuslavová, 2012).

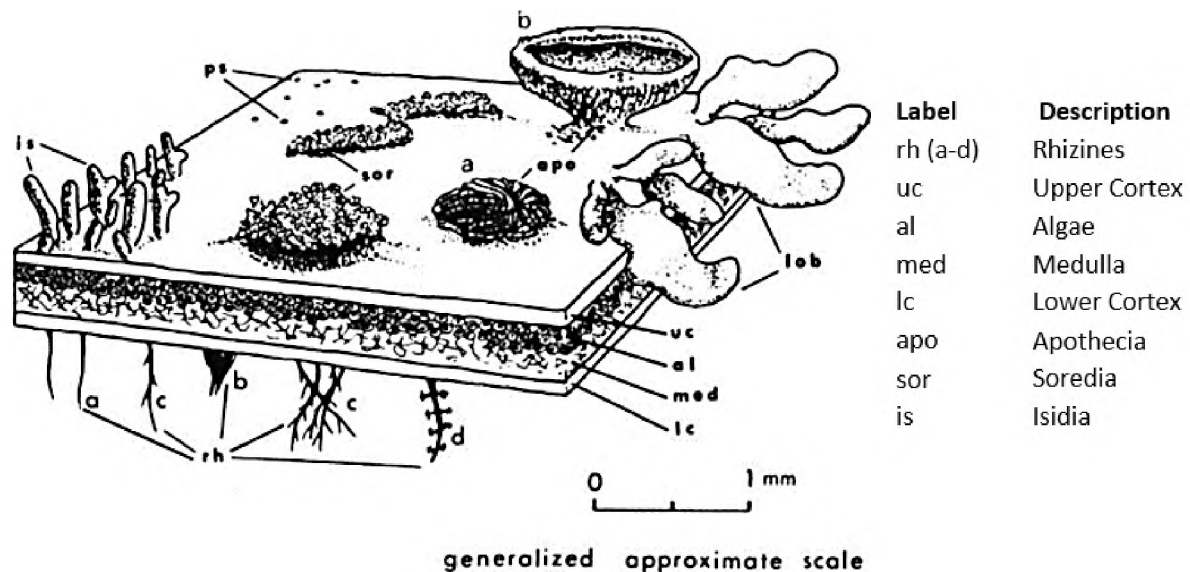


Figure 2: Morphological features of lichens. Adapted from Easton (1994).

### Reproduction and Dispersion

Lichens are capable of vegetative and sexual reproduction, but for a lichen to successfully reproduce and disperse itself, both partners of the composite species need to be present (Dobson 2003). This complication is counterbalanced by an evolutionary solution: isidia and soredia that contain both the symbiotic participants (Seymour *et al.*, 2005). As seen in Figure 2, soredia are structures containing photosynthetic cells in the hyphae network that diffuse over the thallus surface. Isidia are structures that project out of the thallus's upper cortex in a smooth, finger-like form (Easton, 1994; Seymour *et al.*, 2005). Both structures can be dispersed by wind, rain or animals and both the mycobiont and photobiont can be dispersed simultaneously, allowing these organisms to rapidly establish new thalli (Ott 1987 in Seymour *et al.* 2005; Dobson 2003; Bohuslavová 2012). However, this is not common, and in most cases, sexually produced spores (ascospores) from propagules (apothecia) are exclusively fungal derived (Seymour *et al.*, 2005). Apothecia are organs of the mycobiont that eject ascospores into the atmosphere from disc-shaped structures (see Figure 2) (Easton 1994). Ascospores are effective when dispersing over long distances, but suitable photobionts need to be encountered for establishment of symbiosis (Seymour *et al.*, 2005). The purpose of these two strategies is to rapidly spread locally-adapted genotypes in local environments (using the asexual propagules), and to potentially disperse novel genotypes to broader environments (via sexually produced ascospores) (Seymour *et al.*, 2005). Reproductive strategies like these, promote resilience in the harshest of conditions, and permits lichens to

flourish in the most extreme environments on earth, such as the ice-free areas of Antarctica (Øvstedal and Smith 2001; Seymour *et al.*2005).

## **Antarctic Vegetation**

As expected, Antarctic vegetation growth corresponds to distinct climatic regions or zones, which have been identified as the continental Antarctic, maritime Antarctic and sub-Antarctic (Marshall and Pugh 1996; Caruso *et al.*2010; Convey 2011). Two vascular plant species are known to occur on the continent. These are found only in maritime Antarctica – Western Antarctic Peninsula, as well as in the archipelagos of South Shetland, South Orkney and South Sandwich Islands ( Kappen 2000; Øvstedal and Smith 2001; Cannone 2004; Passo *et al.*2015). Vegetation exists where the geomorphology provides habitat, and this is why scattered terrestrial communities dominated by cryptograms<sup>8</sup> have established themselves in continental Antarctica (Cannone 2004; Cannone and Seppelt 2008; Convey 2010; Hughes *et al.*2015). These terrestrial ecosystems are restricted to four percent of the lands that become ice-free during summer (Passo *et al.*2015). Continental Antarctica is the largest biogeographic zone, covering all of the continent and its offshore islands, excluding the western side of the Peninsula north of 70°S (Figure 3). Within this expanse, it has its own coastal, slope and inland provinces (Øvstedal and Smith 2001). The inland provinces are not climatically favourable, with higher altitudes and aridity, which confine the biotic diversity to few lichen taxa (Block 1994; Øvstedal and Smith 2001). This is because lichens are a pioneer species in arid environments through their ability to occupy niches suitable for colonisation (Holder *et al.*2000). According to Longton (1988), lichens account for 70 percent of plant biodiversity in the continent's terrestrial ecosystems. More specifically, Kappen (2000) reported c. 360 taxa of lichens. Work by Bargagli (2005) produced an estimate of 260 lichen species, with 40% of these being endemic to the continent. To date, there are approximately 427 species in Antarctica (Seppelt 1995; Øvstedal and Smith 2001), whereas worldwide there are over 20 000 species (Bohuslavová 2012). These figures are, however, based on existing knowledge and collections, as there remain regions, such as WDML, that have yet to be visited for lichenological and bryological surveying (Øvstedal and Smith 2001). Furthermore, some macrolichen communities are only detectable by specialists of the field, and very few botanists visit these areas (Engelskjøn 1986; Øvstedal and Smith 2001). Taking this into account, all existing knowledge for WDML is based on observational and collecting work by British and Norwegian expeditions (Lindsay 1978; Kappen 1985).

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<sup>8</sup> Flowerless and seedless plants that reproduce through spores e.g. mosses, lichens, liverworts (Hughes *et al.*2015).

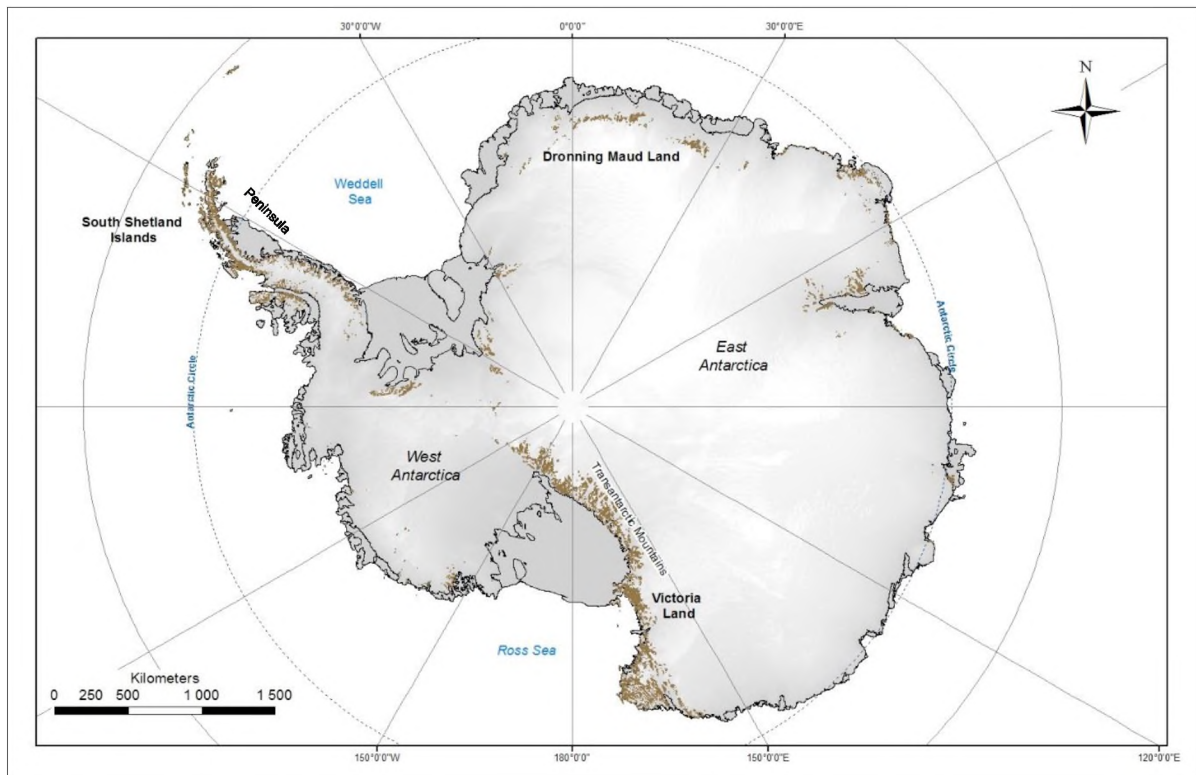


Figure 3: The major regions of Antarctica referred to in the text. Source: Easton (1994).

### History of Lichen Investigations in the Antarctic

The first report of lichen (*Usnea faciata*) from Antarctica was by Torey (1823). The sample was collected during the United States Sealing Expedition in the early exploration of the southern polar lands at what has been assumed to be the Cathedral Crags of Deception Island (Øvstedal and Smith 2001). Sealing expeditions produced vague descriptions of vegetation, with the earliest lichen-focussed documentation being formed by naturalist, J. Eights, of the United States Exploring Expedition in 1830 (Eights 1833 as cited in Øvstedal and Smith 2001). From the early 1880s to the 1920s, a major exploration period for Antarctica, the lichen collections developed substantially until the First World War, during which exploration radically decreased (Øvstedal and Smith 2001). Since the adoption of the Antarctic Treaty in 1961, the British Antarctic Survey (BAS) embarked on botanical research. However, this was concentrated at Signy Station and later, Rothera Station (Øvstedal and Smith 2001). From the mid 1960's, botanical investigations developed further, with notable contributions from scientists of other national stations producing plant records in other regions (Øvstedal and Smith 2001). The Convention on Biological Diversity in Rio de Janeiro (UNEP 1992) was a significant turning point in lichenological research, as many biologists began to realise that lichens – the most diverse form of vegetation - held great importance in these ecosystems. The upsurge of interest stimulated concentration on lichen taxonomy, whereby

lichenologists have been revisiting accounts and collections, as well as further developing the current knowledge of their evolution (Øvstedal and Smith 2001).

Most of the investigations in WDML were focussed on the Earth Sciences (Ryan *et al.* 1989; Engelskjøn 1986). To prevent interruption to any geological or geophysical party, biologists took the opportunity to document terrestrial flora by conducting preliminary surveys or research at accessible nunataks (Ryan *et al.* 1989; Engelskjøn 1986; Øvstedal and Smith 2001). This means records exist for WDML, but they are limited to specific sites or nunataks, and are subjective. Lichens that have been accounted for in WDML can be seen in Table 1 and Table 2.

There is discrepancy in the identification of *Acarospora gwynnii*. Ryan *et al.* (1989) conducted a preliminary survey at Robertskollen, which listed *A. gwynnii* as a taxon (Table 2). This survey has since been used as a reference to identify species on Vesleskarvet by Steele *et al.* (1994) and Dwight (2014) respectively. The genus *Pleopsidium* recently split off *Acarospora*, and is represented in Antarctica by one species: *Pleopsidium chlorophanum* (Castello and Nimis 1994; Øvstedal and Smith 2001). It has been confirmed that what was thought to be *A. gwynnii* at Vesleskarvet and Robertskollen, is in fact, *P. chlorophanum* (Ott, *pers comm.*, 2016). The assumption is that previous surveys in WDML, which identified *P. chlorophanum*, have documented it as *A. gwynnii*. Observations, images, and data from seven surveys (see pg.30) conducted at two nunataks confirmed the presence of some species, listed below.

Table 1: Table adopted from Steele et al. (1994).

<b>Preliminary species list for fungi, lichens, nematodes, tardigrades and mites at Vesleskarvet.</b>
<p><b>Fungi</b></p> <p><i>Alternaria</i> sp.  <i>Altergillus ustus</i>  <i>Aspergillus</i> sp.  <i>Aureobasidium pullulans</i> var. <i>melanigenum</i>  <i>Capnodium</i> sp.  <i>Cladosporium</i> cf. <i>macrocarpium</i>  <i>Cladosporium</i> sp.  <i>Fusarium</i> sp.</p> <p><b>Lichens</b></p> <p><i>Acarospora gwynii</i>  <i>Buellia</i> sp. A  <i>Buellia</i> sp. B</p> <p><i>Lecanora expectans</i>  <i>Pseudephebe minuscula</i>  <i>Rhizocarpon acographicum</i>  <i>Umbilicaria decussata</i>  <i>Usnea sphacelata</i>  <i>Xanthoria elegans</i> ?</p> <p><b>Nematoda</b></p> <p><i>Eudorylaimus nudicaudatus</i>  <i>Chiloplacoides antarcticus</i>  <i>Plectus antarcticus</i></p> <p><b>Tardigrada</b></p> <p><i>Diphascoen sanae</i>  <i>Hebesuncus</i> sp.  <i>Macrobiotus</i> sp.</p> <p><b>Arthropoda</b></p> <p><i>Tydeus</i> sp. ?</p>

Table 2: Table adopted from Ryan and Watkins (1989).

<b>Provisional list of lichens recorded from Robertskollen (sequence after Poelt 1973).</b>	
<i>Ascomycetes</i>	
<i>Lecanorales</i>	
<i>Lecanorinae</i>	
<i>Lecideaceae</i>	<i>Lecidea</i> sp. <i>Rhizocarpon</i> ? <i>flavum</i>
	<i>?Lecanora</i> cf. <i>expectans</i>
<i>Lecanoraceae</i>	<i>Rhizoplaca melanophthalma</i> (formerly <i>L. melanophthalma</i> )
	<i>Usnea antarctica</i> <i>U. sphacelata</i> (formerly <i>U. sulphurea</i> <i>Pseudephebe minuscula</i> (formerly <i>Alectoria minuscula</i> )
<i>Usneaceae</i>	
<i>Umbilicariineae</i>	
<i>Umbilicariaceae</i>	<i>Umbilicaria aprina</i> <i>U. decussata</i>
	<i>Acarospora gwynii</i> <i>A. chlorophana</i> (formerly <i>Biatorella antarctica</i> , <i>B. cerebriformis</i> , see Øvstedal 1983b, Engelskjøn 1986)
<i>Acarosporineae</i>	
<i>Acarosporaceae</i>	
	<i>Candelariella antarctica</i> (= <i>C. hallettensis</i> , see Øvstedal 1983b)
<i>Buelliineae</i>	
<i>Candelariaceae</i>	
	<i>Caloplaca citrina</i> <i>Xanthoria elegans</i> <i>X. candelaria</i>
<i>Teloschistaceae</i>	
	<i>?Buellia</i> cf. <i>frigida</i> <i>?Buellia</i> cf. <i>soredians</i> <i>Physcia caesia</i> <i>?Rinodina</i> sp.
<i>Physciaceae</i>	
	<i>?Lepraria</i> sp.
<i>Fungi Imperfecti</i>	

### ***Acarospora gwynnii***

*A. gwynnii* (Figure 4 and Figure 5) has a squamulose thallus with a yellow, smooth upper surface, and pale to white lower surface that consists mainly of white rhizomorphs extending into rock (Øvstedal and Smith 2001; Castello 2003). This lichen has brown, disc-shaped apothecia (Figure 4) that emerge flat, and reach diameters of up to 0.5mm (Øvstedal and Smith 2001; Castello 2003). It is an endemic species known to colonise rock in small colonies of thalli up to 1cm throughout continental Antarctica (Øvstedal and Smith 2001; Castello 2003; Dwight 2014). A study by Dwight (2014) suggested it was the most abundant species on Vesleskarvet (WDML), however, it may have been misidentified.



Figure 4: *Acarospora gwynnii* showing apothecia. Source and identification: S. Ott.

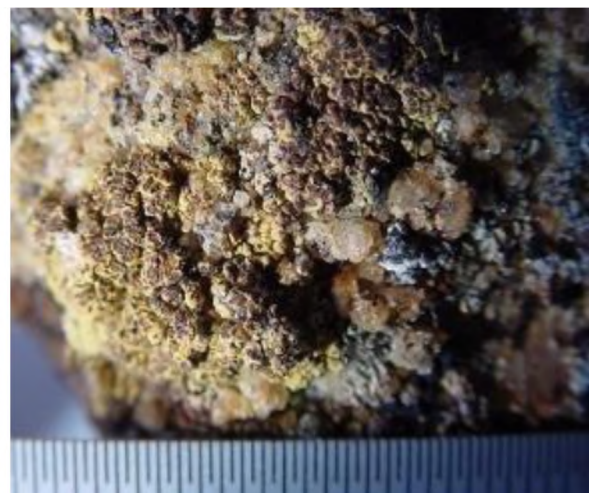


Figure 5: *Acarospora gwynnii*. Source: C.W Dodge and E.D Rudolph.

### ***Buellia* species**

Crustose Antarctic *Buellia* species were monographed by Lamb (1968), with little reconsideration since (Øvstedal and Smith 2001). As they are difficult to distinguish in the field by the layman (Dwight 2014), they are sometimes considered “Species A, Species B...” etc. as seen in Table 2.

Species A, is identifiable as the Antarctic endemic *Buellia frigida* (Figure 6). This lichen has radiating marginal lobes that are grey to black, or whitish to grey or black (Øvstedal and Smith 2001; Castello 2003). It grows on exposed rock at both sea-level and inland, with exceptionally large thalli (15-20cm in diameter) being documented in Victoria Land (Øvstedal and Smith 2001). Studies have shown that this species is very slow growing, with a rate of 1mm per century in its radial growth (Green *et al.* 1999 in Øvstedal and Smith 2001).

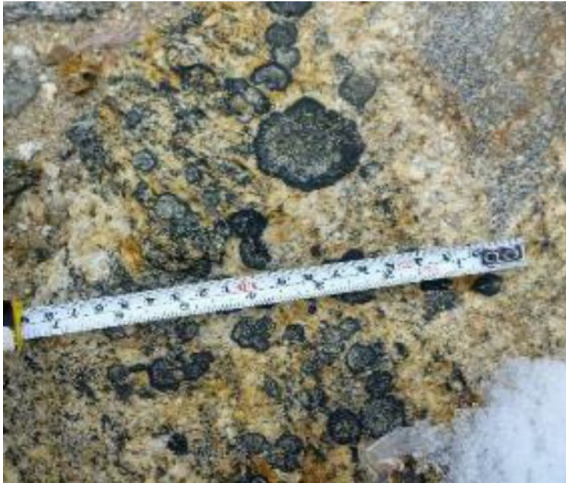


Figure 6: *Buellia frigida* (sp. A). Source: C. Hansen.



Figure 7: *Buellia* sp. (sp. B) with *Pleopsidium chlorophanum* (yellow). Source and identification: S. Ott.

### ***Lecanora expectans***



Figure 8: *Lecanora expectans*. Source: R. Dwight.

The endemic *L. expectans* (Figure 8) is found growing on mosses both inland and at the coast of Antarctica (Øvstedal and Smith 2001). It was documented as an abundant species in WDML by Dwight (2014). It's thallus is white-grey and has black, disc-like apothecia that can appear brown when wet (Øvstedal and Smith 2001). Apothecia cover the thallus and are irregular (Castello 2003). Øvstedal (1983), Botnen and Øvstedal (1988), Engelskjøn (1986), Thor

(1997) Thor (1995), and Dwight (2014) all recorded this species in Dronning Maud Land, with some authors originally classifying the species as *Lecanora griseomarginata* and *Lecanora lilacinofusca*.

### ***Pleopsidium chlorophanum***

*P. chlorophanum* (Figure 9) is a sulphur-yellow crustose lichen that is bipolar in distribution (Castello 2003; Øvstedal and Smith 2001). The thallus variably ranges from areolate<sup>9</sup> to squamulose<sup>10</sup>, and has a diameter of ~2cm, and height of ~1cm (Castello 2003; Øvstedal and Smith 2001). Areoles appear smooth to cerebriform (brain-like folds) (Castello 2003). This species is widespread, yet scarce; often colonising shaded rock in small quantities (Øvstedal

<sup>9</sup> Having areoles; portions of crustose thalli divided by cracks or fissures (Castello 2003).

<sup>10</sup> Rhizine free, scale-like lobes lifting from the surface, at least at the edges (Castello 2003).

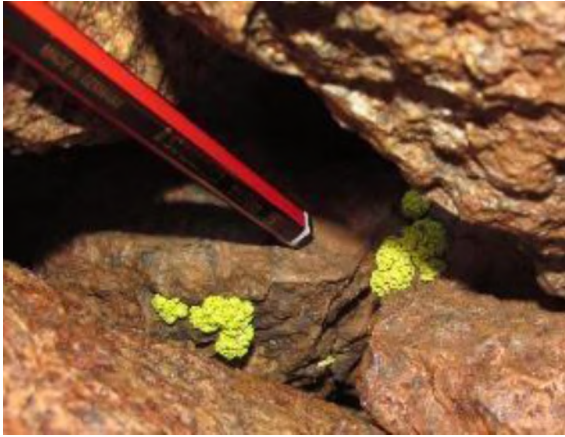


Figure 9: *Pleopsidium chlorophanum*. Picture taken at Vesleskarvet.

and Smith 2001). Dwight (2014) found this species to be most abundant on Vesleskarvet with a uniform distribution, but documented it as *A. gwynnii*. This coincides with information from Øvstedal and Smith (2001), which identified it to be most frequent in continental Antarctica and on inland nunataks of high altitudes. In WDML, Engelskjøn (1986) referred to this species as *Acarospora chlorophana*, whereas Lindsay (1972) named it *Biatorella antarctica*, both of which are now considered

synonyms for this species. To reiterate, this species has been misidentified as *Acarospora gwynni* (e.g. Dwight 2014; Steele *et al.* 1994; Ryan *et al.* 1989), with this error being corrected by a lichenologist (Ott 2016, *pers. comm.*).

### ***Pseudephebe minuscula***



Figure 10: *Pseudephebe minuscula*. Source: R. Helmstad.

*P. minuscula* (Figure 10) - or *Alectoria minuscula*, as cited in WDML by Lindsay (1972) - is a common fruticose lichen found on rock (Øvstedal and Smith 2001; Castello 2003). It is brown-black in colour and usually forms a circular-shaped thallus ~5cm in diameter (Øvstedal and Smith 2001). Species that *P. minuscula* are usually associated with include: *B. frigida*, *Umbilicaria decussata* and *Usnea sphacelata*. According to Øvstedal and Smith (2001), it is found in a number of environments,

but in Antarctica specifically, is one of the most widespread species that is easy to identify by its (usually) shiny branches. *P. minuscula* may be a widespread species, but was found by Dwight (2014) to have a low abundance on inland nunataks.

### ***Rhizocarpon geographicum***

*R. geographicum* (Figure 11), a crustose species, has a flat, areolate, yellow-green thallus which is ~2mm in height and diameter (Øvstedal and Smith 2001; Castello 2003). It has protruding black apothecia that take a flat shape when young, and a convex shape when older (Øvstedal and Smith 2001). These lichen often clump together to form colonies that can be larger than 20cm across (Øvstedal and Smith 2001). Engelskjøn (1986) documented the species habitat as sheltered and narrow

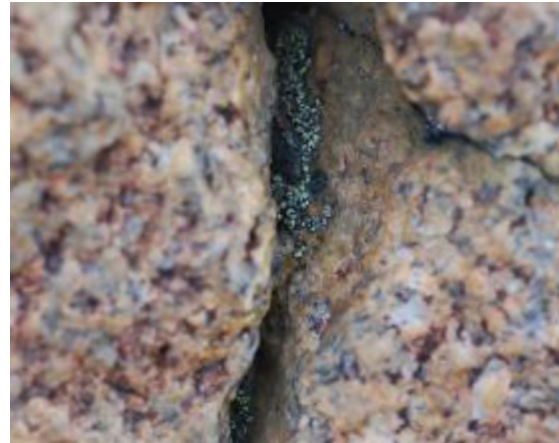


Figure 11: *Rhizocarpon geographicum*.  
Source and identification: S. Ott.

crevices, with intermittent water seepage. This is similar to Dwight's (2014) findings, which documented *R. geographicum* growing on flat rocks near meltwater. Contrary to both authors, Øvstedal and Smith (2001) proposed that the cosmopolitan species was found in the Antarctic on dry, exposed rock faces amongst other lichens.

### ***Rhizoplaca melanophthalma***

*R. melanophthalma* (Figure 12) has a thallus that can vary from yellow-green to grey-green to black, depending on its habitat (Øvstedal and Smith 2001). This lichen typically grows on rock and soils in polar regions, becoming more abundant at higher latitudes, colonising far inland nunataks in continental Antarctica (Øvstedal and Smith 2001). The thallus can reach up to 3mm in diameter, and is obscured by its large and numerous apothecia (Øvstedal and Smith 2001; Castello 2003). *R. melanophthalma* has been found in WDML by

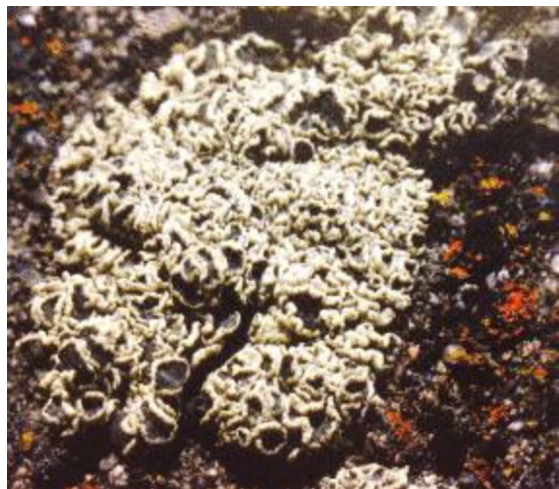


Figure 12: *Rhizoplaca melanophthalma*.  
Source: Australian Antarctic Data Centre.

Lindsay (1972), Øvstedal (1983), Engelskjøn (1986), Ryan *et al.*(1989) and Thor (1997).

### ***Umbilicaria decussata***



Figure 13: *Umbilicaria decussata*. Source: C. Hansen.

Bargagli *et al.*(2000) suggesting the species are found on rocks sheltered from wind in depressions that collect snow in the summer months. Conversely, Øvstedal and Smith (2001), state they are found on exposed, dry rock. *U. decussata* has a high abundance in WDML (Lindsay 1972; Engelskjøn 1986; Dwight 2014).

The foliose lichen *U. decussata* (Figure 13) has an umbilicate<sup>11</sup> and monophyllous<sup>12</sup> thallus that is grey to black in colour (Øvstedal and Smith 2001). They are a bipolar species, and are often associated with *B. frigida*, *P. minuscula* and *Usnea sphacelata* (Dwight 2014). In addition to this, Bargagli (1999) found *U. decussata* with *A. gwinii*, and *R. geographicum*. The species is found in cold regions and is more abundant in higher latitudes (Øvstedal and Smith 2001). Habitats vary for this species, with Bargagli (1999) and

### ***Usnea sphacelata***



Figure 14: *Usnea sphacelata*. Photo taken at Robertskollen.

Typically, these species form a community with various other species, and are usually

*U. sphacelata* (Figure 14) is a hair-like macrolichen that can be found colonising exposed rocks, boulders and stones at dry, windy sites (Hancock and Seppelt 1988; Øvstedal and Smith 2001). Although bipolar, it is the most widespread species in continental Antarctica, with records of it growing at sea level through to altitudes of 2000m.a.s.l (Øvstedal and Smith 2001; Seymour *et al.*2007). Its thallus is fruticose, black to yellow-black in colour, and can reach up to 10cm in height (Øvstedal and Smith 2001). Branches

<sup>11</sup> Attached by a single and central point (Castello 2003).

<sup>12</sup> Being single lobed (Castello 2003).

associated with *B. frigida*, *P. minuscula* and *U. decussata* (Hancock and Seppelt 1988; Øvstedal and Smith 2001).

### ***Xanthoria elegans***

*X. elegans* (Figure 15) has an orange to red thallus that is foliose to crustose in form (Castello 2003). Due to its wide distribution, its occurrence in WDML has been well documented (e.g. Lindsay 1972; Engelskjøn 1986; Ryan *et al.* 1989; Thor 1997; Dwight 2014). Castello (2003) typifies the species as occurring below 1880m.a.s.l, and growing on rocks and/or on lichens and moss. This coincides with Øvstedal and Smith (2001), who also describe the species as cosmopolitan and bipolar, extending from



Figure 15: *Xanthoria elegans*. Source: C. Hansen.

sea level at the Antarctic Peninsula, through to continental Antarctica, up to 1700m.a.s.l. *X. elegans* is a component of many vegetation communities, particularly those influenced by bird colonies (e.g. Ryan *et al.* 1989; Ryan and Watkins 1988). Depending on the environment, the species varies morphologically (Lindsay 1972). In continental Antarctica, this lichen is often found loosely attached to rock or dry moss, and forms part of distinct communities with other crustose lichens such as *C. murrayi* (Øvstedal and Smith 2001).

### ***Xanthoria mawsonii***

*X. mawsonii* (Figure 16) has been documented in WDML by Castello (1995) and Thor (1995, 1997). The lichen has a foliose to sub fruticose, red-orange thallus that reaches up to 1.5 cm in diameter and often joins with other thalli (Øvstedal and Smith 2001; Castello 2003). *X. mawsonii* is an Antarctic endemic found colonising loose rock/soil, or dry moss (Øvstedal and Smith 2001). In continental Antarctica, it is particularly abundant on sandy soil and forms communities with *C. murrayi*, *C. flava* and *L.*



Figure 16: *Xanthoria mawsonii* (dark orange), *Caloplaca* spp. (orange) and *Lecanora expectans* (grey-white) growing on dead moss. Source: Australian Antarctic Data Centre.

*expectans* (Øvstedal and Smith 2001). It is abundant in areas that have nesting birds (Øvstedal and Smith 2001).

To reduce error of subjectivity when surveying lichens, some scientists collect samples for later identification by specialists (e.g. Ryan *et al.*1989). However, this is not a consistent procedure; there are surveys whereby species are not sampled for reasons such as low abundance of lichens (e.g. Steele *et al.*1994). Due to accessibility, ecological studies that have been conducted at or near permanent stations, are more comprehensive (e.g Lindsay 1972; Øvstedal 1983 in Øvstedal and Smith 2001; Engelskjøn 1986; Goran 1997). Convey (2011) attests to baseline survey data/full taxonomic accounts being unavailable, and therefore limiting terrestrial biological research. However, existing baseline survey data provides the opportunity to develop lichen studies towards a focus on lichen-environment interactions (e.g. Ryan and Watkins 1989; Sancho *et al.*2007; Dwight 2014). So, although biological studies are requiring more reliable data, geomorphological research is advancing with an interdisciplinary purpose.

### **Lichens in the Antarctic Environment**

Polar desert landscapes in both hemispheres are characterised by periglacial landforms. The occurrence and activity of these landforms contribute to shaping vegetation colonisation and succession (Dwight 2014; Cannone and Guglielmin 2010; French 2007; Bockheim 2002). Although acknowledged in literature (e.g. Bockheim 2002), there is limited investigation into the interactions and processes for Antarctica, as explained by Cannone and Guglielmin (2010). Periglacial features affect microtopographical and micro-edaphic conditions for vegetation, which may alter the shelter and disturbance of plants as well as the snow accumulation and transience patterns (Cannone and Guglielmin 2010). Contrary to this, vegetation may influence soil characteristics, as seen in Cannone *et al.*(2008). This may be the cause of vegetation having a buffering effect on the ground thermal regime, which in turn can have feedbacks on the active layer and freeze-thaw cycles that may alter the chemical characteristics of soil (Cannone and Guglielmin 2010; Cannone *et al.*2006). Such interactions are discussed below, with specific reference to lichens where possible.

### **Environmental Influences**

It is without question that Antarctica's conditions are considered to be harsh relative to other global regions, and, therefore, the establishment and persistence of vegetation on the continent is considered impressive (Sancho *et al.*2007). Conversely, Robinson *et al.*(2003) considers these conditions "normal" for lichens. As explained by Kappen (2000), lichen tend to inhabit bare rock and stable soil surfaces, but follow a gradient of exposure and water

availability. These habitat preferences are due to a lichen's response to environmental factors which are discussed below.

### Nutrients and soils

Nutrient availability plays a role in the lichen colonisation of continental Antarctica (Robinson *et al.* 2003; Ryan and Watkins 1989). Terrestrial environments have poor nutrient availability, unless there is a presence of sea spray, weathering, and bird colonies (Lindsay 1978). Lichens that are found near bird colonies are nitrophilous, making them tolerant to high levels of nitrogen, whereas other species are usually adapted to low levels of nitrogen (Øvstedal and Smith 2001). Certain species are also adapted for high salinity levels, especially in the coastal regions, but foliose and fruticose lichens prefer restricted environments.

Contrary to nutrient availability, lichens become part of the nutrient cycle once they have colonised an area (Lindsay 1978). This is because they are agents for rock weathering, breaking down substrate and contributing to soil formation (Chen *et al.* 2000). The main soil forming processes, however, remain as oxidation and salinisation (Beyer *et al.* 1999). Soils from Antarctica have distinct properties that classify them as gellisols, as they tend to have permanent permafrost within one metre below the surface (Beyer *et al.* 1999).

### Active layer and permafrost

In permafrost terrains, including WDML, most biological and hydrological activity is limited to the active layer, which acts as a boundary layer between the atmosphere and terrestrial cryosphere for heat, moisture and gas exchanges (Dwight 2014; Anisimov *et al.* 2007; French 2007). The active layer thaws annually and forms the uppermost part of permafrost - a layer of earth material that remains below 0°C for two or more consecutive years (Anisimov *et al.* 2007; French 2007). The thermal regime and distribution of permafrost is modifiable through vegetation changes, because the vegetation provides a layer of protection by reducing the heat flux of the ground, especially during summer months. This makes it important to determine and monitor lichen habitats, as such data can then be used as a proxy in determining future active layer activity. This activity can then be used as a "geoinicator" to monitor and assess other environmental changes (Berger 1997). The interpretation is further simplified by the relatively simple ecosystems that have few species influencing ecosystem processes.

## Temperature and water availability

Higher plant colonisation success in maritime Antarctica is limited by temperatures not exceeding  $\sim 5^{\circ}\text{C}$  in the summer months, whereas other plant groups, such as lichens, are capable of achieving optimal growth at zero to sub-zero temperatures (Ott 2004). This differs to Alpine areas, where the growth rate of some species is 80% lower than that of the same species occurring in Antarctica, which indicates that lichens are more suited to establishing greater diversity and biomass in higher latitude conditions (Ott 2004; Sancho and Pintado 2004). However, for lichens to survive the Antarctic's aridity and freezing temperatures, they have developed mechanisms that allow them to remain active. One such mechanism is highlighted by Kappen (2000), who explains how lichens are poikilohydric; having the ability to dehydrate and survive long periods of desiccation. Due to their poikilohydrous nature, lichens rely entirely on their ambient water availability (Schroeter and Scheidegger 1995). Green *et al.* (1999) suggests that lichens receive water through snow melt (especially in continental Antarctica) and water vapour but, during winter when lichens are covered by snow, they dehydrate themselves to prevent cell damage from the cold, which allows them to remain viable and active (Schlensog *et al.* 2004). The desiccation process also prevents the cells from becoming damaged by high radiation or freezing temperatures. However, should damage occur whilst in a dehydrated state, the lichen will not be able to repair itself until it is hydrated again (Robinson *et al.* 2003). It must be noted that the snow regime and meltwater is controlled by the topography, wind patterns and insolation during snow free periods (Schroeter and Scheidegger 1995). This means water availability, surface microclimate, and vegetation is determined by relative topography (Longton 1985; Schroeter & Scheidegger 1995). In relying on the ambient environment for moisture, microclimate and microhabitats are influential factors in lichen habitat preferences.

Microclimate accounts for rock surface features, including the presence of lichen (Waragai 1998). Temperatures of the substrate may be influencing lichen substances, which are needed for a lichen's success (Hamada 1983). It may also influence the habitat preference for lichens. A case study by McIlroy de la Rosa *et al.* (2013) looked at stone bioreceptivity<sup>13</sup>, with particular focus on the spatial distribution of lichen in relation to the temporal and spatial variation of the stone surface temperature. The case study revealed that surface temperature does exert some control on the absence/presence of lichen distribution on stone. The study particularly noted that if stone surface temperature exceeded a certain average temperature (critical point), lichen colonisation was inhibited (McIlroy de la Rosa *et al.* 2013). Although

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<sup>13</sup> The ability of a material to be colonised by a living organism (Guillitte 1995).

conducted in a seasonally hot environment, outcomes highlighted a need for a more detailed database about this surface temperature-lichen interaction (McIlroy de la Rosa *et al.* 2013).

### Ultraviolet radiation and climate change

Changes in the climate systems have caused ozone depletion and increased ultraviolet (UV) radiation in the Polar Regions, which has resulted in destruction to organisms' cells (Karentz 1991; de Vera *et al.* 2003). As primary colonisers in the Antarctic, lichens are susceptible to the effects of UV radiation, especially since they are dependent on photosynthetically active radiation (PAR) (Wynn-Williams and Edwards 2002). In response, lichens have developed mechanisms to tolerate UV radiation in order to survive in their environment: the generation of UV-absorbing compounds, quenching of toxic intermediates and the ability to repair damage (de Vera *et al.* 2003; Wynn-Williams and Edwards 2002). UV protecting compounds exist in the lichen's outer fungal cortex, which shelter the thallus' photosynthetic compounds (de Vera *et al.* 2003). Growth forms also play a role in the tolerance of UV radiation, and can have a significant impact on their success in their habitats e.g. macrolichen such as *Usnea* species are particularly tolerant and adapted to this extreme (Ott 2004).

As another response, lichens use antioxidants to protect themselves from free radicals and active oxygen that would normally damage DNA and cell membranes (Robinson *et al.* 2003). It is evident that Antarctic lichens rely on antioxidants for protection, as found by Paudel *et al.* (2008), who claim that temperate lichens had a much lower antioxidant activity. The mechanism of using antioxidants is, however, limited to when cells are hydrated. This means that water availability is an environmental factor controlling the physiological impact on lichens, in addition to UV radiation (Robinson *et al.* 2003). As a result, with increased precipitation, as proposed in current climate change scenarios, lichens may become more exposed to UV damage during hydration, but are expected to be protected by increased snow, which has a high albedo, and will protect lichens from direct UV radiation (Karentz 1991).

Development of pigments that act as a protective screen have also contributed to a lichen's protection (Solhaug *et al.* 2003), with some species producing specific protecting compounds e.g. Usnic acid, which typically occurs in *Usnea* species (Ott 2004). Some lichens that occupy niches, such as shaded and sheltered habitats, avoid UV radiation but display adaptations for lower PAR levels (Wynn-Williams and Edwards 2002).

Vegetation characteristics contribute to climate change research (Robinson *et al.* 2003). Lichens are able to survive at physiological limit, and therefore show a more evident change in their growth compared to plants from less extreme climates, making them suitable proxies

for monitoring and identifying impacts to the environment (Robinson *et al.*2003). The value of their responses supports the need for their conservation.

### **Conservation of Lichens**

Concern about conserving Antarctica is growing, regardless of the Antarctic Treaty System being in place (Hughes and Convey 2010; Shaw *et al.*2014). It is argued that the continent is no longer pristine as a result of increasing anthropogenic activity (Bargagli 2008; Hughes and Convey 2010; Terauds *et al.*2012; Shaw *et al.*2014). This has had a negative effect on biodiversity from habitat to individual level (Shaw *et al.*2014). In addition to increasing human activity, drivers for changing terrestrial systems also include climate change, invasive species, and local pollution (Kennicutt *et al.*2015). Systems in place (e.g. ASPAs) may not necessarily be protecting the terrestrial biodiversity, as survey data exists for selected areas rather than a continent-wide knowledge base (Hughes and Convey 2010).

Being widespread and tolerant to the Antarctic conditions, extensive biomonitoring networks can be established for lichens (Bargagli 2008). In many situations, authorisation is required to visit certain sites for research. Decisions are based on existing knowledge from surveys, and controls that rely on biomonitors and bioindicators, given their ability to respond to environmental changes (Conti and Cecchetti 2001). The effects of changes will first be seen in polar vegetation, which is why lichens of continental Antarctica must be preserved, protected and monitored (Sancho *et al.*2007; Robinson *et al.*2003).

## CHAPTER 3: SETTING AND STUDY SITES

On December 1<sup>st</sup> in 1959, South Africa was one of twelve countries that signed the Antarctic Treaty in Washington D.C. This agreement has since managed research and activity on the continent of Antarctica (ATS 1959). As signatory, South Africa committed to peacefully utilising the continent for scientific investigation, as outlined in the Treaty's Article II (ATS 1959). Following the Treaty, the Scientific Committee for Antarctic Research materialised to initiate, develop and coordinate scientific enquiry on the continent through offering objective and independent advice (SCAR 2016). South Africa became party to SCAR, maintaining its engagement as the South African National Antarctic Programme (SANAP). The current base SANAE IV, located on Vesleskarvet nunatak in WDML (Figure 17), was developed in January 1997, which has facilitated a more permanent presence in Antarctic research and exploration for South Africa (SANAP 2016).

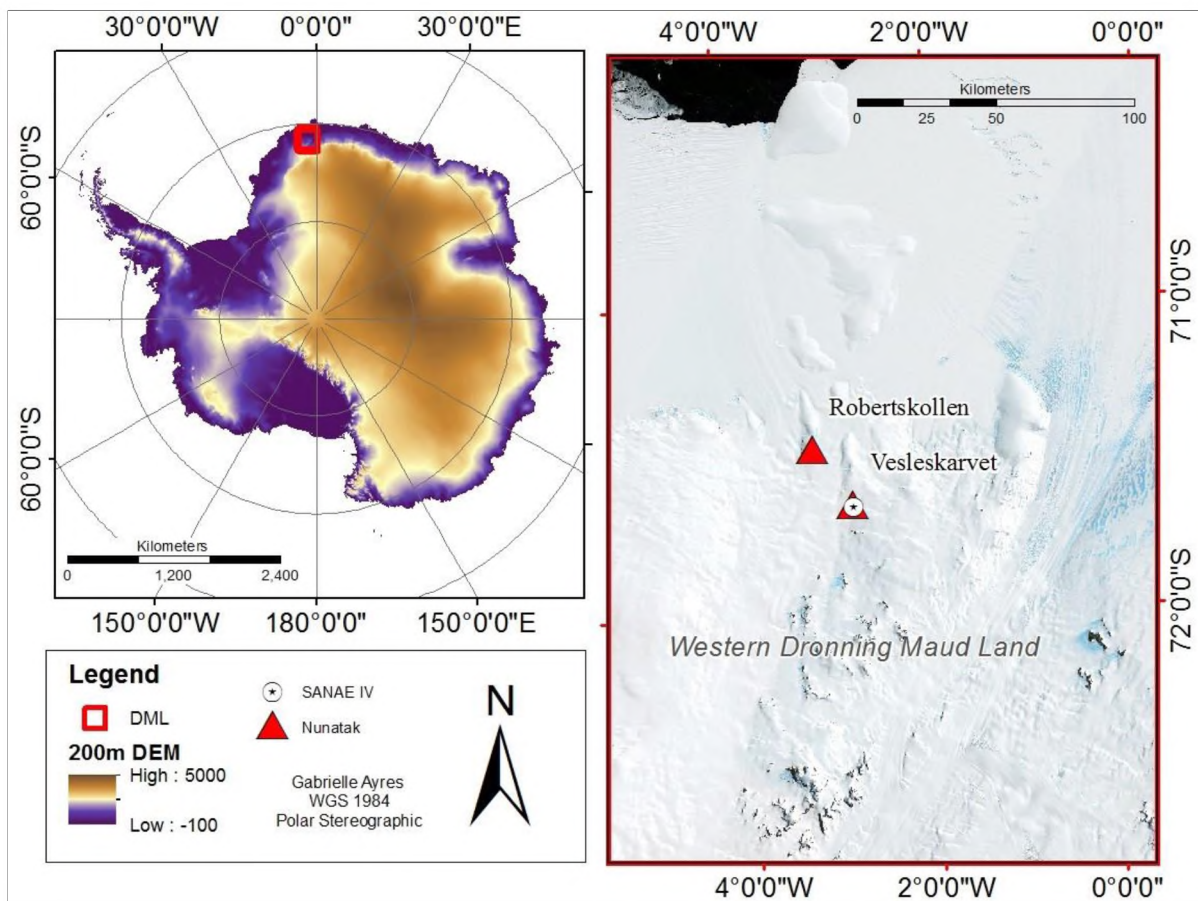


Figure 17: Map of study sites in western Dronning Maud Land, Antarctica.

Dronning Maud Land (DML) (also referred to as Queen Maud Land) was discovered by the Norwegian born Riiser-Larsen, who adeptly named it after his Queen in 1930 (Stewart 2011). WDML represents the part of DML to the west of the Jutulstraumen Glacier. It is one of the larger regions of East Antarctica, situated inland off the Princess Martha coast in the North-Eastern parts of Maudheimvidda (Hansen 2013). The two sites of focus are located within WDML on the Ahlmannryggen Ridge (Ahlmann Ridge) (Figure 17). This Northeast trending ridge is 112km long, bound between the Jutulstraumen Glacier (Eastern side) and the Schyttbreen Glacier (Western side) (Kotzé 2015).

DML mountains are documented to have granitic gneisses, migmatite, charnockite, and diorites (Øvstedal and Smith 2001). The nunataks in this study form part of a 400m thick suite of ultramafic, mafic and intermediate sills and dykes of the Borgmassivet suite, which intruded into the Mesoproterozoic Ritscherflya Supergroup 1107Ma years ago (Marshall *et al.* 1995; Grosch *et al.* 2007; Kotzé 2015). The igneous doleritic and dioritic sills, or minor dykes, of the Borgmassivet intrusives are resistant to weathering (Briggs 1977; SASCAR 1984; Grosch *et al.* 2007). However, according Hansen (2013), large crystal sizes in the intrusive have increased susceptibility to mechanical and chemical weathering. Nevertheless, there are processes responsible for the weathering of the nunataks – as seen by the block shaped boulders in the flat lying area (Figure 18). One such process is argued to be frost shattering (Marshall *et al.* 1995). Conversely, Hall (2013) highlights that frost shattering is disputed by the scientific community, and attests a number of weathering processes. Therefore, it is prudent to acknowledge a combination of processes at play, including chemical weathering, thermal stress, freeze-thaw and a continuum of wetting and drying. Landscape processes, coupled with the origin and length of exposure of these nunataks, have increased susceptibility to rock weathering, and have therefore contributed to the formation of existing landforms and habitat morphologies (Hansen 2013). Dolerite contains pyroxene and calcium feldspar, whereas diorite contains alkali feldspar, calcium feldspar and amphibole (McCarthy and Rubridge 2005; Hansen 2013). The greater concentration of pyroxene in dolerite is indicated through the colour boldness, which explains its darker appearance when compared to that of diorite (Hansen, 2013). Typically, dolerite varies from light grey (weathered) to dark grey (non-weathered) (Hansen, 2013). Soils in WDML, often classified as gelisols<sup>14</sup>, are poorly developed. They have little to no organic content, but contain minerals that act as a source of nutrients and are important for geochemical cycles (Convey *et al.* 2013). Carbon

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<sup>14</sup> Soils of very cold climates containing very little organic matter which, are usually formed through oxidation and salinisation processes ; can be found in the scattered ice-free areas of Antarctica (Beyer *et al.* 1999).

concentration is much lower near the surface, due to cryoturbation, which restricts life in the soils.

Different to the Arctic, Antarctica experiences very cold temperatures during its summer months – generally considered December to February (Øvstedal and Smith 2001). Temperature, precipitation and day length have a wide disparity across the latitudinal range, due to the geometry of the sun-earth relationship (i.e. amount of incoming solar radiation being received), giving regions their own individual climatic conditions (Øvstedal and Smith 2001; Cassano 2013; Kotzé 2015). Differences are seen between coastal and interior temperatures, with inland regions experiencing  $\pm -30^{\circ}\text{C}$  during summer, and  $\pm -65^{\circ}\text{C}$  during winter, and coastal regions experiencing  $\pm 0^{\circ}\text{C}$  during summer, and  $\pm -15^{\circ}\text{C}$  during winter (Øvstedal and Smith 2001; Cassano 2013; Kotzé 2015). Air temperatures in WDML are variable, and according to Kärkäs (2004), these large temperature changes correspond with changes in wind speed and direction as low pressure systems pass, which transport warm, moist air towards the south. WDML has a prevailing easterly wind, measured as having an average velocity of  $11\text{m}\cdot\text{s}^{-1}$  (Kärkäs 2004; Hansen 2013). Recorded data show temperatures in the interior are increasing, which was also documented for coastal regions (King and Turner *in* Øvstedal and Smith 2001). Simply put, the near surface climate of the region can be said to be characterised by ephemeral cyclones passing parallel to the coastline; producing a series of katabatic and synoptic winds, and thus, a dynamic climate (Kärkäs 2004; Kotzé 2015). Precipitation in the form of snow occurs inland on the WDML plateau (Schroeter and Scheidegger 1995; Hansen 2013). WDML receives an annual 55-81mm of water equivalent (w.e.), which differs in coastal areas that typically receive a 150–200mm w.e. (Reijmer and Van Den Broeke 2001; Hansen 2013). Ice core data - conditional to the depth of the core - indicates that the mean accumulation rate for WDML varies between 62–100mm w.e., annually (Noone *et al.* 1999; Reijmer and Van Den Broeke 2001). Low precipitation inland results from the cold temperatures (mean annual air temperature at  $-40^{\circ}\text{C}$ ) and isolation from warm air masses, typically occurring at the coast (Bargagli 2005; Turner *et al.* 2009). Snowfall originates orographically, enabled by the scattered nunataks in the high interior (Kärkäs 2004).

### **Vesleskarvet (S71° 39.99' W2° 51.00')**

Vesleskarvet is a flat topped nunatak divided into a northern and southern buttress that covers an area of approximately 22.5ha (Figure 18) (Steele *et al.* 1994). It is an autochthonous blockfield consisting of metamorphosed doleritic and dioritic sills and minor dykes (Hansen *et al.* 2013). Although the landform has an altitude of 856m.a.s.l., only 200m of it lies above the surrounding ice plain (Steele *et al.* 1994; Hansen 2013; Dwight 2014). A 'wind scoop' follows the base of the steep western and northern edges of the northern buttress, whereas the

eastern and southern edges gradually develop into a sloping ice-sheet (Steele *et al.* 1994; Dwight 2014).

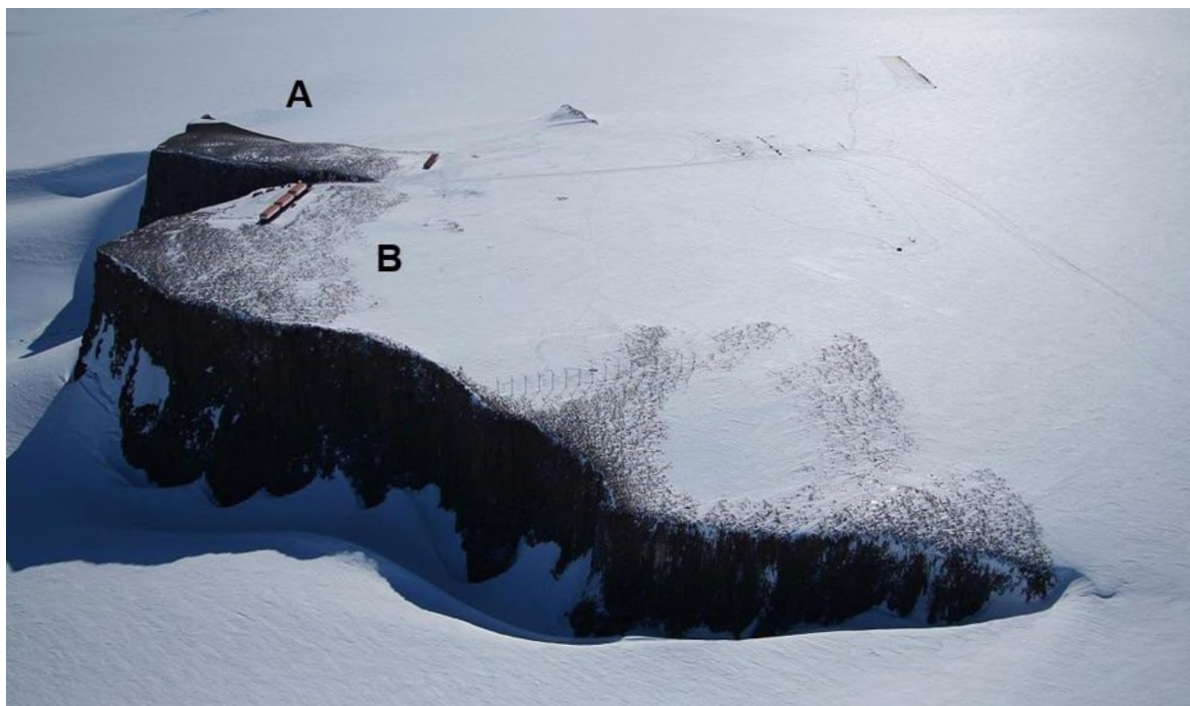


Figure 18: Vesleskarvet, western Dronning Maud Land. (A) northern buttress (B) southern buttress. Source: S. Hofmeyr.

SANAE IV is built on the southern buttress. Although bird activity is low; South Polar skuas, Snow Petrels, and a Wilson's Storm Petrel have been sighted at Vesleskarvet, which modifies findings from earlier expeditions (e.g. Dastych and Harris, 1995; Steele and Newton, 1995). To maintain site integrity and minimise the impact of humans, the South African Department of Environmental Affairs (DEA) has designated parts of the northern buttress as a Scientific Exclusion Zones (SANAP 2009). The study site for this research falls within the exclusion zone and permission to conduct field work on the northern buttress was granted by the DEA.

### **Robertskollen (S71° 29.21' W3° 12.66')**

Robertskollen consists of a group of nunataks, ranging between 200 and 500m.a.s.l., and covering an area between 100m<sup>2</sup> and 12 500m<sup>2</sup>, respectively (Ryan *et al.* 1989). It is a layered (ultramafic and mafic) dome-like igneous complex; eroded and lacking planar surfaces (Krynauw 1986). The nunataks are closer to the ice shelf than Vesleskarvet, located approximately 25km Northeast of SANAE IV on the margin of an ice rise (Kotzé 2015). The landforms are characterised by high cliffs on the eastern side, which extend to the Western side, and comprise mostly of boulder slopes and loose scree (Ryan *et al.* 1989; Dwight 2014). Snow Petrels, Antarctic Petrels, and Wilsons' Storm Petrels were sighted in sites A-C at

Robertsollen (Figure 19). This coincides with findings from Ryan and Watkins (1988), where sightings of South Polar Skuas were recorded. Two large nunataks were investigated in this study: Ice Axe Peak and Petrels Rest. Relatively rich in biota, Robertsollen has the potential to be labelled as a protected area. Permission was granted by the DEA to investigate the site with caution.

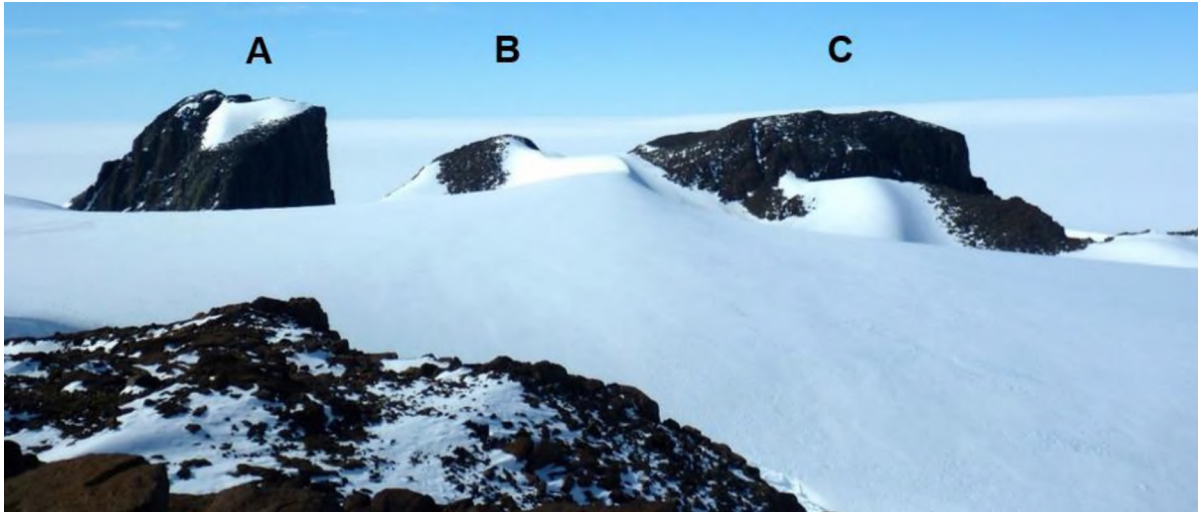


Figure 19: Robertsollen, western Dronning Maud Land. (A) Cairn Peak (B) Kleinfjell (C) Ice Axe Peak.

## CHAPTER 4: HABITAT HETEROGENEITY

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This chapter covers the foundations, procedures and outcomes for Objective 1 (Chapter 1, pg.4) of the study, which investigates the habitat heterogeneity of two nunataks in WDML. It provides a section on methods used across all objectives, which will be referred to later in text.

### Introduction

Species diversity is a measure of diversity in a community that takes two aspects into consideration: species richness (abundance) and evenness (Hamilton 2005). Specific lichens dominate a habitat as a result of interacting environmental factors, which control the constitution of a lichen community (Gupta *et al.* 2014). For this reason, the most acceptable explanation (though not entirely exclusive) in ecology for species-area relationships is rooted in the fact that species richness is linked to habitat heterogeneity (Báldi 2008). Species-area relationships entail the increase of species richness with increasing area. Decades of ecological research have shown this connection between habitat complexity and species diversity in local scale environments (e.g. MacArthur and MacArrthur, 1961; Pianka, 1966a; Murdoch *et al.* 1972; Otte, 1976; Davidowitz and Rosenzweig, 1998). The 'habitat heterogeneity hypothesis' posits that a greater heterogeneity has more complex and available structural habitats that provide ecological niches to a higher number of coexisting species (Tews *et al.* 2004; Kadmon and Allouche 2007; Travassos-De-Britto and Rocha 2013). Simply put, a larger number of (micro)habitats are available, which offer a greater variety of niches (both ecological and structural) to be colonised by different species (Tews *et al.* 2004).

With this hypothesis in mind, the aim of this study was to calculate the species diversity (hereafter referred to as "diversity") of Vesleskarvet and Robertskollen, which, in turn, gives a reasonable indication of habitat heterogeneity. Such exploration will provide understanding into habitat preference at a macro-scale, particularly for lichens, as they are the pioneers of (micro- and macro-) topography in the WDML regions. Habitat heterogeneity was not measured to characterise habitat colonisation, because there has been great inconsistency across studies in quantifying it as an index (Tews *et al.* 2004). Alternatively, lichens are used as indicators of habitat variability and the changes thereof (Rai *et al.* 2012). A species diversity index also gives valuable species distribution and richness data, which are needed for the Antarctic, as the current database is relatively lacking (Øvstedal and Smith 2001). This objective deals with the influence of macro-scale environmental variables affecting the diversity and distribution of lichens in WDML, through the exploration of habitat heterogeneity.

## Methods and Materials

To achieve the four objectives outlined in the introductory chapter (Aim and Objectives, pg.4), data have been collected since 2006 through an earlier project, entitled “Geomorphology and Climate Change in Antarctica.” The project morphed to be the current overarching project, “Landscape Processes in Antarctic Ecosystems” in 2012. All data collections were completed over the austral summer months, which is when relief expeditions to the SANAE IV base take place. The initial lichen survey was completed in 2009/10 by Meiklejohn and Lee. Hansen later conducted two surveys in 2010/2011, and 2011/12 on Vesleskarvet’s northern buttress for her Master’s dissertation, “The characterisation of an openwork block deposit, northern buttress, Vesleskarvet, Dronning Maud Land, Antarctica”. Dwight completed two additional surveys during the expeditions of 2012/2013 and 2013/14 for her Master’s field work component, “Geomorphic and ambient environmental impacts on two inland nunataks in Western Dronning Maud Land, Antarctica.” Subsequently, two surveys were conducted during 2014/15 and 2015/16 for this study.

All methods employed in the field were adapted to local conditions and project requirements, unless otherwise stipulated. As recommended for equipment that records qualitative data, daily calibrations were completed the field (e.g. GPS), so as to minimise collection error (Briggs 1977). In the event of multiple datasets from different seasons being used for analysis, all GPS points were cross-checked to minimise replication of data. The horizontal inaccuracy (3-5m) of the GPSTMap (Garmin® 2007) does not allow this replication to be completely avoided. Specifications for the equipment referenced are presented in Appendix A.

Vesleskarvet and Robertskollen were selected for this study due to their accessibility from SANAE IV base, and presence of lichens. As previously mentioned, surveys and investigations completed by candidates of the projects, have documented the presence of lichens at both sites. This study developed the database by detailing the small-scale environmental conditions at each site, which characterise these habitats as suitable colonisation sites.

The survey conducted during the austral summer of 2014/2015 was for reconnaissance purposes, and involved a pilot study to test field methodologies. The most appropriate methodologies were incorporated into the 2015/2016 survey design, which was completed in a more systematic approach. Data collection referred to herein took place over the austral summer of 2015/2016, unless otherwise stipulated.

## Data Collection

### *Lichen Identification*

Ryan *et al.* (1989) identified 20 lichen taxa in a preliminary survey at Robertskollen. Results from the survey were later used for species reference in an environmental impact assessment (EIA) of Vesleskarvet by Steele *et al.* (1994), which produced a record of nine species. This study utilises the EIA's published records and existing databases of species occurrence in WDML to reference lichen identification. Øvstedal and Smith's (2001) taxonomic account provided supporting distribution and identification data to account for observed species in the field. Identification cards were issued to all field assistants for identifying lichen species. For those species which proved unidentifiable in the field, a photograph was taken for review at a later stage. Species were cross-checked by a lichenologist, and entered into the Victoria 2.0 dichotomous key (Castello 2003).

### *Survey Structure*

Each nunatak's area of interest was identified via aerial and Landsat® imagery for Vesleskarvet and Robertskollen respectively. Locations favouring lichen colonisation were selected and sampled based on outcomes in Dwight's (2014) research. In the study, Dwight investigated the relationship between selected environmental factors and lichen distribution/abundance at a nunatak scale. Using BaseCamp™ and the geographical information systems software package, ArcGIS™, these areas were georeferenced and demarcated for structuring the survey strategy.

Fishnet grids were created in ArcMap using the Data Management Tool. The generated grid was overlaid onto each demarcated nunatak. A 600m x 600m fishnet grid with 40m x 40m grid squares was created for Vesleskarvet and a 1200m x 600m grid with 40mx40m grid squares was generated for Robertskollen. Grid squares provided corner points to be loaded onto a handheld Garmin™ Geographical Positioning System (GPS). These points were used in the field to navigate during traverse across the nunatak, ensuring the greatest coverage of the area. Upon site arrival, spatial inconsistency between the GPS and imagery in ArcMap was detected, which was countered by opportunistic sampling of areas outside the grid boundary. Furthermore, not all GPS points along transects were accessible or practical to reach for reasons such as accessibility and safety. Consequently, these points were removed from the survey on site. The GPS unit provides an (horizontal) accuracy of 3-5m, explaining the unaligned sample points across transects seen in Figure 20 and Figure 21 (Garmin®, 2007).

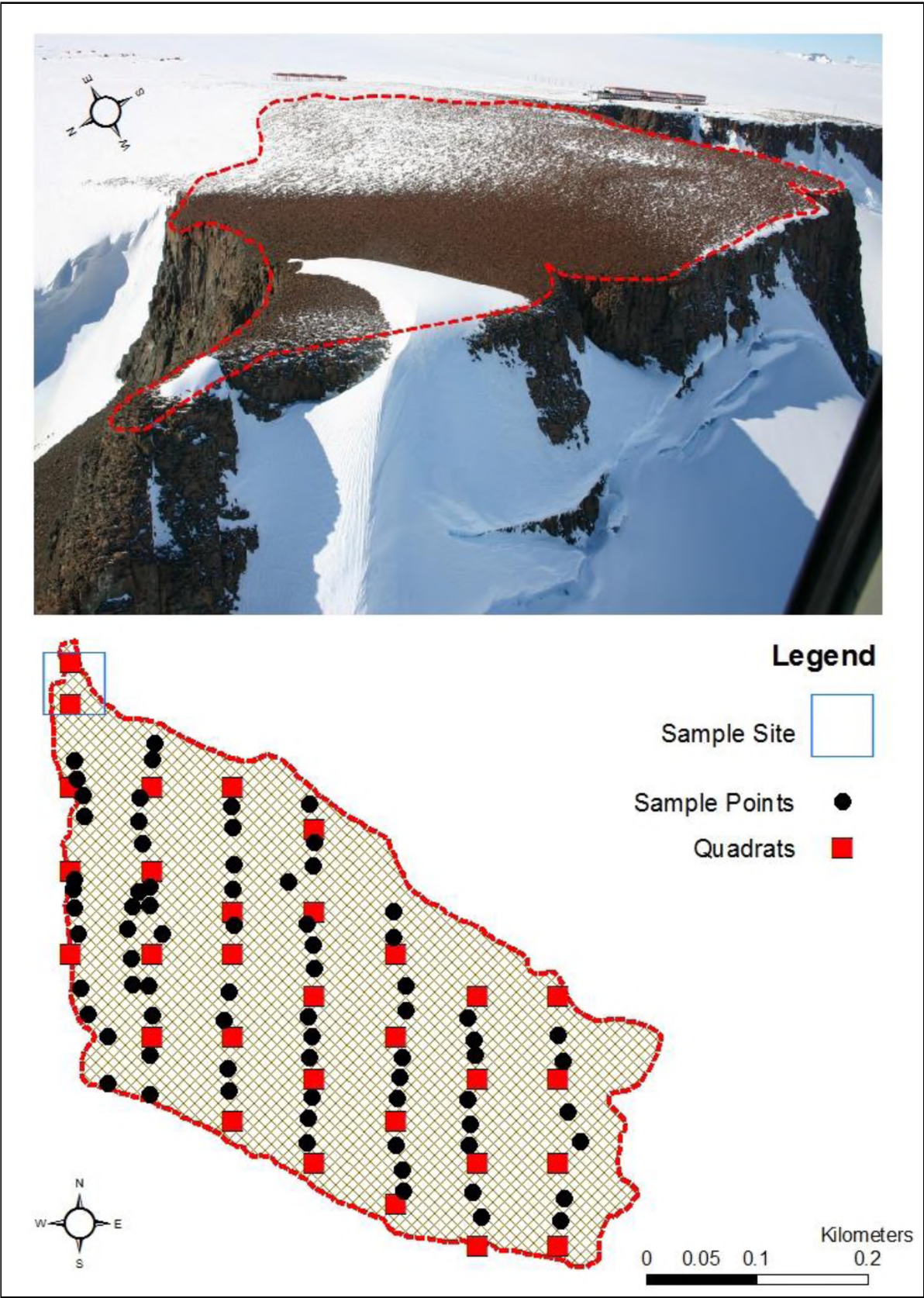


Figure 20: Survey structure for the northern buttress, Vesleskarvet.

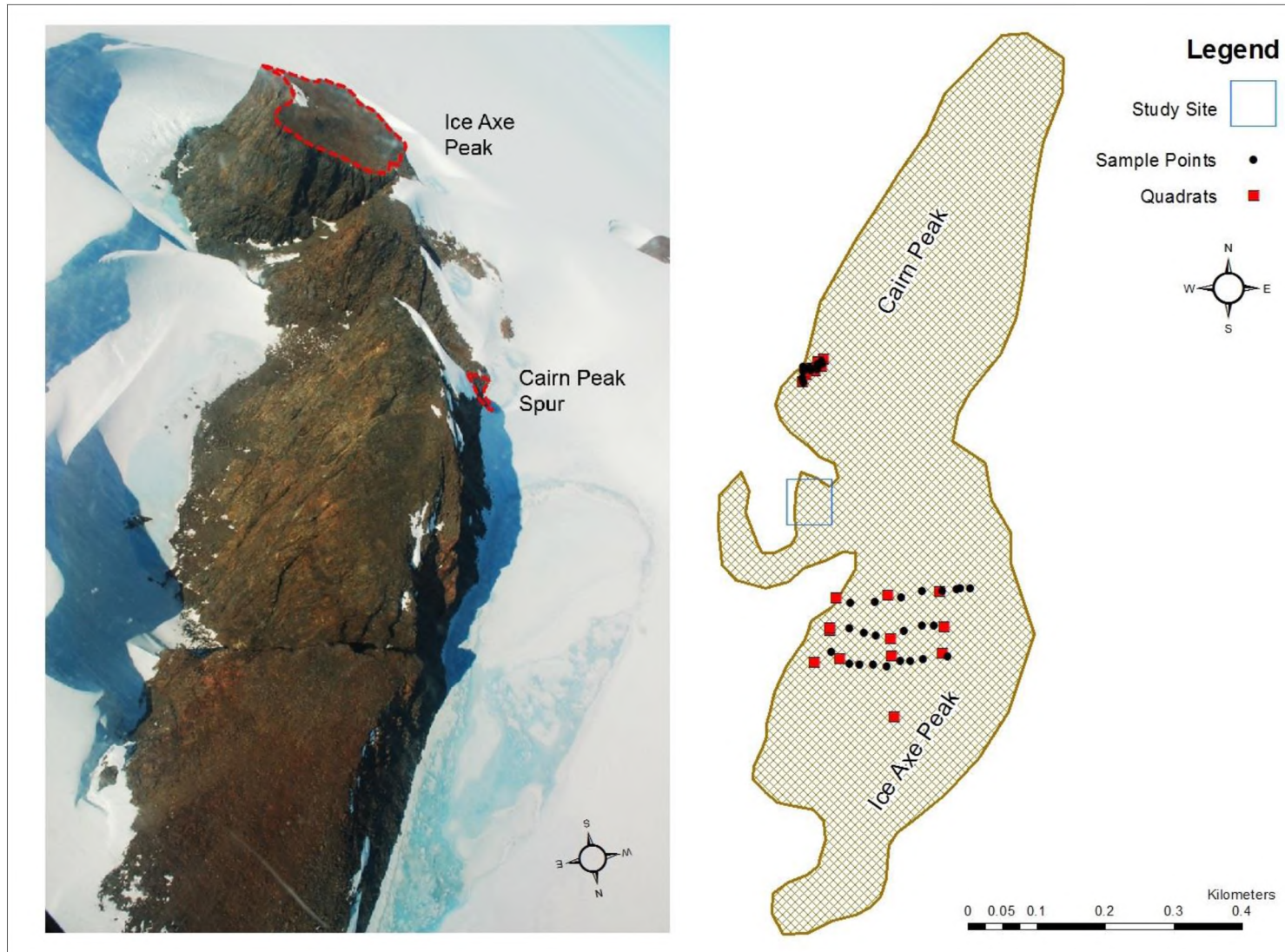


Figure 21: Survey structure for two nunataks at Robertskollen.

## Quadrats



Figure 22: 1m<sup>2</sup> Sampling square (with 100 sub-units) used to estimate cover (%) of lichens.

A 1m x 1m sampling square was used to estimate the percentage cover of lichen at each nunatak (Figure 22) (Lewis Smith 1988), as it is the most useful measurement for local species diversity (Pianka 1966b). The sampling square was placed every 40m along each traverse at both sites. The survey at Robertskollen included 8 quadrat samples for Cairn Peak, and 11 for Ice Axe peak. Vesleskarvet's northern buttress had 29 quadrats sampled. Similarly to Lewis Smith's

(1988) approach, the quadrat was subdivided by vertical and horizontal string into 100 sub-units for aiding visual estimation (Figure 22).

## Data Analysis

### *Species Diversity Index*

Diversity of the lichen communities at both sites was evaluated by the ecological diversity index ( $H'$ ) by Shannon-Weiner. For this study,  $H'$  was based on percentage cover (Moser *et al.*, 2007), and calculated in Microsoft® Excel using the formula below [1]. Within this formula,  $H'$  is the diversity index;  $S$  is the total number of species;  $I$  is the species; and  $p_i$  is the total number of organisms of a particular species.

$$H' = - \sum_{i=1}^S (p_i)(\ln p_i) \quad [1]$$

The species diversity of each quadrat at both sites was first calculated, followed by a calculation for the average diversity to give a more accurate representation of the species diversity across the nunataks. Following this, Simpson's dominance index ( $J'$ ) was calculated to determine the evenness of the communities at each site, using the formula below [2] (Smith and Wilson 1996).  $J'$  represents Shannon's equability, which assumes a value between 0 and 1, with 1 being complete evenness.

$$J' = H' / \ln(S) = H' / H'_{max} \quad [2]$$

Once the mean index was calculated for each site, the student's t-test (hereafter referred to as a t-test) was used to test the hypothesis of whether the diversity between each site was significantly different. This was completed in the XLSTAT extension, following a Fisher's two-tailed F-test that tested the assumption of the t-test's equal variance. A t-test was suitable, as it assumes normality and does not require the sample number to be the same for both populations/sites. It was conducted at a 95% level of confidence, which is considered the most realistic certainty in Physical Geography (Briggs 1977).

**H<sub>0</sub>**: Robertskollen and Vesleskarvet differ in species diversity and thus, contrast in habitat heterogeneity.

**H<sub>al</sub>**: Robertskollen and Vesleskarvet do not differ in species diversity and thus, do not contrast in habitat heterogeneity.

## Results and Discussion of Findings

Often in structured surveys, not all species are represented in the data. This was particularly evident at Vesleskarvet, where there is a small area (its northern tip) with greater lichen coverage and species diversity. To account for this, the table below indicates the species of lichen identified at each site:

Table 3: List of species identified at each site for this study.

Vesleskarvet	Robertskollen
<i>Acarospora gwini</i>	<i>Acarospora gwini</i>
<i>Buellia sp. A</i>	<i>Buellia sp. A</i>
<i>Buellia sp. B</i>	<i>Buellia sp. B</i>
<i>Candelaria flava</i>	<i>Candelaria flava</i>
<i>Lecanora expectans</i>	<i>Lecanora expectans</i>
<i>Pleopsidium chlorophanum</i>	<i>Pleopsidium chlorophanum</i>
<i>Pseudephebe minuscula</i>	<i>Pseudephebe minuscula</i>
<i>Rhizocarpon geographicum</i>	<i>Rhizocarpon geographicum</i>
<i>Umbilicaria decussata</i>	<i>Rhizoplaca melanophthalma</i>
<i>Usnea sphacelata</i>	<i>Umbilicaria decussata</i>
<i>Xanthoria elegans</i>	<i>Usnea sphacelata</i>
	<i>Xanthoria elegans</i>
	<i>Xanthoria mawsonni</i>

## Shannon Diversity Index

Presence of lichens indicates habitat suitability, which was explored and discussed through the habitat heterogeneity hypothesis (MacArthur and MacArthur 1961). Of the nine previously recorded species on Vesleskarvet, only five species were identified in the 29 quadrats (Figure 23). The study, however, identified 11 species on the northern butress (with the addition of *C.flava*), which meant a 50% representation of all lichen species in quadrats from Vesleskarvet. Robertskollen had a total of 10 identified species and showed a more even distribution than that of Vesleskarvet's northern butress.

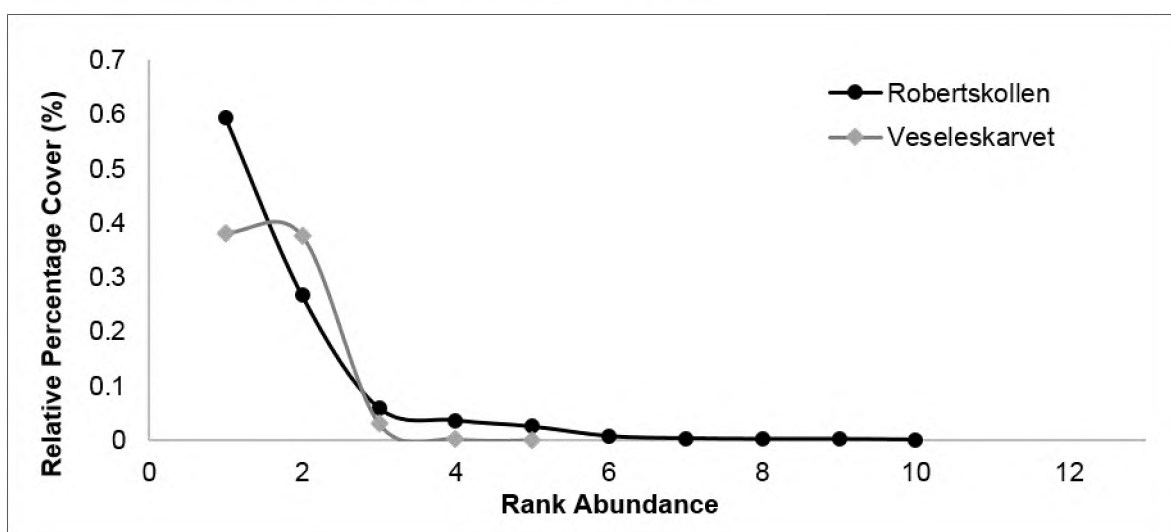


Figure 23: Rank-abundance plot for lichen species in part of WDML.

A visual representation of relative species abundance, species richness and species evenness is seen in Figure 23. Robertskollen has a higher species richness, which is more evenly distributed across the nunatak due to abundances of each lichen being similar. The steep gradient of the Vesleskarvet graph indicates low evenness, with the higher ranked species having much greater abundance than the lower ranks (Figure 23). Vesleskarvet is dominated by two species and the calculation of  $J'$  further confirms this at 0.06 (Table 4).

Table 4: Diversity and evenness of lichens in part of WDML.

Site	H'	H'max	J'	Level of Diversity	Evenness
Vesleskarvet	0.15440834	2.302585	0.067059	Low	Very Low
Robertskollen	0.84253961	2.995732	0.281247	High	Low

It is clear that Vesleskarvet has a lower species diversity (0.154) than Robertskollen (0.843) (Table 4). A t-test indicated that the difference in species diversity between the two nunataks

is highly significant (p-value < 0.05 at 0.0001). Equality of variance was assumed (F-test where p-value > 0.05 at 0.7). Results accept the null hypothesis that Robertskollen has significantly higher species diversity. This justifies the assumption that habitat heterogeneity is greater at Robertskollen, signifying a preference for colony establishment and apparent tolerance of environmental influences documented at this site.

Corresponding to results in Dwight's (2014) study, two dominant species (*L. expectans* and *P. chlorophanum*) adopt the northern buttress as a suitable habitat, shown by their higher abundance and distribution. *P. chlorophanum* is typically found colonising small fissures in exposed conditions (Øvstedal and Smith 2001). Low coverage of the species on Vesleskarvet is represented in the abundance curve (0.38%) (Figure 23). The nunatak has only recently deglaciated, given the small difference in altitude between the bare rock and ice sheet. It features jointed bedrock (from doleritic and dioritic sill intrusions) that yields elongated and rectangular blocks (Hansen *et al.* 2013). Additionally, there is a high proportion of angular shaped rocks; a typical, yet not exclusive, product of freeze-thaw weathering (Hall 1999; Hansen *et al.* 2013). Therefore, these block features characterise the homogenous topography at Vesleskarvet. A homogenous environment explains the lack of species diversity, and more specifically, the predominant presence of *P. chlorophanum*. Fine features, *P. chlorophanum*'s preferred habitat, are controlled primarily by the lithology and geology of the site, and influenced by *in situ* weathering – which corroborates with the idea of Vesleskarvet as a block deposit, as seen in Hansen (2013).

Dominant lichen species at Robertskollen are *U. decussata* and *U. sphacelata*. Lichen abundance and diversity (0.843) are greater at this site, which supports the findings from Dwight's (2014) study. The dominant species *U. decussata* typically colonises sheltered areas that collect snow in the summer (Øvstedal and Smith 2001). Figure 24 and Figure 25 below show the difference in this habitat heterogeneity in terms of surface topography. Robertskollen (Figure 25) has a rugged terrain, offering a variety of sheltered niches, whereas Vesleskarvet is homogenous (Figure 25). Robertskollen deglaciated prior to Vesleskarvet, meaning it has been exposed to weathering processes for a longer period. Prolonged exposure explains the topographic heterogeneity. Robertskollen is also a popular nesting site for polar birds (see pg.27). Presence of birds influences lichen growth (Ryan and Watkins 1989), but also promotes chemical weathering of the rock (Michel *et al.* 2006). Weathering of exposed substrates will increase the heterogeneity of the landscape, which in turn offers more niches to a greater variety of lichens, as seen in the results above. Such weathered spaces provide shelter from winds and collect drift snow (which explains the high abundance of *U. decussata*), while promoting the establishment of diverse lichen communities.

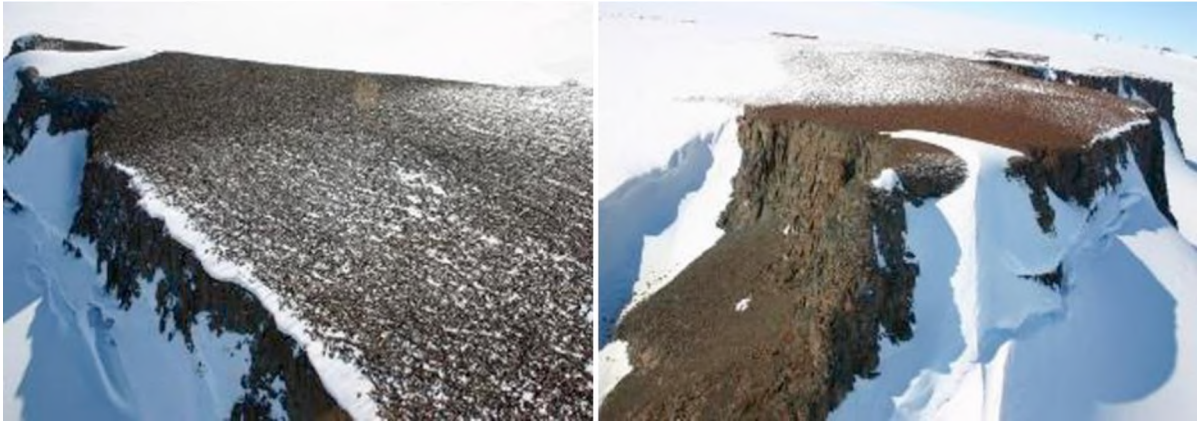


Figure 24: Homogenous topography of Vesleskarvet. Source: I. Meiklejohn.



Figure 25: Heterogeneous topography of Robertsollen. Source: I. Meiklejohn.

Snow cover influences the availability of water and PAR received by lichens, but also has insulating properties that form stable thermal regimes below its cover (Kappen *et al.* 1995). For continental Antarctica, accumulated winter snow insulates the ground but inhibits metabolic activity by retaining and maintaining a cold, stable environment. Although this decelerates lichen growth, it ensures metabolic activity when snow margins retreat – during summer where availability of moisture, insolation and warmer temperatures permit photosynthesis (Pannewitz *et al.*, 2003). A landscape's topography will determine snow cover transitions. Snow cover on homogenous nunataks is likely to be a transient variable, whereas at heterogenic nunataks it will regularly accumulate winter cover at the same microtopographical locations (Pannewitz *et al.*, 2003). Robertsollen's terrain, therefore is expected to have a higher snow carrying capacity, as snow is trapped between its features. This provides niches that will preserve lichens during extreme winters. Contrary to Robertsollen, niches on Vesleskarvet are limited to sheltered spaces only, as the angular block features reduce its snow carrying capacity.

A heterogeneous macrotopography, increases the availability of niches for lichens; controlling their colonisation. Inhabited spaces are, therefore, governed by the terrain's environmental controls, but influenced by local microtopography, which in turn, determines the lichens' response to their surroundings. Robertskollen is a model system displaying these landscape characteristics.

## CHAPTER 5: HABITAT MORPHOLOGY AND CHARACTERISTICS

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Objective 2 was to determine the morphology and characteristics of lichen habitats by measuring rocks and sub-metre scale topographical features. This chapter introduces and presents the results of Objective 2, providing a discussion as well as a description for implemented methods.

### Introduction

The composition of biotic and abiotic constituents in an environment forms a unique set of conditions allowing for the establishment of a species population. This is known as a species' habitat (Molau 2008). Rock outcrops, such as Vesleskarvet and Robertskollen, are extreme but relatively stable habitat sites for plant life, especially lichens (Bjelland 2003). In colonising these environments, lichens face extreme stresses and frequent disturbances, which may influence habitat suitability (Bjelland 2003). These environmental variables, coupled with micro-environmental variables are pivotal to determining species distribution (John and Dale 1990).

Previous research on (macro- and micro-) biotic distribution has been conducted in the Antarctic, however, most of these studies are from Victoria Land (Figure 3, pg.10) (Magalhães *et al.* 2012). Previous studies show the environmental constraints on lichen distribution and abundance (e.g. Bjelland, 2003; Dwight, 2014; Gupta *et al.*, 2014), but to gain further understanding of the processes acting on lichen establishment in preferred habitats, finer scale measurement is required. There is ample knowledge of lichens at a community level, but there have been few attempts to study the micro-environment at single lichen level (Bjelland 2003). The research has not undertaken integrative and interdisciplinary approaches, which are necessary to investigate such ecosystem-wide relationships (Magalhães *et al.* 2012). Therefore, lichens in Antarctica are suitable agents for study. They are the prominent species at continental nunataks and with the absence of higher taxa (constituting the simple biodiversity) (Hughes and Convey 2010), they make suitable proxies for investigating finer-scale interactions with the environment. This is especially needed, as there is little knowledge of lichens beyond coastal zones, which are known to effect environment-lichen interactions greatly (Bjelland 2003).

This chapter assesses the influences of the natural environment on inland lichens in continental Antarctica, while focussing on micro-topographical features (hereafter referred to as "micro-topography", "microhabitat" and/or "feature"). It is hypothesised that certain abiotic characteristics of the environment are the main drivers of the colonisation and succession of



lichens. This is based on Longton's (1985) scenario for Antarctic vegetation, whereby relative topography at sites would permit cryptogamic growth. Environmental parameters considered in this objective include rock shape, orientation, dip and micro-topography. Observations indicated that micro-topography may offer suitable habitats for lichens due to their regular occurrence in these features (e.g. Ryan and Watkins 1989; Hansen *et al.* 2013; Dwight 2014). Certain species habituated different features (personal observation), and these too, were investigated for aspects of preference. To date, no data for the preferred features and the characteristics of the abovementioned species exists. Environmental influences on microhabitats were also investigated so as to identify any controls on colonised features, which would indicate habitat suitability through evidence of colonisation. The investigation is achievable in a landscape where ecosystem presence/absence is controlled by glacial advance and retreat (Magalhães *et al.* 2012). WDML is an example of a region where emergent ice-free areas exist. This chapter represents some of the first research into multi-disciplinary and fine scale datasets from WDML, Antarctica.

## **Methods and Materials**

### Microtopography

Several definitions of microtopography exist, and they differ according to the field of research concerned. Authors have defined it as topographic variability on the scale of individual plants (Huenneke and Sharitz 1986; Titus 1990; Bledsoe and Shear 2000). According to Moser *et al.* (2007), microtopography includes patterns of elevation in numerous spatial scales formed by geologic, hydraulic, physical and biological processes – all of which form part of the broader notion of surface features, or topography. Given these variations in description, the following definition of microtopography was used for this study: natural and physical features (including sub-metre landforms) of the earth's surface, ranging from zero to one metre in size, and encompassing vertical relief. Landform features, presented in Table 5, were distinguished from the broader term 'microtopography' and referred to as micro-topography.

Table 5: Micro-topography measured at Vesleskarvet and Robertsollen.

	
<p><b>Crack</b> A mechanism of rock deformation that has split the rock into two or more parts, and but forms in response to stress (Simmons and Cooper 1978).</p>	<p><b>Fracture</b> The separation of a rock into two or more parts along its weakest plane. It often leads to deep crevices.</p>
	
<p><b>Flake</b> An area on rock where a fragment of the rock surface has broken off.</p>	<p><b>Pitting</b> Small surface cavities, or excavations on the rock, that are formed by various processes e.g. aeolian abrasion, lithology, solution weathering, etc.(Basilevsky <i>et al.</i>1999).</p>
	
<p><b>Tafoni</b> Cavities in the rock surface typically characterised by rounded entrances, concave walls and overhanging visors. Debris and sediment often covers the floor of this feature (Strini <i>et al.</i>2008).</p>	<p><b>Overhang</b> A rock that extends outwards and/or covers other substrate.</p>

## Survey Structure

### Transects

The second objective (Chapter 1, pg.4) in the study required documenting the occurrence of lichens in micro-topography across each nunatak in order to provide an overview of preferred habitat niches (microhabitats) for colonisation. Presence of lichens indicates habitat suitability, which was explored and discussed below.

Table 6: Summary of data collection for both sites.

Measurement/Observation	Instrument	Date	Objective
<b>Transects</b>			
a-, b-, c- axes (cm)	Measuring tape	2010/11; 2011/12	1,2
Lichen presence	Observation	2015/16	1
Micro-topographical feature	Observation	2015/16	1
Dip (°)	Brunton Compass	2015/16	1,2
Orientation (°)	Brunton Compass	2010/11; 2012/13; 2015/16	1,2
Substratum	Observation	2015/16	1
<b>Rock Characterisation</b>			
a-, b-, c- axes (cm)	Measuring tape	2010/11; 2011/12; 2015/16	2
Rock Hardness (RH)	Proceq Equotip	2015/16	2
Rock Support (rock, ice, or mixed)	Observation	2010/11; 2011/12; 2015/16	2
Substrate Type	Observation	2010/11; 2011/12; 2015/16	2
Presence of Snow	Observation	2015/16	2
Face Dip (°)	Brunton Compass	2015/16	2
Face Orientation (°)	Brunton Compass	2015/16	2
<b>Micro-topography Characteristics</b>			
Lichen presence	Observation	2015/16	2
Micro-topographical feature	Observation	2015/16	2
Feature length, breadth, depth (cm)	Measuring tape; Callipers	2015/16	2
Feature Orientation (°)	Brunton Compass	2015/16	2
Feature Dip (°)	Brunton Compass	2015/16	2

The sampling methods, lichen identification, and survey structure followed the methods discussed in Chapter 4 (pg.30). During traverse, the colonisation of micro-topography by

lichens was surveyed in order to investigate their microhabitat preference. As seen in Figure 20 and Figure 21, the sampling strategy differed between Vesleskarvet and Robertskollen. Lichen presence was recorded every ~10m along the traverse. Traverses across Vesleskarvet were completed ~80m apart in a north-south direction (vertical lines of grid), and produced 111 lichen samples. At Robertskollen, two sites were traversed. Four transects at ~10m intervals were carried out on the northwest-facing spur of Cairn Peak, which produced 15 samples, but did not follow any grid square points due to its small area. Transects were run in a north-south direction, and sample points were generated when necessary. Traverses across Ice Axe Peak differed slightly in that they ran in a west-east direction due to the uneven topography of the nunataks. 35 sample points were generated from three transects, ~50m apart from each other. Despite variation in the sampling strategies at each site, results are not compromised as procedures were followed consistently throughout data collection (refer to Chapter 4, Pg. 31).

Table 6 summarises the data recorded at each sample point. The long, short and intermediate axes of rocks (hereafter referred to as axes a, b and c) were measured, which classified rocks into either blades, rods, spheres or discs (Briggs 1977). However, these data were retrieved in 2010/11 and 2011/12 by Hansen (2013). During traverse, lichens were examined for colonisation of micro-topography, and the substrate type was recorded, which gave an indication of habitat preferences. Additionally, the presence of snow was observed. Snow offers a source of moisture for lichens, and although it is a transient environmental parameter, its presence indicates that *in situ* moisture is available to surrounding lichen colonies – even if only during the summer months. This is somewhat related to rock support, which was observed and classified as ice-, rock- or mixed-supported (Hansen, 2013). Orientation and dip data were used to identify any preference of aspect and angle of descent in habitats.

#### Microhabitats

As part of Objective 2, the study aimed to determine the morphology, topography and characteristics of colonised rocks (Objective 2, pg.4). To achieve this, data for rock dimensions, face hardness, lichen presence, face orientation, face dip, rock support and presence of snow were measured/observed.

Sampling locations were selected based on lichen abundance and accessibility. Results from Dwight's (2014) study revealed higher abundance and species diversity at the tip (most northern section) of the northern buttress of Vesleskarvet. Coupled with the areas' accessibility from SANAE base, this data designated it a suitable area for sampling at Vesleskarvet. The sampling area at Robertskollen was identified in the 2014/2015 season when visiting the nunataks. At each sampling area, three sites were selected for measuring,

and two rocks were measured in each site: one colonised and one non-colonised. A total of six rocks were sampled at each nunatak location based on the criteria below:

- Rock axes (a, b, c) were to be measured and, therefore, these dimensions had to be accessible (Hansen, 2013);
- All rocks had to be of similar size to ensure consistency in the thermal imaging; lichens have been found to have no preference for rock size in extreme environments (Warren-Rhodes *et al.* 2013) and so this was not considered;
- The two rocks per site were to be within close proximity to each other (within a 3m radius);
- All rock faces were to be accessible for rock hardness measurements and therefore surrounding rocks could not block these faces (Hansen, 2013);
- Where possible, rocks with micro-topographical features were to be selected.

For each selected rock the a-, b- and c-axes were measured. These data were combined with data from Hansen (2013), where the author measured the a-, b- and c-axes of rocks across Vesleskarvet, as well documented rocks that were colonised by lichens. Hardness values of rocks, referred to as rock hardness (or “hardness”), were measured at each face using an Equotip®, which indicates the mechanical characteristics of the material that lichens are colonising. Hardness, according to Kompatscher (2004), is the ability of a material to withstand any deformation when under the pressure of an indenter, in this case the Equotip’s impact device (*in* Hansen *et al.* 2013). The impact device yields a rebound value, or the R-value, that correlates to the properties pertinent to the degree of weathering of the rock’s surface (Sumner and Nel 2002; Goudie 2006; Hansen 2013). A lower R-value will suggest a more weathered surface, based on the expectation that weathered surfaces have a lower mechanical strength, and thus, have poor elastic recovery and decreased hardness (Ericson 2004; Hansen 2013). Orientation and dip were also measured.

Five Thermochron iButtons were placed (at ~1m) around each rock, within a radiation shield, to record high frequency ambient air temperatures (Figure 26). The shield shelters the iButton from direct solar radiation and wind, which would otherwise interfere with the temperature readings (Dwight 2014). Air holes and heat resistant spray prevent shields from developing their own microclimates within. Readings occurred every minute at a precision of 0.0625°C., which was used to investigate temperature as a habitat control.



Figure 26: Radiation shield used in the field. Source: R. Dwight.

For each rock face, micro-topography was detailed (according to Table 5) with the absence or presence of lichens in each feature. The length, breadth and depth were measured using callipers for finer features, and a measuring tape for larger features. The data were used to identify any preference of feature sizes. The orientation and dip of each feature was recorded determine if there was a preference for aspect and angle of descent.

## Data Analysis

### *Environmental Influences*

#### Rock shape

The shape of a rock depends on factors such as its original shape, it's physical and chemical properties, and the extent to which it has weathered (Briggs 1977). Physical and chemical properties of rock, along with lichen colonisation, control different microenvironments and microhabitats (De Los Ríos *et al.*2002). By looking at rock shape, one can speculate on the weathering processes it has been subjected to, which is determined by the physical and chemical properties of the substrate (Briggs 1977). Once colonised, a rock will be subjected to weathering from lichen (Favero-Longo *et al.*2015), which will further alter rock shape. The purpose was to determine whether there is preference for lichen colonisation on specific rock shapes.

A Zingg diagram was drawn to determine the shape index of rocks (Briggs 1977). This involves grouping the data set into four categories based on the rock axes: rods, spheres, discs and blades - using the formula below [3]. Statistical analyses are restricted, as the data is nominal. However, the data indicates a three-dimensional form, which is closely related to structure (Briggs 1977). A preference of rock size was not investigated, given findings by Warren-Rhodes *et al.*(2013), who indicated it is not a controlling factor in lichen colonisation.

$$b/a > 0.67 ; c/b > 0.67 \quad [3]$$

#### Orientation and Dip

As it affects multiple environmental controls, orientation data was analysed for both Vesleskarvet and Robertskollen so as to identify whether lichen presence was influenced by aspect. Recorded measures in the field represent magnetic bearing, which were adjusted to true bearing using magnetic declination and change per year. The relevant declination for each field season was determined for the location (72°S) and time of year (January/February) (National Oceanic and Atmospheric Administration 2016). Following Dwight's (2014) method, a rose plot was created in order to identify preferred orientation and dip at both study sites,

using a freeware package created by Lakes Environmental™, called WRPLOT View™. The package usually presents meteorological data, but to display results for this study, data were inserted appropriately, i.e. aspect data were entered into wind direction and dip values were entered into wind speed.

### Substrate

The same approach for analysing preference of support type was adopted to analyse preference for substrate. During the survey, lichen substrates were recorded as saxicolous<sup>15</sup>, terricolous<sup>16</sup>, muscicolous<sup>17</sup> (Seppelt *et al.*2010). It is known that lichen contribute to paedogenesis (Chen *et al.*2000), however, they have also been found to stabilise substrate formed by erosion, and subsequently retain solid water (Büdel *et al.*2009). Different species of lichen are frequently found colonising certain substrate types (Smith and Wilson 1996). To investigate the preferences of lichens in WDML, a series of pie charts were generated using data from a frequency analysis in Microsoft® Excel.

### Microhabitats

#### Boosted Regression Trees Analysis

To quantify the relationship between lichen absence/presence and the microhabitat environmental variables, a statistical Boosted Regression Tree (BRT) technique was used. This is a relatively new, machine learning, method that uses an algorithm to depict species-environment relationships, during which it assumes complexity in the data-generating process (in this case, the ecology of WDML) (Elith *et al.*2008). The BRT model is superior to traditional modelling methods due to its ability to: handle different types of explanatory variables (meaning data can be categorical, numerical, binomial etc.), accommodate missing data, maintain insensitivity to outliers, and remain unaffected by different scales of measurement among the predictor variables (Elith *et al.*2008). Simply put, these models can fit complex, non-linear interactions or relationships between measured variables. Variables investigated at this microhabitat scale included: temperature (maximum and minimum), dip, aspect, rock hardness, and elevation. Given any limitations in data collection, and the data itself, the abovementioned properties of BRT make it a suitable approach for this analysis.

The model for lichen-environment interactions was fitted in RStudio Version 1.0.44 (RStudio Team 2016), using the generalised boosted regression models (gbm) package from

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<sup>15</sup> Colonising rock.

<sup>16</sup> Colonising soil/finer sediments.

<sup>17</sup> Colonising moss.

Ridgeway (2007). Default settings were used unless otherwise stipulated. To improve accuracy and reduce overfitting, stochasticity was used in the gbm as a 'bag-fraction' of 0.75 (meaning 75% of the data are drawn at random). To improve model performance in presence/absence responses, this fraction is known to produce the best the results (Elith *et al.*2008). Sample size influences optimal settings for BRT models. Therefore, the recommended settings to be modelled involved simple trees (tc=3) and a slow learning rate (lr=0.0001) so as to allow at least 1000 trees (Elith *et al.*2008). Coding followed the ecological modelling tutorial by Elith and Leathwick (2016), as seen in Appendix B.

### Feature Characteristics

Investigation into microhabitats was conducted to further scale down habitat preference. During surveying, the occurrence of lichen in a feature was recorded. These data were used in a frequency analysis for each species, as well as a relative frequency analysis, which displays preference of features at each site and at a species level.

Features with the highest frequency of occurrence were additionally investigated for feature characteristic preferences. The characteristics of each feature were described in terms of length, breadth and depth, with four subdivisions in each category. Contingency tables were produced, placing each measurement under a respective descriptive category of length (shortest, short, long, and longest), breadth (very narrow, narrow, wide, and widest) and depth (very shallow, shallow, deep, and deepest). Categories were calculated based on the first, second and third quantiles in order to divide the distribution of each dataset into equal groups (Appendix C)

The tables developed above were used to test the significance of observed trends. A chi-squared test statistic [4] was used in conjunction with a Fisher's exact test, which compensated for cells that had frequencies lower than five. In the chi-square formula below, "o" is the observed value, "E" is the expected value, and "i" is the position in the table. For Fisher's exact test, the exact probability is calculated for observed cell frequencies. The data does not incorporate cover or size of lichens. Rather, frequency of occurrence for various micro-topographical features is incorporated, which makes this a suitable approach towards identifying any preference of feature characteristics (i.e. length, depth and breadth).

$$c^2 = \sum_{i=1}^k \left[ \frac{(O_i - E_i)^2}{E_i} \right] \quad [4]$$

## Results and Discussion

### Environmental Influences

#### *Rock shape*

The Zingg diagram (Figure 27) shows that there is no common form of rock shape colonised by lichens. The results represent data from both study sites. Should the sites have been analysed separately, the possibility of identifying any preference would have been hindered due to Vesleskarvet having a predominant rod shape index (typical of jointed bedrock occurring in blockfields) (Hansen 2013). Lichens are known to have no preference for rock size (Warren-Rhodes *et al.* 2013), and these data suggest they have no preference for rock shape either. The results comply with the opportunistic life strategy of lichens (Kappen 1993; Kennedy 1995), indicating that there is another aspect governing their habitat selection, such as surrounding habitat structure (Ryan and Watkins 1989). This advocates the need for finer scale measuring in order to identify any lichen habitat preferences.

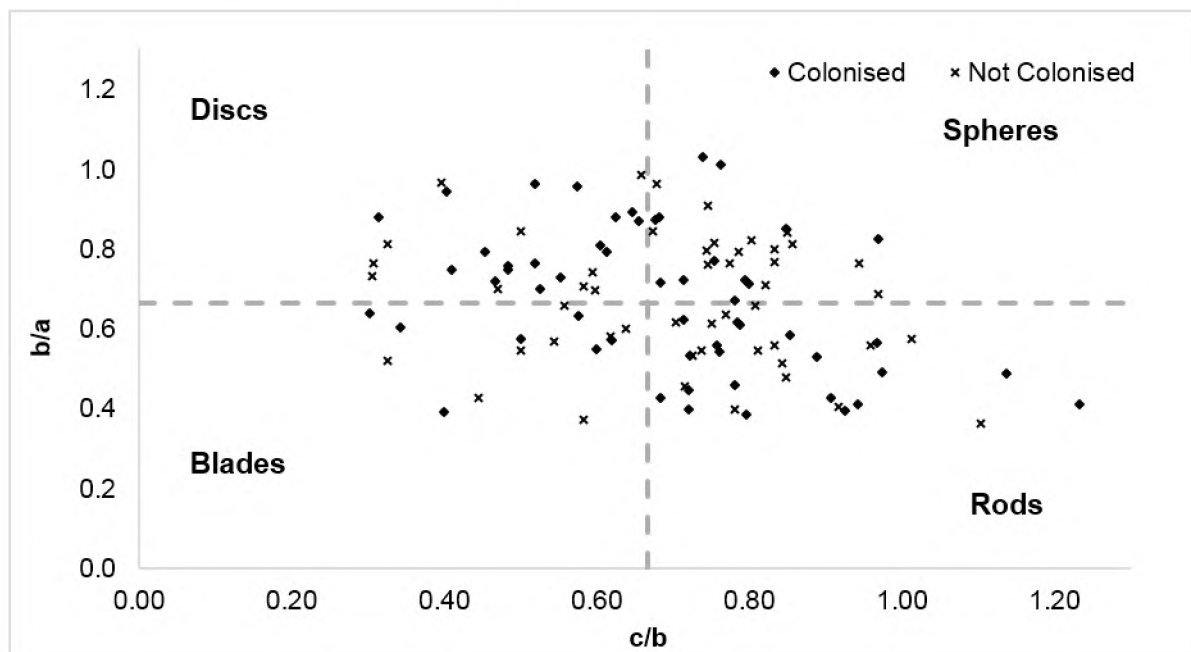


Figure 27: Zingg diagram showing no lichen colonisation preference for rock shape (n=106).

#### *Orientation and Dip*

The results of data from 2009/10 and 2015/16 surveys are presented in a rose plot for simple representation. Orientation data were categorised into eight aspects (Figure 28). The prevalent aspect of colonised rock faces was north-west, with fewer accounts of lichens occurring on southwest-facing rock faces (Figure 28). Dwight's (2014) study, however, found they dominated north- and south-facing rock faces. In contrast, this study's prevalent aspect

findings were similar to results from Hansen (2013), who calculated lichen presence to be greatest on north- and west-facing rock faces. It is known that WDML has its own regional climatic conditions, one of which is the predominant wind from the East (Kärkäs 2004; Hansen 2013). In WDML, the sun is at the highest from the North, which means that north-facing rock faces are exposed to direct, harmful UV radiation. Photosynthesis requires a PAR of 400-700 nanometres, which means lichens, to some extent, have to be exposed to insolation. In conjunction with the predominant easterly wind, this may give reason for lichens favouring northwest-facing rock faces, as they are sheltered from the direct wind, but are still receiving sufficient insolation to photosynthesise. In instances where they colonise the north-facing rock faces, it may be that the species has a mechanism for tolerating UV radiation, e.g. growth form or UV-absorbing compounds (Wynn-Williams and Edwards 2002; de Vera *et al.* 2003). One such species adapted to these extremes are *Usnea* (Ott 2004), which are common in the area.

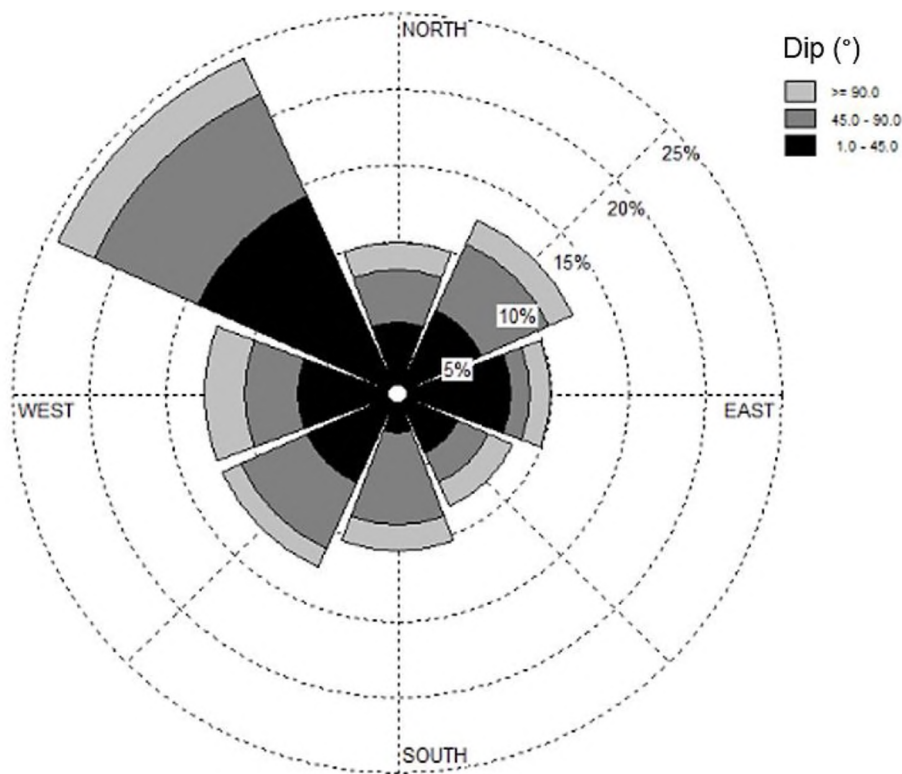


Figure 28: Rose plot representing the orientation and dip of colonised rock faces (n=232).

The preferred inclination of colonised rock faces appears to vary according to the aspect of the rock face. It is evident that any dip exceeding 90° is least favoured for colonisation by lichens. This is due to the fact that cover (protection) decreases with increasing steepness (Ryan and Watkins 1989). Steep angles obstruct solar radiation, meaning lichens receive insufficient insolation. Lichens that colonise any dip greater than 90° tend to be adapted for such conditions, and rely on other controls for growth. *U. sphacelata* was documented

colonising rock faces under overhangs, but its branches extend outward to trap drift snow. An adaptation like this suggests it colonises places where (like *U. decussata*) it can use its structure to take up water from the air, rather than soil (Sancho and Kappen 1989). Evidently, rocks with steep inclinations, surrounding topography or lichen morphological features, must trap drift snow which will make these steeper inclinations suitable for colonisation (by sufficient source of moisture). In macroscale terms, the two nunataks are north-south orientated. Observations indicated that there was greater lichen abundance on these sites compared to the surrounding nunataks, which are orientated differently. For nunataks orientated differently, less direct solar radiation is received due to the low elevation of the sun at midday, which may explain the lower abundances of lichens (Longton 1985).

As found in Dwight's (2014) study, it is likely that colonisation is dependent on aspect-related factors, as well as local surface topography - further highlighting the role of habitat heterogeneity in habitat preference.

### *Substrate*

Lichen communities are influenced by availability of suitable substrate (Gupta *et al.* 2014), but preference for substrate may be species specific. Figure 30 indicates the colonisation of certain substrates is more common in some species than others. Results from the survey coincided with a study in the Himalayas (Alpine environment), where lichens were found to be predominantly saxicolous (Table 7) (Gupta *et al.* 2014). Rocks have larger faces, meaning solar radiation affects a larger surface area. Therefore, saxicolous lichens must depend greatly on solar radiation, indicating a possible strategy adopted by species such as *U. decussata* and *Buellia* sp. A and *Buellia* sp. B (Figure 31).

Table 7: Percentages (%) calculated for lichen-colonised substrates (n=423).

<b>Substrate</b>	<b>Saxicolous (Rock)</b>	<b>Terricolous (Soil)</b>	<b>Muscicolous (Moss)</b>
<b>Count</b>	329	76	18
<b>% of Total</b>	77.78	17.97	4.26

Seppelt *et al.* (2010) found that lichens colonising soil had to be adapted to a less stable substrate, but, for this study, terricolous lichens were found in depressions that were very sheltered from wind and collected moisture (making them somewhat stable). This is directly related to the surrounding macro- and micro-topography, which will determine the exposure of finer sediments to wind. Sediments observed in places that were exposed to wind were not colonised. As expected, where sediment remained static (i.e. in depressions, discontinuities

or micro-topography, e.g. Figure 29 and Figure 35), lichens colonised the loose substrates. These findings coincide with the proposed scenario originally highlighted in (Longton 1985).

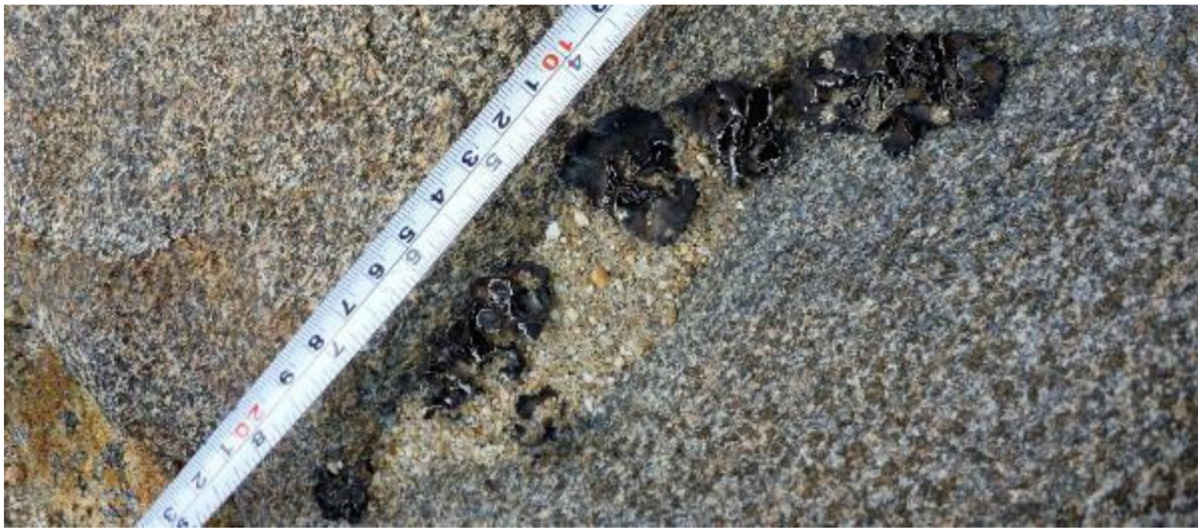


Figure 29: *U. decussata* colonising a discontinuity with loose substrate.

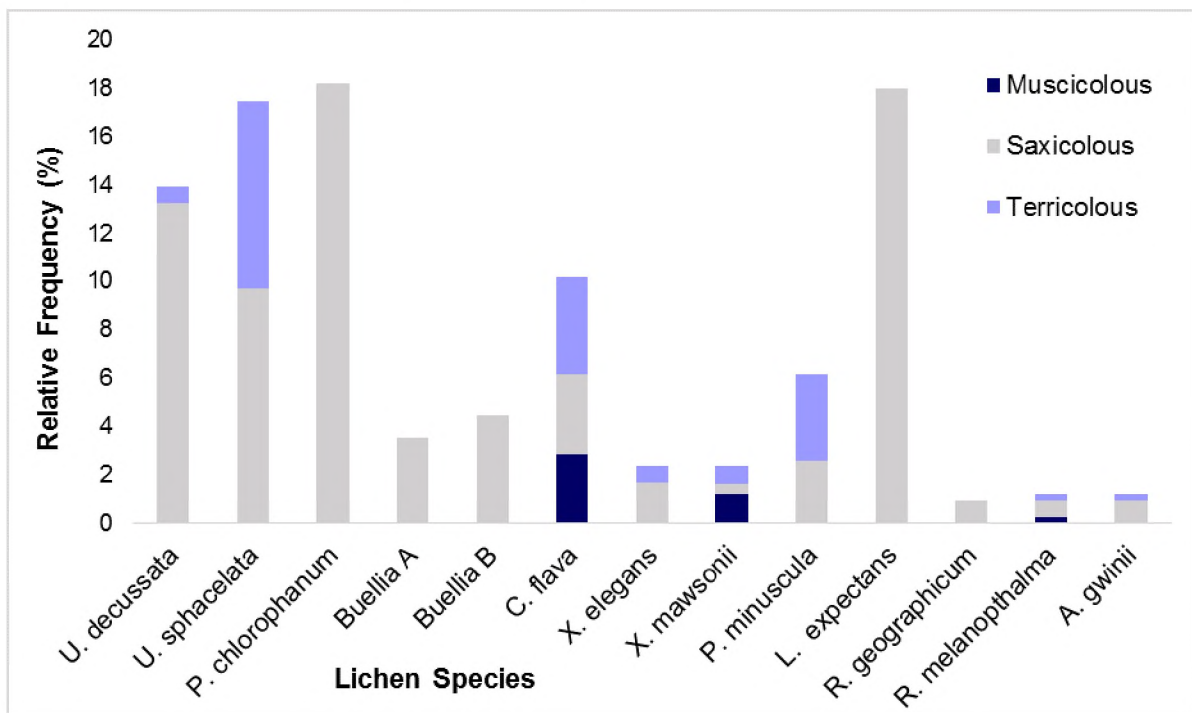


Figure 30: Relative frequency (%) of occurrence for substrate type for documented lichen species.

In instances where lichens colonise moss (or amidst lichens), there is often a relation to greater nutrient availability, supplied primarily by bird colonies (Seppelt *et al.* 1995). An example of this was documented at Robertskollen – a nesting site for Skua and Petrel species (Ryan and Watkins 1988; Ryan and Watkins 1989) - where muscicolous lichens were identified. This suggests that some lichens may require these conditions for successive growth, which is why they are more abundant at Robertskollen. The nutrient availability

promotes plant diversity, which in turn provides suitable substrate types preferred by certain species. For example, Figure 31 shows that 55% of documented *C. flava* lichens were colonising moss. Similar findings were documented for *Xanthoria* species, with approximately a third of their occurrences on moss. These data coincide with classifications by Øvstedal and Smith (2001), giving reason as to why they prefer Roberts skollen as a habitat. A high proportion of *U. sphacelata* was terricolous and possibly epiphytic (44.6%), as it was colonising on and amongst *U. decussata* (Figure 31). This suggests that the species thrives when in association, making habitats inhabited by *U. decussata* colonies, preferable. In addition to nutrient supply, moss (and lichen) temperatures are commonly warmer than the ambient air temperature (especially at night), which reduces frequency and severity of diurnal temperature changes (Longton 1985) – providing a more stable environment for lichens and giving explanation for species associations. The heterogenic nature of Roberts skollen has produced a biodiverse system of multiple feedbacks, giving rise to more substrate types and thus, preferred habitat conditions.

Figure 31 exhibits the preference of substrate for lichen species accounted for. Species *C. flava*, *X. mawsonni* and *R. melanophthalma* appear versatile, with no substrate preference, indicating an opportunistic approach and highlighting that there may be other habitat conditions controlling their colonisation. Most species are saxicolous, with their occurrence on rock constituting the highest frequency, as indicated in Table 7 (77.8%). *Buellia* species, *L. expectans*, *P. chlorophanum*, and *R. geographicum* were found to be saxicolous only. This suggests that these species rely on rock surface availability for colonisation, which may be related to its geology.

Dolerite contains pyroxene (iron, calcium and magnesium silicates) as well as plagioclase (potassium, sodium and aluminium silicates). Diorite has alkali feldspar and amphiboles (calcium, iron, aluminium and magnesium). Both rock types are common in WDML (Krynauw 1986; Groenewald *et al.* 1995). Minerals in substrates influence hyphal penetration and control lichen thallus development (Chen *et al.* 2000). Silicate minerals in WDML, then, are suited to the lichens present as they have the ability to penetrate the rock and detach the mineral fragments from its parent material (Chen *et al.* 2000). Feldspars and calcium are especially known to decrease in concentration when their parent material has been colonised by lichens (Ariño *et al.* 1995). Lichens may, therefore, prefer these minerals as they are more easily broken down, which explains why they are favoured in the extremes (quicker thallus establishment and development).

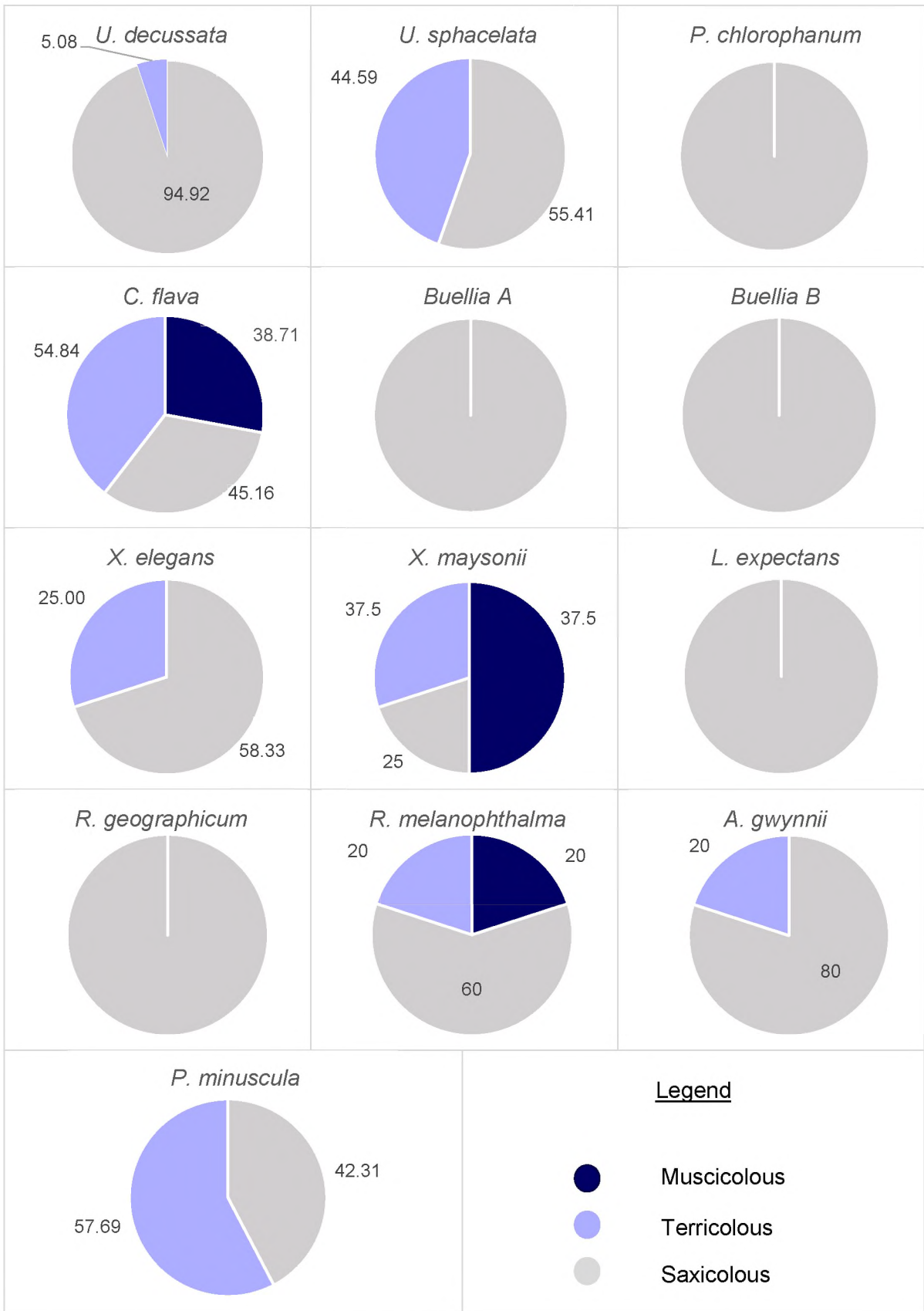


Figure 31: Percentage (%) of substrate colonised by each documented lichen species.

## Microhabitats

### *Boosted Regression Trees Analysis*

Environmental influences for twelve rocks were run through a model to investigate micro-scale habitat preferences for lichens. The simplification procedure indicated dip, minimum temperature and maximum temperature to be the strongest correlates of lichen presence. Dip was presented as the most influential (31.71%), followed by the relative influence of minimum and maximum temperatures at 19.84% and 16.83% respectively (Figure 32). Through 10-fold cross validation, a moderate predictive performance (AUC = 0.594) was suggested, with a low predictive deviance of 11.06% (Table 8).

Table 8: BRT model performance of lichen presence/absence.

Number of Trees	Deviance				Correlation		AUC	
	Null	Residual	se	Percent	Cor	se	auc	se
nt								
4400	1.383	1.222	0.014	11.06	0.143	0.091	0.594	0.042

Fitted functions from the BRT model indicate that lichens prefer dip values  $< 50^\circ$ , temperatures ranging from  $-9.5^\circ\text{C}$  through to  $\sim 8^\circ\text{C}$ , and lower hardness values (weathered surfaces) (Figure 32). The inclination of a rock surface, as previously discussed (pg.51), will influence the amount of solar radiation it receives, which explains why steeper faces are preferred by lichens. It is recognised that temperature is a determining factor in lichen colonisation (Kappen *et al.* 1998; Øvstedal and Smith 2001), as explained in the results of the model (Figure 32). This means that microhabitats, which maintain optimal temperatures, will be preferential sites of colonisation. Moisture, although temperature dependent, is also influenced (pg.61). Meltwater runs of an inclined rock faces. Lichens (e.g. *U. decussata*) in arid environments are adapted to uptake moisture from the air/snow rather than meltwater due to the inhibition of photosynthesis when saturated, which further explains why inclined preferences are preferred. The results from the study coincide with those from Dwight (2014), which showed that minimum temperature was a significant control on lichen distribution. It highlighted that maximum temperature also influences lichen, but to a lesser extent. This study reflected Dwight's (2014) findings, with minimum temperature influencing lichen colonisation 3% more than maximum temperatures (Figure 32), and proposed the reason for minimum temperature having the greatest influence due to its control on snowmelt and sublimation of the active layer.

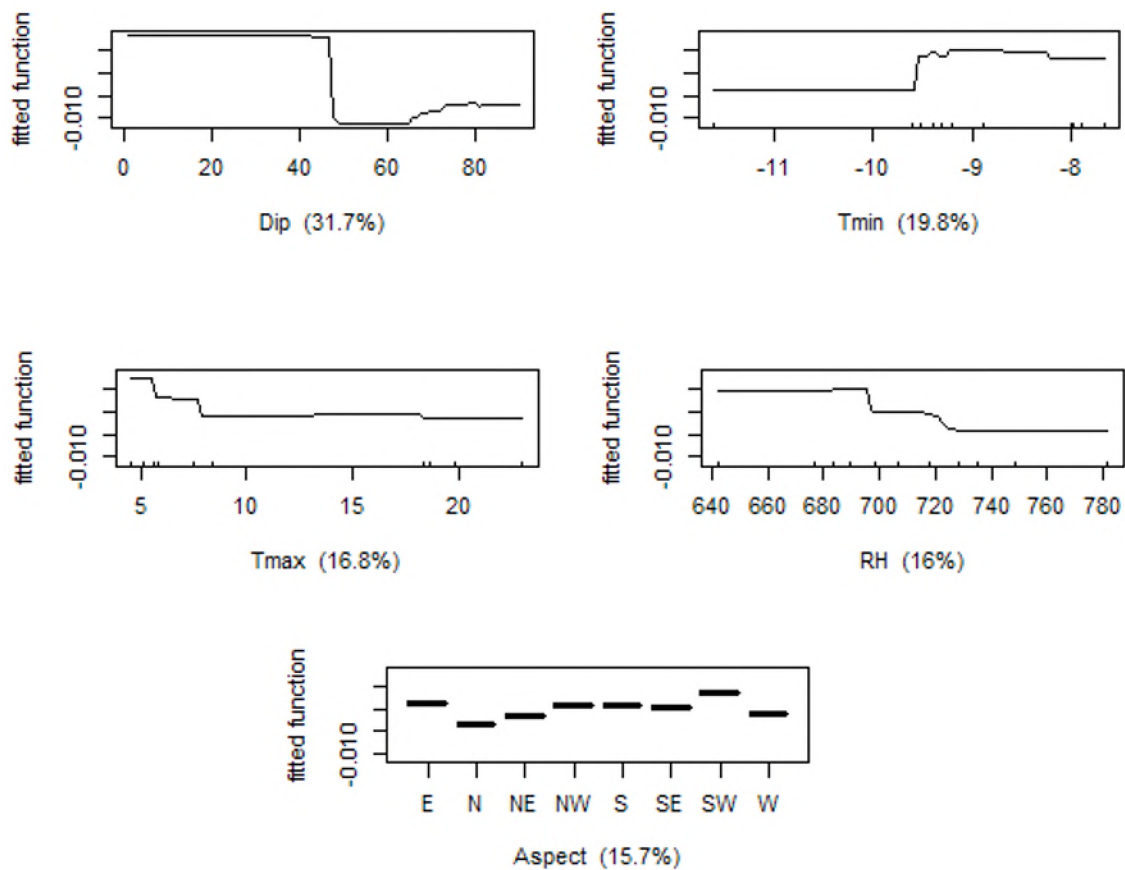


Figure 32: Lichen response curves showing the functions fitted for the most important influences on lichen presence by a boosted regression trees (BRT) model.

Lower rock hardness values (R-value < 730) are more suited to lichen colonisation. These measurements indicate a more weathered surface (Ericson 2004; Hansen 2013), which means that the rough rock faces provide a heterogenic texture and, therefore, more points of attachment for spores (Miller *et al.*2012). The same habitat heterogeneity hypothesis (Chapter 4, pg.29) is suited here, but relative to the rock surface (a much finer scale). Surface roughness also alters wind speed and consequently influences the trapping of drift snow (Schroeter and Scheidegger 1995; Cannone and Guglielmin 2010). It can then be assumed that the more weathered a rock surface (lower R-values), the more preferable it is for colonisation, as trapped drift snow provides a moisture source for thalli.

Contrary to studies that found aspect to be a critical influence on lichen distribution (e.g. McIlroy de la Rosa *et al.*2013; Dwight, 2014), the simplified BRT model indicated that aspect had the lowest influence on lichens (15.7%) (Figure 32). The two sites for this data collection have a north and north-east aspect (Dwight 2014), which coincides with the results in this study. It can then be presumed that local macroscale topography controls the influence of aspect on lichen colonisation, which is why aspects at a microhabitat level are marginal in habitat suitability and preference. This inference is plausible considering that the sun orients

around rocks during summer months, meaning every rock face receives solar radiation, unless the surrounding topography obstructs it.

#### *Lichen Habitat Preferences for Rock Surface Discontinuities*

Lichens have been documented in small, protected niches or micro-topography since early Antarctic expeditions. In this study, lichen presence was characterised by its micro-topography to investigate preference of certain niche types across species. A frequency analysis showed that lichens colonise a variety of micro-topographical features (Figure 33), which emphasises their opportunistic occupation of discontinuities, but also indicates their preferred type. Each feature offers a set of environmental and geomorphic controls that influence its suitability as a habitat for particular species of lichen, which is why lichen species have their own preferences (Figure 36 and Figure 37).

Features frequently colonised by lichens include cracks, flakes and flat surfaces (Figure 33). However, in instances where lichens colonise rock surfaces, they were sheltered by surrounding topography. This was seen at Robertskollen in particular (e.g. Figure 34) due to the topographic heterogeneity providing a number of suitably sheltered niches for lichens (Figure 37). The results from the frequency analysis show there is greater proportion for rock surface colonisation (25%) at Robertskollen (Figure 33). A t-test compared surface colonisation between the sites, showing that lichens favoured surfaces at Robertskollen ( $p < 0.05$ ). As expected, lichens on Vesleskarvet prefer to colonise features that shelter them from the harsh elements (e.g. cracks = 25% and flakes = 24%), since the homogenous topography does not provide these depressions or protected niches across the nunatak (Figure 36).

Results from Chapter 4 (pg.36) suggest that Vesleskarvet is limited in terms of habitat suitability and it, therefore, has a lower species diversity index. Figure 36 displays its low species diversity, and identifies two dominant lichens (*P. chlorophanum* and *L. expectans*). 19% of *P. chlorophanum* colonised flakes, and 16% colonised cracks. This coincides with Øvstedal and Smith's (2001) account for the species forming small colonies in fine fissures and shaded spaces. In instances where *P. chlorophanum* colonised the rock surface (5%), the surface was sheltered (e.g. Figure 9, pg.15) The occurrence of this species at Robertskollen was much lower, forming only 1.3% of total lichens (Figure 37) in comparison to Vesleskarvet, where it contributed 45% of lichens (Figure 36). These results support Chapter 4 outcomes such that the homogenous landscape of Vesleskarvet (pg. 35), limits the establishment and abundance of various lichens.

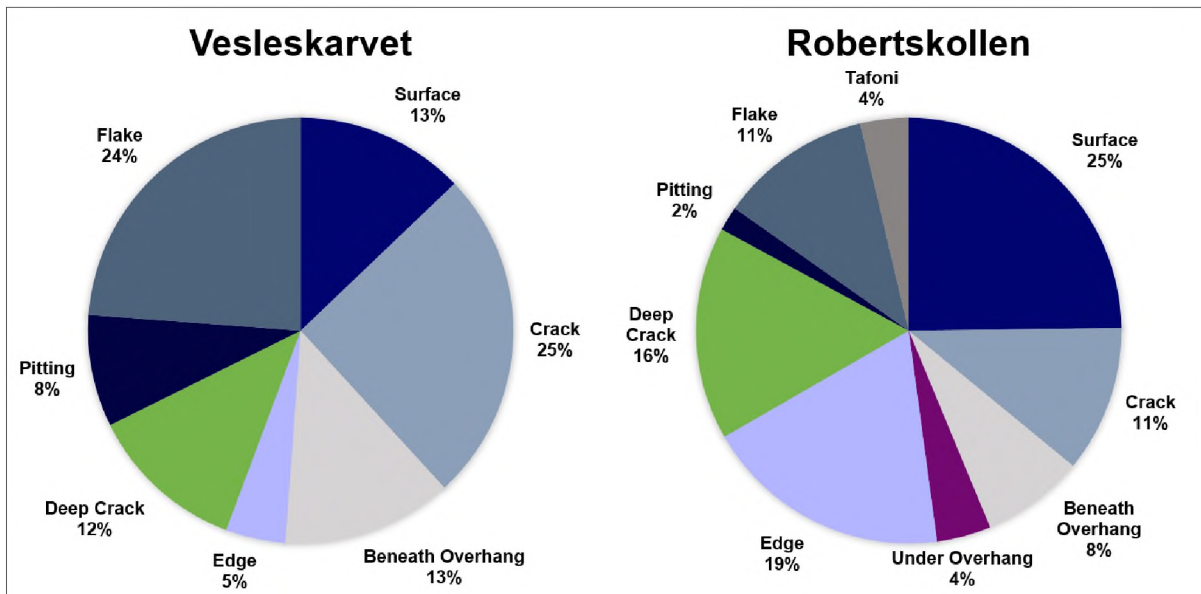


Figure 33: Percentage (%) of lichens colonising micro-topographical features at Vesleskarvet (n=334) and Robertskollen (n=526).

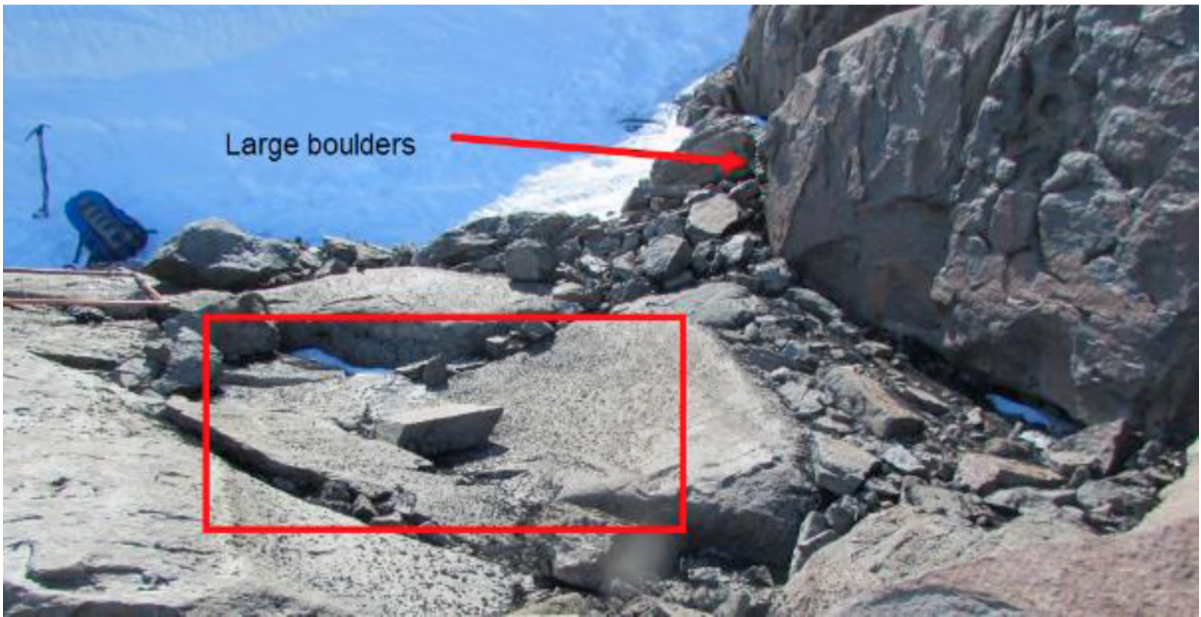


Figure 34: Sheltered niche on Cairn Peak, Robertskollen.

Figure 37 offers a visual representation of the higher species diversity measured at Robertskollen in Chapter 4 (pg.36). It shows presence (and abundance) of species types, each with more than one preferred micro-topography. *P. minuscula* and *U. decussata* were found in all nine features (Figure 37), supporting the assertion that these species are more opportunistic than others, but also highlighting their ability to tolerate various environmental factors. The morphological structure of *U. decussata* makes it more suited to colonise features that have greater humidity levels and protect them from contact with snow (Sancho and Kappen 1989). The species is found colonising all features, as the immediate surrounds

influence these conditions. Features such as rock fractures, under/beneath overhangs and rock surfaces had the greatest abundance of *U. decussata*. Steep faces or overhanging rocks prevent direct contact with snow, which is a limitation to the species. In addition, their photosynthetic activity is adapted to cold temperatures (Sancho and Kappen 1989), further explaining their higher occurrence in more exposed features: flakes, cracks and rock surfaces (Figure 37).

The results display how habitat exposure is a primary factor in habitat preference; complementing results from Ryan and Watkins (1989). It is evident that at both sites, lichens prefer to colonise micro-topographical features (Figure 36 and Figure 37). Reasons for this characteristic habitat selection by lichens can be ascribed to exposure and, especially moisture availability; since lichens can only photosynthesise when moist (Bjelland 2003). The environmental (microscale) conditions in features are influenced by macroscale factors (discussed earlier), but it is important to note that small spaces trap drift snow, shield wind and maintain moderately stable temperatures. Some features will vary accordingly to these elements of exposure. For example, tafoni (with distinctive visors) provide hollows that effectively protect from wind, catch snow and form favourable niche pockets (e.g. Figure 35).

Interestingly, such features tend to gather weathered sediment, which is known to consist primarily of minerals and, more importantly, retain moisture (Lindsay 1972). This explains why such a feature is favoured by some lichens (Figure 37). Vesleskarvet has less tafoni than Robertskollen, observed only on a small section of the northern buttress. Colonisation of tafoni at Robertskollen demonstrates how surrounding topography plays a role in habitat preference. It indicates that a more heterogenic habitat promotes colonisation, and explains higher species diversity at Robertskollen (Chapter 4, pg.36).

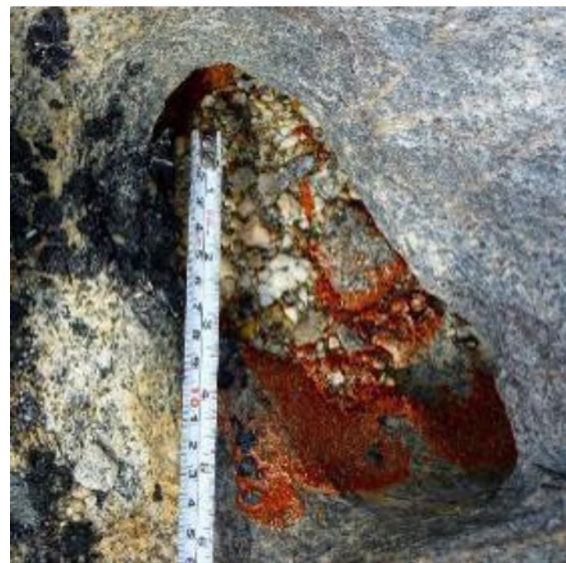


Figure 35: Tafoni with favourable habitat conditions for lichens.

Some features will be favoured for different characteristics, separate to those discussed above. Features that are more exposed to the extreme elements, such as flakes, are expected to be uninhabited, but results show them to be one of the favoured habitat sites. This implies that the features have other characteristics that are favoured more, and by more species, which can be seen in Figure 36 and Figure 37. It explains why flakes at Vesleskarvet, a recurring feature, are colonised: their availability and suitability for many species make it a

preferred habitat site (Figure 36). When fragments of rock break away, a rough, textured surface is left behind. This gives opportunity for attachment of spores, and provides fine crevices for hyphae to penetrate, allowing for the rapid establishment of a thallus. Rocks on Vesleskarvet exhibit case hardening (Hansen *et al.* 2013). Consequently, the availability of planes of weakness - typically suitable for colonisation - is reduced (Favero-Longo *et al.* 2015). Flakes, a common feature on Vesleskarvet (Hansen 2013), are then colonised for reasons previously discussed.

Synonymous with multiple studies in the region (e.g. Ryan *et al.*, 1989; Steele and Newton, 1995, and Dwight, 2014), most lichens were found inhabiting cracks. Cracks accumulate drift snow and are shaded from direct insolation. This serves preference for moisture availability due to lower evaporation rates, yielding a suitable habitat condition. Rock fractures are more sheltered, but some lichens may prefer colonising finer, surface cracks, e.g. *P. chlorophanum* and *Buellia* sp. B (Figure 36). Øvstedal and Smith (2001) describe this as the characteristic habitat type for *P. chlorophanum*, which is supported by these results. Smaller cracks act as runnels for meltwater (from drift snow), and in most cases, are less shaded. These features, then, are preferred by lichens tolerant of insolation. Observations in the field supported this assumption, with exposed crack-colonising species appearing desiccated, suggesting that the lichens were either damaged by insolation, or in a desiccation-tolerant stage (Kappen 1993; Bargagli 1999).

It is evident that lichens are opportunistic colonisers of landscapes; inhabiting spaces that are suited to their morphological structures, adaptive mechanisms and life strategies. The only species that appears to colonise micro-topography irrespective of exposure was *B. frigida* - a repeated observation across the literature (e.g. Seppelt, 1995), however, this is suggestive that the species absorbs moisture from saturated air (Longton 1985). Micro-topographical features exist as stable microenvironment/niches suitable for lichen colonisation, but such environments are governed by macroscale environmental conditions, which ultimately control the colonisation of such landscape features. Preference of features appear to be species-specific, however, this is dependent on the species' morphological and physiological adaptations.

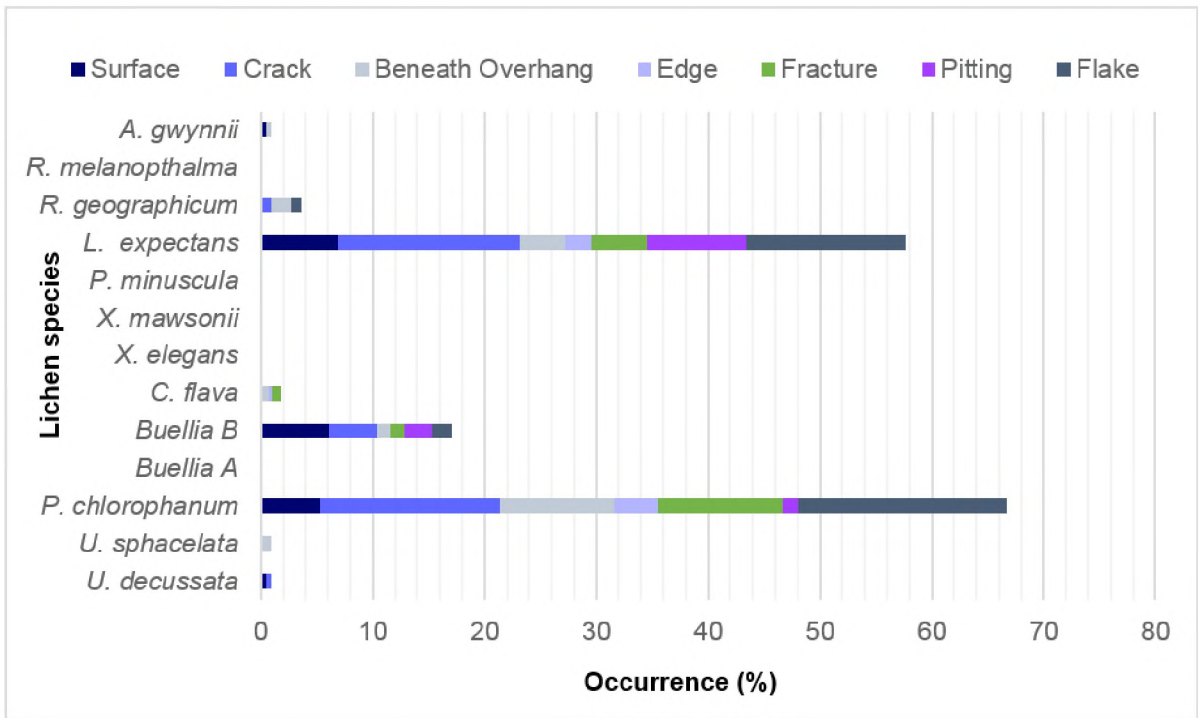


Figure 36: Relative frequency (%) of micro-topography colonised by lichen species at Vesleskarvet.

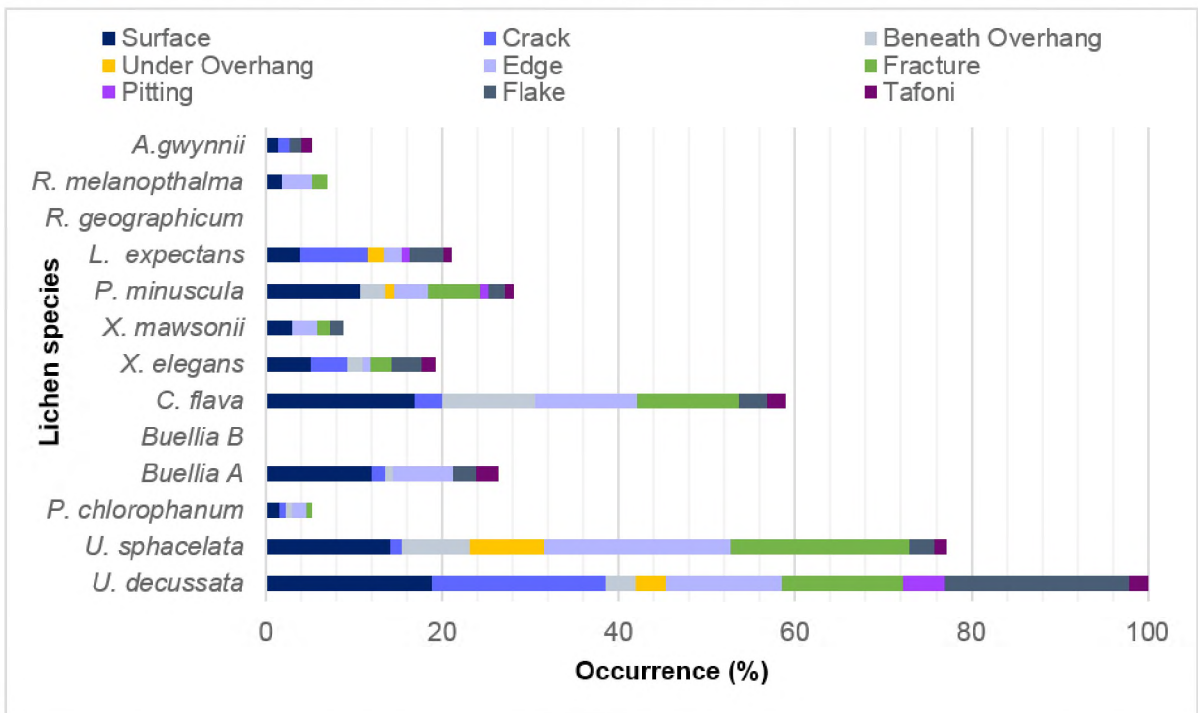


Figure 37: Relative frequency (%) of micro-topography colonised by lichen species at Robertskollen.

### Feature Characteristics

Cracks and flakes are two preferred micro-topographical features, and are therefore recurrently colonised by lichens. These features offer suitable environmental conditions (for reasons earlier discussed), but both features' geomorphic characteristics vary greatly across the landscape, particularly in size. Preference for sizes is investigated and discussed to assess what geomorphic processes may be influencing colonisation of these two features.

Table 9: Calculations for chi-squared test on contingency table of lichen presence in cracks.

<b>Length</b>	Size Interval (cm)	<b>Long</b>	<b>Longest</b>	<b>Short</b>	<b>Shortest</b>
	Absent	0.004	0.496	1.184	0.201
	Present	0.005	0.55	1.314	0.222
	Total	0.009	1.046	2.498	0.424
	Chi-square (Observed value)	3.976			
	Chi-square (Critical value)	7.815			
df = 3; p = 0.26; n = 116					
<b>Breadth</b>	Size Interval (cm)	<b>Narrow</b>	<b>Very Narrow</b>	<b>Wide</b>	<b>Widest</b>
	Absent	1.0355	0.037	0.522	0.332
	Present	1.147	0.041	0.579	0.368
	Total	2.182	0.078	1.102	0.700
	Chi-square (Observed value)	4.062			
	Chi-square (Critical value)	7.815			
df = 3; p = 0.25; n = 116					
<b>Depth</b>	Size Interval (cm)	<b>Deep</b>	<b>Deepest</b>	<b>Shallow</b>	<b>Very Shallow</b>
	Absent	0.659	0.350	1.039	0.332
	Present	0.731	0.389	1.152	0.369
	Total	1.390	0.739	2.191	0.701
	Chi-square (Observed value)	5.021			
	Chi-square (Critical value)	7.815			
df = 3; p = 0.170 ; n = 116					

Results of the chi-square test on presence/absence of lichens in various lengths, breadths and depths of cracks are shown in Table 9. In all cases, the observed values of 3.976 (length), 4.062 (breadth) and 5.021 (depth), are below the critical value of 7.815. At  $\alpha = 0.05$ ,  $H_0$  (described under Feature Characteristics, Page 10) cannot be rejected. This accepts that size classes are not independently colonised by lichens, suggesting lichens do not have a preference for crack sizes. Cyanobacteria, algae and (lichenised) fungi have a chasmoendolithic<sup>18</sup> life strategy to protect them from excessive temperature, radiation and

<sup>18</sup> Crack-inhabiting

drought (Favero-Longo *et al.*2015). These organisms reportedly colonise igneous and sedimentary rocks in all environments, including cold deserts and periglacial environments (Gorbushina 2007; Favero-Longo *et al.*2015). The premise is, therefore, that that finer cracks (narrow and shallow) are preferred over wider ones and have a higher occurrence of lichen growth. Results show a higher chi-square calculation for presence of lichens in narrow (1.147) and shallow (1.152) cracks, but no preferred sizes are observed Table 9; possibly a consequence of inadequate amounts of data – a common limitation in Antarctic research.

Table 10: Calculations for chi-squared test on contingency table of lichen presence in flakes.

<b>Length</b>	Size Interval (cm)	<b>Long</b>	<b>Longest</b>	<b>Short</b>	<b>Shortest</b>
	Absent	0.000	0.884	1.081	0.024
	Present	0.000	1.534	1.875	0.042
	Total	0.000	2.418	2.956	0.066
	Chi-square (Observed value)	5.439			
	Chi-square (Critical value)	7.815			
df= 3; p-value= 0.142; n=93					
<b>Breadth</b>	Size Interval (cm)	<b>Narrow</b>	<b>Very Narrow</b>	<b>Wide</b>	<b>Widest</b>
	Absent	0.039	0.174	1.332	0.884
	Present	0.068	0.301	2.311	1.534
	Total	0.108	0.475	3.643	2.418
	Chi-square (Observed value)	6.644			
	Chi-square (Critical value)	7.815			
df = 3; p-value= 0.084; n=93					
<b>Depth</b>	Size Interval (cm)	<b>Deep</b>	<b>Deepest</b>	<b>Shallow</b>	<b>Very Shallow</b>
	Absent	0.174	0.024	0.066	0.622
	Present	0.301	0.042	0.114	1.079
	Total	0.475	0.066	0.179	1.700
	Chi-square (Observed value)	2.420			
	Chi-square (Critical value)	7.815			
df= 3; p-value=0.490; n=93					

Matthews and Owen (2008) described lichen as clearly visible and present along flake margins of rocks from a recently exposed glacier in Jotenheimen, Norway. In their conformity, lichens were consistently found colonising rock flakes on Vesleskarvet and Robertskollen. Studies elsewhere have shown that lichens prefer colonising certain sized flakes, particularly deeper flakes (e.g. Mol and Viles, 2012). The results from this study were similar, with greater occurrences in deeper flakes. However, there was no significant difference between the size intervals. This was tested, in conjunction with preferences of length or depth, at significance of 0.05 ( $\alpha$ ).  $H_0$  (described under Feature Characteristics, pg.48) cannot be rejected, since the

observed values of 5.439 (length), 6.644 (breadth) and 2.420 (depth) are below the critical value 7.815 (Table 10).

Although no significant difference exists between the size classes of cracks and flakes, higher and lower observed values do give some indication of preferences. Depths of cracks appear to have the greatest influence on their preference (observed value of 5.021), which differs from flakes, where breadth was shown to have the greatest influence (observed value of 6.644) (Table 9 and Table 10). Deeper cracks provide more shaded environments for lichens and broader flakes increase the availability of rough surfaces. Thus, greater opportunity for thallus establishment exists.

## CHAPTER 6: RELATIONSHIPS BETWEEN ROCK, SURFACE TEMPERATURE AND LICHENS

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This chapter details the discussion of results and methodologies of Objective 3 (Chapter 1, pg.4). The relationship between rock surface temperature and lichen colonisation are investigated using two-dimensional, thermal imagery.

### Introduction

A number of studies indicate that environmental temperature influences distribution and/or the diversity of lichens (e.g Dwight 2014; Gupta *et al.*2014), but it is not likely to influence their habitat selection (Nash 2008 *in* Anstett and Coiner 2010). With climate change becoming a global issue, it has triggered recent research into the impact of global warming and changing temperatures on lichen communities, especially Antarctic communities (e.g. Kennedy 1995; Hughes 2000; Sancho *et al.*2007). Despite substantive research, there has been little focus on the effect surface temperatures on lichen colonisation. Geomorphological research that considers surface temperature and lichen interactions exists as investigations into weathering and bioprotection (e.g. Carter and Viles 2003).

Viles and Pentecost (1994) suggest that lichens increase rock surface temperature (RST), which coincides with remote sensing studies of Satterwhite *et al.*(1985) and Ager and Milton (1987), who showed that reflectance properties were found to alter surface temperature and in response, lichen colonisation (*in* Carter and Viles 2004). RST will, however, vary according to a number of factors; Jenkins and Smith (1990) categorise these factors into two categories. The first are the rock properties (i.e. albedo, thermal conductivity, heat capacity and moisture content) and the second are climatic and meteorological controls at different spatial scales (i.e. solar radiation, cloud cover, wind conditions, ambient air temperature and relative humidity). This explains why RST has been used as a proxy for sun exposure (e.g. Anstett and Coiner 2010).

The use of thermal imaging cameras can be applied to monitor and map (using GIS) thermal changes in rock (McIlroy de la Rosa *et al.*2013). Using the same concept, thermal imagery can be used to monitor and map thermal changes, and the relationships of microhabitats and the lichens colonising them. Although ambient air temperatures may be below freezing, solar radiation can heat up rocks to biologically favourable temperatures (Friedmann 1986), which suggests that microhabitats may offer warmer microenvironments irrespective of air temperature. This highlights the importance of studying thermal regimes in microhabitats: to extend investigations on previous studies that have taken only air temperature into account

(e.g. Dwight 2014). Studies on the influences of surface temperature on lichen colonisation have shown that moisture affects rock face temperatures as well as the internal rock temperature - particularly when certain lichen species absorb water - creating a buffer system from UV radiations (e.g Carter and Viles 2003). This, however, may not be as influential in continental Antarctica due to the harsh conditions of aridity.

The purpose of this objective was to investigate relationships between measured rock surface temperature, surface micro-topography and lichen colonisation. Images and thermal photography display associations between these factors, and were used to assess the interactions.

## Methods and Materials

Preliminary data collection was completed during the 2014/15 summer season. Data assessed in this objective, was collected during the final 2015/16 summer season. Sampling remained consistent throughout data collection unless otherwise stipulated. To reiterate, specifications for equipment referred to, can be found in Appendix A.

### Data Collection

#### *Thermal Imagery*

Using a Forward Looking Infrared Radiometer (FLIR) E8 handheld camera (FLIR® Systems, Wilsonville, OR), the images of 12 rocks (6 in each Study Site, Figure 20 and Figure 21) were captured at eight hour intervals during a 72-hour period. The FLIR E8 (Figure 38) was used for its ability to capture calibrated temperatures in images that can be viewed and processed at a later stage. The selection criteria of the 12 rocks can be viewed in Chapter 5 (pg.44), under Microhabitats. RST can rapidly fluctuate due to short term-insolation interruptions, such as cloud passage and wind (Carter and Viles 2003). To minimise interruptions on thermal readings, images were captured during three days of good weather. Readings in the field were standardised by setting the camera at a 1m alignment distance. Ground reference points around the rock at different angles (at ~1m distance) were marked for placement of



Figure 38: FLIR® camera. Model E8.

the camera's handle base; maintaining similarity across images. A camera mount could not be used due to uneven topography. To minimise bias, images were captured by the same field operator at each 8 hour interval. To supplement thermal imagery readings, high frequency iButton temperature measurements during the same time periods were used (refer to Chapter 5, pg.44) to identify any relationships between RST and ambient air temperature.

Data from Robertskollen were collected between the 19<sup>th</sup> January (22:00) and the 22<sup>nd</sup> January (14:00). The same procedures were carried out at Vesleskarvet between the 24<sup>th</sup> January (06:00) and the 26<sup>th</sup> January (22:00). Due to time limitations in the field and adverse weather, only three days of sampling were possible. Thermal monitoring over three days does, however, give insight into the thermal regimes of single rocks and micro-topography.

### Data Analysis

Images captured were uploaded and processed in FLIR® Tools. Thermal imagery of all rocks can be seen in Appendix D, however, only one rock was investigated for RST-lichen interactions, from which resulting thermal patterns can be expected across the dataset. The examined rock was part of the Vesleskarvet survey and showed colonised micro-topography (Figure 40). The FLIR camera captures each image with its own calibrated temperature scale. In order to compare the rock face (with its microtopographical features), temperatures during the 72-hour period were standardised with the same temperature scale. A maximum of 25°C and minimum of -40°C was set and applied to all images in FLIR® Tools. Spot measurements on the image were used where necessary to retrieve temperature readings.

Air temperature data from the iButtons were downloaded and processed in Cold Chain Thermodynamics from Fairbridge Technologies (Pty) Ltd. Average temperatures were calculated and plotted as a line graph for the 72-hour period (24<sup>th</sup> January – 26<sup>th</sup> January 2016). A bar chart was created to display the average air temperatures recorded at each time interval (06:00, 14:00 and 22:00).

### **Results and Discussion**

Possible relationships between lichens and RST are presented via thermal images (Table 11). A higher quality image of the dominant face (seen in Figure 40) is provided for reference and clarity due to poor resolution reference images captured by the FLIR camera (Figure 38). During the Austral Summer, rock surfaces experience diurnal, but large-scale (up to ~23°C) temperature oscillations (McKay and Friedmann 1985), which can be seen in the results. Sun altitude and angle, in respect to a rock face, will determine its temperature oscillations. In addition to this, rock temperature generally follows changes in ambient air temperature. The

results in Figure 39 below are taken from a single rock on Vesleskarvet, which clearly demonstrates these expected trends in WDML.

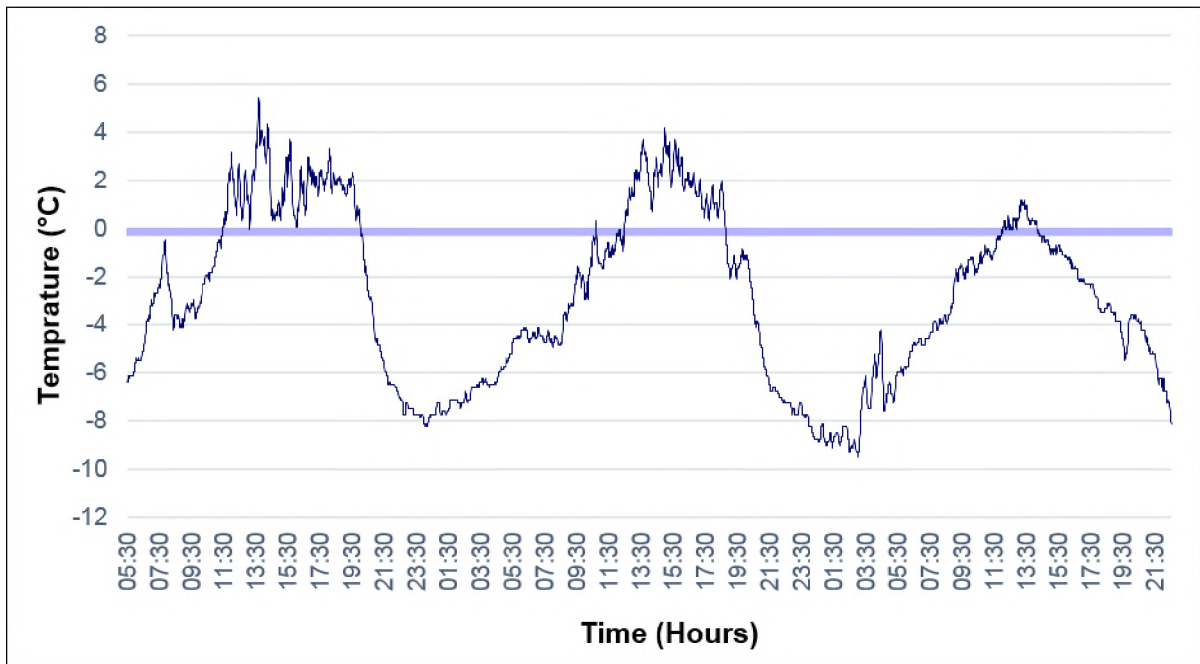


Figure 39: iButton temperature (°C) recordings of a colonised rock with micro-topography from 05:30 on January 24<sup>th</sup> to 22:30 January 26<sup>th</sup>, 2016.



Figure 40: Higher resolution image of the rock face seen in thermal images (Table 11), showing lichen colonisation along flake margins and in cracks, and micro-topographical features (in red).

The rock surface is noticeably warmer than its ambient air; with mean temperatures measured between  $-6.74^{\circ}\text{C}$  and  $3.82^{\circ}\text{C}$  (Figure 41). This trend was also seen in southern Victoria Land (Kappen *et al.*1998), but also in laboratory conditions (Carter and Viles 2004). Air temperatures increased during the day, peaking to  $\sim 5.5^{\circ}\text{C}$  (Figure 39). Warmest conditions occurred between 11:00 and 19:00, which was similar to findings at Granite Harbour in Victoria Land (Figure 3, pg.10), where the highest temperatures were recorded between 13:00 and 19:00 (Kappen *et al.*1998). Sharp declines in this period were likely to be the cause of shading from surrounding topography, cool winds, and passing clouds (Figure 39), especially as the sun orients around the rock – evident in Table 11. The orientation of this insulation explains the low air temperature ( $\sim 6.66^{\circ}\text{C}$ ) (Figure 41), and cooler RST readings at 22:00: when the rock is in shade (Table 11). Shadows resulted in temperatures lower than  $-10^{\circ}\text{C}$  being recorded, which further displays the association between incoming solar radiation and RSTs (Table 11). Diurnal temperature oscillations affect the rock temperature more than its RST, which will fluctuate according to incoming solar radiation (McKay and Friedmann 1985). These oscillations characterise an inconsistent habitat, indicating that only resilient species, such as a *U. decussata* (Figure 39), are suited to them, particularly in continental Antarctic sites with continental climates. Rapid freeze-thaw cycles are an abiotic factor, and are intolerable for most microorganisms, which may contribute to the low lichen abundances (Dwight 2014), and species diversity of WDML (Chapter 4, pg.36).

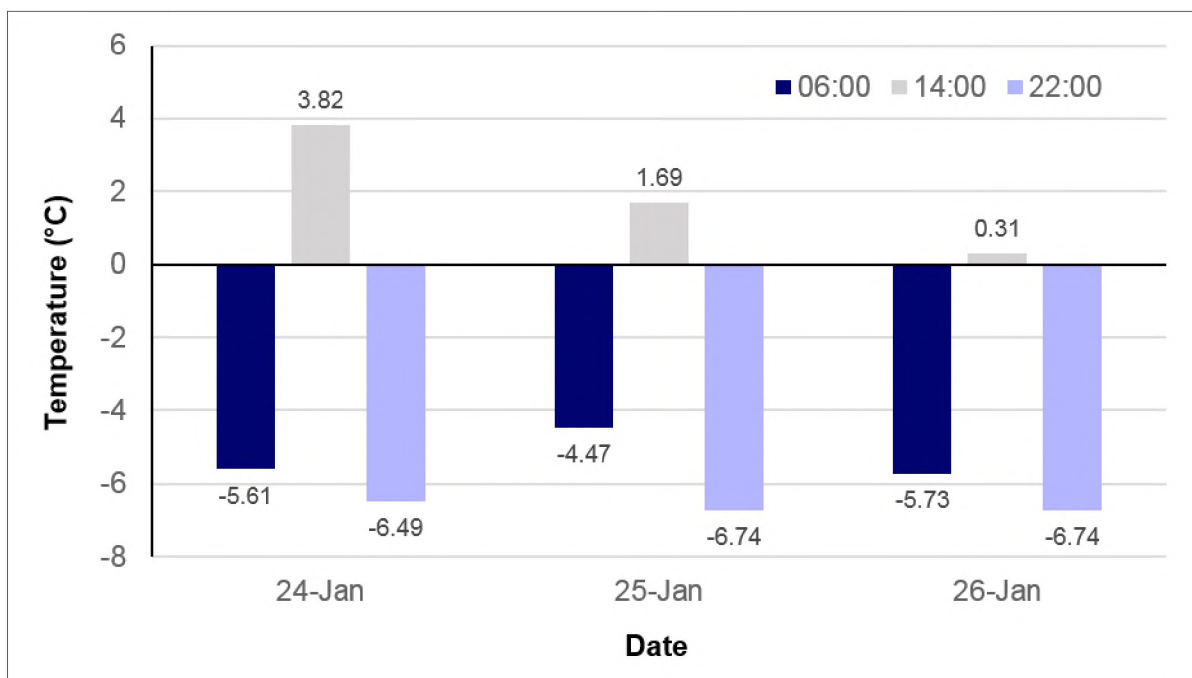
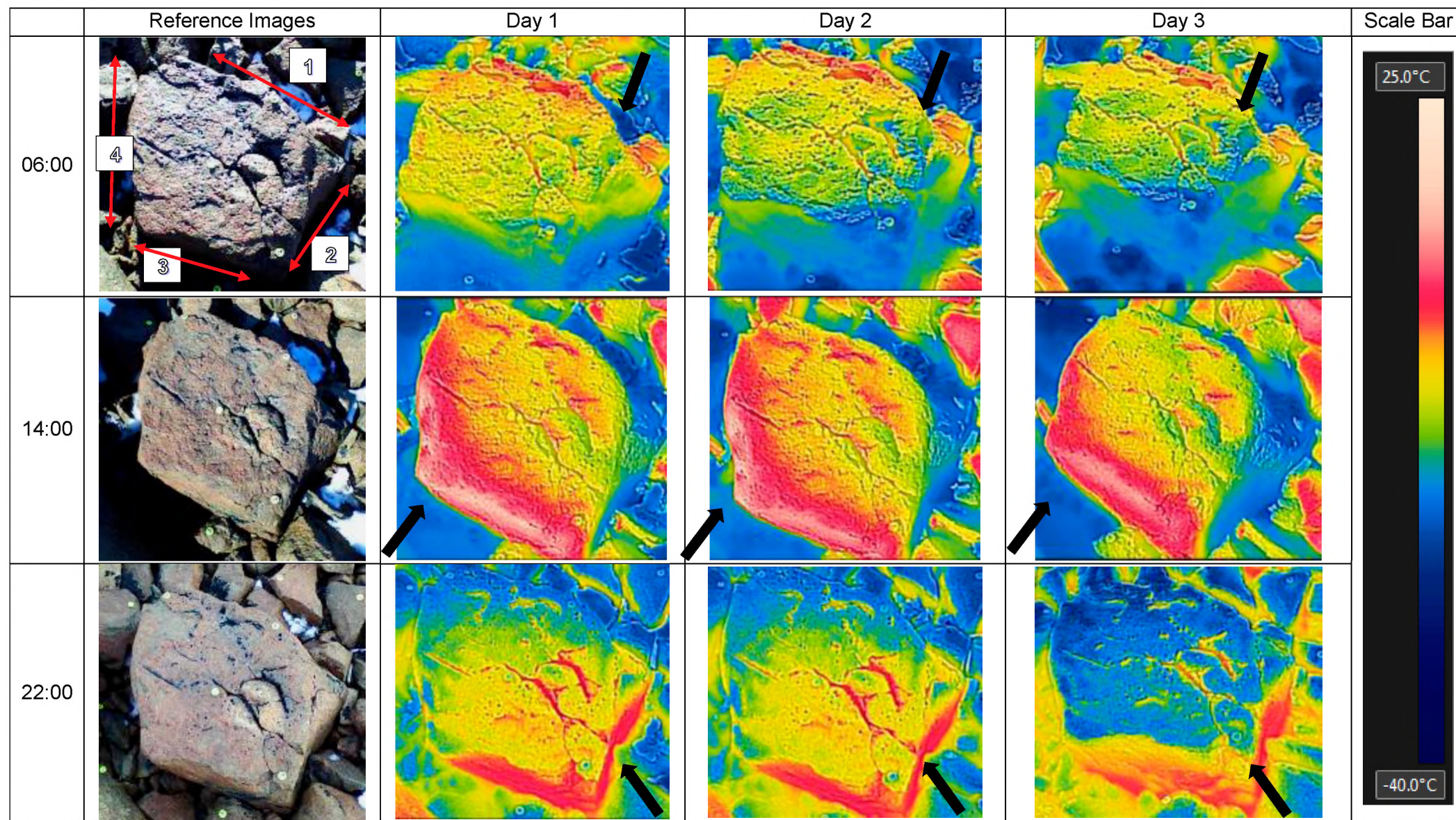


Figure 41: Temperature recorded by iButtons at 8 hour intervals between 24<sup>th</sup> January and 26<sup>th</sup> January, 2016.

Table 11: FLIR imagery showing surface temperature (8 hour intervals) of rock faces and micro-topography between 24<sup>th</sup> and 26<sup>th</sup> January, 2016. Black arrows are used to display the direction of incoming solar radiation and face edges are marked 1-4 for reference in text.



It is evident that RSTs are determined primarily by the solar radiation received – having warmer measurements on surfaces facing the sun (Table 11). Observations show that rock orientation is responsible for RST differences, suggesting that microclimate and the surrounding topography control its temperature (Waragai 1998), which confirms results found in Chapter 5 (pg.55).

Temperature of rounded rock edges (see edge 3,4) receiving direct solar radiation (at 14:00) suggest that rock face shape influences thermal conductivity displayed by the greater extent of warm surface area. Aspect and slope greatly influence thermal conditions (Hall 1999), which is shown in the temperature readings of this irregularly shaped rock (Table 11). It can also be seen at 06:00, when the sharper edge (1) receives direct solar radiation and warmer temperatures do not extend across the surface area (Table 11). Rounded edges yield larger surface angles that face the sun, allowing heat to transfer through and across the rock surface. Sharp edges have acute angles, limiting surface area and, thus, reducing thermal conductivity. Although the readings (of edge 3) display warmer temperatures across a greater surface area, temperatures drop considerably from  $\sim 15^{\circ}\text{C}$  to  $\sim -17^{\circ}\text{C}$  in a day, showing that these surface features experience extreme diurnal RSTs. Given that lichen colonisation appears to be low or nearly absent at this section, it is reiterated that lichens prefer to colonise more stable habitats. Rock shape does not factor in lichen habitat preferences (Chapter 5, pg.49), but the shape of rock faces (i.e. the angularity of edges and features) appears to somewhat influence habitat selection contingent to its level of exposure.

Suitability of micro-topographical features as habitat sites for lichens is reiterated in thermal imagery (Table 11). Flake margins and cracks on the rock face are warmer relative to the surrounding surface: promoting lichen thallus establishment, as discovered in a BRT analysis (Chapter 5, pg.55). More importantly, the features do not exhibit extreme temperature changes in the 72-hour period. Spot measurements on the images indicated that crack temperatures were lowest at 06:00 and 22:00 ( $\sim -11^{\circ}\text{C}$ ) and highest at 14:00 ( $\sim 9^{\circ}\text{C}$ ) - showing mild temperature conditions. Contrary to this, exposed surface temperatures experienced larger temperature differences, with a low of  $\sim -15^{\circ}\text{C}$  (22:00) and a high of  $\sim 8^{\circ}\text{C}$  (14:00). Due to their protected environments, micro-topographical features are able retain the heat from adjacent parent rock material, which explains why they remain warm (Table 11), when air temperatures decrease (Figure 39). Table 11 demonstrates that cracks constantly remain warmer than their surrounding rock, indicating that heat may be sourced from the parent material during the day (when temperatures are highest) and is released at a slower rate than its immediate, exposed rock surface. This can be explained by Newton's Law of Cooling whereby the rate of change in temperature is dependent on the difference in temperature between two collections of matter (in this case the rock and ambient air), which will be greatest

where this difference is largest (Hall 1999). Put simply, the rock surface exposed to cooler ambient air temperature will lose its heat quicker than the rock surface within a micro-topographical feature. The same concept can be applied to immediate air temperature conditions of the rock.

Conforming to air temperature trends, RSTs experience short-term temperature oscillations (Table 11), but for different reasons. On Day 3 at 22:00, the rock face appears much cooler than its previous thermal readings. Air temperatures for the day were much cooler (Figure 39 and Figure 41), and winds were experienced during the temperature reading (22:00). Therefore, cool winds interrupt RST heat supply; causing a rapid decrease in temperature (Carter and Viles 2004). The rock surface exposed to a cold wind can be seen to have no lichen colonisation (Figure 40). If it were colonised, lichens would almost certainly desiccate due to wind abrasion, extreme temperature fluctuations and lower moisture availability (Anstett and Coiner 2010). This supports findings in Chapter 5 and explains why they prefer to colonise protected features like cracks and flake margins (Figure 40). To confirm, these conditions are favourable for the following reasons: drift snow is trapped during windy conditions, humidity levels are higher from shading, temperatures are more stable, and exposure to direct harmful UV radiation is reduced. In the late afternoon/evening the temperatures are higher where lichen are on the surface, indicating that they may be regulating RSTs. This, however, does not negate the fact thalli temperature changes will alter the surface indirectly through freeze–thaw, and may display the effect of albedo on lichens.

Lichen thalli and the microenvironments that they create as a community, experience freeze–thaw due to temperature fluctuations (Chen *et al.*2000). Freezing and thawing of thalli has been documented in Arctic Alpine zones, temperate regions, and more pertinently, Antarctica (Chen *et al.*2000). It is evident in both Table 11 and Table 12 that lichen thalli experience these documented temperature changes. Such evidence reaffirms the role of Newton’s Law of Cooling in these habitats where temperatures regularly fluctuate (Hall *et al.*2005), but in this case the fluctuation is between the thallus, substrate, and ambient air (Figure 39). Table 12 displays four examples where lichen thalli differ in temperature to their substrate and surrounding microhabitat. Thallus temperature is dependent on the metabolic activity of the lichen (Schroeter and Scheidegger 1995), such that it varies according to its microhabitat conditions (e.g. proximity to meltwater or on exposed boulders). Most lichens were documented on boulders (e.g. Table 13), which suggests that they remain inactive for longer periods due to intermittent snow fall, on which their metabolic activity depends. These lichens utilise the frozen water (e.g. Figure 42) to rehydrate at sub-zero temperatures. This ability indicates morphological and physiological adaptation, and suggests that habitats are suitable only to species adapted for the conditions. Their adaptation to uptake frozen water displays

their poikilohydrous nature discussed in Chapter 2 (Temperature and water availability, pg.21). Meltwater, another water source (Green *et al.*1999), was documented at Robertskollen and noted in Dwight's study (2014). On warmer days, meltwater was seen in micro-topographical features (e.g. tafoni) as melted snow, which soaked lichen thalli. Temperature of lichen thalli will vary according to this moisture content but, the water potential of a system is controlled solely by its air temperature (Schroeter and Scheidegger 1995). RST, in particular, governs surface humidity levels (McIlroy de la Rosa *et al.*2013). This emphasises the suitability of sheltered micro-topographical features as preferred sites for colonisation such that their relatively warmer environments (see Table 12) have greater water potential, at least for longer periods. With access to higher humidity levels for longer periods of time, lichens are more metabolically active in these environments, which stimulates thallus establishment and promotes the lichen's success. Taking their responses into consideration, it appears that lichen follow a positive-feedback strategy in colonisation, which is directly related to geomorphic and environmental conditions. Should moisture conditions reach critical point, a negative-feedback loop will develop, as explained in Kappen *et al.*(1986), where it was demonstrated that high thallus water content limited the lichens metabolic activity. This explains their preference for temperature ranges which do not drop below  $-10^{\circ}\text{C}$  and do not exceed  $20^{\circ}\text{C}$  (Figure 32, pg.56), such that photosynthesis would become inhibited (Kappen 1989; Barták *et al.*2007; McIlroy de la Rosa *et al.*2013).



Figure 42: Snow as a source of moisture for *P. chlorophanum* on Vesleskarvet. Pencil for scale.


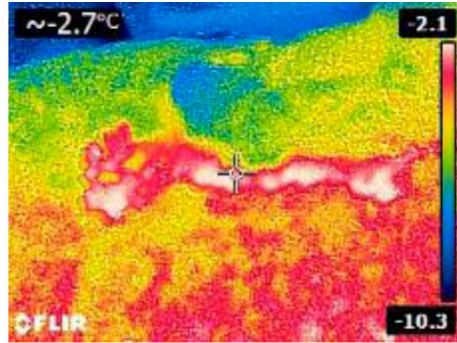
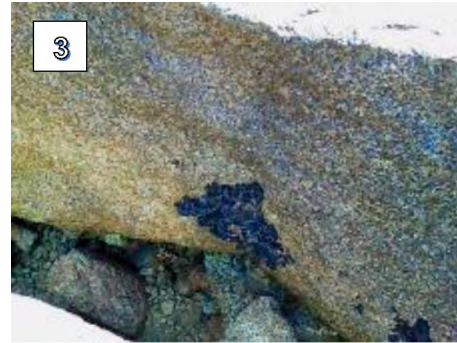
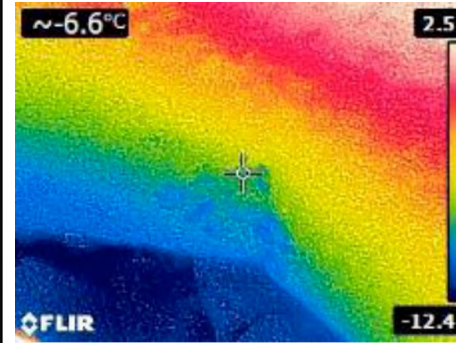

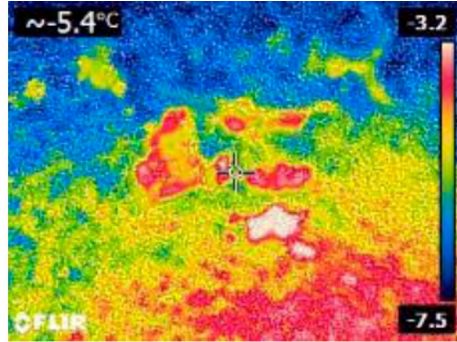

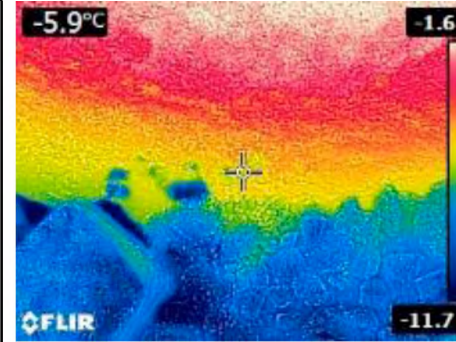
To some degree, the colour of a lichen's thallus controls its temperature, and in turn, the thermal response of the rock below (Garty 1990; Arocena and Hall 2004; Carter and Viles 2004; Strini *et al.*2008). A lichen's albedo, thus, alters RST at the lichen-rock interface. Dark coloured lichens are expected to absorb and retain heat, appearing warmer than their lighter substrate, but observations indicate it is not always the case (e.g. Table 13, lichen 3 and 4). Similar outcomes have been found in lichens that contradict the paradigm that low albedo permits a warmer temperature in surfaces (e.g. Arocena and Hall 2004). Rocks exhibited the same contention in an experiment by Hall *et al.*(2005), with the explanation that convection of heat into surrounding air will occur. In cold environments, such temperature regulation is

common due to diurnal, short-term temperature changes (Table 12 and Figure 39). It is then assumed that, although albedo may factor in heat transfer, RST at the interface is more dependent on *in situ* temperature differences. Furthermore, a thallus' colour correlates to water content (Sancho and Kappen 1989), yet moisture content is controlled by temperature conditions.

Similarly, the rock colour will also affect the water availability. Dark rock - especially dolerite (rock type for both Vesleskarvet and Robertskollen) - has low albedo, which (a) maintains stable diurnal temperatures suited for lichens, and (b) melts snow as a rapid rate and increasing water availability for lichens. Therefore, Longton's (1985) association of lichen colonisation on dark rock can be confirmed in this study. In effect, temperature governs the system of regulation through multiple and indirect interactions between the air and the lichens/rock surfaces.

The complexity of factors influencing the thermal regimes of lichen microhabitats is evident, making it difficult to identify clear RST-lichen relationships. Rock properties and microclimate conditions determined surface temperatures (Jenkins and Smith 1990), but thermal imagery provides evidence that RSTs will govern surface and sub-surface humidity fluctuations – directly influencing lichen physiology. It must, however, be noted that the combined effects of temperature differences, wind, orientation, and other microhabitat variables create complex feedback loops that consequently influence lichen success in their habitat. Outcomes emphasize that lichens prefer colonising the (relatively) constant habitats of micro-topographical features, which regulate RSTs and the immediate environmental conditions respectively. As a result, a lichen's success is higher in such a setting – justification of their occurrence in these spaces.

Table 12: Temperature (°C) fluctuations of lichen thalli in comparison to its substrate surface temperature (°C). Image sets are labelled 1-4 for reference in text. Lichens 1-2, display warmer temperatures than their substrate whereas lichens 3-4 display cooler temperature.

Lichen Warmer		Lichen Cooler	
Reference Image	Thermal Image	Reference Image	Thermal Image
 <p>1</p>	 <p>~<math>-2.7^{\circ}\text{C}</math> 2.1 -10.3 CFLIR</p>	 <p>3</p>	 <p>~<math>-6.6^{\circ}\text{C}</math> 2.5 -12.4 FLIR</p>
 <p>2</p>	 <p>~<math>-5.4^{\circ}\text{C}</math> -3.2 -7.5 CFLIR</p>	 <p>4</p>	 <p>-5.9°C -1.6 -11.7 FLIR</p>

## CHAPTER 7: ROCK-LICHEN INTERACTIONS

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In compliance with Objective 4 in Chapter 1 (pg.4), the biogeomorphic impacts of lichens on rock for WDML are examined in this chapter. For sake of consistency, sections for introduction, methodologies, results and discussion are presented, together with detail on how Objective 4 was achieved in the study.

### **Introduction**

For many years, the impact of lichens on their environment was considered to be unimportant until research showed that these organisms biodeteriorated their substrata in a relatively short period (Seaward 1997). Different opinions have been formulated over their impacts, with some authors suggesting lichens contribute to weathering and pedogenesis, and other authors arguing their impacts are exaggerated (Chen *et al.*2000). Recent studies have, however, indicated that they do, in effect, play an important role in landscape evolution (e.g. Chen *et al.*2000; Adamo and Violante 2000; Bjelland and Thorseth 2002; Matthews and Owen 2008). Saxicolous lichens impact their substrates biophysically and biochemically through various mechanisms (Seaward 1997), which are summarised in Figure 43. It is accepted that lichens are not only influenced by their surrounding environment, but act as instruments in (positive) feedbacks of their environment, specifically through weathering (Dwight 2014).

### Physical Weathering

Mechanical weathering of lichen substrates is a result of simultaneous erosion and weathering processes whereby mineral grains are loosened and removed by thalli and hyphae/rhizines (McKechnie *et al.*2007). Other physical mechanisms include freeze-thaw of thalli in micro-topography, the expansion and contraction of the lichen thallus during wetting and drying as well as hyphae penetration into rock voids (Seaward 1997; Chen *et al.*2000; Bjelland and Thorseth 2002; Chen and Blume 2002; McKechnie *et al.*2007). These physical processes all result in microfractures, surface spalls and greater porosity, as well as aid in the exfoliation of the rock surface (Chen *et al.*2000; McKechnie *et al.*2007).

### Chemical Weathering

According to Bjelland and Thorseth (2002), biogeochemical weathering is facilitated by the lichens' life processes, which directly and indirectly interact with its substrate. During respiration, lichens release carbon dioxide that forms carbonic acid when in contact with water. Organic acids produced by lichens increase the rate of weathering by lowering the pH but the effect on mineral dissolution by metal-complexing compound and acid reactions is most

important at near neutral pH (Bjelland and Thorseth 2002; McKechnie *et al.*2007). Hence, biochemical weathering may lead to changes in the rock/substrate's texture, chemical composition, and mineral composition (Syers and Iskander 1973 *in* Bjelland and Thorseth 2002).

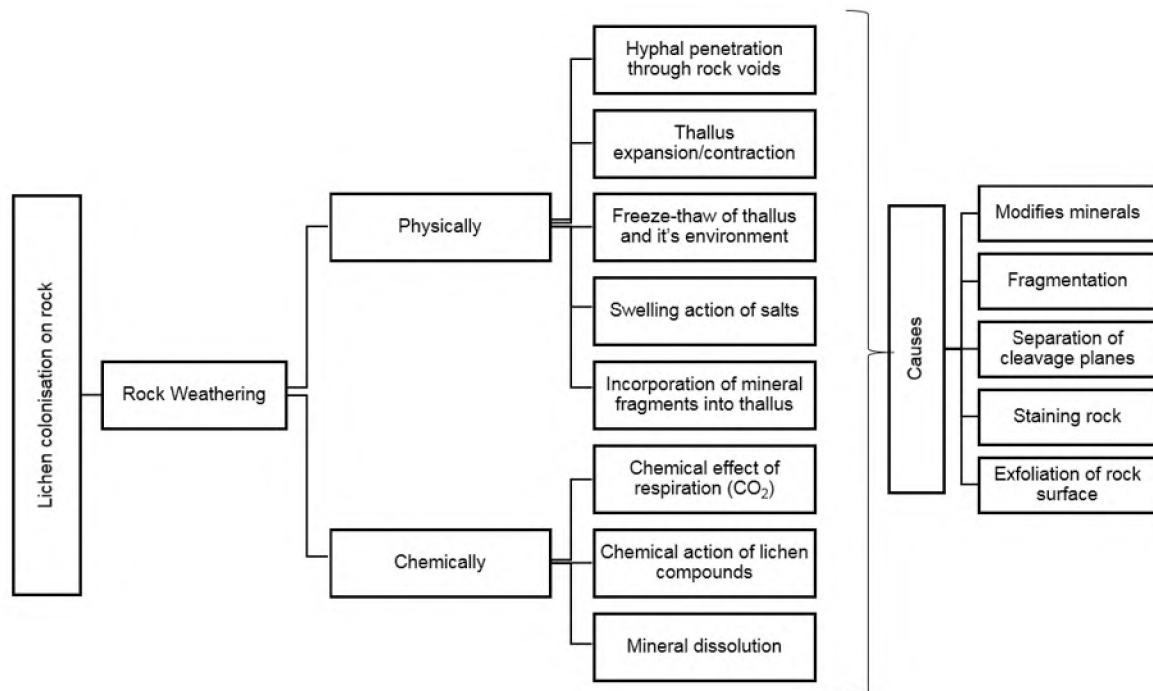


Figure 43: Summary of weathering impacts of lichens. Adapted from Chen *et al.*(2000).

The study of rock weathering by lichens is in its infancy due to the difficulty of quantifying their effect on landscapes (McKechnie *et al.*2007). This is exhibited in the case of Antarctica, where lichens have been described as the most important vegetative component in the ecosystems (Kappen *et al.*1986), yet few studies have been completed on the role they play in shaping their terrestrial landscape. Chen and Blume (2002) highlight a number of studies in Antarctica that provide evidence of lichens weathering their substrate (e.g. Ascaso *et al.*1990), which contradicts earlier proclamations by Lindsay (1978), who described the role of lichens in soil development as “minimal”.

In its authenticity, Antarctica offers an ideal base for investigations on rock weathering and soil formation induced by lichens (Chen and Blume 2002). The absence of higher plants and simple community structure permits studies on biotic weathering by lichens alone, as there is minimal involvement of other biotic agents (Chen and Blume 2002). In addition to this, lichen colonisation in Antarctica is in its most ‘natural’ state owing to its remoteness, low loss rates, absence of grazing, and minimal human interference (Chen and Blume 2002). Results from

Antarctic studies are, therefore, expected to be accurate in comparison to studies from other world regions (Blume 1999). This has led to the development of the objective in consideration.

The aim was to provide preliminary evidence for sub-surface weathering by the lichen species: *Buellia* sp. B, *P. chlorophanum*, *U. decussata*, and *U. sphacelata* on dolerite in WDML. As there have been several authors to use scanning electron microscopy as a method for successfully identifying lichens as geomorphic agents on rock (Adamo and Violante 2000; McKechnie *et al.* 2007), this approach was applied to examine the rock-lichen interface and activity. Most investigations into lichens as agents for rock weathering have been conducted in regions exclusive of Antarctica (Chen and Blume 2002). Results from WDML can therefore be used as a platform for lichen induced weathering on the continent.

## **Methods and Materials**

### Data Collection

Colonised rocks were sampled to examine the biogenic impacts of hyphae action in the surface and sub-surface. Rocks were (opportunistically) selected based on their size and lichen colonisation. Samples had to be of suitable size for laboratory practices (no larger than the size of a fist), and colonised by one lichen species. Four samples were collected and stored in brown paper bags to prevent moisture development.

### Data Analysis

#### *Thin Sectioning*

The preparation for thin sections of lichen-colonised rocks was carried out in the Rhodes University Geology Department. It is difficult to maintain lichen-rock attachment during the process. The most successful technique is impregnating the rock with a resin (Welton 1984). The resin used was Epofix™, a cold mounting epoxy resin and hardener developed by Struers. The mixture was poured over each rock sample and then placed into a vacuum chamber to allow impregnation of the sample. Epofix™ does not degas in the vacuum chamber of a scanning electron microscope (SEM), which made it the suitable choice of resin. Each sample was sliced to ensure the lichen thallus would be in the thin section. After gluing the sample to a frosted glass slide (1.3mm), it was cut to 2mm on a Buehler® IsoMet® Low Speed Saw. The slow speed saw was used due to the fragility of the samples. Each sample was then ground down on a Struers Accutom™ to 40-50µm with a grinding wheel. Using a Leco® GPX 200 polisher, each thin section was then polished using polisher mats and a 6µm, 3µm and 1µm diamond solution respectively (Akasel® Diamaxx Mono). These preparation methods are

based on the Struers preparation processes for a type two specimen (polished thin section) (Figure 44).

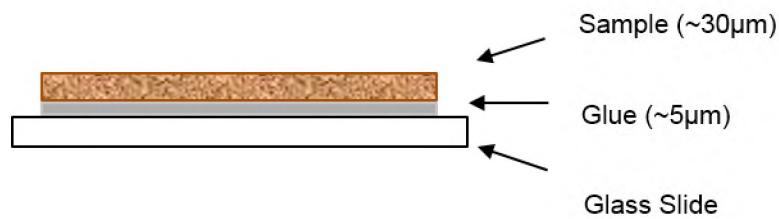


Figure 44: Diagram of a type two specimen thin section, as described by Struers (2016).

### *Scanning Electron Microscope Analysis*

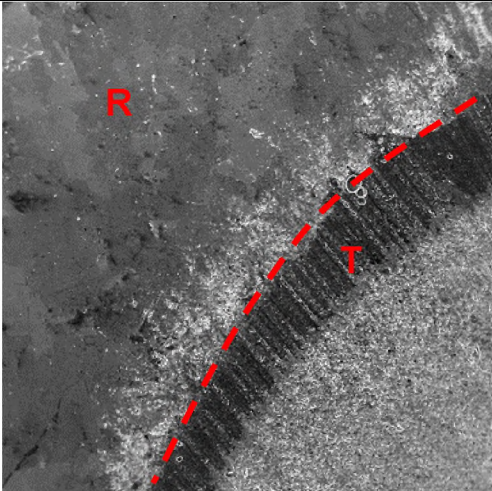
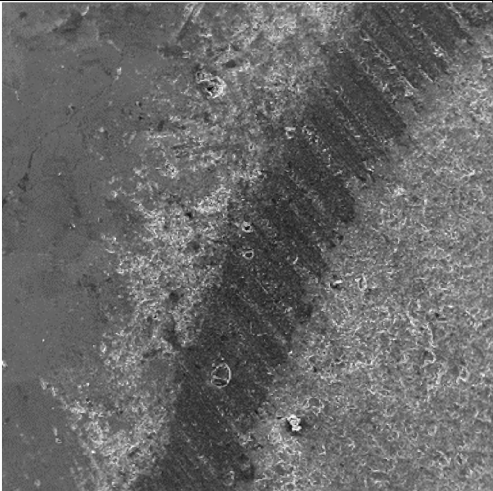
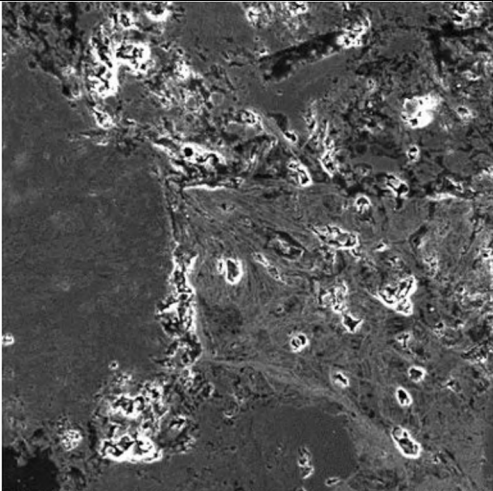
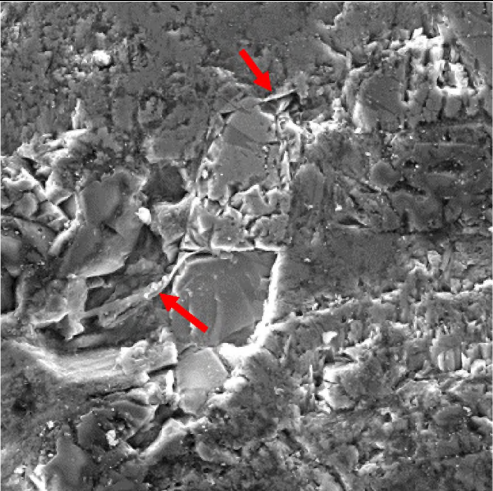
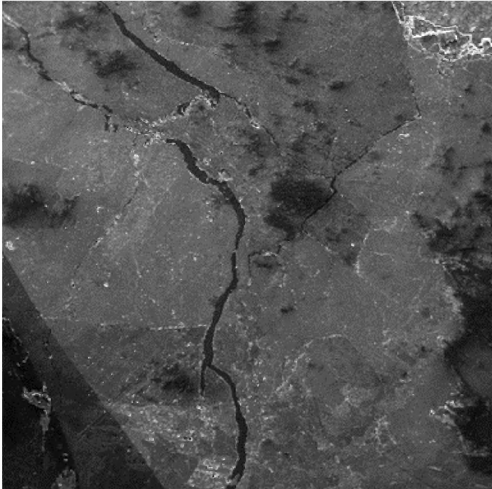
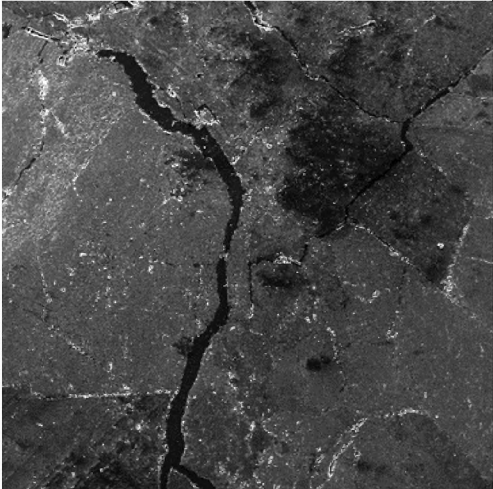
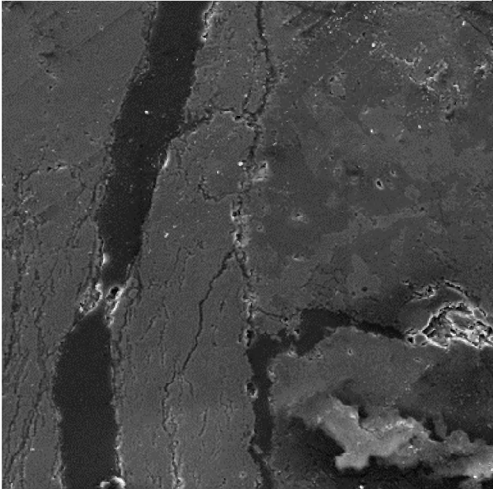
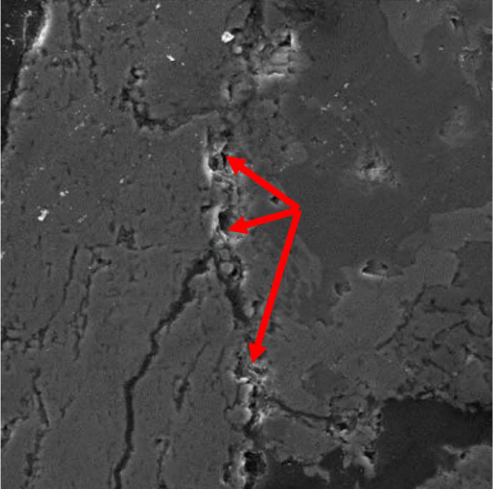
Optical observations of (a) the rock below the rock-lichen interface, and (b) rock surrounding hyphae were made under a scanning electron microscope (SEM) (Jones *et al.*1981). The optical analysis was carried out in the Rhodes University Electron Microscopy Unit. Thin sections were placed under a Tescan Vega LMU SEM and viewed at 20kV. All samples were sputter coated in gold (Welton 1984), using a Quorum Q150 Rotary-pumped sputter coater. This prevents the sample from discharging electrons that would otherwise cause flash-over and white streaking during photographic imaging - reducing noise in the optical view (Welton 1984; McKechnie *et al.*2007).

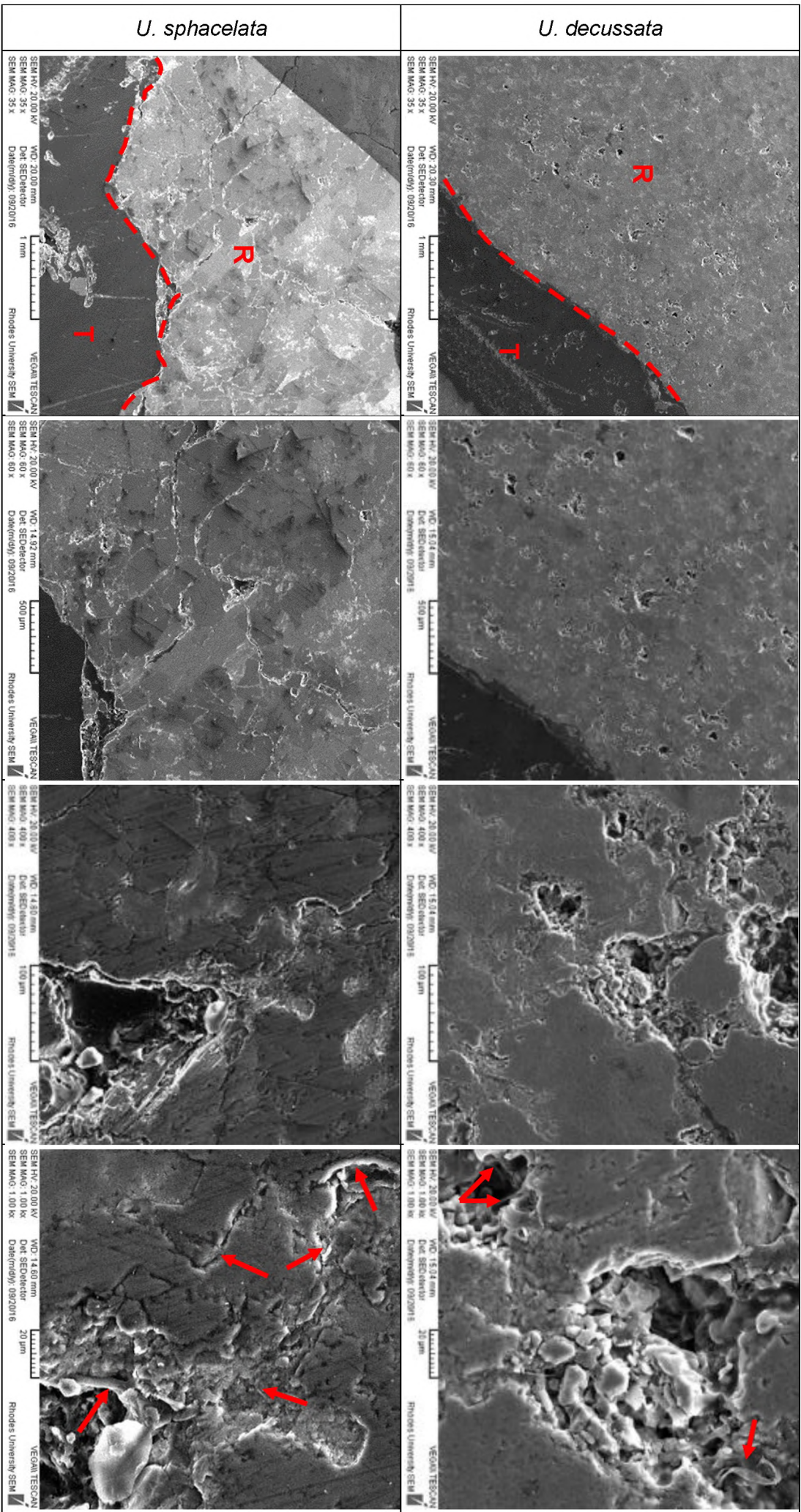
Images were examined qualitatively in a desktop analysis. To standardise images, each sample was photographed as a set of magnifications: 35X, 60X, 400X and 1000X. Four species of lichen were examined under the SEM: *U. sphacelata*, *U. decussata*, *Buellia* sp. B, and *P. chlorophanum*. Where possible, more than one set of images was captured for the same species (see Appendix E).

## **Results and Discussion**

Cross-sectional SEM photographs of lichen-colonised surfaces are presented below and provide preliminary evidence that lichens weather their substrate in WDML. Various bio-weathering processes are displayed between species, which is related to their physiological differences (Adamo and Violante 2000). Since the nature of this study is geomorphic, these differences were not investigated for species-specific weathering action. Instead, the weathering mechanisms were observed and documented for lichens in WDML.

Table 13: Surface and subsurface images of rock-lichen interface under a SEM. Images were captured at various magnifications to display the depth of hyphal penetration and rock material in contact with hyphae. Where possible, arrows identify the lichen hyphae and lines indicate the interface between the lichen thallus (T) and rock (R).

Sp.	Magnification			
	35X	60X	400X	1000X
<i>Buellia</i> sp. B	 <p>SEM HV: 20.00 kV WD: 20.30 mm VEGA\\TESCAN SEM MAG: 35 x Det: SEDetector SEM MAG: 35 x Date(m/d/y): 09/20/16 1 mm Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 13.51 mm VEGA\\TESCAN SEM MAG: 60 x Det: SEDetector SEM MAG: 60 x Date(m/d/y): 09/20/16 500 µm Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 10.67 mm VEGA\\TESCAN SEM MAG: 400 x Det: SEDetector SEM MAG: 400 x Date(m/d/y): 09/20/16 100 µm Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 10.52 mm VEGA\\TESCAN SEM MAG: 1.00 kx Det: SEDetector SEM MAG: 1.00 kx Date(m/d/y): 09/20/16 20 µm Rhodes University SEM</p>
<i>P. chlorophanum</i>	 <p>SEM HV: 20.00 kV WD: 20.31 mm VEGA\\TESCAN SEM MAG: 35 x Det: SEDetector SEM MAG: 35 x Date(m/d/y): 09/30/16 1 mm Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 20.00 mm VEGA\\TESCAN SEM MAG: 53 x Det: SEDetector SEM MAG: 53 x Date(m/d/y): 09/30/16 500 µm Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 15.10 mm VEGA\\TESCAN SEM MAG: 400 x Det: SEDetector SEM MAG: 400 x Date(m/d/y): 09/30/16 100 µm Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 15.10 mm VEGA\\TESCAN SEM MAG: 1.00 kx Det: SEDetector SEM MAG: 1.00 kx Date(m/d/y): 09/30/16 20 µm Rhodes University SEM</p>



Species *Buellia*, *U. decussata* and *U. sphacelata* all display chemical weathering action, utilising solubilisation mechanisms – described by Chen *et al.*(2000) - on the mineral elements of their substrate (Table 13). For mineral dissolution to have occurred, hyphae must have penetrated their substrate's surface, which can be seen by the rock disintegration at magnification of 35X for *Buellia* sp. B. The image shows disintegration to about 1mm, suggesting hyphae have penetrated to this depth. Furthermore, the parent material appears to be broken down into grains (1000x), a typical result of hyphal growth and penetration in quartzite and feldspars (Chen *et al.*2000), both of which are associated to Vesleskarvet (Hansen 2013). The average 1mm penetration depth of the crustose *Buellia* sp. in Table 13. displays similar to results to a study in South Africa's Magaliesberg, where a crustose lichen penetrates quartzite to a depth of 1.12mm (Cooks and Otto 1990 *in* Chen *et al.*2000). Penetration depth of crustose species will, however, vary according to the geology of the rock and species itself (e.g. Wessels and Schoeman 1988; Cooks and Otto 1990). Crustose lichens, such as *Buellia* sp. B, are also known to bring about surface exfoliation of dolerite (Chen *et al.*2000). Weathering of rock on Vesleskarvet is evident through its discoloured surface and sporadic thin exfoliation (Hansen 2013). Since *Buellia* sp. B was found to be a dominant, yet dispersed species on the blockfield (Chapter 5, pg.61), it can be assumed that it is contributing to the weathering (exfoliation) of the rock to a moderate extent (thin surface disintegration of 1mm seen in Table 13).

Visually, the crustose species *P. chlorophanum* shows less weathering impact (Table 13). Hyphae were found to penetrate via rock voids (see at 400X and 1000X). Sites containing feldspars, such as Vesleskarvet and Robertskollen, promote colonisation; especially in crustose species. Intersecting cleavage planes of feldspars form rectangular blocks with irregular ends and fine grooves (plagioclase): offering accessible spaces for hyphae to penetrate (as seen in images of rock colonised by *P. chlorophanum* and *U. sphacelata* at 30X and 65X in Table 13). Chemical weathering of minerals is, therefore, limited to the immediate contact with hyphae. A photograph of *P. chlorophanum* hyphae (at 1000x) displays this relationship, showing rounded minerals (lighter coloured material) in contact with its hyphae, but limited to that vicinity only (Table 13)..

Weathering by the foliose species *U. decussata* differs such that its chemical weathering actions form what appear to be solution basins or hollows within the parent rock (Table 13). The rounded edges, especially visible at 400X and 1000X, are indicative of chemical weathering. Dissolution appears to occur only in the lighter coloured material, which suggests that these are soluble minerals in parent rock with preferred trace elements. *U. decussata* uptakes a variety of trace elements – from its substrate, documented to be successful mafic volcanic rocks (Bargagli 1999). Its high occurrence and abundance at both sites (Chapter 5,

pg.61) justifies habitat preference and lichen success. Explanation for this may lie in the availability of favoured minerals such that trace element uptake and release (progressive weathering) can occur, giving better understanding in to the microhabitat of the species. Element bioavailability is both essential and toxic to a lichen's metabolic activity and, therefore, its success (Bargagli *et al.*2000). Their concentration in minerals will control a community's structure by influencing the competitive ability between species (Bargagli *et al.*2000). Inferences from the images (Table 13), coupled with results showing *U. decussata*'s dominance at Robertskollen (Chapter 4, pg.36), suggest that it is a preferable site for colonisation. The nunatak is closer to the coast than Vesleskarvet and harbours a number species of birds (Ryan *et al.*1989). Therefore, increased nitrogen, phosphate and potassium concentrations (from guano), and exposure to marine aerosols offer a more favourable habitat, which is evident in their larger thalli sizes (e.g. Ryan and Watkins 1989; Bargagli 1999).

*U. sphacelata* shows a similar weathering mechanism to *P. chlorophanum* and *U. decussata* in that it exploits existing fissures in its substrate and progressively disintegrates the material from the point of hyphae contact (Table 13). Progressive weathering action was also characteristic of *Buellia* sp. B but from rock-thallus interfaces (Table 13). *U. sphacelata* was observed and documented to be associated with *U. decussata* (Bargagli 1999; Øvstedal and Smith 2001), conveying a preference for similar habitat conditions. Magnifications at 400X and 1000X, however, show more extensive rock disintegration in penetrated voids from chemical weathering (Table 13). Hyphae penetrate in multiple directions, reacting with immediate minerals, and create larger voids that will weaken and break down the rock. In addition to this, it is seen (35X) at the interface that the lichen has broken and incorporated a small piece of rock into its thallus (Table 13). This mechanism was also documented for *U. decussata* at Robertskollen (Figure 45), and is known to occur for *P. chlorophanum* (Figure 46).

Figure 47 and Figure 50 display clearer SEM photographs of hyphae weathering rock physically and chemically. It is evident in Figure 48 that the visible weathering impact progressively declines towards the interior of the rock, unless there are cleavage planes for the hyphae to infiltrate. Figure 50 displays early stages of weathering and dissolution hollows at the microscale starting to form near the tips of penetrated hyphae. As lichens dissolve the minerals in their substrate, remaining precipitates accumulate and chemical weathering is further induced in the pores or basins (McKechnie *et al.*2007), which can be seen in Figure 48. Similar to previous results, dissolution of minerals near the surface may be related to moisture retention.

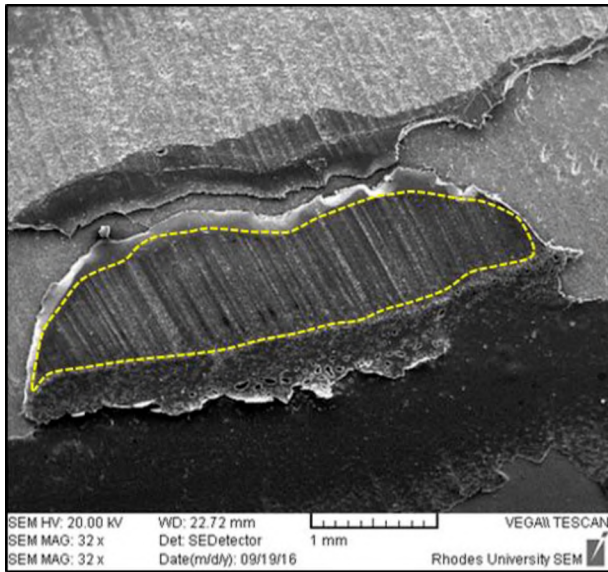


Figure 45: SEM photograph of embedded rock (outlined) in *U. decussata*.

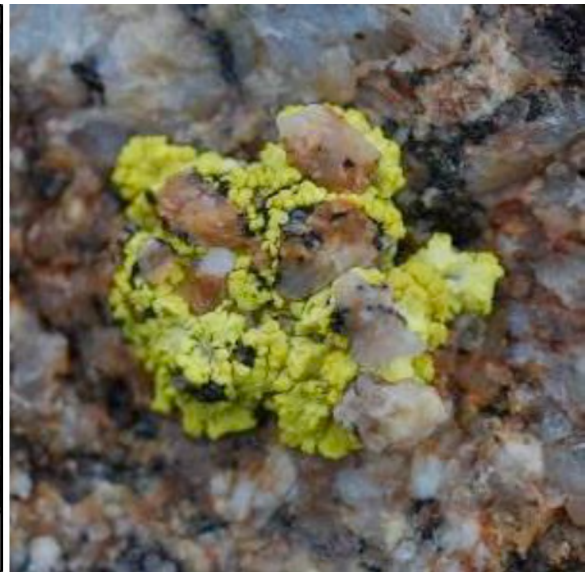


Figure 46: *P. chlorophanum* with embedded rock fragment. Source: S. Ott

Underlying rock for the study area is silicified, and has low porosity and permeability - Vesleskarvet to a greater degree than Robertskollen (Hansen 2013). This precludes moisture absorption by the rock (Friedmann and Weed 1987). Hydrolysis of minerals by metabolic activity will only occur when there is moisture in the system, suggesting that the rate of chemical weathering increases when thalli are metabolically active (i.e. have sufficient moisture content and temperature ranges). Most lichens at these sites absorb moisture from the air, which indicates moisture is within the thallus rather than the rock, and justifying visible dissolution of surface minerals within ~2mm of the rock-lichen interface (Table 13, Figure 48, and Figure 50). Medullas of epilithic lichens are known to have great water holding capacity, up to 300% of their dry weight when moisture is available (Chen and Blume 2002), which may produce weathering at the rock-hyphae interface, particularly in continental Antarctica. Furthermore, a thallus will expand on contract synchronously with its moisture content (Chen *et al.*2000). In summer months, alternate wetting and drying is most frequent, which may cause considerable impact (Chen *et al.*2000). Lichens are, therefore, suited to colonising specific rock, depending on their capacity to retain moisture (McKechnie *et al.*2007).

As hyphae penetrate through rock voids, they contribute to micro-scale weathering and erosion by dislodging and displacing granules with their interlaced movement and activity (Figure 47). This weathering effect has been documented in various areas and rock types respectively (e.g. McKechnie *et al.*2007). Due to hyphal penetration, water can reach depths in the substrate where an “ice-wedging” action is experienced once temperature drops sufficiently for freezing of the water to take place (Chapter 6, pg.68). This is caused by the freezing expansion of a “moist” thallus and surrounding microenvironment and may be playing

a significant role in rock weathering in WDML (Chen *et al.*2000). It is also a weathering action associated with exfoliation (Friedmann and Weed 1987), which is observed at both Robertskollen and Vesleskarvet.

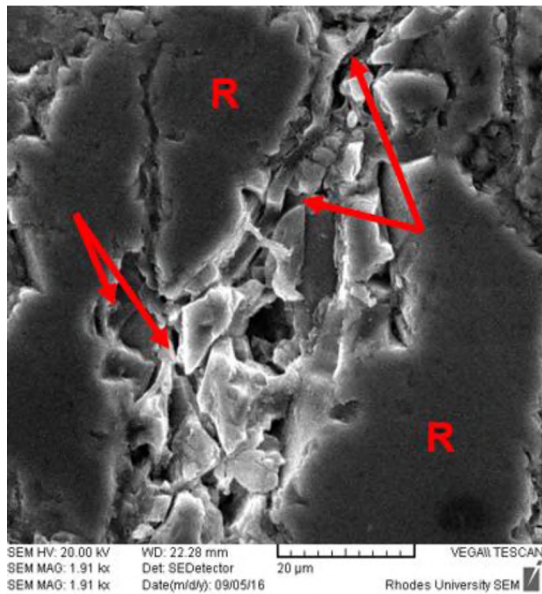


Figure 47: Hyphae 1.5mm below surface (*U. sphacelata*).

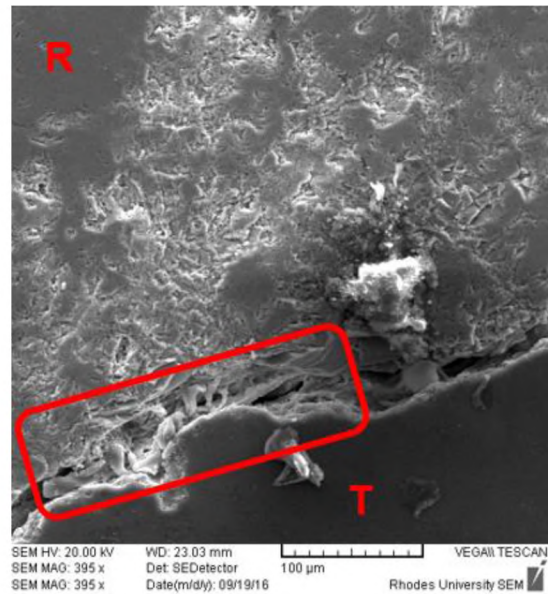


Figure 48: Rock-lichen interface (*U. decussata*).

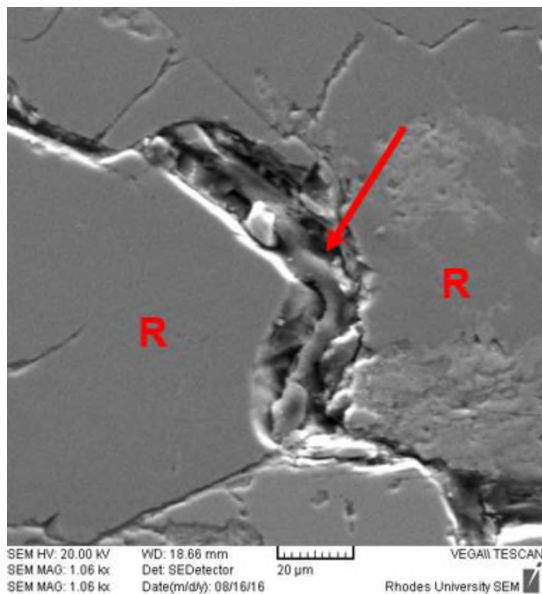


Figure 49: Hyphae (*U. decussata*) 2mm below rock surface.

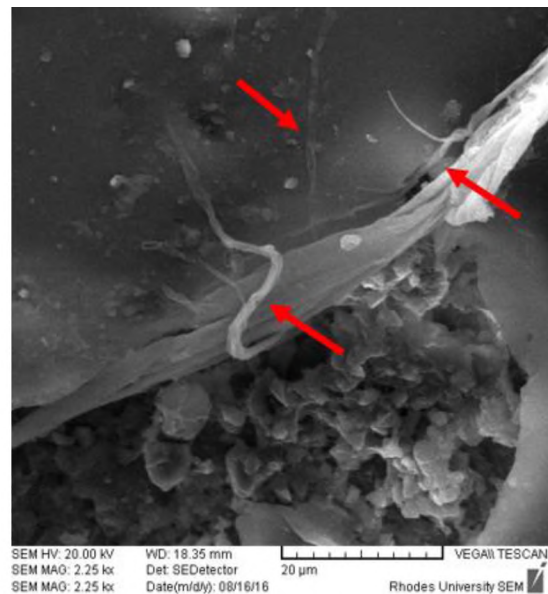


Figure 50: Hyphae (*U. decussata*) penetrating surface of rock.

Summer is a suitable time to investigate active weathering impacts by lichen due to the increased moisture levels in the system. Preliminary findings from the study display physical (hyphal penetration) and chemical (mineral dissolution) weathering. Other weathering mechanisms (Figure 43) can be inferred from data in this study but all processes are determined by the existence of favourable environments in rocks. Conclusively, biotic

weathering is controlled by an equilibrium of biological and geological processes overlapping and interacting over time such that they contribute towards a bi-directional landscape development i.e. local geomorphology shapes these species; which in response shapes their geomorphology.

## CHAPTER 8: SYNTHESIS, CONCLUSIONS AND RECOMMENDATIONS.

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This dissertation is concluded with a synthesis of findings from the four objectives used to achieve the study's aim (Aim and Objectives, pg4.). A conclusion is presented, followed by an outline of limitations and recommendations.

### Synthesis

Lichen colonisation of ice-free regions in continental Antarctica is characterised by macro- and microscale environmental parameters and landscape processes. These aspects form niche opportunities for the colonisation of various lichens (Table 14). When a species exploits a niche (micro-topographical feature) in the landscape, environmental conditions are presumed to be suitable. Alternatively, the species has modified morphologically and/or physiologically to develop in its niche/microhabitat. The latter has been discovered for widespread species such as *U. decussata*, but endemic species such as *A. gwynnii*, *B. frigida* and *C. flava* have evolved to *in situ* environmental conditions accordingly. Succession of lichens in structural and ecological niches is, therefore, hypothesised to be controlled by environmental aspects in a landscape (Figure 51), particularly its geomorphology.

Vesleskarvet and Robertskollen are situated 25kms apart, yet are noticeably different in topography. Robertskollen's heterogeneous landscape offers a variety of niches, which in turn has led to the higher species diversity on its ice-free areas. Lichen habitats are determined by surrounding microtopography, but in terms of macroscale controls, the system offers a nutrient rich and moist environment that promotes bi-directional interactions between the landscape and its lichen-dominated vegetation (Figure 51). Bird colonies add (guano) to the geochemical cycle, increasing nutrient concentrations in the system (Ryan *et al.* 1989); and moisture levels (humidity) are higher due to evaporation of meltwater and sublimation of the active layer (Dwight 2014; Kotzé 2015). These two constituents comprise immediate habitat suitability, however, their mechanisms also stimulate a corrosive environment that weather the landscape and augment heterogeneity (Figure 51). Increased heterogeneity results in lichen succession, which speeds up the weathering process by creating a complex feedback system; Robertskollen provides excellent examples of this. Additionally, its heterogenic environment holds more late-lying snow as it collects amid sheltered microtopography. In addition to supplying moisture, snow cover acts as an effective insulator in Antarctica. In continental sites specifically, it keeps surface conditions cold, which delays active metabolism in lichens until the snow cover dissipates (Pannewitz *et al.* 2003). Lichen

activity is, therefore, suppressed until reliable periods of warmer air temperatures and water supply (Seppelt *et al.*2010). Activity is, however, species specific, which may explain varied habitat preferences (Table 14). *B. frigida* are active for several hours each year (Kappen *et al.*1998), therefore, their colonisation of larger exposed rock surfaces ensures insolation for photosynthesis. In contrast, *C. flava* remains inactive until thalli come close to saturation from snow melt (Pannewitz *et al.*2003). This mechanism explains their preference for fine sediment/mosses in wind-protected depressions (less evaporation), such that they receive sufficient moisture for photosynthesis during summer months.

In contrast, Vesleskarvet is characterised by a homogenous topographic blockfield that is autochthonous in nature (Hansen 2013), and features angular and elongated blocks. As a result, niche locations that provide the potential for colonisation are restricted and species diversity is low. The northern buttress receives a low nutrient input, positing the probability of mineral content (in the substrate) acting as the primary source of nutrients for lichens (Figure 51). Moisture and nutrient availability is further limited at Vesleskarvet due to the overlying blockfield that protects the active layer (Kotzé 2015). Its homogeneity restricts snow cover, increasing the susceptibility of lichens to severe desiccation. In instances where snow cover is observed, it is evidently transient due to the topography prohibiting any establishment of a durable layer (from the easterly wind). Snow-free areas have low rock hardness values, which suggests relatively dynamic weathering environments (Hansen *et al.*2013; Dwight 2014). The northern tip of Vesleskarvet is exemplary of this and features higher abundances of lichens when compared to the rest of the nunatak. As a result, the success of attachment and development rate of lichen diaspores is increased, due to the availability of heterogenic rock surface topography (Ott 2004).

Snow and meltwater are vital for lichen growth in Antarctica, as they provide a source of moisture necessary for metabolic activity (Kappen *et al.*1998; Sancho *et al.*2007). Its availability is regulated by complex feedback mechanisms (Figure 51), governed primarily by macro- and microtopography. Depending on the topography, insolation can directly and/or indirectly influence moisture availability (Figure 51): directly, it thaws snow and ice and/or increases humidity; indirectly, it warms rock surfaces, which contributes to thawing and/or determines surface and subsurface humidity levels. Originally proposed by Longton (1985), this creates preferable microenvironments (niches) for lichens, which was evident through their colonisation of ice-supported rocks, as well as microtopography that trapped drift snow. If these niches are inhabited, a lichen will, as discussed, speed up the weathering processes in the system. Investigations into these rock-lichen interactions show multi-directional relationships that incorporate other environmental constituents (Figure 51).

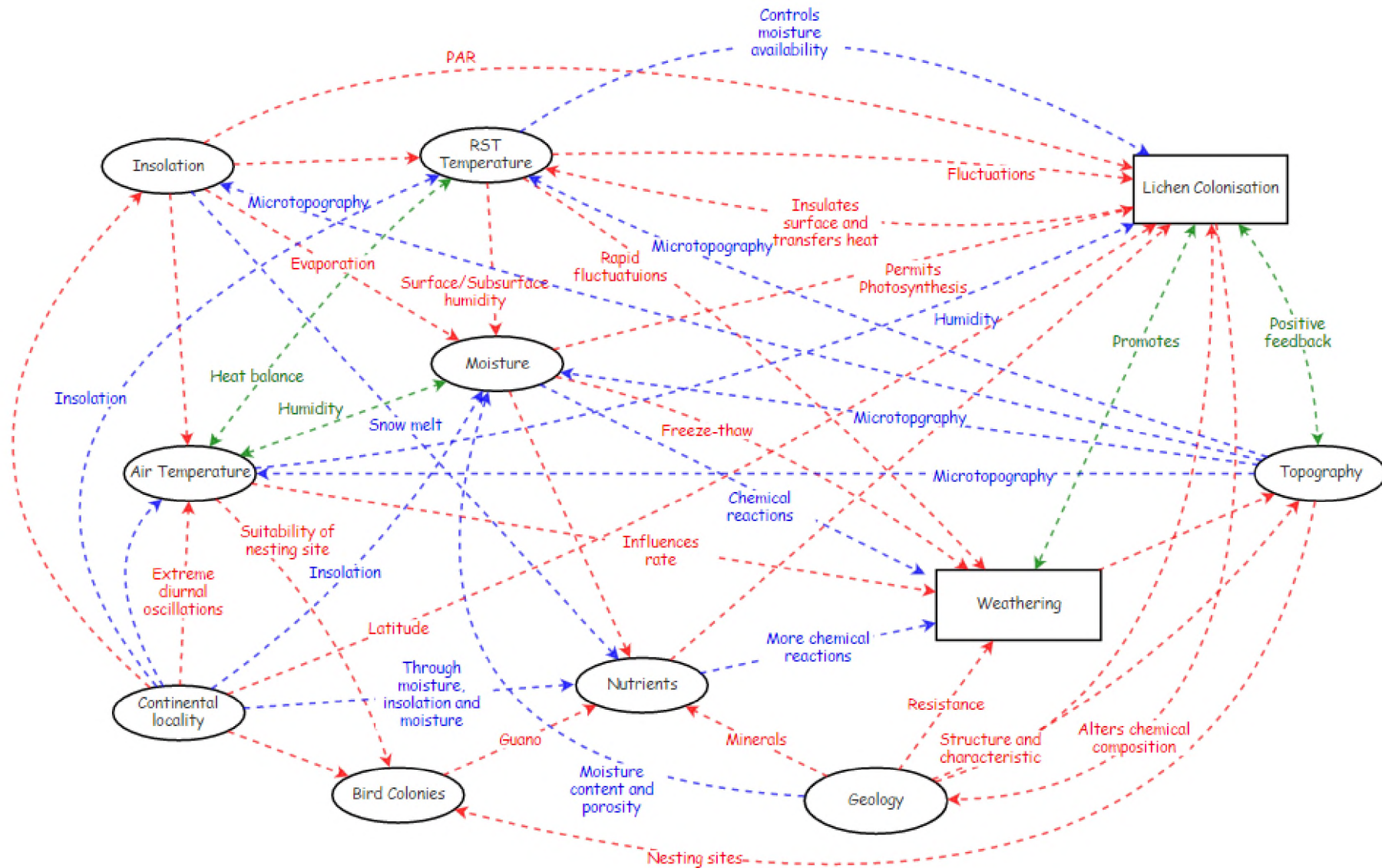


Figure 51: Environmental interactions at lichen-colonised ice-free regions in WDML. (Red = Direct Influence, Blue= Indirect Influence, Green= Feedback Mechanisms). Diagram created in InsightMaker® (<https://insightmaker.com/>).

RSTs fluctuate according to insolation, however, environmental elements such as clouds, shadows and winds confirmed interference in received solar radiation. Therefore, rapid RST fluctuations are experienced in exposed rock. On the contrary, sheltered micro-topographical features are more guarded, maintaining energy from the sun (heat) for a longer period and forming a more temperate and stable RST regime. Subsequently, these features develop warmer environments with higher surface/subsurface humidity levels - presenting a preferred reliable habitat for most lichens (Table 14). The lichen's mycobiont is responsible for nutrient uptake from its substrate or air humidity (Bohuslavová 2012). Moisture uptake from these elements promotes thallus development and hyphae growth, which attach to their substrate and weather its material both physically and chemically. Lichen weathering action may show similarity, but was discovered to be species specific. Apparent influences by *Buellia* sp. B, *P. chlorophanum*, *U. decussata*, and *U. sphacelata* include hyphal penetration and mineral disintegration, however, these will promote additional lichen-weathering action e.g. thallus freeze-thaw and thallus expansion/contraction (Chen *et al.* 2000). These processes contribute to rock disintegration and soil formation; developing a more heterogeneous topography that offers greater niche opportunities for species such as lichens (Figure 51). In this study, Robertskollen represents a model system for such circumstances. Vesleskarvet is not without such measures: lack of insulation from both lichens and snow (Guglielmin 2012; Hansen 2013), directly exposes rock to weathering processes, however, the landform is characterised by weathered surface-layer flakes and exfoliation (especially where there is presence of lichens), suggestive that lichens (specifically the dominant *Buellia* sp. B) enhance the formation of these features.

Table 14: The habitat preferences identified in this study which are responsible for lichen colonisation at the selected ice-free regions of WDML, Antarctica.

SPECIES	PREFERRED SUBSTRATES	PREFERRED MICRO-TOPOGRAPHICAL FEATURES	ENVIRONMENTAL CONTROLS	SPECIES ASSOCIATIONS
<i>Acarospora gwynnii</i>	Rock.	On rock surfaces, usually in slight depressions under overhangs or in fine cracks.	Drift snow, snow and ice.	/
<i>Buellia frigida</i> (sp. A)	Rock.	Large rock surfaces; base of relatively large rocks.	Weathering-resistant substrate. Rock minerals.	/
<i>Buellia</i> sp. (sp. B)	Rock.	Rock cracks/runnels in sheltered depressions or under overhangs. Appearing in tafoni and pitting when in association.	Drift snow, snow, and ice.	<i>P. chlorophanum</i> <i>U. decussata</i> .
<i>Candelariella flava</i>	Loose, yet stable, fine sediment and moss/other lichens.	Very sheltered depressions i.e. ground surface, tafoni, base (edges) of rocks.	Soil moisture (permafrost and snow melt), wind, nutrients (N).	<i>X. mawsonii</i> <i>R. melanopthalma</i>
<i>Lecanora expectans</i>	Rock.	Rock cracks and depressions, particularly flakes and pitting.	Drift snow.	<i>P. chlorophanum</i>
<i>Pleopsidium chlorophanum</i>	Rock.	Rock cracks, shaded in depressions and under overhangs.	Drift snow, snow, and ice. Insolation. Geological rock structure.	<i>Buellia</i> sp. B
<i>Pseudephebe minuscula</i>	Rock and soil.	Rock surfaces; rock edges; rock fractures.	Nutrients (N).	<i>B. frigida</i> <i>U. decussata</i> <i>U. sphacelata</i>
<i>Rhizocarpon geographicum</i>	Rock.	Shaded spaces in cracks, flakes and fractures.	Insolation.	/
<i>Rhizoplaca melanopthalma</i>	Rock surfaces, small rocks/ stable sediment, and some moss.	Depressions, fractures and at edges where rocks meet the ground.	Nutrients (N), wind, active layer.	<i>C. flava</i>
<i>Umbilicaria decussata</i>	Mostly rock, but observed on sediments (small rocks and soil), amongst moss.	Variety of habitats, but mostly in cracks, flakes and on the rock surface.	Air moisture. Rock minerals.	<i>B. frigida</i> <i>P. minuscula</i> <i>U. sphacelata</i>
<i>Usnea sphacelata</i>	Rock and amongst other lichens (especially when terricolous).	Mostly on rock faces in fractures edges, but also beneath/under overhangs.	Wind. Drift snow.	<i>B. frigida</i> <i>P. minuscula</i> <i>U. decussata</i>
<i>Xanthoria elegans</i>	Rock and in some instances, sheltered soil.	Rock faces with slight depressions. Edges where rock faces meet.	Nutrients (N), cracks/runnels, wind.	<i>X. mawsonii</i>
<i>Xanthoria mawsonii</i>	Mostly loose, fine sediment but also on mosses and other lichens. Occasionally on rock surface.	Surface of fine sediment/course grained rock surface. Edges of small rocks and surrounding loose and fine sediment.	Nutrients (N). Wind. Active layer.	<i>C. flava</i>

## Conclusion

The characterisation of epilithic lichen habitats in part of WDML, Antarctica, has developed a platform study for future research. The outcomes of this investigation are testimony to the complexity of, and interactions between, lichens and their environment (Longton 1985; Church 2010). Lichen colonisation is limited to availability of appropriate niches, which is determined by the geomorphic aspects of the landscape. The northern buttress of Vesleskarvet is proxy to this hypothesis, exemplifying how deglaciation and thus, length of exposure, has controlled both weathering and lichen colonisation. Its topographic heterogeneity progressively decreases towards the ice sheet, the most recently exposed region, which justifies its lichen habitat suitability. Robertskollen displays the succession of such a system, whereby a deglaciated nunatak with continued exposure has led to a number of landscape processes, which in turn have formed its heterogeneous topography across the landform – suitable for lichen habitats.

As a final point, the study presents the influences of geomorphology on lichen habitats and indicates the possibility of Vesleskarvet progressively developing a topography and biodiversity similar to Robertskollen, via an increased exposure to landscape-ecosystem processes over time.

## Limitations and Recommendations

Identification of lichens to species level is often difficult. In regions such as Antarctica, atypical morphologies and pronounced variability within species arise, which in turn complexes their identification by structure (Seymour *et al.* 2007). Current records of lichens identified in WDML are limited in that no specialists have visited the area. To date, the only species identified in laboratory conditions, are identified in Ryan *et al.* (1989). With lack of a complete and accurate species record for the WDML region, this study may have instances of species misidentification. Although this study offers a renewed insight into the current diversity of lichens in WDML, morphology was used for identification of species. Morphology of lichens appears to separate and identify species, however some species do share morphological characteristics and all differ molecularly. For the purpose of improving species determination in WDML, it is recommended that lichen samples be collected from the two study sites to provide the molecular data that will resolve the taxonomic uncertainties as well as confirm species identifications of this study.

Solar radiation provides the necessary heat and light for lichens to photosynthesise and establish in their niches. The study did not measure the solar radiation received at the two sites, but instead investigated how insolation, received by lichens and rock surfaces, was

influenced by the macro- and microtopography, respectively. Speculations are, therefore, restricted to observations, which in turn limits data application. Measurements of solar radiation are not readily available and if carried out in Antarctic conditions, limitations within data are likely to arise (e.g. sensor covered by snow, shading of sensors, calibration issues etc.). In absence of valuable solar radiation measurement data, meteorological measurements of air temperature and/or precipitation can be modelled to produce reliable estimates of solar radiation at Vesleskarvet and Robertskollen, which can be quantified. Suggested models are Donatelli and Campbell (1998) and Donatelli and Bellochi (2001), which produce the best estimates (Abraha and Savage 2008). These data will allow investigation into the effects of solar radiation (a key variable in landscape processes) received by landforms and lichens in this environment, which will further elucidate characteristics of lichen colonisation. To further improve the above recommendation, synchronous temperature data collection is suggested for future studies e.g. recording of temperature for rocks at the two sites that have similar aspects and dip. This will elucidate the preference for such environmental conditions.

Thermal imagery was measured for only three days at eight hour intervals, during which air temperatures were recorded. Although this identified large temperature differences across a small-scale (single rock), and displayed similar diurnal temperature trends, an increase in the number of intervals will give better understanding into RST regimes of the rock - which can be directly related to its colonisation of lichens as well as air temperatures. The connections between RST and lichens can be visually displayed on a 3D model. In 2014/15, a pilot study was conducted to test the methodologies involved to create this representation. Preliminary results are presented in Appendix F. Using GIS, thermal imagery was overlaid onto 3D models created using a structure from motion technique. The outcome was a spatially referenced single rock, displaying its thermal variation at 10:30 on the 27 January 2015. In addition to this, FLIR images contain point temperature readings. These data can be analysed using the raster analysis function in GIS, a powerful tool that will depict spatial correlations in temperature over the rock. This will give valuable insight into the transfer of energy in the system, yielding contrasts between rock temperature, rock surface temperature and air temperature. Using air temperatures, insolation measurements can be estimated (refer to above recommendation), rendering the opportunity to correlate temperature data with incoming solar radiation measurements.

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## APPENDIX A: EQUIPMENT SPECIFICATIONS

Equipment	Manufacturer	Model/Version	Specifications
BaseCamp™	Garmin™	Version 4.6.2	12 February 2016©
Canon Powershot	Canon	SX500 IS	16.0 megapixel
Compass and Clinometer	Brunton	Cadet Compass	Azimuthal resolution 2° Azimuthal graduations 2°
DGPS	Spectra Precision®	Epoch®	5-10m accuracy
Electron Microscope	Tescan	Vega LMU SEM	20kV
FLIR camera	FLIR®	E8	IR Resolution 320x240 Thermal Sensitivity <0.06°C
FLIR Tools	FLIR Systems	Version 5.10.16320.1001	2015©
GIS	Esri	Version 10.3	ArcGIS™
GPS	Garmin®	60CSx	3-5m accuracy
Microsoft® Excel	Microsoft®	2013	Extension XLSTAT
Polisher	Leco®	GPX 200	6µm, 3µm, 1µm
Rock Hardness Tester	Proceq®	Equotip	4HL
RStudio	Rstudio Inc.	Version 1.0.44	/
SfM	Agisoft Photoscan®	Version 1.0.0	/
Sputter Coater	Quorum	Q150	Gold
Thermochron iButton®	Fairbridge Technologies	DS1922L	0.0625°C resolution
Thin Section	Buehler®	IsoMet® Low Speed Saw	2mm
WRPLOT View™	Lakes Environmental™	Version 8.0.0	Freeware for wind rose plots

## APPENDIX B: BRT CODE

---

```
> library(sp)
> library(dismo)
> library(raster)
> install.packages("gbm")
>
> Microhabitat_Preference <- gbm.step(data = microhabitat_data, gbm.x=2:7, gbm.y=8,
family = "bernoulli", n.trees=1500, step.size=100, tree.complexity=3, learning.rate=0.0001,
bag.fraction=0.75, plot.main=TRUE)
```

### GBM STEP - version 2.9

Performing cross-validation optimisation of a boosted regression tree model  
for Lichen and using a family of bernoulli  
Using 66 observations and 6 predictors  
creating 10 initial models of 1500 trees

    folds are stratified by prevalence

total mean deviance = 1.3826

tolerance is fixed at 0.0014

ntrees resid. dev.

1500 1.3787

now adding trees...

1600 1.3787

1700 1.3785

1800 1.3782

1900 1.378

2000 1.3779

2100 1.3778

2200 1.3777

2300 1.3776

2400 1.3773

2500 1.3771

2600 1.3769

2700 1.3771

2800 1.3767

2900 1.3765

3000 1.3763

3100 1.3764

3200 1.3761

3300 1.3758

3400 1.3755

3500 1.3752

3600 1.3753

3700 1.3752

3800 1.3751

3900 1.3748

4000 1.3749

4100 1.3747

4200 1.3747

4300 1.3745

4400 1.3744  
4500 1.3745

fitting final gbm model with a fixed number of 4400 trees for Lichen

mean total deviance = 1.383  
mean residual deviance = 1.222

estimated cv deviance = 1.374 ; se = 0.014

training data correlation = 0.744  
cv correlation = 0.143 ; se = 0.091

training data AUC score = 0.929  
cv AUC score = 0.594 ; se = 0.042

elapsed time - 0.18 minutes

> summary(Microhabitat\_Preference)

```
var rel.inf
Dip    Dip 23.20962
Tmin   Tmin 19.99994
Tmax   Tmax 15.02632
Aspect Aspect 14.90274
RH     RH 13.70600
Elev   Elev 13.15538
```

>

> Lichen\_Env <- gbm.interactions(Microhabitat\_Preference)

gbm.interactions - version 2.9

Cross tabulating interactions for gbm model with 6 predictors

1 2 3 4 5

> Lichen\_Env\$interactions

```
      RH Aspect Dip Tmax Tmin Elev
RH    0  0.18 0.36 0.08 0.11 0.07
Aspect 0  0.00 0.10 0.05 0.08 0.02
Dip    0  0.00 0.00 0.10 0.03 0.17
Tmax   0  0.00 0.00 0.00 0.23 0.01
Tmin   0  0.00 0.00 0.00 0.00 0.00
Elev   0  0.00 0.00 0.00 0.00 0.00
```

>

> Lichen\_Env\$rank.list

```
var1.index var1.names var2.index var2.names int.size
1      3      Dip      1      RH      0.36
2      5      Tmin     4      Tmax     0.23
```

>

> gbm.plot(Microhabitat\_Preference)

> gbm.plot.fits(Microhabitat\_Preference)

> PreferencesSimp.tc3.lr0001 <- gbm.step(data=microhabitat\_data, gbm.x =  
preferences\_simp\$pred.list[[1]], gbm.y = 8, tree.complexity = 3, learning.rate = 0.0001)

GBM STEP - version 2.9

Performing cross-validation optimisation of a boosted regression tree model  
for Lichen and using a family of bernoulli  
Using 66 observations and 5 predictors  
creating 10 initial models of 50 trees

folds are stratified by prevalence  
total mean deviance = 1.3826  
tolerance is fixed at 0.0014  
ntrees resid. dev.  
50 1.3842  
now adding trees...  
100 1.3841  
150 1.3841  
200 1.384  
250 1.3841  
300 1.3842  
350 1.3843  
400 1.3843  
450 1.3843  
500 1.3843  
550 1.3842  
600 1.3843  
650 1.3842  
700 1.3842  
750 1.3842  
800 1.3844  
850 1.3844  
900 1.3844  
950 1.3844  
1000 1.3843  
fitting final gbm model with a fixed number of 200 trees for Lichen

mean total deviance = 1.383  
mean residual deviance = 1.375

estimated cv deviance = 1.384 ; se = 0.003

training data correlation = 0.688  
cv correlation = 0.049 ; se = 0.076

training data AUC score = 0.9  
cv AUC score = 0.51 ; se = 0.049

elapsed time - 0.05 minutes  
> summary(PreferencesSimp.tc3.Ir0001)  
var rel.inf  
Dip Dip 31.71452  
Tmin Tmin 19.84057  
Tmax Tmax 16.83311  
RH RH 15.95849  
Aspect Aspect 15.65331  
>

## APPENDIX C: SUPPLEMENTARY MATERIAL FOR CHI-SQUARE

---

Table 15: Categories (based on dataset quantiles) used in the frequency table analyses.

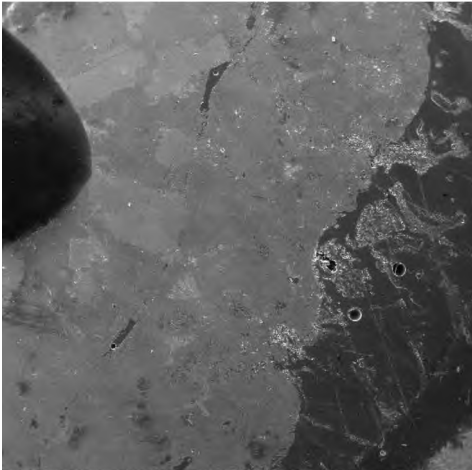
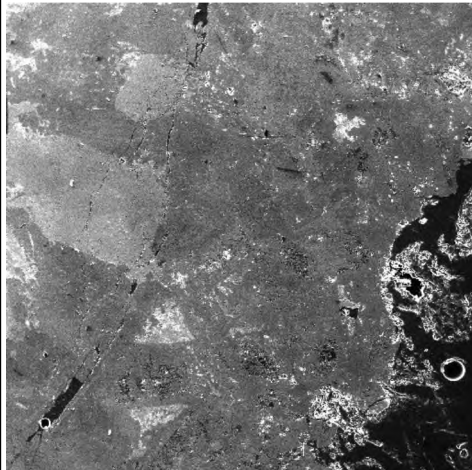
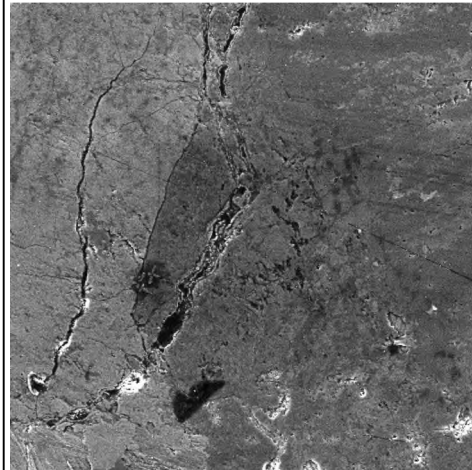
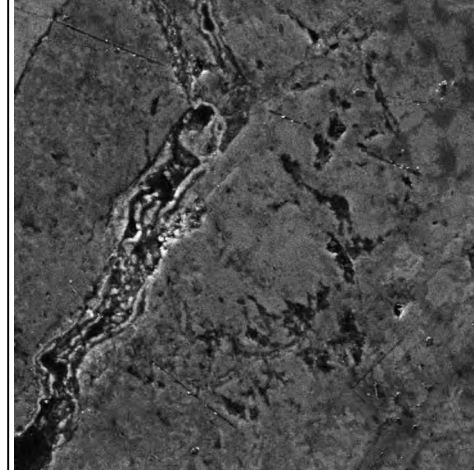
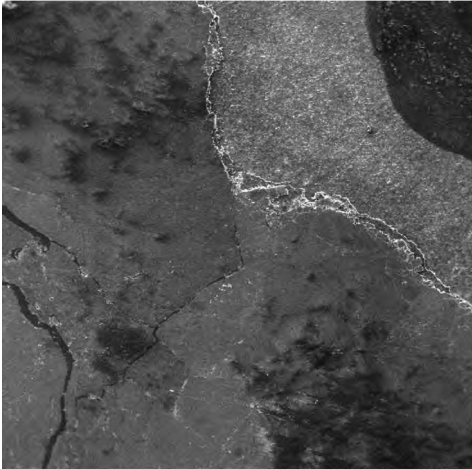
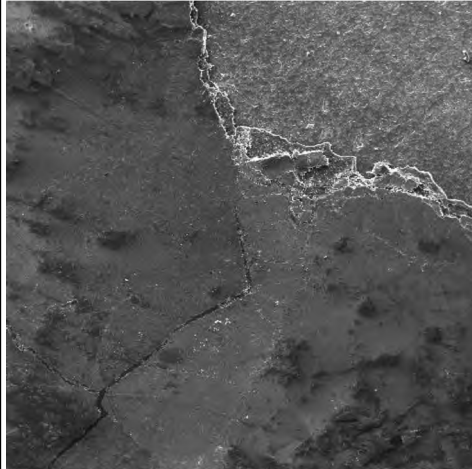
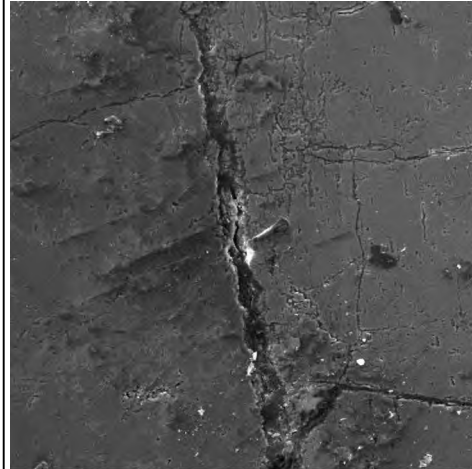
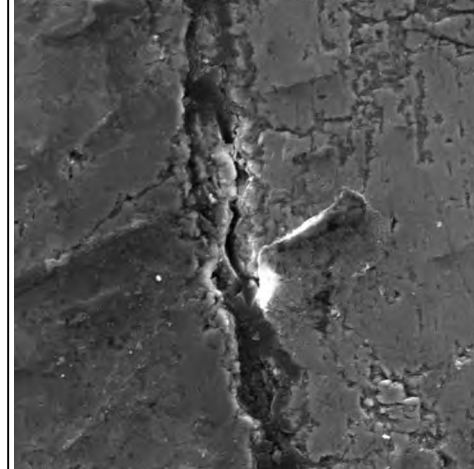
Feature	Characteristic	Category 1		Category 2		Category 3		Category 4	
		Numeric	Classification	Numeric	Classification	Numeric	Classification	Numeric	Classification
Crack	Length (cm)	0-7.28	Shortest	7.29-12.18	Short	12.19-21.1	Long	21.1>	Longest
	Breadth (cm)	0-0.21	Very Narrow	0.22-0.35	Narrow	0.36-0.79	Wide	0.79>	Widest
	Depth (cm)	0-0.1	Very Shallow	0.2-0.3	Shallow	0.4-0.7	Deep	0.7>	Deepest
Flake	Length (cm)	0-10.58	Shortest	10.59-17.5	Short	17.5-25.45	Long	25.45>	Longest
	Breadth (cm)	9-5.23	Very Narrow	5.24-8	Narrow	8.1-14.95	Wide	14.95>	Widest
	Depth (cm)	0-0.65	Very Shallow	0.66-1.2	Shallow	1.21-2.15	Deep	2.15>	Deepest

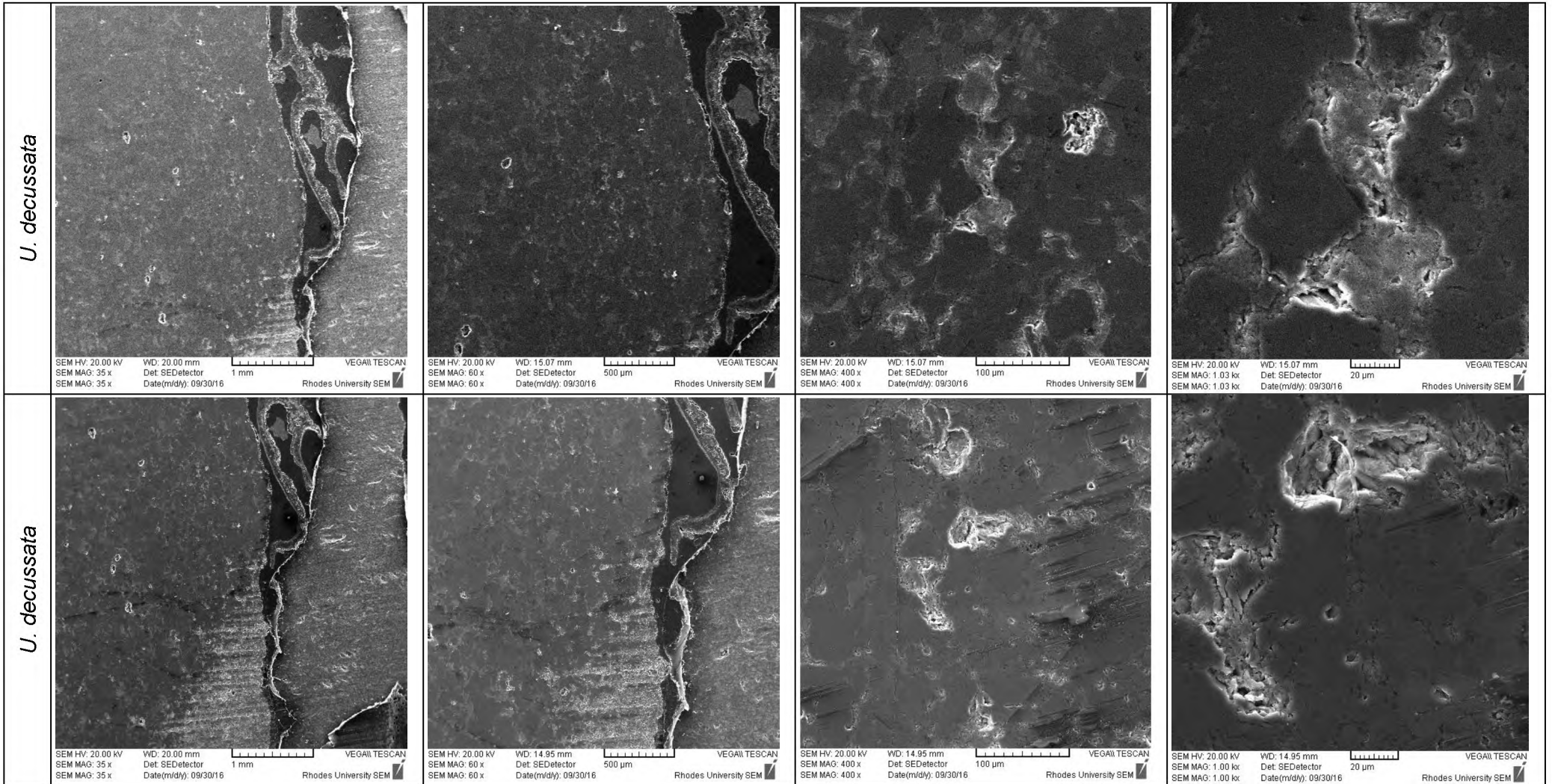
## APPENDIX D: FLIR IMAGERY

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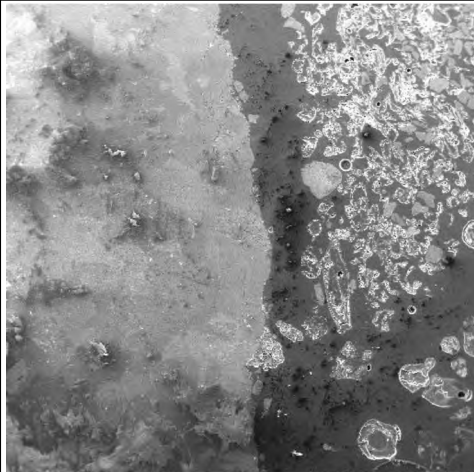
Refer to the CD submitted with this dissertation.

# APPENDIX E: SEM IMAGES

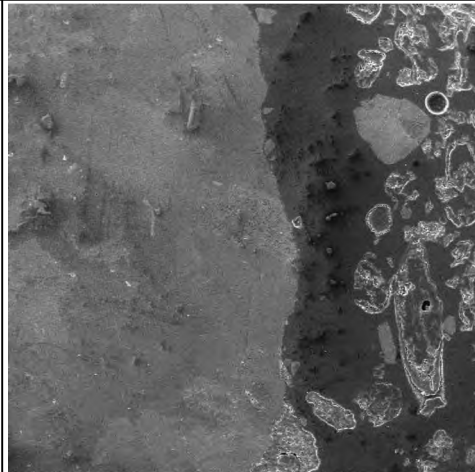
Sp.	Magnification			
	35X	60X	400X	1000X
<i>Buellia</i> sp. B	 <p>SEM HV: 20.00 kV WD: 20.30 mm SEM MAG: 35 x Det: SEDetector SEM MAG: 35 x Date(m/d/y): 09/20/16 VEGAII TESCAN Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 14.80 mm SEM MAG: 60 x Det: SEDetector SEM MAG: 60 x Date(m/d/y): 09/20/16 VEGAII TESCAN Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 14.80 mm SEM MAG: 400 x Det: SEDetector SEM MAG: 400 x Date(m/d/y): 09/20/16 VEGAII TESCAN Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 14.80 mm SEM MAG: 1.00 kx Det: SEDetector SEM MAG: 1.00 kx Date(m/d/y): 09/20/16 VEGAII TESCAN Rhodes University SEM</p>
<i>P. chlorophanum</i>	 <p>SEM HV: 20.00 kV WD: 20.31 mm SEM MAG: 35 x Det: SEDetector SEM MAG: 35 x Date(m/d/y): 09/30/16 VEGAII TESCAN Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 15.10 mm SEM MAG: 60 x Det: SEDetector SEM MAG: 60 x Date(m/d/y): 09/30/16 VEGAII TESCAN Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 15.10 mm SEM MAG: 400 x Det: SEDetector SEM MAG: 400 x Date(m/d/y): 09/30/16 VEGAII TESCAN Rhodes University SEM</p>	 <p>SEM HV: 20.00 kV WD: 15.10 mm SEM MAG: 1.00 kx Det: SEDetector SEM MAG: 1.00 kx Date(m/d/y): 09/30/16 VEGAII TESCAN Rhodes University SEM</p>



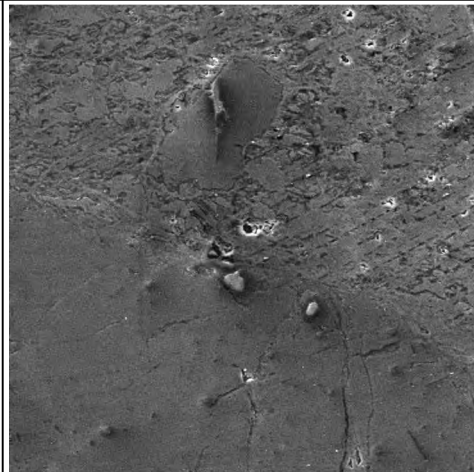
*U. sphacelata*



SEM HV: 20.00 kV WD: 20.00 mm  
SEM MAG: 35 x Det: SEDetector  
SEM MAG: 35 x Date(m/d/y): 09/30/16  
VEGA\\ TESCAN  
Rhodes University SEM



SEM HV: 20.00 kV WD: 14.91 mm  
SEM MAG: 65 x Det: SEDetector  
SEM MAG: 65 x Date(m/d/y): 09/30/16  
VEGA\\ TESCAN  
Rhodes University SEM



SEM HV: 20.00 kV WD: 14.91 mm  
SEM MAG: 400 x Det: SEDetector  
SEM MAG: 400 x Date(m/d/y): 09/30/16  
VEGA\\ TESCAN  
Rhodes University SEM

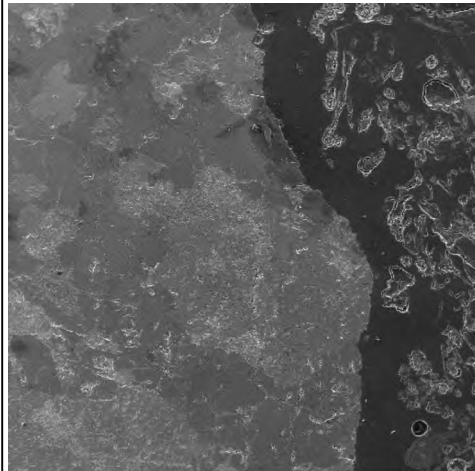


SEM HV: 20.00 kV WD: 14.91 mm  
SEM MAG: 1.00 kx Det: SEDetector  
SEM MAG: 1.00 kx Date(m/d/y): 09/30/16  
VEGA\\ TESCAN  
Rhodes University SEM

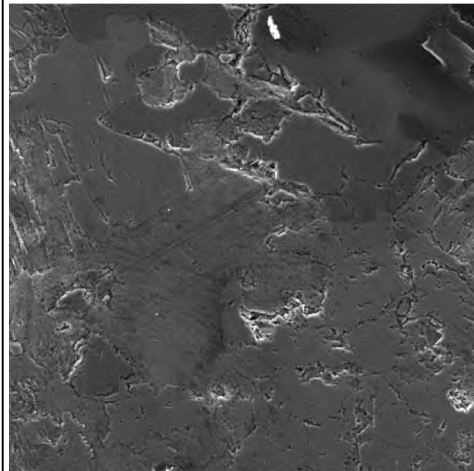
*U. sphacelata*



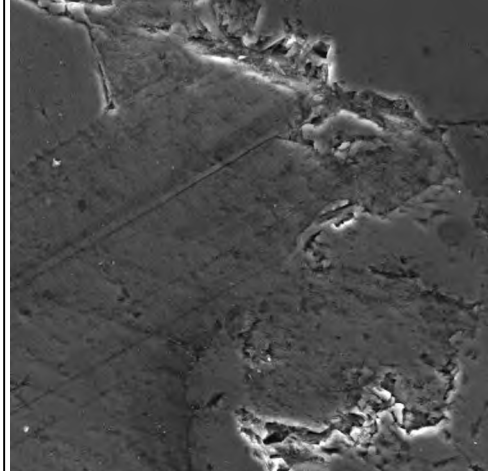
SEM HV: 20.00 kV WD: 20.00 mm  
SEM MAG: 35 x Det: SEDetector  
SEM MAG: 35 x Date(m/d/y): 09/20/16  
VEGA\\ TESCAN  
Rhodes University SEM



SEM HV: 20.00 kV WD: 14.88 mm  
SEM MAG: 60 x Det: SEDetector  
SEM MAG: 60 x Date(m/d/y): 09/20/16  
VEGA\\ TESCAN  
Rhodes University SEM



SEM HV: 20.00 kV WD: 14.88 mm  
SEM MAG: 400 x Det: SEDetector  
SEM MAG: 400 x Date(m/d/y): 09/20/16  
VEGA\\ TESCAN  
Rhodes University SEM



SEM HV: 20.00 kV WD: 14.88 mm  
SEM MAG: 1.00 kx Det: SEDetector  
SEM MAG: 1.00 kx Date(m/d/y): 09/20/16  
VEGA\\ TESCAN  
Rhodes University SEM

## APPENDIX F: DISPLAYING ROCK-LICHEN INTERACTIONS

---

As discussed in text, a pilot study was conducted in the 2014/15 Austral Summer to test methodologies, which would effectively display RST-lichen interactions on a three-dimensional rock model. The output of this study is seen below and can be implemented in future research to display associations between rock characteristics and lichen colonisation. The same concept can be applied to monitor thermal regimes of rock surfaces and their micro-topography, in conjunction with lichen colonisation, to investigate weathering processes at a single rock scale.

### Methods

#### Three-Dimensional Modelling

Agisoft Photoscan® was used to convert photographs of the selected rock into 3D models. This is a software that photogrammetrically processes still images to create advanced, high quality 3D content and it has been used particularly for creating Digital Elevation Models (DEMs) of landscapes (e.g. Scott 2014) (PhotoScan® 2016). The Structure from Motion (SfM) technique allows objects to be mapped and modelled in 3D and space whereby two-dimensional (2D) images are coupled with motion signals (Scott 2014). Multiple images of each clast were captured from various angles and used in Agisoft Photoscan® to generate a textured, 3D model of the rock in order to display its characteristics and micro-topography (e.g. Figure 52).

Prior to image capturing, reference points were set up on, and around, the rock using markers for georeferencing images in the software at a later stage. To ensure adhesiveness, 19mm diameter wooden dowel stick was sliced into ~0.5cm chips to be used as georeferencing points. These markers were numbered and attached to the rock using Epoxy. The position of each marker was recorded using a Spectra Precision® Epoch® differential GPS (DGPS) to give the markers x, y and z coordinates, for bringing a mosaicked 3D model into real space, ready for import into ArcGIS®. Figure 53 displays an example of a georeferenced FLIR image.

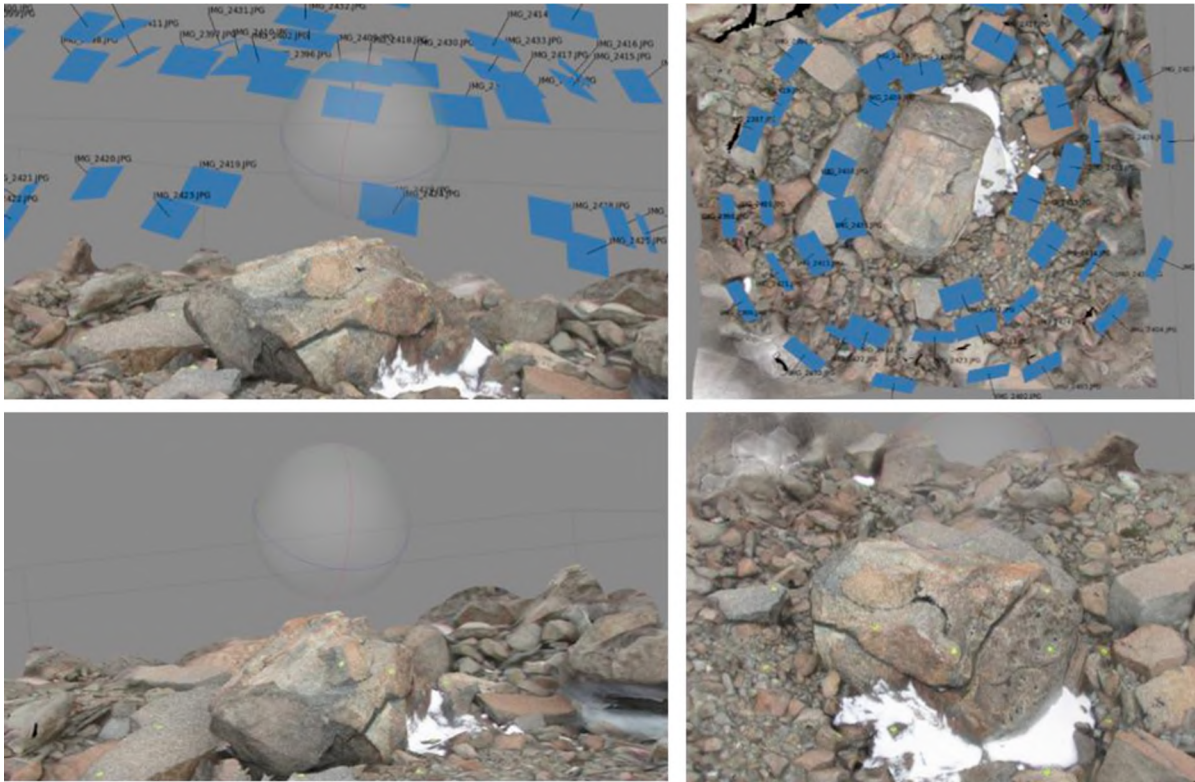


Figure 52: An example of a 3D model (colonised rock at Robertskollen). The blue rectangles represent the angle and height at which the photograph was taken. The yellow indicators are the DGPS markers.



Figure 53: Georeferenced FLIR image in ArcMap®.

## Outcomes of the Pilot Study

Figure 54 shows a screenshot of the 3D rock model produced in Photoscan®. A FLIR image displaying RSTs at 10:30 on 27 January 2015 was georeferenced (Figure 53), and draped over the model in ArcScene (Figure 55). It can be concluded that these methodologies are successful in developing spatially referenced representations of rocks in their environments. Results from the pilot study can, therefore, be used as reference in future research to display other environmental relationships.

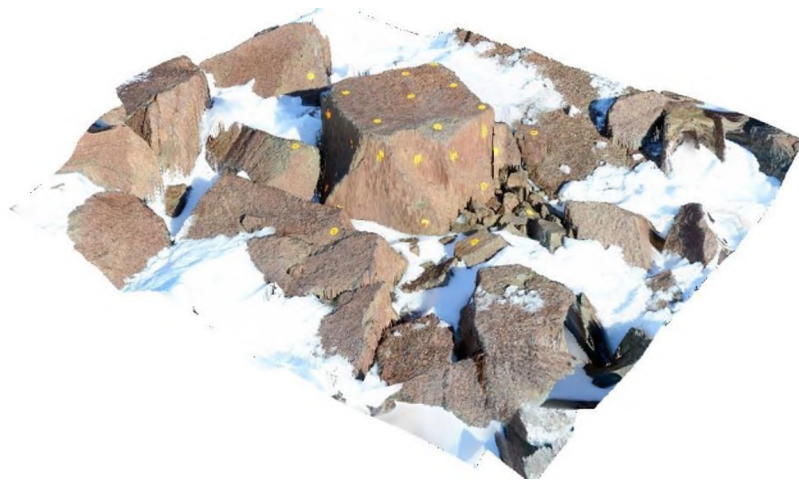


Figure 54: 3D Model of a spatially referenced rock on the southern buttress of Vesleskarvet.

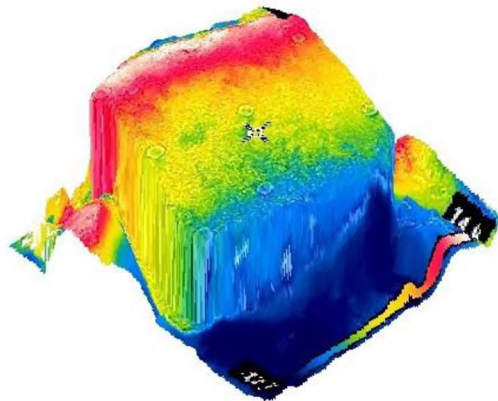


Figure 55: Draped thermal image on 3D model displaying the large scale RST differences across the rock.