Soil chronosequences and bacterial communities of the Central Transantarctic Mountains, Antarctica

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Abstract

The Beardmore Glacier region of the Central Transantarctic Mountains (CTAM), approximately 600 km south of the McMurdo Dry Valleys (MDV), has been studied to a much lesser extent than the accessible MDV and other regions of the continent. The CTAM were visited in the 2010/2011 austral summer, and two concurrent studies undertaken; these are presented in the form of manuscripts for publication in peer-reviewed journals, as a thesis by publication.

Soil chronosequences in three of the largest ice-free areas (Ong Valley, Mount Achernar, and the Dominion Range), at altitudes above 1600 m along the polar plateau margin, were examined. Transects perpendicular to the current ice edge reveal a gradual increase in soil depth (from 2 cm to > 80 cm to underlying ice), weathering, horizonation, salt content, and a decrease in pH; all of these factors are consistent with increased soil development since time of deglaciation. Such fine scale variation in soil properties, previously overlooked in the CTAM region, cannot be mapped by Soil Taxonomy subgroups, as commonly utilised in Antarctic soil mapping. Patterns of soil thickness, clast abundance and soil chemistry all indicate a bi-modal form of soil development. It is proposed that the soil profile deepens by addition of englacial debris to the subsoil via the sublimation of underlying ice, and the weathering of supraglacial clasts at the soil surface.

The molecular characterization of bacterial communities in CTAM soils is the southernmost culture-independent soil survey to date. Community fingerprinting (ARISA) and 16S rRNA gene pyrosequencing demonstrated significantly different bacterial communities between eight discrete CTAM locations (5 at low altitude near the Ross Ice Shelf coast, 3 near the polar plateau > 1600 m). Abiotic environmental variables, especially those related to long-term exposure of soils to the atmosphere, correlate well with inter-site community variation. Mount Howe, the southernmost soil on the planet (87° S), harbours an extremely low biomass bacterial community, of a fundamentally different composition to all other sites. It appears that observed DNA sequences at Mount Howe are the result of atmospherically deposited bacteria, the soil being unable to support edaphic life due to extreme local climatic conditions.

These two studies extend previous knowledge of soil development and distribution, and microbial ecology, to the southernmost extent possible. These observations may serve as important baseline data for monitoring of this fragile system in the face of future and ongoing environmental changes.

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Chapter 1 - Introduction

1.1. Overview

This thesis documents the findings resulting from a one-month field season in the Beardmore Glacier region of the Central Transantarctic Mountains (CTAM) during the 2010/2011 austral summer. Two independent investigations were undertaken concurrently:

- Soil-landscape relationships in recessional deposits at glacier margins
- Bacterial community structuring throughout the CTAM region

1.2. The Latitudinal Gradient Project

This current study was instituted within the framework of the international Latitudinal Gradient Project (LGP). The LGP is a collaborative multidisciplinary program, which seeks to investigate ecosystem responses along an environmental/climatic gradient; latitude is used as a coarse proxy for this gradient (Howard-Williams *et al.*, 2006). The Victoria Land Coast of the Ross Sea Region, running roughly north-south, provides this latitudinal gradient; from Cape Hallet in the north (approximately 72° S), to the Beardmore Glacier (site of current study, approximately 83°S to 85°S) in the south (Figure 1.1).

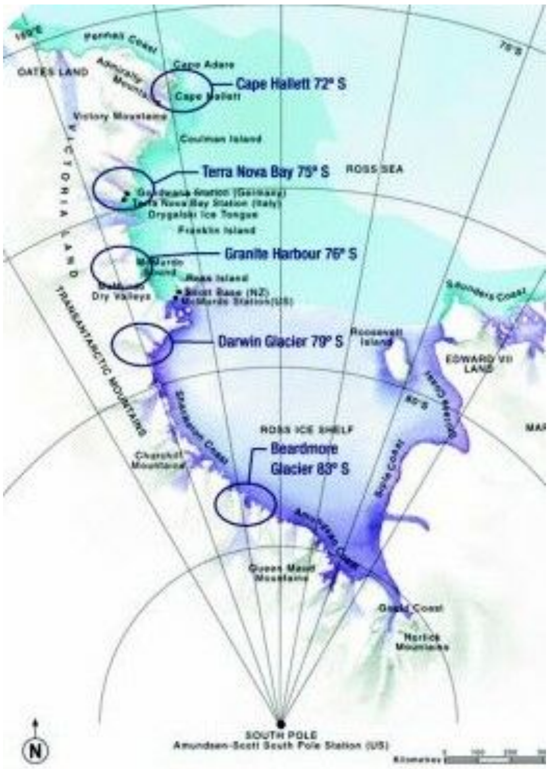

Figure 1.1: Main LGP study areas along the Victoria Land Coast, Ross Sea Region, Antarctica. (From: http://www.lgp.aq/abouttheproject/)

At each latitudinal site a longitudinal gradient is recognized, capturing the change in altitude with distance from the coast, and the associated climatic variables (Howard-Williams *et al.*, 2006). This work constitutes the southern-most extent of the Ross Sea Environmental Domains Classification program run by Landcare Research. Classification of the various terrestrial ecosystems in the region will aid monitoring of change over time and the protection of these ecosystems.

The LGP is structured around eight key questions (Howard-Williams *et al.*, 2006. Page 468), two of which are relevant to this current study:

> 1. “What aspects of, and to what extent does, ecosystem structure and function (diversity/complexity) change with latitude, and why?”
>
> 7. “To what extent does soil development (e.g. degree of weathering, carbon content and nutrient accumulation) change with latitude and therefore influence terrestrial ecosystems?”

1.3. The Central Transantarctic Mountains – Beardmore Glacier Region

The Transantarctic Mountains (TAM) constitute the division between "West Antarctica" and "East Antarctica". The TAM extend across the continent, from Cape Adare, along the Ross sea/ice shelf coast, and into the Weddell sea region. At roughly 3,500 km long, the TAM are one of the longest mountain ranges on Earth.

This thesis focuses on ice free areas in the CTAM (Figures 1.2 and 1.3). The most prominent feature of the CTAM region is the Beardmore Glacier; at around 160 km long, it is one of the largest glaciers on Earth. The Beardmore is an outlet glacier of the East Antarctic Ice Sheet (EAIS), draining ice from the polar plateau out to the Ross Ice Shelf (RIS). Several other major glaciers are present in the region, as well as a multitude of smaller alpine glaciers.

While largely covered in ice, the CTAM region contains several relatively large ice-free areas, consisting of either bare rock mountaintops and nunataks, or glacial deposits of moraine/till material.

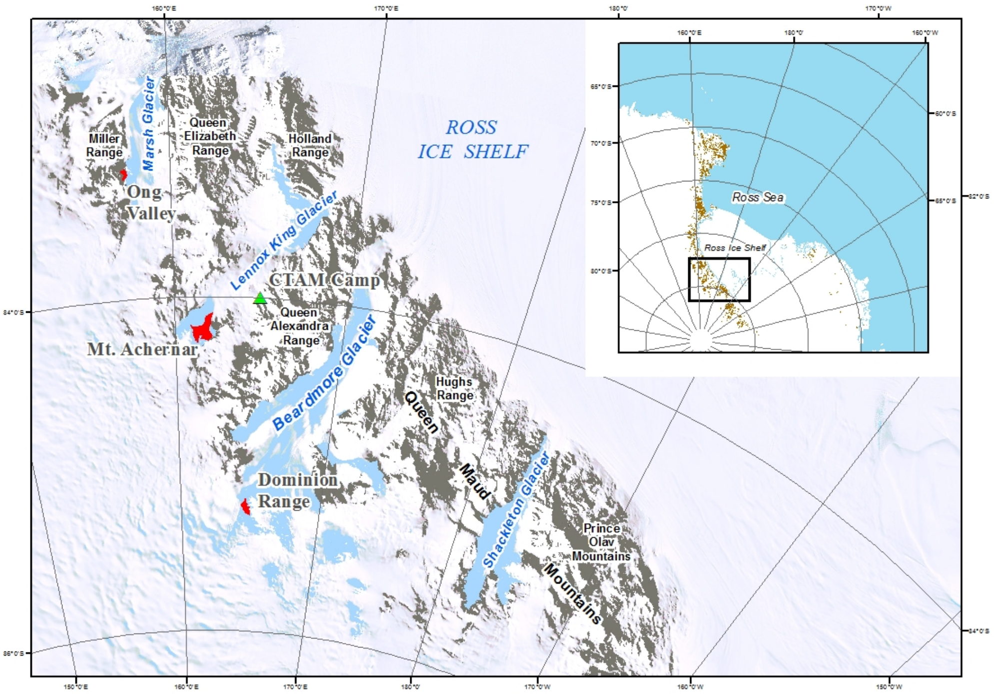

Figure 1.2: Map showing ice-free areas targeted for soil-landscape investigations in the Central Transantarctic Mountains (CTAM), study sites in red; inset greater Ross Sea Region.

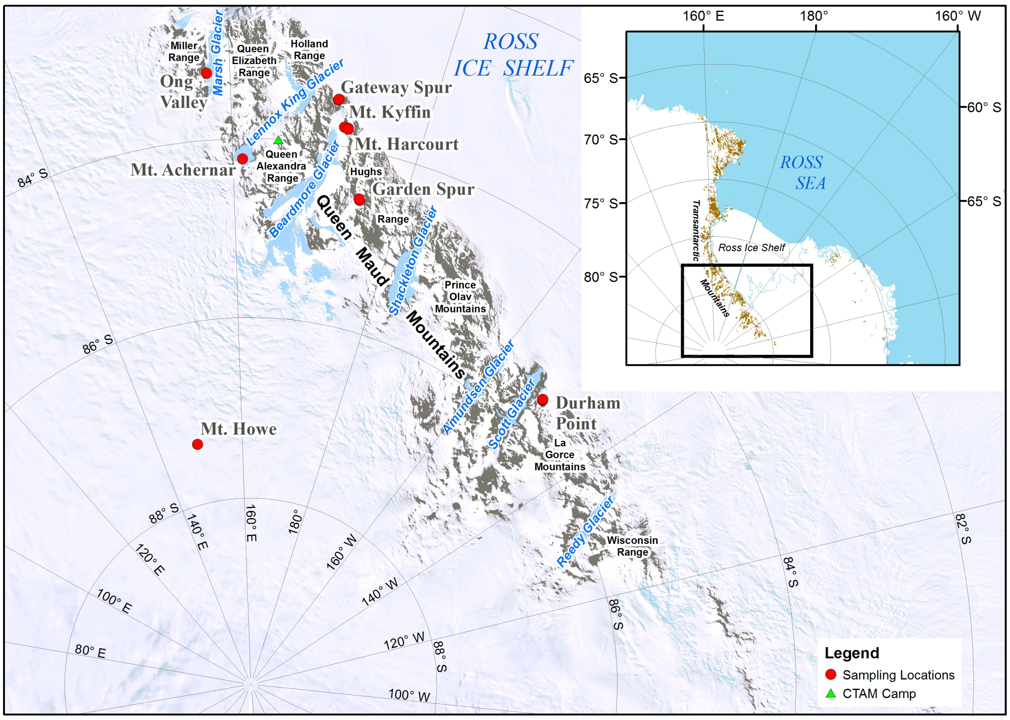

Figure 1.3: Map of microbial community sample locations within the Central Transantarctic Mountains (CTAM); inset greater Ross Sea Region.

1.4. History of Exploration

The Beardmore Glacier is of particular historical importance and interest, being used by both Shackleton and Scott as the path from the Ross Ice Shelf to the Polar Plateau *en route* to the South Pole.

Sir Ernest Shackleton discovered the Beardmore during the 1908 *Nimrod* expedition, and was the first proven way up onto the plateau. On seeing the glacier for the first time from the summit of Mount Hope, Shackleton wrote:

> *"[T]here burst upon our view an open road to the south, for there stretched before us a great glacier running almost south and north between two huge mountain ranges. As far as we could see, except towards the mouth, the glacier appeared to be smooth, yet this was not a certainty, for the distance was so great."* – Shackleton, 1909 (In Shackleton, 1983)

Although the pole was not reached on this expedition, Shackleton had flagged a clear path for subsequent attempts.

Captain Robert Falcon Scott and his team successfully reached the pole in January 1912 via the Beardmore Glacier; although the achievement had been preceded by the Norwegian team led by Roald Amundsen, who travelled up the, till-then unknown, Axel Heiberg Glacier. Almost 100 years on, observations made by Scott differ little from what was seen during the 2010/2011 season:

> *"Except Mount Kyffin, little bare rock is visible… There are no moraines on the surface of the glacier either…Higher up the valley there is much bare rock and stratification, which promises to be very interesting, but oh! for fine weather; surely we have had enough of this oppressive gloom."* – Scott, 1911

The Southern/plateau part of the region was extensively mapped/ surveyed in the summer of 1961/1962 by the 'New Zealand Geological and Survey Expedition'; led by Sir Walter "Wally" Herbert (UK), and including Peter Otway (surveyor), Vic McGregor (geologist) and Kevin Pain (field assistant) (Herbert, 1963). The 84-day sledging expedition resulted in a comprehensive map of the region, which remains relatively accurate and reliable today. The 1961/62 expedition was concluded by a relatively treacherous descent of the Axel Heiberg Glacier, made famous by Amundsen's pole-ward ascent.

1.5. Previous Scientific Investigation

Previous soil work in the Beardmore Glacier region has largely focused on correlating drift sheets along the Transantarctic Mountains, for the purpose of reconstructing past glacier and ice sheet limits (Denton *et al,* 1989a; Denton *et al,* 1989b). Soil data from these investigations has also been incorporated into soil development work for the broader Transantarctic Mountains system (Bockheim, 1990).

Biological interrogations of the area have yielded mites, *Collembola* (Springtails)*,* lichens and mosses in the coastal regions near Mount Kyffin and Mount Harcourt (Tyndale-Biscoe, 1960). Reports of microbial life are limited, with bacteria and/or yeasts being obtained via culture methods from Mount Howe (Cameron, 1971) and nearby La Gorce Mountains (Aislabie *et al.*, 2006). No reports of culture independent (i.e. – molecular identification) studies exist at present for the CTAM region.

1.6. Objectives of Current Study

The overall objective of this study was to investigate and characterize soils and their associated microbial communities in previously unexplored regions of Antartica. The specific objectives were to:

(1) Map and characterize the soils of three large ice-free ‘windows’, in order to establish a soil-landscape relationship model for the wider region. The three ‘windows’ were (Figure 1.2,):

- The Ong Valley
- The western side of the Dominion Range
- A broad suite of moraines at the foot of Mount Achernar

(2) Assess how soil bacterial communities are structured in the wider CTAM region (Figure 1.3), in comparison to communities in the McMurdo Dry Valleys especially; and (3) determine the abiotic/spatial factors which may be important for such community structuring.

1.7. Structure of Thesis

This thesis is structured as two manuscripts, one submitted, and one in preparation for submission, to peer-reviewed journals.

- Chapter 2 provides a broad literature review encompassing both soils and bacterial communities of Antarctica.

- Chapter 3 comprises a manuscript entitled: *Three soil chronosequences in recessional glacial deposits near the polar plateau, in the Central Transantarctic Mountains, Antarctica* - submitted to the journal *Antarctic Science* on the 7th of June, 2013.

- Chapter 4 comprises a manuscript entitled: *The southernmost soil bacterial communities, Central Transantarctic Mountains, Antarctica* – in preparation for submission.

- Chapter 5 provides a discussion of limitations of the studies, explores potential future directions for research in the CTAM region, offers a synthesis of the two studies, and discusses the value of the research presented in this thesis.

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Chapter 2 – Literature Review

This chapter aims to review previous studies into Antarctic soils and the microbial communities therein, providing context for the research in this thesis. Most of the previous work has been conducted in the McMurdo Dry Valley region, as this is the most easily accessed ice-free region in the Ross Sea sector; an effort has been made to assess all studies in the Central Transantarctic Mountain region. Concepts pertaining to broader microbial ecology are also examined.

2.1. Antarctic Soils and Permafrost

2.1.1. Soil in Antarctica

For quite some time, the legitimacy of assigning the name *soil* to the unconsolidated mineral deposits of Antarctica was disputed, largely due to the lack of higher plant life in most Antarctic soils. The recognition by several authors that the deposits are affected by pedogenic processes, and may be differentiated from the initial deposit over time, support the argument for Antarctic surficial deposits to be classified as soils (Ugolini & Bockheim, 2008). The definition of soils, in the USDA Soil Taxonomy, was revised to include Antarctic soils:

"a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment. This definition is expanded from the previous version of Soil Taxonomy to include soils in areas of Antarctica where pedogenesis occurs but where the climate is too harsh to support the higher plant forms". – Soil Survey Staff (2010).

Acknowledged pedogenic processes in the Antarctic include desert pavement formation, salt redistribution within the profile, reddening/increase in colour, deepening of ice/ice-cemented permafrost due to ablation effects, and weathering of clasts/materials *in situ* (Ugolini & Bockheim, 2008).

2.1.2. Physical weathering and glacial processes

Physical weathering processes are by far the dominant soil forming mechanisms in continental Antarctica, with chemical alterations being extremely limited by the low water availability in the cold, arid, Antarctic environment. While processes such as frost wedging/cracking are often relatively unimportant in Antarctica (due to the lack of water, and in some cases minimal temperature deviations above the 0°C freeze/thaw point), differential expansion due to solar heating, and wind-driven erosion can contribute considerably to *in situ* weathering of rocks; the plate-like flaking of darker rocks is a fairly common site in many areas, and the scouring of rocks by airborne sand (or similar) particles is attributed as the cause of the characteristic sculpted or ventifacted clasts observed on older surfaces (Campbell & Claridge, 1987).The expansion of salt crystals in interstitial spaces between rock grains is also implicated in the breakdown of rocks, although this haloclasty is somewhat reliant on certain humidity thresholds and cycles in order for the crystallization process to occur. *In situ* soil formation usually only occurs on surfaces at high altitudes that have not been affected by ice level fluctuations (i.e. – the bedrock is not buried by moraine or till, at least to an extent as to inhibit weathering of the bedrock), although actively eroding surfaces may also be observed at lower altitudes (e.g. – on steep slopes; Campbell & Claridge, 1987).

Glacial action is the dominant driver of landscape and soil formation throughout most of the continent, and is particularly relevant in the CTAM region. Antarctic glaciers are generally dry-based, thus sub-glacial abrasion is not very important, although may have been in the past when a warmer climate facilitated a more energetic wet-based regime (Campbell & Claridge, 1987). Glaciers contribute to Antarctic landscapes principally via the transport of material within and on top of the ice. The transported/entrained material is deposited at the margins of glaciers as lateral/terminal moraines, or as ablation till when ice level drops and the glacier retreats. Deposits that soils form in may be rather different, geologically, from the rocks of the local area; thus source geology must be considered, often at a distance from the deposit, when evaluating local pedogenesis.

Claridge & Campbell (1968) suggest that particle size analysis may allow differentiation between the two principle forms of physical weathering/origin (i.e. – *in situ* vs. glacial deposition). A till-derived soil was found to have a much greater proportion of fines within the profile, compared to a soil resulting from the breakdown of a coarse dolerite. Till and bedrock derived soils were the extremes of a series of soils sampled from the Shackleton Glacier region. Also, some of the fines in the till soil may be derived from finer grained sediments (Claridge & Campbell, 1968), thus particle size data must be interpreted carefully if used to determine physical weathering pathways.

Due to the coarse-grained nature of many of the rocks, and the modes of weathering that dominate, most soils have a sandy or loamy sand texture, with a high proportion of coarser clasts, and clay and silt contents of < 10% (Bockheim, 1997).

A desert pavement is often present at the surface of Antarctic soils; commonly thought to be driven by wind deflation removing fines from the surface and resulting in a "lag gravel" deposit, which eventually protects the surface from further wind erosion (Campbell & Claridge, 1987). A desert pavement is characterized by "*a continuous mantle of flat-lying, densely packed or partially overlapping clasts*" (Bockheim, 2010. p. 433). Desert pavements are more common on older, more stable surfaces, where the disruptive cryoturbation processes are no longer active. A recent study by Bockheim (2010) provides an alternative mechanism for desert pavement formation, based on evidence/observations from a variety of locations in the Transantarctic Mountains. Weathering *in situ* of clasts is implicated, with a silt-enriched and clast-deprived layer often forming as a result of the breakdown products below the pavement; this layer often has a vesicular porosity, especially on older surfaces (Bockheim, 2010). The vesicles are suggested to be the result of water infiltrating the silty layer during a snowmelt, and the resultant ice crystals subliming out of the soil.

2.1.3. Chemical Weathering

Chemical weathering is restricted by the low availability of liquid water in the environment, a consequence of both the low temperatures and minimal precipitation. However the presence of clays in some Antarctic soils demonstrates that chemical weathering occurs to some extent. Claridge (1963) analysed soils from a variety of localities within the Ross Dependency, Antarctica. Clays were found to be largely micaceous, presumably resulting from both physical and chemical weathering of micas. Montmorillonite was present in several soils, particularly one from a dolerite moraine, and one in greywacke south of the Beardmore Glacier. Montmorillonite is generally formed in arid conditions and high pH (Claridge, 1963), thus its presence may be construed as evidence for contemporaneous clay formation. Claridge (1963) also noted that considerable amounts of reactive bases were readily released to solution in many of the Shackleton soils (hence the high pH), which migrate upwards and contribute to the salt concentrations typically formed at or near the surface. Hydration of micas was cited as the dominant clay forming process, with hydration/expansion increasing with age of the soil, the final product being vermiculites. Clay crystalinity also increases with age with those materials most recently transported/emplaced (e.g. – the youngest moraines) generally exhibiting a larger proportion of amorphous clay materials, showing up as a lack of sharp lines in X-ray diffraction analyses (Claridge, 1963).

The presence of liquid water, and facilitation of chemical processes therein, was illustrated by two radioactive tracer studies in the Wright Valley, Antarctica (Ugolini & Anderson, 1972; 1973). Injection of either Na^{22} or Cl^{36} at the top of the ice-cemented permafrost, and subsequent detection of these radioisotopes higher up in the profile, conclusively demonstrated active ionic migration under present climatic conditions. Upward migration was attributed to thin films of liquid water between ice and mineral surfaces, which must remain unfrozen at temperatures considerably below 0°C. Markedly slow migration rates were measured however (7 cm over 25 days for Cl^{36}; 5 cm over 2 years for Na^{22}), pointing to the thinness of such films, and the diffusive constraints enforced by such a narrow and tortuous path through these coarse textured soils (Ugolini & Anderson, 1972). Differences in migration rates of the two ions were attributed to their differing charges. Migration is generally in the direction from warm to cold front; thus upward migration may only happen during the winter months (~ March – September), when surface temperatures are lower than the more thermally stable ice-cement. Deepening of ice-cemented permafrost, and near-surface concentration of salts over time is cited as further evidence of this net upward migration of both water and solutes (Ugolini & Anderson, 1972).

2.1.4. Biological influences

Apart from the special cases of Ornithogenic soils (Hofstee *et al*., 2006) near/in penguin colonies, and moss peats in the Peninsula region (Balks *et al.,* 2013), biota have a negligible influence on soil development and properties in Antarctica. In fact, *"Antarctic soils are considered to be soils in which the biological factors are reduced to a minimum although they never quite reach zero"* (Claridge & Campbell, 1968). Biological input decreases markedly with altitude/distance from the coast, thus is likely extremely unimportant in the areas of this current study.

2.1.5. Climatic zonation

Tedrow (1977) named the continental Antarctic a 'cold desert zone', which differs considerably from the 'polar desert zone' delineated at comparable latitudes in the Arctic; this is partly due to the extreme lack of vegetation on the continent, with the exception of lichen and algae. The polar desert and tundra zones in the Southern hemisphere are restricted to the tip of the Antarctic Peninsula, sub-Antarctic islands, and the southern tip of South America.

Campbell and Claridge (1968) proposed a classification of continental Antarctic soils on a climatic basis; according to available moisture, there are three categories.

Ultraxerous soils, found at high altitudes or close to the polar plateau, are "rarely, if ever, moist". The combination of low temperatures and snowfall in these areas results in moisture availability being essentially "inconsequential". A frozen ground/ice-cemented permafrost is thus absent in these soils. A horizon of salt accumulation is usually characteristic of the ultraxerous soils, although this is dependent on the age of the soil (i.e. – older soils have thicker/stronger salt horizons).

Xerous soils occur in regions of intermediate climate relative to the plateau and coastal zones, and are the most widespread within the Ross Sea region. Higher temperatures and precipitation result in greater moisture availability, generally from the melting of snowfalls in summer. Soluble materials may leach from the profile, and the salt concentrations are thus lower and less localized than those in the ultraxerous soils. Ice-cemented permafrost is generally present in xerous soils, and a vesicular structure within the soil may arise from the cycles of wetting and drying associated with the intermittent melt events (Campbell & Claridge, 1968).

The third class of soils is termed subxerous (Campbell & Claridge, 1968); subxerous soils have the greatest amount of moisture availability, and are situated at low altitudes relatively close to the coast. Liquid water is often evident in the coastal areas during a period of summer, with small ponds, lakes, and running streams observed for up to several weeks. The subxerous soils may be very moist, and the higher temperatures may result in considerable melting of the frozen ground (ice-cemented) layers. Weathering of subxerous soils is thus more advanced compared to similar aged soils in the more arid zones, with more potential for clay formation.

2.1.6. Salts

Salt accumulation is a common feature of desert soils, the arid conditions do not allow much leaching of salts from the profile, and sublimation of snow (in the cold desert region) leaves salts behind; any salts deposited (i.e. – in snow, blown as marine aerosols) or produced *in situ* tend to persist in the soil (Campbell & Claridge, 1987). Salts found include the ions of sulfate, chloride, nitrate, sodium, potassium, magnesium, and calcium. Almost all crystalline combinations of these ions may be found in Antarctic soils (Claridge & Campbell, 1977).

Salt concentrations, measured via conductivity, have been used as a proxy for age/stage of soil development (Table 2.1). The salt-stage scale was calibrated on drift units in the McMurdo Dry Valleys with established numerical age constraints.

Table 2.1: Soil salt stages (after Bockheim, 1997).

Salt Stage	Appearance	EC (ds/m)	Approx. Age
0	None	<0.6	<10 ka
1	Coatings beneath stones	0.6-5.0	10-18 ka
2	<20% of horizon with flecks 1-2 mm	5.0-18	18-90 ka
3	>20% of horizon with flecks 1-2 mm	18-25	90-250 ka
4	Weakly cemented salt pan	25-40	250 ka - 1.7 Ma
5	Strongly cemented salt pan	40-60	1.7 Ma - 3.9 Ma
6	Indurated salt pan	60-100+	>3.9 Ma

A correlation between rock/mineral type and cation composition within the soil is evident in many parts of Antarctica; dolerites yield high magnesium and calcium proportions, while weathering of granites results in greater amounts of potassium (Claridge & Campbell, 1977; Campbell & Claridge, 1987). The standout cation is sodium, which often occurs at higher concentrations than can be accounted for by *in situ* mineral weathering, indicating an important marine contribution; either evaporation of trapped sea water at coastal sites due to past sea level changes, or atmospheric aerosol deposition. Anions, however, exhibit more divergence from the parent material, providing more information about atmospheric deposition processes. Claridge and Campbell (1987) describe a general pattern with distance from the coast, with the chloride: nitrate ratio decreasing markedly as soils were sampled up the Shackleton Glacier valley (an analogous system to the Beardmore). Keys and Williams (1981) also identified a negative salt concentration gradient with distance from the coast in the McMurdo Dry Valleys, particularly the chloride and sodium ions, indicating an important marine role in Antarctic soil salt distributions. It is suggested that these salts are an important determinant of the high/alkaline pHs generally encountered in Antarctic soils. Magnesium, calcium and carbonate ions were attributed to the chemical weathering of rocks (Keys & Williams, 1981), either *in situ* or from sources distant from the soil site.

Based largely on their work on the Shackleton Glacier, Claridge and Campbell (1977) suggested two modes of atmospheric salt deposition, resulting in the spatially disparate salt distributions. The chlorides (and sodium) are attributed to air blowing in off the nearby ocean carrying abundant marine aerosols. The nitrates and sulphates are linked to the larger scale global air circulation; proteins (containing sulfur and nitrogen) from tropical surface waters are transported to the Polar Regions, and the oxidized forms thus deposited as snow that is blown to the ice-free areas (Claridge & Campbell, 1977). Subsequent sublimation then leaves the ions behind; resulting in substantial accumulation over long (up to millions of years) time scales.

Claridge and Campbell (1977) recognized a distinct relationship between climate, age, and salt accumulations. Soils developing under ultraxerous conditions tend to have salt horizons near the surface, with thickness depending on age of the soil. Salt rich horizons may be comprised almost wholly of soluble materials, and can be hard/cemented. Xerous soils do not feature a discrete salt zone/horizon; salts are dispersed throughout the profile, although deposits may form under surface clasts (Claridge & Campbell, 1977).

Salts are implicated in the general trend of decreasing pH with distance from the coast (Claridge & Campbell, 1977; Campbell & Claridge, 1987), particularly the chloride:sulfate ratio. Lower pHs correlate well with increased relative importance of sulfate in the soil. The pH is thus dependent on the balance of the two atmospheric pathways described above, although local sources such as sulfur minerals or marbles ($CaCO_3$) may be more important in determining pH over smaller spatial scales.

2.1.7. Permafrost and patterned ground: processes and features

Permafrost, being soil/subsurface materials below 0°C for two or more years, is a ubiquitous feature of mainland Antarctic landscapes. An “active layer”, a thickness of soil that thaws in summer, usually overlies permafrost. Temperatures and solar insolation, and the albedo of the surface influence the depth of the active layer. Adlam *et al.* (2010) found that the combination of four variables were able to predict 73% of active layer depth variation; mean summer air temperature, mean winter air temperature, total summer solar radiation, and mean summer wind speed. Active layer depth is, by definition, the depth to where liquid water may potentially occur. As a culmination of many field seasons, Campbell and Claridge (2006) reviewed general distribution and landscape patterns of permafrost in the TAMs. An important distinction was made in the case of dry (or ice-free) permafrost; very low water content in the profile (6-7% gravimetric; Campbell & Claridge, 2006) leaves the materials loose and non-cohesive, with ice crystals acting similarly to sand grains. Permafrost is thus only defined via temperature, as opposed to the more typical ice-cemented permafrost, which is easily identified by its massive cohesive nature. Another prominent feature of Antarctic soils is buried ice; *"typically stagnant or old residual glacial ice… associated with patterned-ground-covered glacial retreat surfaces and also younger land surfaces with thermokarst terrain"* (Campbell & Claridge, 2006. p. 218). Buried ice is suggested to be up to several million years old in some cases, but the ages are the cause of some debate. Sugden *et al* (1995) proposed that buried glacial ice in Beacon Valley, Antarctica, had been stable for at least 8.1 million years, on the basis of $^{40}Ar/^{39}Ar$ dating of a volcanic ash within the overlying till. However, cosmogenic ^{3}He profiles measured by Ng *et al.* (2005) suggest a much younger age for the same ice, in the order of 310-43 thousand years. Bockheim *et al* (2007) report a relationship between surface age and permafrost type in the McMurdo Dry Valleys. Ground/buried ice is attributed to Holocene surfaces, ice-cemented ground on late Quaternary surfaces, and older surfaces exhibit dry-frozen permafrost. It is suggested that dry permafrost *"develops on surfaces >115 ka due to sublimation"* (Bockheim *et al.*, 2007).

Both dry and ice-cemented permafrost, and active layer depth, exhibit a trend along the longitudinal/altitudinal gradient from the coast inland in the TAM region. Dry permafrost becomes much more prevalent, over ice-cemented permafrost, with distance from the coast, as higher altitudes and lesser precipitation are experienced. Despite relatively low soil temperatures, the soil at higher altitude (or closer to the polar plateau) remains generally non-cohesive due to the absence of sufficient moisture to bind it. Active layer depth shallows markedly along this altitudinal gradient also, this being attributed to the adiabatic lapse rate (Campbell & Claridge, 2006); i.e. –warming of the soil at altitude is prevented/diminished by the greater heat-sink capacity of the air. Adlam *et al.* (2010) found that air temperatures predicted by the dry adiabatic lapse rate were fairly concordant with those observed along an altitudinal gradient from Wright

Valley (150 m) to Mount Fleming (1700 m), and the air temperatures were reliable predictors of active layer depth. The relationship between active layer depth and altitiude was complicated by site-specific factors; for example melt water at one site conducted thermal energy into the subsoil and thus increased the active layer depth (Adlam *et al.*, 2010). The altitudinal effect on active layer depth is also related to the local climate, with higher sites generally being closer to the plateau and/or experiencing less precipitation. Active layer depths in the McMurdo Dry Valleys range from 45-70 cm along the coast, to <20 cm near the plateau (Bockheim *et al.*, 2007). Active layer depth also varies with latitude in the McMurdo region, ranging from > 90 cm at Granite Harbour (77°S) to 22 cm at Minna Bluff (78.5°S; Adlam *et al.,* 2010).

The topography of a deposit overlying glacial ice (termed "ice-cored moraine") evolves as the glacier retreats/ablates (Campbell & Claridge, 1982). Ablation may occur via melting or sublimation. Thermokarst topography is typical of the early stages of ablation; the thin veneer of moraine mimics the underlying ice surface, which is often rough and hummocky due to spatially differential heating, ablation rates, and depth of overlying insulating mineral material. The soil material is moved and mixed considerably during this phase, thus soil development (e.g. – horizonation) is limited. As ablation progresses, and the overlying 'soil' layer thickens, the ice becomes more buffered from temperature changes, thus sublimation and melting rates diminish over time, and the surface becomes more stable, allowing soil development to progress (Campbell & Claridge, 1982). Sublimation rates have not been explicitly quantified, although cosmogenic ^{3}He depth profiles in till over buried ice in the Beacon Valley (McMurdo region) suggest average sublimation rates exceeding 10-100 metres per million years (Ng *et al.,* 2005). Hagedorn *et al.* (2007) suggested that snow cover may halt and indeed reverse water vapour transport from the ice-cement/ice to the atmosphere, thus allowing the shallow ice frequently observed in Antarctic landscapes. There is some evidence that suggests lateral advection of glacial ice may 'recharge' ice levels from below (Fogwill *et al.,* 2012), which may help explain discrepancies between predicted ice volume loss and inferred past ice levels.

Patterned ground is a relatively common feature of glacial recessional landforms. Patterned ground is most commonly expressed as a mosaic of polygons across the ground's surface; polygons are distinguished by cracks between them, which often have greater relative concentrations of coarser clasts (cobbles to boulders) within/near them, compared to the polygons themselves. Cracks may be initiated by freeze/thaw contraction causing cracking of the underlying ice. These cracks are in filled by sand from the surrounding surface material and/or windblown material, preventing them from closing fully. Thus the cracks progressively develop into "sand wedges", with intersecting cracks dividing the landscape into polygons. Compressive stresses resulting from the added material preventing lateral expansion of the ice may cause vertical deformation of the surface expressed as either high-centered polygons or raised 'shoulders' bordering the cracks (Sletten & Hallet, 2003). The landscape may contain a combination of mature inactive cracks and younger cracks at various stages of initiation/development. Kessler and Werner (2003) developed a numerical model in order to explain the processes that result in 'self-sorting' patterns. Two main feedback mechanisms were identified in Kessler and Werner's model; lateral sorting, and stone domain squeezing, both requiring freeze/thaw cycling (within active the layer). Areas of higher stone density are less compressible, and cool faster due to less pore-held water. Thus a 0°C isotherm moving down through the profile will mimic the topology of stone domains. As expansive forces operate perpendicular to the "freezing front", stones are pushed towards stone domains, and a positive feedback is established. Hill-slope was found to be an important parameter with steeper angles resulting in more elongated polygons, with the long axis orientated downslope (Kessler & Werner, 2003). Changes in patterned ground character with distance from current ice margin are indicative of stagnation and recession of underlying ice sublimation (Levy *et al.,* 2006; Hallet *et al.,* 2011).

2.1.8. Soil classification

Continental Antarctic soils are classed as "gelisols" in USDA Soil Taxonomy (Soil Survey Staff, 2010). Gelisols are defined by either permafrost within 100 cm from the surface, or gelic materials (those affected by cryoturbation) within 100 cm, and permafrost within 200 cm, of the soil surface. Suborders within the gelisols are histels (typified by organic materials, restricted to coastal/peninsula localities in Antarctica), turbels (cryoturbation evident), and orthels (i.e. – do not fulfill requirements for either histel or turbel suborders (Soil Survey Staff, 2010).

2.2. The Central Transantarctic Mountains – Beardmore Glacier Region

This section reviews current knowledge of the CTAM region relevant to soil development and distribution.

2.2.1. Topography and geology/parent materials

As continental Antarctic soils are predominantly mineral in nature, the composition and origin of parent materials is an important factor in the development and distribution of the soils. Soils may form from *in situ* weathering of the bedrock, in colluvial deposits, or in the moraine/till materials deposited by glaciers, which may be some considerable distance from the geological source. The composition of soil parent materials determines the initial elemental composition of resultant soils, thus the raw material for pedogenic processes to act upon. Due to the minor extent of soil development in the arid, cold environment, soil properties are rarely very divergent from the parent material.

The geological descriptions below were obtained from United States Geological Survey (USGS) reconnaissance maps produced in the 1970's.

Situated between the head of the Beardmore and Nimrod Glaciers, the Dominion range has a broad (approximately four kilometers wide) sweep of lateral moraine adjacent to its western margin. The lateral moraines are strikingly characterized by a strong curvi-linear patterning of alternating red and grey ridges, corresponding to differing lithologies dominating the moraine surfaces, separated by shallow swales, thus, forming a landscape with up to 6 m of relief. The influence of smaller alpine glaciers, flowing down off the Dominion Range's plateau is evident as a series of terminal moraines adjacent to the Range on the ice-distal limit of the lateral moraines. On the edge of the Polar Plateau, ice level is 2200 m above sea level, with minimal altitude variation (~ 50 m) across the moraine suite. Local geology is dominated by Ferrar Dolerite and Buckley Formation sedimentary rocks (including shale, sandstone, coal, and glossopterid fossils; Elliot *et al.,* 1974).

Mount Achernar is bounded to the North by the Law Glacier, with a 6-10 km-wide expanse of lateral moraine deposits at the eastern foot. A banding pattern, similar to that at the Dominion Range, is evident in the Law Glacier lateral moraines, and the influence of several smaller glaciers from the south is also observed. The moraines lie between 1800 and 1900 m above sea level. The Mount Achernar bluffs adjacent to the moraine suite are comprised of Ferrar Dolerite and Buckley Formation sediments, with Fremouw Formation sedimentary rocks (sandstones and mudstones, some shale) prevalent nearby (Barrett & Elliot, 1973).

Ong Valley is a narrow (roughly two kilometers at the widest) ice-free valley approximately eight kilometers long. The steep valley walls are primarily composed of the *Hope Granite* (Barret *et al.,* 1970), frequently mantled with scree. The valley floor is covered with glacial deposits of mixed geology emplaced by the Argosy Glacier that has advanced up from the mouth of the valley in the past. A smaller unnamed glacier intrudes into the head of the Ong Valley, and evidence of greater previous extent of this glacier is observable. The ice level (Argosy Glacier) at the mouth of the Valley is around 1500 m above sea level; the valley floor rises to around 1700 m at its head.

2.2.2. Climate

The field season of the current study approximately coincided with the period of highest air temperatures for the region, taking measurements made at the CTAM camp as proxy for the wider region (Figure 2.1). The CTAM camp was situated, by necessity, in one of the more sheltered parts of the region, thus may underestimate extremes in outlying areas more exposed to the katabatic influence of the plateau. Nevertheless, our visit was in the warmest part of the relatively short summer at this latitude, thus it is probable that the region does not experience higher air temperatures over the rest of the year. Mean annual temperature has been estimated at -40° C, and an estimated annual (water) accumulation of 36 mm per year (Beardmore South Camp - 84° 03' S 164°15' E; Bockheim, 1990).

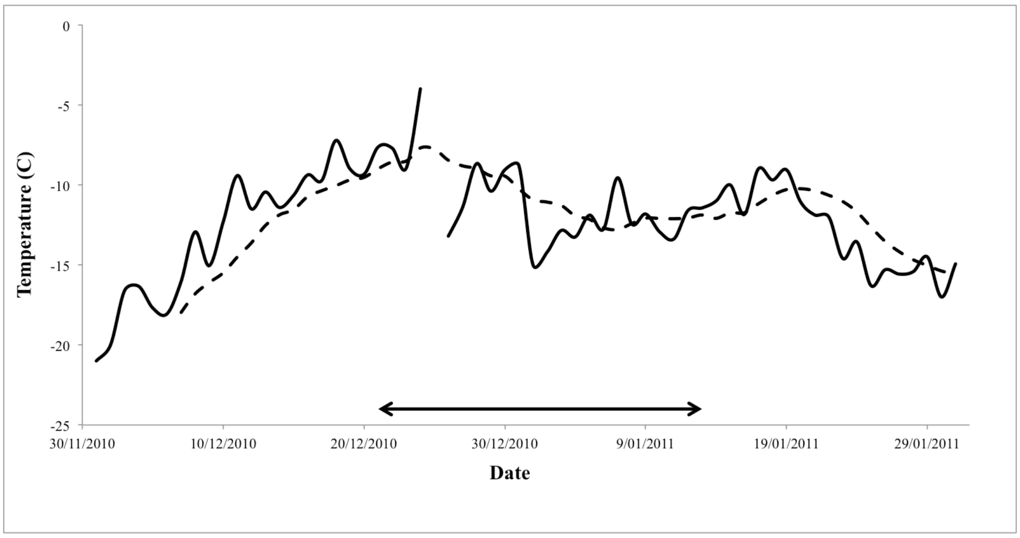

Figure 2.1: Daily mean (solid line), and seven day moving average (dashed line), air temperatures at CTAM camp, December 2010 to January 2011. Arrows represent field season of this study. Data from: ftp://amrc.ssec.wisc.edu/pub/fieldcamps/

The southernmost soil site, Mount Howe is at an altitude of ~ 2800 m where the climatic conditions are extreme; Cameron and colleagues (1971) reported maximum air and soil surface temperatures of -11 °C and -4 °C respectively between 30th December 1970 and 4th January 1971.

2.2.3. Time

Glacial deposits examined in the Dominion Range and Mount Achernar sites correlate to the Plunket and Beardmore Drifts (Table 2.2) as described by Denton *et al.* (1989a), with an estimated maximum age of 23.8 ka (Bockheim, 1990). The older Sirius Drift (Denton et al, 1989a) was not encountered in the sites covered in this study. However, cosmogenic exposure age dating of quartz-bearing rocks within the moraines suggests the moraines at Mount Achernar are much older (than ages according to weathering and salt stages) at 300 to 500 kyr (Faure & Nishiizumi 1994; Mathieson *et al.,* 2012).

Table 2.2: summary of major glacial drift units associated with the Beardmore Glacier. *WS: weathering stage, SS: salt stage

Drift unit	**Relative position** (from Denton et al, 1989a)	**Key features** (from Denton et al, 1989a)*	**Correlated numerical age** (from Bockheim, 1990)
Plunket	7-30 m above, and parallel to, current ice surface	Average 16 cm to "ice-cement", WS 1, SS 0	6.0 ka
Beardmore	35-40 m above current ice surface near plateau, 1100 m above current ice surface at glacier mouth	Average 55 cm to "ice-cement", WS 1, SS 1	10.3-23.8 ka
Meyer	30-50 m above and parallel to Beardmore drift	Average 83 cm to "ice-cement", WS 2-3, SS 2-3, 'ghosts' and matrix salts common	130 - 190 ka

2.3. Antarctic Soil Microbiology

The desert soil habitats of continental Antarctica represent some of the simplest soil ecosystems on the planet, with the McMurdo Dry Valleys (MDV) encompassing *"some of the oldest, coldest, driest and most oligotrophic soils on Earth"* (Cary *et al*., 2010). The continent is devoid of year-round vertebrate species, the largest permanent animal inhabitants are tiny springtails and mites, and vegetation is limited moss and lichens (excluding the Antarctic Peninsula). These microbially dominated ecosystems, with incredibly limited trophic structures, are thought to represent a system in which biotic interactions are largely unimportant (Hogg *et al.,* 2006). This inherent simplicity allows researchers to investigate the ecology of soil-dwelling microorganisms at a fine scale, without the confounding factors of higher trophic level influences and interactions.

2.3.1. Microbial ecology of Antarctic cold desert soils

The majority of studies reviewed in this section are also summarized in a book chapter entitled: *Bacterial Community Structures of Antarctic Soils* (Bottos *et al*., In Press), of which I am a contributing author.

The Antarctic continent is largely covered in ice, often kilometres thick, with only ~0.4% of the landmass permanently ice-free (Peat *et al.,* 2007). Apart from the large congregations of sea birds and mammals at the coast during the summer season, these ice-free regions do indeed resemble "*a valley of the dead*" (Scott, 1905). 'Open soil' habitats in the Dry Valleys are characterized by low water availability (derived from snow or soil humidity), high levels of both photosynthetically active and UV radiation, primarily aeolian and lacustrine carbon sources, and nitrogen being chiefly atmospherically derived (Cary *et al*, 2010).

As with microbial ecology throughout the rest of the world, culture dependent surveys in the Antarctic vastly underestimated the full diversity in the soils. Many soils were reported to be sterile, and any recovered microbes were doubted to be indigenous (Horowitz *et al*., 1972). The development and application of molecular, rather than culture-dependent, methods introduced a paradigm shift into the Antarctic microbiology field. Microbes were revealed to be more abundant and widespread than previously recognised, and a much greater diversity (Cowan *et al.*, 2002; Barrett *et al.*, 2006; Smith *et al.*, 2006; Yergeau *et al.*, 2007). MDV soil communities are typically dominated by members of the *Actinobacteria, Bacteroidetes* and *Acidobacteria* (Figure 2.2a). *Proteobacteria* are under-represented, and *Deinococcus-Thermus* frequently recovered from MDV soils (Babalola *et al.*, 2009; Cary *et al.,* 2010). Conversely, *Proteobacteria* are relatively abundant community members throughout the Antarctic Peninsula (Figure 2.2b), with members of the *Alpha, Beta, Delta,* and *Gamma Proteobacteria* classes frequently identified (Yergeau *et al.,* 2007).

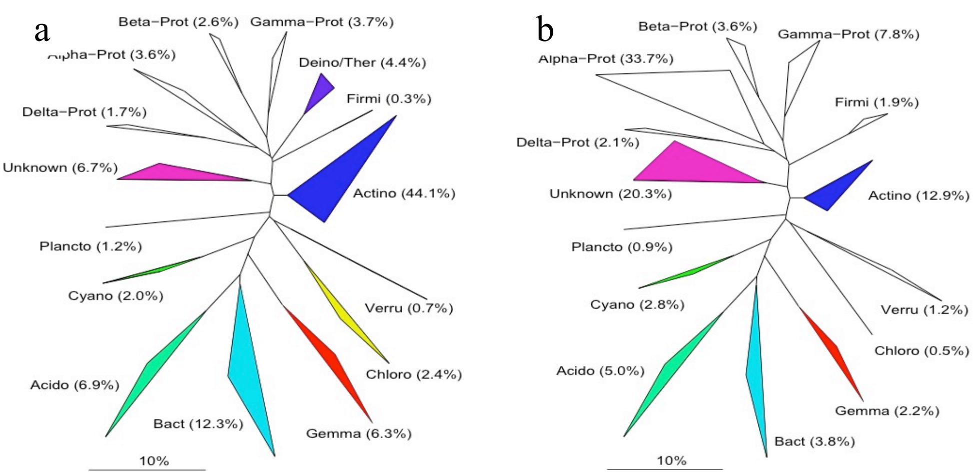

Figure 2.2: Phylum level diversity of bacterial 16S rRNA gene sequences from (a) Victoria Land and (b) Antarctic Peninsula. Trees constructed using ARB (Ludwig *et al.*, 2004), with DNADIST and Neighbor joining analysis, and the percentage of sequences in each phyla is shown (in brackets). Abbreviations: Acido – *Acidobacteria*; Actino – *Actinobacteria*; Bact – *Bacteriodetes*; Chloro – *Chloroflexi*; Cyano – *Cyanobacteria*; Deino/Ther – *Deinococcus/Thermus*; Firmi – *Firmicutes*; Gemma – *Gemmatimonadetes*; Plancto – *Planctomycetes*; Prot – *Proteobacteria*; Verru – *Verrucomicrobia.* Adapted from: Bottos *et al*., In Press.

Work extending beyond simple surveys has addressed some fundamental questions pertaining to Antarctic soil ecology, and challenged certain long-held assumptions. Lee *et al.* (2012) found microbial communities to be distinct between locations within the MDV, although phyla-level diversity was relatively constant, and geochemical properties (especially salt content, altitude and copper content) of the soil correlated well with the community heterogeneity. Such spatially distinct communities suggest a certain degree of endemism, and refute expectations of a low diversity community dominated by widespread ‘cosmopolitan’ taxa (Vishniac, 1993), indeed only two phylotypes were found to be present in all four valleys (Lee *et al.,* 2012). Water availability (albeit ephemeral) is likely an important determinant of community structures. Dry soils at Luther Vale (North Victoria Land) were conspicuously dominated by members of the *Deinococcus-Thermus*, while wetter soils exclusively contained members of other phyla, notably the *Betaproteobacteria*, and *Gammaproteobacteria* (Niederberger *et al.*, 2008). *Deinococcus-Thermus* and *Actinobacteria* (especially the *Rubrobacter* genus) also dominated the dryer soils of Wright Valley (Aislabie *et al*., 2006a). A specific investigation into sediments in/alongside the Onyx River (Wright Valley, MDV) also found water to be important; wet sediments dominated by the *Bacteroidetes*, and dryer sediments at the margins of the stream-bed harbouring an *Acidobacteria* dominated community (Zeglin *et al.*, 2011).

Primary productivity is limited in Antarctic desert soils; mosses and lichens are the only prominent vegetation, and these are sparsely distributed. Significant photoautotrophic communities are generally restricted to chasmolithic and endolithic microhabitats (Pointing *et al.*, 2009). Soil communities are thus predominantly heterotrophic, and several studies suggest aeolian redistribution of cyanobacterial mats from water body margins to be the main input of carbon into distal soil systems (Moorhead *et al.*, 2003; Hopkins *et al.*, 2006; Wood *et al.,* 2008).

Investigations into the relationship between metazoan and bacterial communities fail to identify any significant co-variation. Presence and abundance of nematodes (potential predators) did not correlate with bacterial diversity or community structure, thus top-down predatory control of bacterial populations is unlikely to be a determinant of distribution or community structuring (Barrett *et al.,* 2006).

A unique experiment conducted in the Miers Valley challenged the view of limited activity in polar soils (Moorhead *et al.,* 1999). The introduction of a mummified seal carcass to an ‘open soil’ site, showed the potential for soil microbial community to respond rapidly to changes in the abiotic environment (Tiao *et al.*, 2012). Within three years, a ‘pristine soil’ community was altered to more closely resemble communities present under seal carcasses (some in place for > 750 years) than nearby control sites (Tiao *et al.*, 2012). These changes in community structure were accompanied by a measurable increase in community respiration (CO_2 flux; Tiao *et al.*, 2012). Similarly, significant shifts in community composition was observed within three years at several sites throughout the Antarctic Peninsula region, under experimentally induced warming (Yergeau *et al.*, 2012).

While the aerial redistribution of organic matter is recognised as an important factor in MDV ecosystems (Hopkins *et al.*, 2006), the specific phenomenon of bacterial immigration between distinct communities is unlikely, with little similarity found between Miers Valley soil communities and the bacterial component of the overlying air (Bottos *et al.,* 2013).

The Latitudinal Gradient Project (LGP; see chapter 1) prompted and enabled studies both North and South of the MDV along Victoria Land and the Transantarctic Mountains The LGP aimed to examine changes in ecosystems with respect to environmental/climatic conditions, latitude along the Victoria Land coast being a proxy for climate (Howard-Williams *et al.*, 2006). Culture-independent microbial investigations further south in the Transantarctic Mountains has been restricted to the Darwin Mountains region (Figure 2.4; another LGP site). Magalhaes *et al.* (2012) found significant differences in community structure (at multiple trophic levels) at sites along a soil development sequence; greater salt accumulations in older soils was associated with decreased diversity and ecosystem complexity. Similar diversity decreases with soil age were found by Aislabie *et al.* (2013) at Lake Wellman (Darwin Mountains), with communities residing within older glacial drift units being considerably different to those within recently (~10 ky) deglaciated soils. Clone library sequences revealed communities to be dominated by members of the *Deinococcus-Thermus*, *Actinobacteria* and *Bacteroidetes* phyla (Figure 2.3).

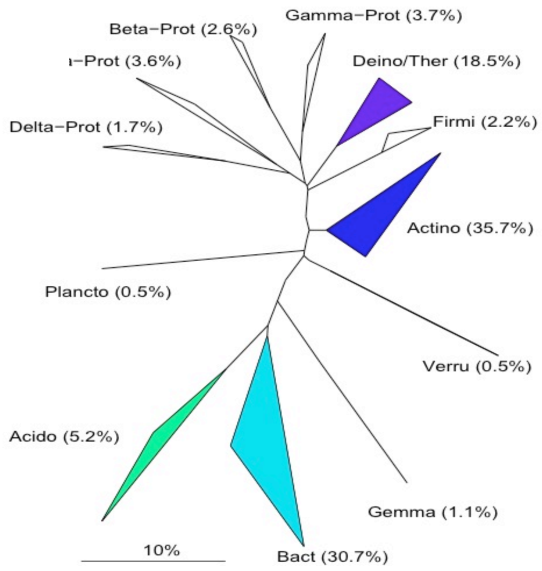

Figure 2.3: Phylum level diversity of bacterial 16S rRNA gene sequences from the Darwin Mountains. Abbreviations as defined in Figure 2.2. Adapted from: Bottos *et al.*, In Press

Studies further south have been culture-dependent; Aislabie *et al.* (2006) isolated members of the *Actinobacteria*, *Bacteroidetes* and *Proteobacteria* from the La Gorce Mountains (86°S), and Cameron *et al.* (1971) reported *Arthrobacter* sp. and *Corynebacterium* sp. as well as some yeasts at Mount Howe, the southernmost soil on the planet. A recent study incorporating two sites (Mount Kyffin and Cloudmaker) along the Beardmore Glacier, and several sites in the MDV, used community fingerprinting (t-RFLP and ARISA) to investigate the contrasting influences of environmental and spatial (i.e. – dispersal) variables on bacterial and cyanobacterial ‘metacommunities’ at a range of scales (Sokol *et al.*, 2013). While pH and moisture content influenced bacterial community structuring, at least at the coarse resolution allowed by the applied methods, cyanobacteria did not co-vary with environmental parameters, suggesting a degree of biogeography at finer phylogentic scales. No studies incorporating high-throughput sequencing of soil bacterial communities have been reported south of the Darwin Mountains region to date.

Figure 2.4: Locations of soil microbial community investigations throughout the Antarctic and Sub-Antarctic region; from Bottos *et al.* (In Press).

The Antarctic Peninsula is recognized as significantly different from the rest of the continent biologically, with few invertebrate and plant species common to both regions. This biogeographic divide, termed the 'Gressit Line' lies south of Alexander Island (Figure 2.4) and the English and Bryan Coasts on the West of the Peninsula, South of the Wakefield Mountains on the East of the Peninsula, and North of the nunataks of Ellsworth Land (Chown & Convey, 2007). The presence of considerable vegetation in habitats throughout the Peninsula has an important influence on bacterial abundance and diversity (Yergeau *et al.*, 2007; Yergeau *et al.*, 2007b). The influence of vegetation is suggested to be due to amelioration of environmental stressors such as temperature fluctations and water availability (Yergeau *et al.*, 2007). Vegetation, both mosses and angiosperms, support drastically different bacterial communities to nearby unvegetated soils on both Livingston Island (Ganzert *et al.*, 2011) and King George Island (Teixeira *et al.*, 2010). As in the MDV (e.g. – Lee *et al.*, 2012), few phylotypes are shared between disparate soil communities on Alexander Island (part of the wider peninsula region) despite fairly similar phyla level composition; pH and copper content were found to correlate well with compositional variation (Chong *et al.*, 2011).

Microbial communities throughout East Antarctica have been studied to a lesser extent than either the MDV or Antarctic Peninsula, and generally restricted to locations relatively close to research stations. Denaturing gradient gel electrophoresis (DGGE - a community fingerprinting technique) did not reveal any significant relationship between environmental parameters and community structure near Casey Station, despite the range of soils surveyed including those heavily impacted by human and Adelie penguin disturbance (Chong *et al.*, 2009). The majority of sequences recovered from DGGE bands were assigned to the *Bacteroidetes* phylum (Chong *et al.*, 2009). Members of the *Actinobacteria, Acidobacteria, Proteobacteria, Bacteroidetes, Cyanobacteria*, and *Chloroflexi* were found to dominate soils along a deglaciation sequence in the Larsemann Hills (Figure 2.4), with the *Bacteroidetes* most abundant in the direct vicinity of the glaciers (Bajerski & Wagner, 2013). *Actinobacteria* distribution correlated with the magnesium, calcium and potassium contents of the soil, while soil pH and moisture were linked to the *Cyanobacteria*, *Deltaproteobacteria*, and *Gemmatimonadetes* (Bajerski & Wagner, 2013). Members of the *Gammaproteobacteria* were found to dominate the clone library generated from soil in the Shirmacher Oasis (Figure 2.4); the phyla *Gemmatimonas*, *Bacteroidetes*, *Actinobacteria*, *Chloroflexi*, *Chlamydiae*, and *Protebacteria* (Alpha and Beta) were also represented (Shivaji *et al*., 2004).

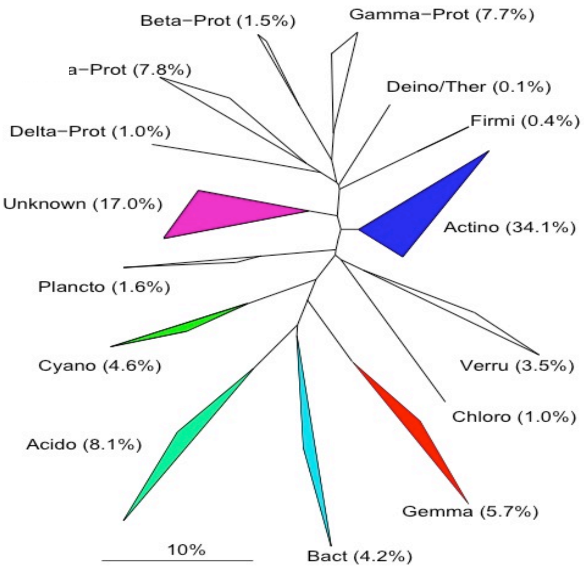

Figure 2.5: Phylum level diversity of bacterial 16S rRNA gene sequences from East Antarctica. Abbreviations as defined in Figure 2.2. Adapted from: Bottos *et al*., In Press

Molecular genetic methods have contributed much more than the realization of an unexpected microbial diversity in the Antarctic. Ice sheet reconstruction models based on geological and geomorphic data (e.g. – Denton & Hughes, 2002) predict the majority of terrestrial habitats in Antarctica to have been covered by ice during the Last Glacial Maximum (LGM, approximately 22-17 kya), and thus contemporary Antarctic taxa are the result of subsequent colonization of the Continent. Recent molecular studies refute this however, with time-calibrated phylogenetic analyses of both microbes and invertebrates suggesting considerable persistence of multiple taxa across this time period, and thus a surprising degree of endemism within the Continent (Convey *et al*., 2009; Vyverman *et al*., 2010).

2.3.2. Microbial biogeography and aerial microbes

Biogeography is a fundamental concept in our understanding of life on Earth; it describes the non-random distribution of organisms through both space and time. In classical, macro-faunal/floral, ecology this phenomenon is widely accepted and is in fact an underpinning tenet of the field. Microbial ecology is less wedded to this concept however; due to the small 'body' size and generally large population numbers, it has been assumed that microbial dispersal is unlimited across the globe. This idea is often quoted as *"everything is everywhere, but the environment selects"* (Baas-Becking, 1934 – as quoted in: de Wit & Bouvier, 2006). Global ubiquity of all microbial taxa, via atmospheric circulation, is proposed to allow the colonization and exploitation of any habitat by the suitable organisms; this should be evident in that similar microbial community structures are found in similar environments, regardless of geographic location.

As with classical ecology, islands have been convenient starting points for the study of microbial biogeography. Recently several researchers have focused on the thermophilic communities inhabiting geothermal hot springs (an island analogue – extreme environment 'stranded' in the middle of more temperate environs) in a variety of locations around the world; cyanobacteria in North America, Japan, New Zealand and Italy (Papke *et al.*, 2003), archaea in North America, Russia and Iceland (Whitaker *et al.,* 2003), and localized populations of the *Sulfurihydrogenium* genus within Yellowstone Park, USA (Takacs-Vesbach *et al.*, 2008). These studies all identified patterns in microbial distribution that could not simply be explained by the current environmental conditions measured. The implication is that dispersal of these organisms is not ubiquitous, geographical separation may result in differentiation of populations/communities over time; the question remains whether this holds true for other systems, or if a globally distributed microfauna is more relevant in less extreme habitats.

Sokol *et al.* (2013) identified a biogeographic signal in the distribution of cyanobacteria throughout the Transantarctic Mountains, but environmental factors (soil moisture and pH) determined the coarse (i.e. – Phyla level) structuring of the overall bacterial metacommunity. The use of DNA fingerprinting methods used in this study limited the resolution at which these opposing modes of community organization could be examined.

In order to successfully colonize available soil habitats, air-borne microbes must survive the time spent in the atmosphere, remain viable and able to resume activity after deposition. Conditions encountered during atmospheric transport may be relatively extreme and variable; temperatures range from typical surface values (i.e. ~ 15° C) to - 57° C at 20,000 m altitude, with UV radiation exposure increasing markedly also (Womack *et al.*, 2010). Thus it is of little surprise that 16S rDNA sequences recovered from snow at the South Pole had high identity for *Deinococcus sp.* sequences in the databases (Carpenter *et al.*, 2000); this genera is well known for its remarkable tolerance to radiation and desiccation. *Deinococcus sp.* are often found in Antarctic soils, and the sequences at the South Pole can only have originated from the atmosphere (excluding contamination). An air-sampling study located near the Weddell Sea coast (Antarctica) by Pearce *et al.* (2010) highlights the lack of knowledge regarding aerial microbial dispersal; of 373 clones constructed, only 31 matched 16S rRNA sequences deposited in the databases at the time. Of these identifiable 31, only eight were assigned to terrestrial (i.e. – soil) organisms (Pearce *et al.,* 2010). Recently, a more comprehensive survey (facilitated by high-throughput 454 pyrosequencing) of aerosolized bacteria in the McMurdo Dry Valleys (Bottos *et al.*, 2013) revealed minimal similarity between local soil communities and overlying air masses; air samples were dominated by *Bacilli* while soils are dominated by *Actinobacteria*. Interestingly, despite relative proximity to the sea, little evidence of marine-derived organisms was found in the air samples, although local volcanism (Mount Erebus) was implicated in the injection of significant amounts of thermophilic organisms into the atmosphere (Bottos *et al.*, 2013).

2.3.3. Latitudinal gradients

In contrast with the above biogeographical studies, a survey of soil bacterial communities across North and South America found little evidence for geographic distance being a determinant of community composition; latitude, a strong factor in macro-biogeography, had little importance as well (Fierer & Jackson, 2006). Ecosystem type (e.g. – ‘boreal forest/tundra’ vs ‘humid temperate forest') was found to be a much more significant predictor of bacterial communities, and this was largely attributed to soil pH. This led Fierer and Jackson (2006) to propose that edaphic parameters are the primary factor for controlling microbial communities, thus microbial biogeography is fundamentally different to that observed in higher organisms. A similar study in China found some clustering of microbial communities according to latitudinal position, although most of the differences between communities could be explained by soil pH differences (Wu *et al.,* 2009); it must be noted that vegetation was present and varied between sites. In a study of bacterial diversity along a latitudinal transect in the Antarctic peninsula however, increasing latitude was found to correlate with a decrease in diversity in non-vegetated areas (Yergeau *et al.*, 2007); no such pattern was found in soils containing plant life, despite its relative simplicity (i.e. – bryophyte dominated flora at some sites). The contrasting findings between these large scale surveys (Fierer & Jackson, 2006; Yergeau *et al.*, 2007) highlights the importance and difficulty of interpreting microbial community data in the presence of higher organisms, as they may significantly alter the local environment either abiotically (e.g. – increase humidity, decrease wind disturbance) or biotically (e.g. – facilitating symbioses etc).

2.3.4. Glaciation and succession

Kastovska *et al.* (2005) described a successional pattern in the microbial communities of periglacial soils in Svalbard, relating to the glacial retreat history of the soil. Younger (newly uncovered) soils tended to be dominated by cyanobacteria and eukaryotic microalgae, with some representatives (as defined by morphology) potentially fixing nitrogen and thus increasing the nutrient status of these barren mineral soils. Older soils featured a much more prominent heterotrophic community, supported by the biomass established by the primary colonizing phototrophs (Kastovska *et al.*, 2005); the soils examined in the Dry Valleys have been ice-free for a long time, and are heterotroph dominated. Bacterial communities were found to be structured in relation to glacial history in the Darwin Mountains, Antarctica. Young, poorly developed soils contained much more diverse bacterial communities than older soils, thought to be due to the high salt levels in the older soils restricting the community to the more halo-tolerant members (Magalhaes *et al.,* 2012). Soil development associated with deglaciation of a landscape was also linked to a successional pattern of bacterial communities in the Larsemann Hills (Bajerski & Wagner, 2013).

2.3.5. Molecular ecology and microbial communities

Culture-dependent methods employed in microbial ecology frequently underestimated the true diversity of microbes in a given environment, as media used cannot perfectly replicate the environment, thus introducing significant biases between the grown/cultured community observed and the ‘real’ community. Molecular techniques, divorced from manipulation of the community in question, allow the interrogation of all organisms/molecules present in the environment. Extraction of environmental DNA from a sample allows much information to be gained in the form of phylogenetic markers (e.g. – 16S rRNA gene) and genes coding for functional proteins from which potential ecosystem roles can be deduced.

Community fingerprinting techniques such as ARISA (Automated Ribosomal Intergenic Spacer Analysis; Fisher & Triplett, 1999) rely on the amplification of a certain section of DNA, which differs in length from taxa to taxa. ARISA utilizes the hypervariable intergenic spacer between the 16S and 23S rRNA genes. A fluorescently labeled primer allows fragments to be detected when run through capillary electrophoresis. Each different length fragment potentially represents a different species/taxa, and diversity and relative abundance (from relative peak intensity) can be estimated from the resultant flowgrams. ARISA has been employed successfully in a variety of Antarctic microbial studies (Wood *et al.*, 2008; Lee *et al.*, 2012; Magalhaes *et al.*, 2012; Tiao *et al.*, 2012; Sokol *et al.*, 2013). While unable to explicitly identify individual members, ARISA (and similar techniques) allow a relatively high resolution comparison of overall structure between communities.

Next-generation high-throughput sequencing allows interrogation of microbial communities to an unprecedented resolution. Because the chemistry of these sequencing platforms (e.g. 454 pyrosequencing, Roche; Iontorrent, Life Technologies) does not rely on termination of strand synthesis, multiple templates (and indeed multiple samples) can be sequenced simultaneously (Ronaghi *et al.*, 1996). By sequencing an appropriate phylogenetic marker (usually the 16S rRNA gene) amplified from the bulk environmental DNA, identities and relative abundances of community members can be elucidated. The 16S rRNA gene is most commonly used due to the extensive database entries based upon it, and widely used standardized protocols (Madigan *et al.*, 2009). This gene is conserved across all bacteria, as it codes for an essential part of the translational machinery, and contains universally conserved regions suitable for primer binding, alongside hypervariable regions capable of differentiating between species (Woese, 1987) and often between strains. Typically a "species" (often referred to as an Operational Taxonomic Unit – OTU) is defined by > 97% similarity of the 16S rRNA gene, and ≥ 70% total DNA homology (Stackebrandt & Goebel, 1994).

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Chapter 3 - Three soil chronosequences in recessional glacial deposits near the polar plateau, in the Central Transantarctic Mountains, Antarctica

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3.1. Abstract

Soil chronosequences on moraine deposits emplaced during glacial retreat in the Central Transantarctic Mountains, Antarctica, are described. Study sites (Dominion Range, Mount Achernar, and Ong Valley) were located between 83° and 85° South, at altitudes of 1600-2200 m on the edge of the Polar Plateau.

Soil landscape maps show a gradation of soil properties across landscape units that were designated as homogenous/single-event drifts in previous larger scale studies. Along transects away from the current ice edge, the depth to underlying ice thickened (from 2 cm to > 80 cm), soil became more weathered, saltier, and acidic, and horizonation became more pronounced.

Soil thickness, clast abundance, and soil chemistry are all consistent with a two-layer soil formation model. A thin clast-rich surface horizon, originating from weathering of supraglacial debris, overlies a thick clast-poor sublimation till. The supraglacial debris has a finite contribution to soil volume, whereas sublimation offers an ongoing source of soil material at the bottom of the profile.

Keywords

Beardmore, Gelisol, Cryosol, cold desert, ultraxerous, sublimation

3.2. Introduction

Systematic characterization of soils in the Ross Sea sector of Antarctica has recently been advanced as part of multidisciplinary science campaigns targeting strategic sites along a latitudinal gradient within the Latitudinal Gradient Project (Howard-Williams *et al.,* 2006), and by reconnaissance soil survey that uses the taxonomy of Gelisols (Soil Survey Staff, 2010) as a basis for defining map units (McLeod *et al.,* 2009).The great majority of ice-free areas with soil cover occur in the Transantarctic Mountains, which constitute the division between West Antarctica and East Antarctica. At roughly 3,500 km long, the Transantarctic Mountains are one of the longest mountain ranges on Earth, extending from Cape Adare, along the Ross Sea/ice shelf coast, and into the Weddell Sea region. Most of the detailed soil characterization and soil survey in the Ross Sea sector has been in the area of the McMurdo Dry Valleys in the northern part of the Transantarctic Mountains at about 77°S latitude. The Central Transantarctic Mountains (CTAM) region contains the Beardmore glacier, an outlet glacier of the East Antarctic Ice Sheet draining ice from the polar plateau out to the Ross Ice Shelf, remain less comprehensively studied. Although largely covered in ice, the CTAM region contains several ice-free areas of up to 10000 ha, consisting of either bare rock mountaintops and nunataks, or glacial deposits comprising drift sheets and moraines. The purpose of this paper is to report on soil surveys of three ice-free areas in the Central Transantarctic Mountains (CTAM, Figure 3.1). The work extends the characterization of soils to the southern-most part of the latitudinal gradient of the "Latitudinal Gradient Project".

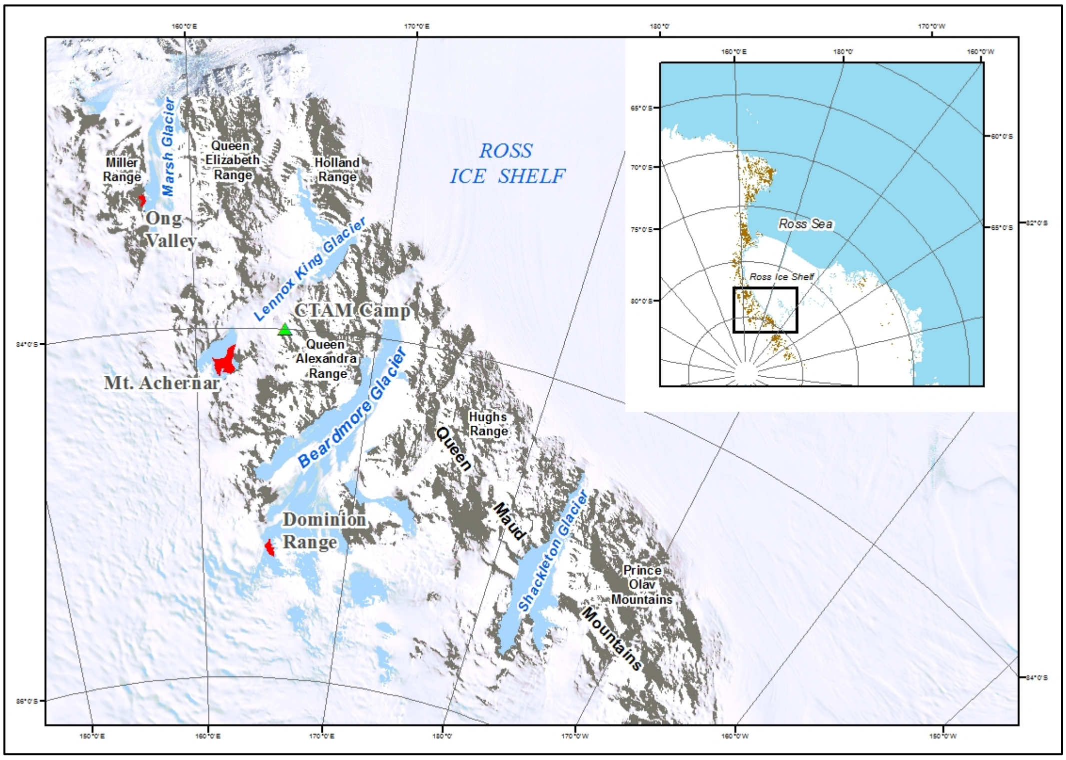


Figure 3.1: Map of Central Transantarctic Mountain region with study sites located at Dominion Range, Mount Achernar and Ong Valley. Green triangle indicates position of Central Transantarctic Mountains (CTAM) base camp.

3.2.1. Antarctic soils

The soils of Continental Antarctica are at the extreme end of the spectrum of what is regarded as a 'soil'. Evidence of pedogenic processes such as desert pavement formation, salt redistribution, *in situ* weathering of clasts, staining by Fe oxides, increasing soil coherence, and increasing depth of ice/ice-cemented permafrost with soil age (via sublimation) are found throughout Antarctica. Evidence of pedogenic processes enable soils to be differentiated from the initial unconsolidated mineral deposit, and supported the inclusion of Antarctic soils within the USDA soil classification (Ugolini & Bockheim, 2008).

The majority of soils in the CTAM region are formed in glacial deposits. Glacial activity is the major driver of landscape evolution on the Antarctic Continent (Campbell & Claridge, 1987). *In situ* soil formation (i.e. – soils forming directly in bedrock) is generally limited to higher altitudes or steep slopes where the bedrock has not been covered by till deposited during past ice level fluctuations.

Antarctic soils are commonly evaluated in terms of weathering stages (Campbell & Claridge, 1975) and associated morphogenetic salt stages (Bockheim, 1997; Table 3.1). The approximate ages assigned to the salt stages are based on numerical constraints of landform units in the McMurdo Dry Valley region; to extrapolate these ages to other regions assumes a similar rate of salt deposition and accumulation, which is dependent on local climatic factors.

Table 3.1: Weathering stages (Campbell & Claridge, 1975) and salt stages (after Bockheim, 1997).

Weathering Stage	Horizonation	Soil colours	Salt Stage	EC (ds/m)	Approx. Age
1	minimal	5Y	0	<0.6	<10 ka
2	weak	2.5Y - 10YR	1	0.6-5.0	10-18 ka
			2	5.0-18	18-90 ka
3	distinct	2.5Y - 10YR	3	18-25	90-250 ka
4	very distinct	10YR	4	25-40	250 ka - 1.7 Ma
5	very distinct	10YR - 5YR	5	40-60	1.7 Ma - 39.9 Ma
6	very distinct	7.5YR - 5YR	6	60-100+	>3.9 Ma

Previous soil work in the Beardmore Glacier region has largely focused on correlating drift sheets along the Transantarctic Mountains, for the purpose of reconstructing past glacier and ice sheet limits. (Denton *et al.,* 1989a; Denton *et al.,* 1989b). Several major drift units, corresponding to different stages of glacier thickening due to ice grounding in the Ross Sea, and Plateau ice level fluctuations, have been recognized and described throughout the CTAM area (Table 3.2).

Table 3.2: summary of major glacial drift units associated with the Beardmore Glacier.*WS: weathering stage, SS: salt stage

Drift unit	**Relative position** (from Denton et al, 1989a)	**Key features** (from Denton et al, 1989a)*	**Correlated numerical age** (from Bockheim, 1990)
Plunket	7-30 m above, and parallel to, current ice surface	Average 16 cm to "ice-cement", WS 1, SS 0	6.0 ka
Beardmore	35-40 m above current ice surface near plateau, 1100 m above current ice surface at glacier mouth	Average 55 cm to "ice-cement", WS 1, SS 1	10.3-23.8 ka
Meyer	30-50 m above and parallel to Beardmore drift	Average 83 cm to "ice-cement", WS 2-3, SS 2-3, 'ghosts' and matrix salts common	130 - 190 ka

Soil data from Denton *et al.,* (1989a) has been incorporated into a broader study of soil development in the greater Transantarctic Mountain region (Bockheim, 1990). Denton *et al.* (1989a) described soils in the Meyer Desert, ~ 25 km to the northeast of our study site at the Dominion Range where *"Plunket drift flanks Beardmore Glacier across the entire western Dominion Range"* (Denton *et al.*, 1989a). Soils described reached maximum salt and weathering stages of 3 within the older Meyer drift, indicating soil development of an intermediate stageand an age of approximately 90 – 250 ka based on correlation with numerically dated drifts in locations further north (Denton *et al.*, 1989a). Soils in the Meyer Desert ranged from 14 cm (Plunket drift) to 82 cm (Meyer drift) of soil material over ice, with the presence of ghosts (clasts weathered *in situ* within the soil profile) being a feature nearly exclusive to soils of the Meyer drift (Denton *et al.*, 1989a).

Claridge and Campbell (1968) described a range of soils in the Shackleton Glacier region (to the South of the Beardmore Glacier). The extreme aridity was cited as a major determinant of soil development (or lack thereof) in the Shackleton region (Claridge & Campbell, 1968), and the soils described have formed under similar conditions to those in the Beardmore region. Soils examined in the Shackleton Glacier region were formed in a variety of parent materials including scree slopes and *in situ* bedrock, and covered landscapes of a wide (inferred) exposure age range. Strongly developed soils on the Roberts Massif, at elevations over 300 m above present ice level, exhibited weathering characteristics indicative of millions of years of development. Weakly developed, thin unconsolidated soils were common in deposits closer to current ice level, with much less salt accumulation evident (Claridge & Campbell, 1968).

The objective of this study was to undertake a reconnaissance-level mapping and characterization of soils at selected sites in the Beardmore Glacier region of the Transantarctic Mountains, this being the southernmost site of the Latitudinal Gradient Project (LGP; Howard-Williams *et al.*, 2006). Our study contributes to the LGP question: "To what extent does soil development (e.g. degree of weathering, carbon content and nutrient accumulation) change with latitude and therefore influence terrestrial ecosystems?" (Howard-Williams *et al.,* 2006). This southernmost coverage thus complements and contrasts previous LGP work conducted at Cape Hallet (Hofstee *et al.,* 2006) and in the Darwin Glacier region (Aislabie *et al.,* 2012). This study also investigates chronosequences at a finer scale than previous work. Differences within a landscape unit, treated in coarser scale studies (Denton *et al.,* 1989a; Denton *et al.,* 1989b; Bockheim, 1990) as a homogeneous drift, are described.

3.3. Methods

Landform units were initially delineated using a combination of satellite imagery, aerial photographs, topographical and geological maps, and observation from helicopter. The preliminary units were used to target soil investigation. Soil pits were excavated to a maximum practicable depth (generally limited by the presence of massive/glacial ice and no greater than 1 m) within an area observed to be representative of the greater landscape unit or representative of part of a gradient within a soil-landscape unit. Where patterned ground was present, pits were dug in the centre of polygons. Soil descriptions of the pit face (profile) followed standard practice as described in Schoeneberger *et al.* (2002), and soil classification followed USDA soil taxonomy (Soil Survey Staff, 2010). Soil maps were constructed using the soil and landscape descriptions. Soils were sampled as per described horizons: approximately 0.5 kg of soil material (per horizon) was transported back to New Zealand in sealed plastic bags. Soil samples were presieved (2 mm) in the field before transport to New Zealand. Thereafter, all analyses were conducted on the < 2 mm fraction.

Particle size analysis was performed on a lasersizer (Malvern Mastersizer 2000), after H_2O_2 digestion, and dispersion with calgon. The following analyses were conducted at the Landcare Research Environmental Chemistry Laboratory (Palmerston North, New Zealand), using methods described in Mcleod *et al.* (2009). Gravimetric moisture content was measured by calculating mass loss after drying subsamples to constant weight at 105° C. Total carbon and nitrogen values were obtained by combusting a subsample with pure O_2 at 1050° C in a Leco CNS2000 Analyzer. Soil pH was measured on a 1:2.5 soil:water suspension. Water-soluble cations were measured via flame atomic absorption spectrophotometry with an air-acetylene flame and anions were measured via ion chromatography. A temperature compensated probe was used to measure electrical conductivity on a 1:5 soil:water mixture.

3.4. Description of study locations

3.4.1. Topographic and geologic setting

Situated between the head of the Beardmore and Nimrod Glaciers, the Dominion range has a broad (approximately four kilometers wide) sweep of lateral moraine adjacent to its western margin (Figure 3.2a).The lateral moraines are strikingly characterized by a strong curvi-linear patterning of alternating red and grey ridges, corresponding to differing lithologies dominating the moraine surfaces, separated by shallow swales, forming a landscape unit with up to 6 m of relief. The influence of smaller alpine glaciers, flowing down off the Dominion Range's plateau is evident as a series of terminal moraines adjacent to the Range on the ice-distal limit of the lateral moraines. On the edge of the Polar Plateau, ice level is 2200 m above sea level, with minimal altitude variation (~ 50 m) across the moraine suite. Local geology is dominated by Ferrar Dolerite and Buckley Formation sedimentary rocks (including shale, sandstone, coal, and glossopterid fossils; Elliot *et al.,* 1974).

Mount Achernar is bounded to the North by the Law Glacier, with a 6-10 km-wide expanse of lateral moraine deposits at the eastern foot (Figure 3.2b). A banding pattern, similar to that at the Dominion Ranges, evident in the Law Glacier lateral moraines, and the influence of several smaller glaciers from the south is also observed. The moraines lie between 1800 and 1900 m above sea level. The Mount Achernar bluffs adjacent to the moraine suite are comprised of Ferrar Dolerite and Buckley Formation sediments, with Fremouw Formation sedimentary rocks (sandstones and mudstones, some shale) prevalent nearby (Barrett & Elliot, 1973).

Ong Valley is a narrow (roughly two kilometers at the widest) ice-free valley approximately eight kilometers long (Figure 3.2c). The steep valley walls are primarily composed of the *Hope Granite* (Barret *et al.,* 1970), frequently mantled with scree. The valley floor is covered with glacial deposits of mixed geology emplaced by the Argosy Glacier that has advanced up from the mouth of valley in the past. A smaller unnamed glacier intrudes into the head of the Ong Valley, and evidence of greater previous extent of this glacier is observable. The ice level (Argosy Glacier) at the mouth of the Valley is around 1500 m above sea level; the valley floor rises to around 1700 m at its head.

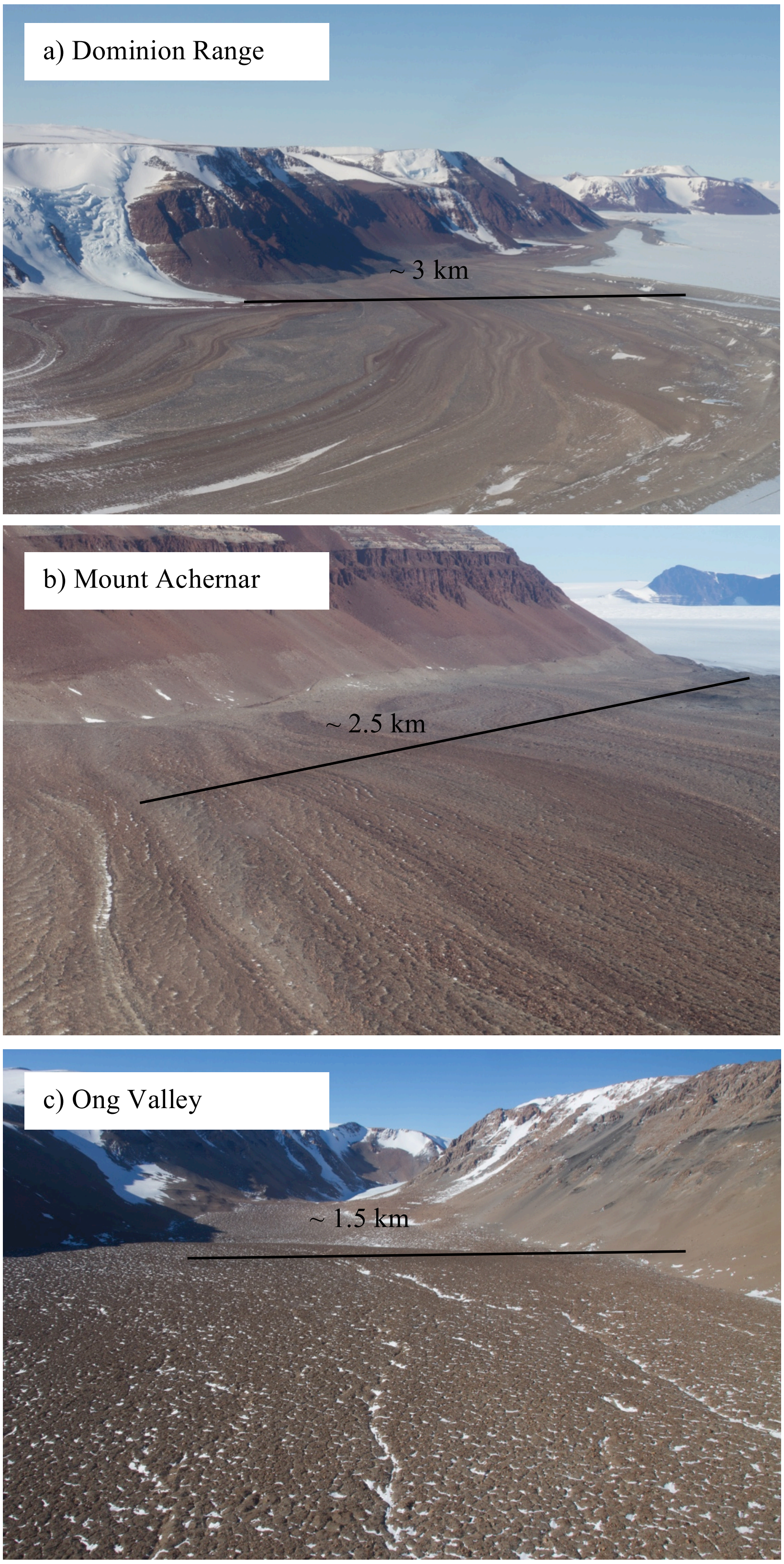


Figure 2.2: Landscapes of main study sites. (a) Dominion Range looking southeast. (b) Mount Achernar looking northwest. (c) Ong Valley looking to head of valley. Photographs: Errol Balks.

3.4.2. Surface ages

Glacial deposits examined in the Dominion Range and Mount Achernar sites correlate to the Plunket and Beardmore Drifts (Table 3.2) as described by Denton *et al.* (1989a), with an estimated maximum age of 23.8 ka (Bockheim, 1990). However, cosmogenic exposure age dating of quartz-bearing rocks within the moraines suggests the moraines at Mount Achernar are much older at 300 to 500 kyr (Faure & Nishiizumi, 1994; Mathieson *et al.,* 2012).

3.4.3. Climate

Few climate data are available for the region. Field observations suggest a scarcity of liquid water; no evidence of melt/liquid moisture was observed, with the exception of margins of snow patches following recent snowfalls that sublimated relatively quickly (within a day). At the three study sites air temperature was never measured to be above 0° C (December 2010 – January 2011). Positive soil surface temperatures (maximum recorded surface temperature of +2° C) were rarely encountered. Summer air temperatures (data collected at the CTAM base camp on the Walcott Neve, Figure 3.3), taken as an approximation of air temperatures for the wider region, showed that our field studies were conducted at the peak of the summer period, and temperatures (and by extension presence of liquid water) higher than those observed are thus unlikely at other times of the year. Mean annual temperature has been estimated at -39.4° C, and a mean annual (water) accumulation of 36 mm per year were reported from unpublished snow pit data (Beardmore South Camp - 84° 03' S 164°15' E; Bockheim, 1990).

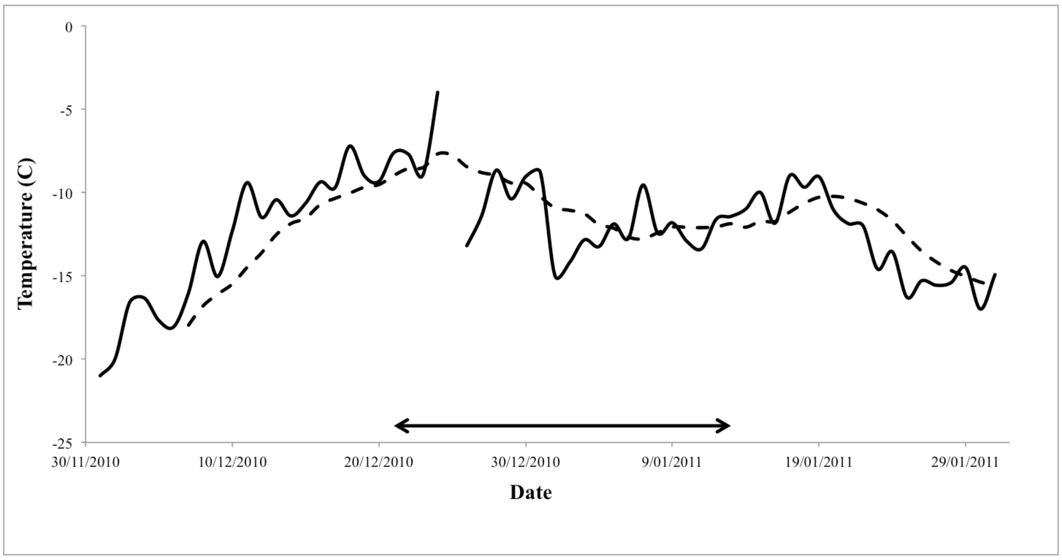


Figure 3.3: Daily mean (solid line), and seven day moving average (dashed line), air temperatures at CTAM camp, December 2010 to January 2011. Arrows represent field season of this study. Data from: ftp://amrc.ssec.wisc.edu/pub/fieldcamps/

Precipitation during the study period was rare and relatively light. 'New' snow did not persist on the ground long, although persistent snow patches were observed in patterned ground cracks throughout the area. Observations lead us to class soils, and the climate, in the study area as ultraxerous (Claridge & Campbell, 1968).

3.4.4. Organisms

Evidence of any higher organisms (e.g. – lichens, mosses, *Collembolla* etc.) was lacking in all sites studied. Microbial life is present (Scarrow, 2013). However, the influence of the microbes on the development of soils in our study areas is negligible.

3.5. Results

3.5.1. Soil distribution in the landscape

The soil maps for the Dominion Range and Mount Achernar sites (Figures 3.4 and 3.5) reflect a succession of ages of drift within the lateral moraine belt. Soils vary from shallow and weakly developed adjacent to the glacier, to deeper and more developed at increasing distance from the adjacent glacier (Table 3.3).

Soil unit A is the zone of soil directly adjacent to the glacier. The unit had the highest relief, in the form of ice flow-parallel ridges up to 6 m high and 30 m wide. Soils of unit A had up to 10 cm of sublimation till over massive ice. There was no horizon differentiation except for the presence of a vesicular surface crust in some places. Distribution of the vesicular crust was patchy and had no apparent relationship with the wider landscape. Soils were lithochromic, with no oxidation evident. Clasts within thesoils were generally unstained, fresh, and angular to sub-angular. Unit A soils were classified as a complex of Glacic Haplorthels and Glacic Haploturbels. We mapped a compound unit including Turbels, despite a lack of evidence for cryoturbation in individual soil profiles, because of the presence of hummocky thermokarst topography and weakly developed patterned ground.

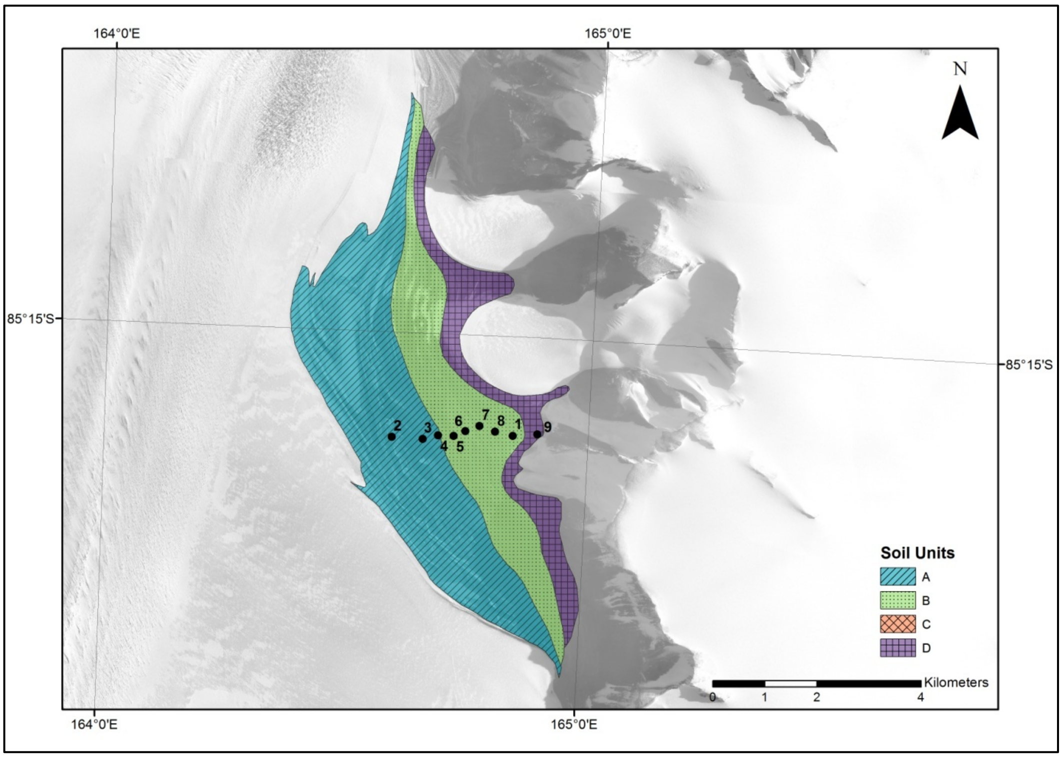


Figure 3.3: Soil map of Dominion Range site. Pit locations marked by numbers.

Unit B soils had 10-30 cm of sublimation till over massive glacial ice. The soils of unit B were also classified as a complex of Glacic Haplorthels and Glacic Haploturbels. At least two horizons could be differentiated within unit B soil profiles, on a colour and/or texture basis (generally more cohesion and a yellower colour in the surface horizon). A vesicular surface crust was generally present (although not always), and in a seemingly spatially patchy distribution irrespective of other landscape features; the thickness of the crust varied from 0.5 to 6 cm. Surface topography within unit B was more regular than unit A, with small high centered polygons (0.5 – 1 m high), and multiple generations of cross-cutting tension cracks distinguishable in some instances. The polygonal network of cracks formed by thermal expansion and contraction of glacial ice suggests ice flow is limited and that the ice is largely stagnant.

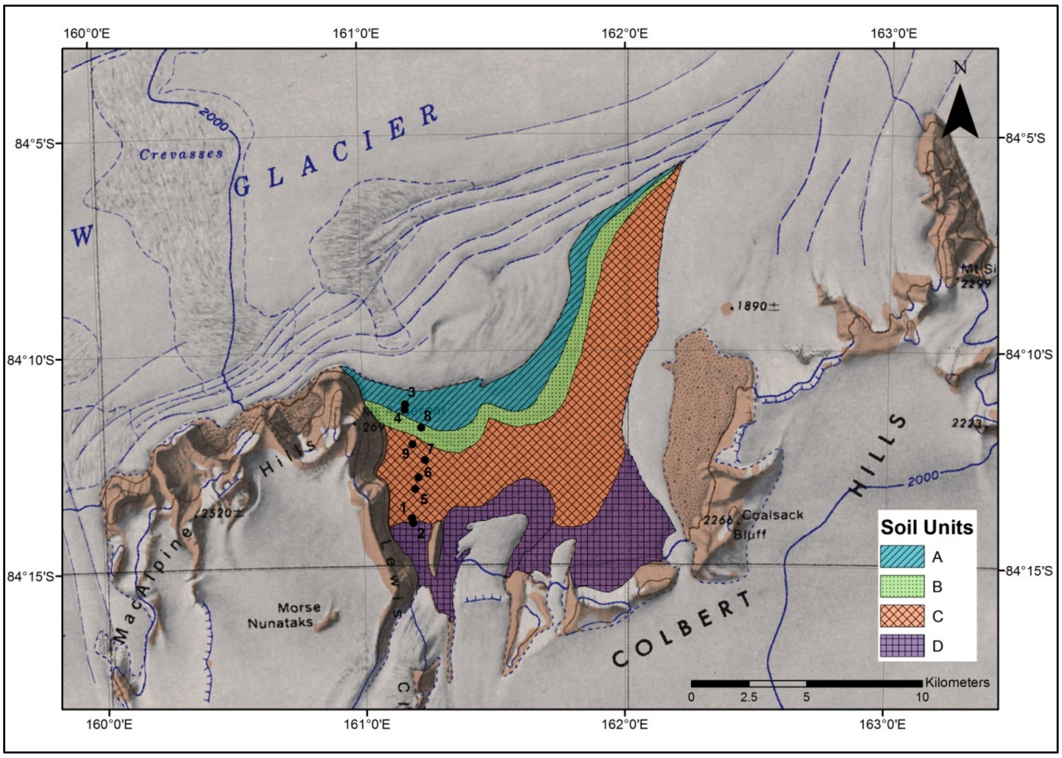


Figure 3.5: Soil map of Mount Achernar site. Pit locations marked by numbers.

Soils of unit C (identified only at the Mount Achernar site) were considerably deeper than units A and B, with massive ice found no shallower than 60 cm from the surface. Soils were classified as either Glacic Haploturbels or Anhyturbels, with one Typic Anhyturbel (with no massive ice or ice-cement within 100 cm of the surface) described. Soil development was more pronounced in unit C, relative to units A and B, with stronger horizonation in all profiles. A somewhat hardened vesicular surface crust was present in all unit C profiles, and oxidation of materials lower in the profile was also discernable. Strongly developed patterned ground defined the topography of unit C, with polygons 1-2 m high a near ubiquitous feature of the landscape.

Unit D soils were recognized as discrete from the chronosequence comprising units A through C, as they have formed in the terminal moraine deposits of the smaller alpine glaciers. Soils of unit D exhibit similar extents of soil development (e.g. – horizonation) and patterned ground evolution as unit C, and are thus considered to be of similar age.

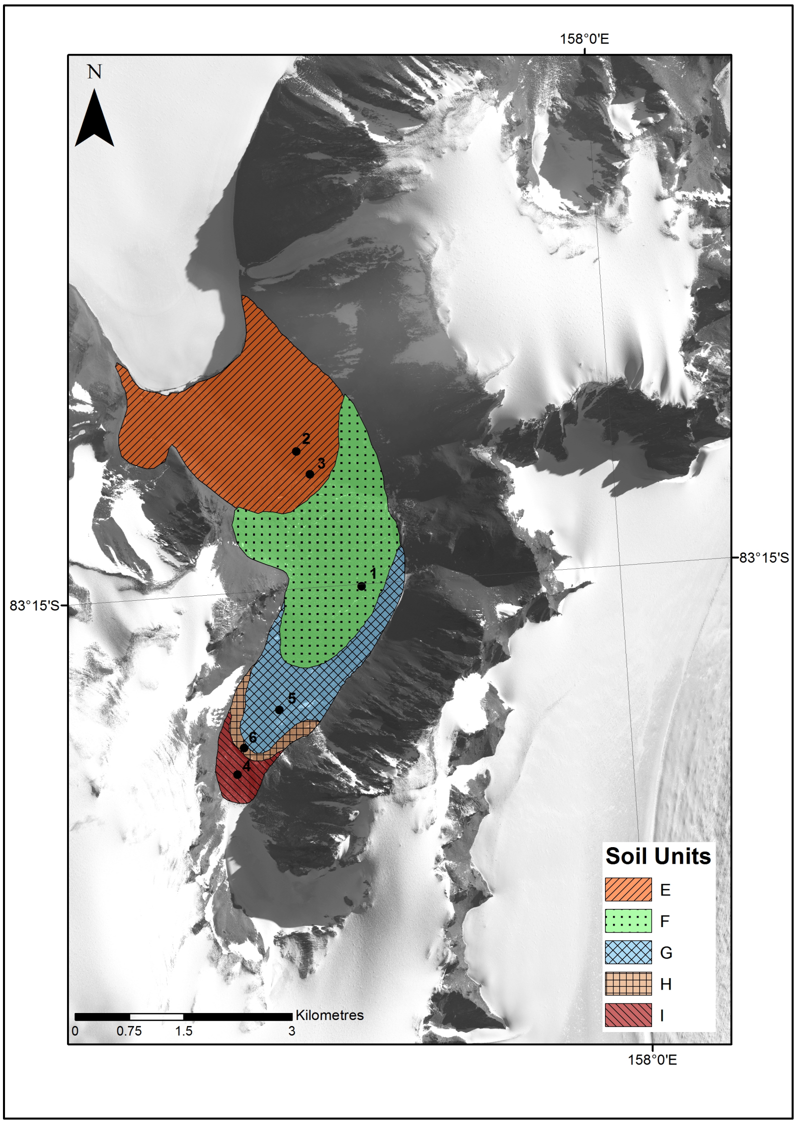


Figure 3.6: Soil map of Ong Valley site. Pit locations marked by numbers.

At Ong Valley a soil chronosequence similar to that at the Dominion Range and Mount Achernar sites was observed, with soil units E through to G (Figure 3.6) increasing in age and development with distance from the glacier. Unit H is distinct from the sequence, comprising soils formed in colluvial material rather than glacially emplaced deposits.

Unit E soils had massive ice no deeper than 50 cm underlying the soil profile. Horizonation was minimal, with a crusty surface layer being the most obvious feature. Soils within unit E were classified as a complex of Glacic Haplorthels and Glacic Haploturbels. Topography within unit E ranged from large hummocky thermokarst features through to weakly developed patterned ground, with polygons of variable size and height.

The soils in unit F had massive ice at least 70 cm below the surface. Two subsurface horizons were distinguishable on a soil consistence basis; upper horizons generally being more cohesive. Unit F contained a complex of Glacic Anhyorthels and Glacic Anhyturbels. High (1-2 m) centered polygons, regularly 5-8 by 6-10 metres across, were the dominant topographic features.

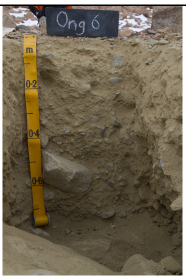
Map unit G, relating to the furthest up-valley (i.e. - oldest) drift, comprised soils in the Typic Anhyturbel/Anhyorthel subgroups, with no massive ice or ice-cement within 80 cm of the soil surface. Multiple horizons were discernible in both texture and consistence. Topography featured high (1-1.5 m) centered six-sided polygons, 6-10 m across.

Map unit H comprised a prominent terminal moraine, approximately four metres high. This very distinct and narrow moraine ridge bore a Typic Anhyorthel soil, with minimal evidence of cryoturbation, although colluvial effects were observed at the margins of the moraine crest. The lower ~ 45 cm of the soil profile contained a considerable amount of larger clasts (Table 8) relative to subsoils in units E, F and G.

Unit I, at the head of Ong Valley, is outside the furthest (visible) extent of the Argosy Glacier. Massive ice was not observed at a depth greater than 70 cm, and the soil is classified as a Typic Anhyorthel. The profile was made up of an accumulation of fine gruss with a sandy matrix showing many millimeter-scale laminations in the top of the profile. A layer of weathered and stained clasts was observed at 45 cm depth. Patterned ground was absent, with maximum relief being 20-40 cm, corresponding to gentle swales within the flat valley fill.

Table 3.3: Typical soil profiles within soil units.

Typical soil profile (Dominion Range and Mount Achernar)		**Typical soil profile** (Ong Valley)	
Map unit A: *1:* 0-4 cm; light yellowish brown (2.5 Y 6/3) slightly gravelly, silty fine to coarse sand; over massive ice.	 *Location:* S 85°16.091 E 164°39.510 Glacic Haploturbel	**Map unit E:** *1:* 0-1 cm; (5Y 6/2) stony, cobbley, gravelly, slightly silty fine to coarse sand; *2:* 1-15 cm; light yellowish brown (2.5Y 6/3) gravelly, silty fine sand; *3:*15+ cm; massive ice.	 *Location:* S 83°13.995 E 157°40.213 Glacic Haploturbel
Map unit B: *1:* 0-2 cm; light gray (2.5 Y 7/2) slightly cobbley, gravelly fine to medium sand; *2:* 2-13 cm; gray (2.5 Y 6/1) very fine gravelly, slightly silty very fine to medium sand; *3:* 13+ cm; massive ice.	 *Location:* S 84°11.773 E 161°13.394 Glacic Haplorthel	**Map unit F:** *1:* 0-0.5 cm; pale yellow (2.5Y 7/3) slightly boulder, stony, cobbley, very gravelly medium sand; *2:*0.5-13 cm; pale yellow (2.5Y 7/3) fine to coarse gravelly, fine and medium sand, soft; *3:* 13-60 cm; pale yellow (2.5Y 7/3) fine to coarse gravelly, fine and medium sand, loose; *4:* 60+ cm; massive ice.	 *Location:* S 83°15.027 E 157°43.701 Glacic Anhyorthel
Map unit C: *1:* 0-5 cm; pale yellow (2.5 Y 7/3) slightly stony, slightly cobbley, gravelly very fine to coarse sand, moderately hard and massive; *2:* 5-60 cm; pale yellow (2.5 Y 7/3) slightly cobbley, slightly fine gravelly very fine to medium sand; *3:* 60+ cm; massive ice.	 *Location:* S 84°13.199 E 161°11.861 Glacic Haploturbel	**Map unit G:** *1:* 0-4 cm; light yellowish brown (2.5 Y 6/3) slightly boulder, cobbley, very gravelly medium to coarse sand, loose; *2:* 4-30 cm; light yellowish brown (2.5Y 6/3.5) gravelly fine to coarse sand, soft; *3:* 30-80+ cm; light yellowish brown (2.5Y 6/3.5) slightly gravelly fine to medium sand, soft;	 *Location:* S 83°15.896 E 157°37.947 Typic Anhyturbel

Map unit D: *1:* 0-1 cm; light gray (2.5 Y 7/2) slightly cobbley, very gravelly fine to coarse sand, slightly hard and platy; *2:* 1-10 cm; pale yellow (2.5 Y 7/3) slightly cobbley fine to coarse sand; *3:* 10-60 cm; light brownish gray (2.5 Y 6/2) slightly fine gravelly, silty, very fine to medium sand; *4:* 60 + cm; massive ice.	 *Location:* S 85°15.989 E 164°53.703 Glacic Haplorthel	**Map unit H:** *1:* 0-1 cm; light yellowish brown (2.5 Y 6/3) very gravelly coarse sand; *2:* 1-4 cm; pale yellow (2.5Y 7/4) slightly gravelly silt, soft; *3:* 4-35 cm; pale yellow (2.5Y 7/4) gravelly, silty fine sand, soft; *4:* 35-80+ cm; light yellowish brown (2.5 Y 6/3) slightly boulder slightly stony, slightly cobbley, very gravelly, silty fine sand, soft.	 *Location:* S 83°16.263 E 157°37.493 Typic Anhyorthel
		Map unit I: *1:* 0-4 cm; greyish brown (2.5Y 5/2) slightly boulder, slightly stony, slightly cobbley, very gravelly coarse sand, loose; *2:* 4-38 cm; pale yellow (2.5Y 7/4) slightly cobbley, gravelly medium to coarse sand, loose; *3:* 38-44 cm; light yellowish brown (10YR 6/4) cobbley, gravelly fine to coarse sand, soft; *4:* 44-70+ cm; light yellowish brown (2.5Y 6/4) slightly bouldery, slightly stony, slightly cobbley, very fine gravelly fine to coarse sand, soft;	 *Location:* S 83°16.422 E 157°36.107 Typic Anhyorthel

3.5.2. Chemical and physical soil properties

Soil chemical and physical properties for all soil horizons sampled are presented in Tables 3.4, 3.5, and 3.6.

Soil moisture in all sampled horizons was low (<5%), well below the approximately 10% threshold required for ice cementation of permafrost (ANTPAS, 2006). Soil moisture was not elevated in the layers directly overlying the buried ice, indicating a lack of moisture recharge from below and validating the ultraxerous designation of these soils.

Soil pH for all horizons was slightly alkaline, ranging from 7.87 to 9.22. Soil pH generally decreased along the gradient from current ice edge.

Table 3.4: Chemical and physical properties of Mount Achernar site soil horizons.

Map unit			A		B	C					D
			Ach3	**Ach4**	**Ach8**	**Ach9**	**Ach7**	**Ach6**	**Ach5**	**Ach1**	**Ach2**
Distance from ice edge (m)			550	800	1500	2200	2900	3600	4200	5300	5500
		Horizon									
Moisture Content (% dry weight)		**1**	2.85	2.91	3.01	2.20	2.25	1.99	1.79	1.23	0.89
		2	3.15	3.57	4.35	2.07	1.89	2.37	1.69	2.24	1.83
		3				2.52	1.90			2.33	1.96
		4									2.75
pH		**1**	8.19	8.26	8.07	8.16	8.15	8.16	8.26	8.36	8.96
		2	8.63	8.53	8.56	7.87	8.15	8.22	8.22	7.94	8.15
		3				8.21	8.33			7.97	8.13
		4									8.22
EC (dS/m)		**1**	0.56	0.62	1.31	1.95	2.24	2.75	2.30	0.26	0.36
		2	0.30	0.21	0.62	2.89	2.10	1.64	1.47	3.60	3.77
		3				1.27	0.97			2.34	4.39
		4									1.70
Total C (%)		**1**	0.27	0.63	0.54	0.18	0.13	0.24	0.13	0.30	0.26
		2	0.33	0.71	0.73	0.35	0.22	0.38	0.34	0.33	0.33
		3				0.83	0.42			1.97	0.31
		4									1.71
Total N (%)		**1**	0.04	0.04	0.07	0.04	0.04	0.08	0.05	0.01	0.01
		2	0.03	0.03	0.05	0.07	0.09	0.05	0.04	0.08	0.07
		3				0.07	0.04			0.13	0.16
		4									0.11
Water soluble cations (mg/kg)	**Na**	**1**	109	54	193	173	248	360	523	134	257
		2	159	95	425	261	303	372	184	796	554
		3				179	204			667	635
		4									312
	Mg	**1**	29	12	49	55	67	96	118	11	13
		2	8	5	12	136	110	42	30	184	111
		3				30	43			102	95
		4									31
	K	**1**	24	12	25	11	13	8	14	7	6
		2	13	11	18	18	19	10	6	12	8
		3				13	15			14	5
		4									3
	Ca	**1**	249	109	494	650	1050	1110	1130	79	69
		2	73	65	186	1170	756	426	375	1540	1600
		3				259	342			681	953
		4									184
Water soluble anions (mg/kg)	**Cl**	**1**	79	107	141	103	72	121	69	45	193
		2	127	78	63	258	191	103	100	377	474
		3				252	140			625	398
		4									734
	SO4	**1**	322	444	1400	3790	3760	4410	3600	506	227
		2	81	107	677	5630	1490	2270	2690	2790	4160
		3				1070	1150			2370	2490
		4									388
	NO3-N	**1**	91	171	323	142	269	577	432	26	69
		2	97	38	109	473	795	397	237	605	754
		3				409	231			750	1560
		4									640
Particle size distribution of 2 mm fraction	**% Sand**	**1**	72.7	61.6	92.7	78.2	89.7	85.7	68.5	86.7	82.3
		2	69.8	73	49.6	62.8	86.9	81.6	86.6	95.8	94.4
		3				68.7	83.7			77.6	79
		4									85.2
	% Silt	**1**	14	21.3	5.1	10.4	7.2	7.9	19.4	9.9	9.4
		2	19.5	18.3	28	19.4	9.4	12.7	7.6	3.1	3.8
		3				15.6	9.5			14.2	16
		4									11.6
	% Clay	**1**	12.8	16.6	2.3	11.3	3.1	6.4	11.8	3.4	8.3
		2	10.7	8.7	21.9	17.4	3.7	5.8	5.7	1.1	1.8
		3				15.2	6.8			8.1	5
		4									3.2

*Sand 63-2000 µm, silt 3.9-63 µm, clay 0.06-3.9 µm

Table 3.5: Chemical and physical properties of Ong Valley site soil horizons.

Map unit			**E**	**F**	**G**	**H**	**I**
			Ong2	**Ong1**	**Ong5**	**Ong6**	**Ong4**
Distance from ice edge (m)			1500	3600	4800	5500	5700
		Horizon					
Moisture Content (% dry weight)		**1**	1.26	0.59	0.34	1.96	0.40
		2	1.60	0.65	0.47	3.03	0.67
		3		0.64	0.40	3.12	0.89
		4				2.18	0.45
pH		**1**	8.82	8.59	8.70	8.37	8.25
		2	9.13	8.50	8.56	8.31	8.42
		3		8.57	8.58	8.44	8.44
		4				8.43	8.80
EC (dS/m)		**1**	0.28	0.81	0.48	2.38	0.04
		2	0.17	1.93	2.10	7.39	2.60
		3		1.41	1.62	5.20	2.80
		4				3.21	1.04
Total C (%)		**1**	0.08	0.08	0.02	0.07	0.01
		2	0.08	0.06	0.02	0.21	0.01
		3		0.09	0.03	0.16	0.02
		4				0.11	0.02
Total N (%)		**1**	0.00	0.01	0.00	0.06	0.00
		2	0.00	0.06	0.03	0.30	0.04
		3		0.03	0.02	0.24	0.03
		4				0.14	0.02
Water soluble cations (mg/kg)	**Na**	**1**	53	169	38	470	55
		2	68	528	348	3630	852
		3		260	224	2010	326
		4				812	91
	Mg	**1**	24	27	12	112	4
		2	9	79	50	578	103
		3		84	44	716	95
		4				404	18
	K	**1**	33	53	42	67	19
		2	23	78	98	299	137
		3		71	75	313	175
		4				178	47
	Ca	**1**	137	477	400	1480	13
		2	61	752	1140	2760	1230
		3		779	1190	1810	1560
		4				1060	126
Water soluble anions (mg/kg)	**Cl**	**1**	22	44	16	151	21
		2	32	108	49	679	86
		3		80	50	551	82
		4				443	74
	SO4	**1**	267	1460	898	3160	25
		2	146	1800	1880	2820	3670
		3		1240	2220	123	4000
		4				83	1760
	NO3-N	**1**	39	81	8	560	3
		2	17	702	289	3850	509
		3		285	121	2390	249
		4				1280	203
Particle size distribution of < 2 mm fraction	**% Sand**	**1**	64.9	84.2	94.4	94.8	89.5
		2	64.1	91	96.1	92.3	56.9
		3		86.3	94.5	91.6	64.9
		4				93.6	75.3
	% Silt	**1**	25.2	11.6	5.5	5.2	9.3
		2	28.2	8.2	3.9	7.6	35.5
		3		12.4	5.3	8	27.1
		4				6.1	19.5
	% Clay	**1**	9.9	4.2	0.1	0	1.1
		2	7.7	0.8	0	0.1	7.6
		3		1.3	0.2	0.3	8
		4				0.2	5.2

*Sand 63-2000 µm, silt 3.9-63 µm, clay 0.06-3.9 µm

Table 3.6: Chemical and physical properties of Dominion Range site soil horizons.

Map unit		A			B					D
		Dom2	**Dom3**	**Dom4**	**Dom5**	**Dom6**	**Dom7**	**Dom8**	**Dom1**	**Dom9**
Distance from ice edge (m)		750	1250	1550	1850	2100	2500	2650	2870	3300
Moisture Content (% dry weight)		4.04	2.25	2.13	1.87	1.66	1	1.68	1.26	1.96
pH		9.22	9.08	8.77	8.57	8.59	8.93	8.65	8.55	8.37
EC (dS/m)		0.09	0.51	0.97	1.57	1.49	1.29	2.23	1.63	3.86
Total C (%)		0.08	0.07	0.13	0.25	0.12	0.17	0.19	0.18	0.96
Total N (%)		0.02	0.02	0.02	0.05	0.05	0.04	0.06	0.04	0.12
Water soluble cations (mg/kg)	**Na**	64	415	738	504	503	570	885	357	1000
	Mg	3	14	49	155	50	62	149	74	438
	K	13	11	13	21	9	9	15	6	27
	Ca	41	57	137	289	159	149	420	196	1460
Water soluble anions (mg/kg)	**Cl**	33	52	46	241	325	395	307	483	656
	SO4	1	611	1550	1680	1600	998	1230	1690	3780
	NO3-N	2	73	122	441	492	404	486	540	740
% Sand		66.2	80.7	79.3	82.1	87.8	96	89.4	93.8	89.6
% Silt		16.6	11.7	11	10.3	7	2.6	5.6	4.2	7.4
% Clay		16.8	7.6	9.6	7.7	5.2	1.4	5.1	1.9	3.1

*Sand 63-2000 µm, silt 3.9-63 µm, clay 0.06-3.9 µm

None of the soils investigated had particularly high salt contents (maximum EC of 7.39 dS/m within the lower 10% of the salt stage scale, Table 3.1), thus confirming observations assigning salt stages of 1 or 2. Salt content generally showed an increase with distance from ice edge (Tables 3.4, 3.5 & 3.6). The anion component of the soil profile salts (Tables 3.4, 3.5 & 3.6) was dominated by sulfates and nitrates, relative to chloride.

Carbon and nitrogen concentrations within all the soils studied were extremely low; generally well below 1%, pointing to the paucity of biomass within the soil. The total carbon measurements include contributions from carbonates, corroborated by the high pH levels (all above 7). One feature of interest is the distinctly higher levels of carbon in the bottom of all Mount Achernar soils, relative to overlying soil layers. The carbon data parallel field observations of darker colours in several of the bottom horizons. Dark clastic fragments are also present within the underlying ice (Figure 3.8). Coal was present at the Mount Achernar site, both as a visible seam in the side of the mountain itself, and as lumps scattered across the surface of the moraine field.

All soils sampled had considerable amounts of gravel and larger clasts; only the < 2 mm fraction was taken from the field and analysed in New Zealand. The grain size of the < 2 mm fraction of all soils (Tables 3.4, 3.5 & 3.6) was dominated by sand sized particles (63 – 2000 µm). Clay (0.06 – 3.9 µm) contents were very low in most cases, with a maximum of 17.4% (Ach 9.2). The proportion of clays in the surface horizons exhibited a general decrease with increasing distance from ice edge. Larger clasts (e.g. cobbles and stones, Tables 3.7 & 3.8) were generally concentrated in the surface horizon (generally < 5 cm deep) of soil profiles, with the bulk of underlying soil being relatively clast poor. Exceptions to this pattern occurred in soils distal to the current ice margin (e.g. Ach 5 & Ach 1, Table 3.7), where larger clasts were found throughout the soil profiles. The surface of the terminal moraine unit at the Ong Valley site (Unit H, profile Ong5) was conspicuously lacking in larger clasts, relative to other soils examined.

Table 3.7: Relative clast abundances of Mount Achernar site soil horizons.

			Soil profile (glacier to leftmost of profile sequence)								
	Map unit		**A**		**B**	**C**					**D**
	Horizon		**Ach3**	**Ach4**	**Ach8**	**Ach9**	**Ach7**	**Ach6**	**Ach5**	**Ach1**	**Ach2**
Depth (cm)		**1**	0-2.5	0-1	0-2	0-2	0-4	0-5	0-5	0-0.5	0-0.5
		2	2.5-8.5	1-8	2-15	2-8	4-30	5-70	5-60	0.5-4	0.5-5
		3	-	-	-	8-65	30-100+	-	-	4-65	5-10
		4	-	-	-	-	-	-	-	-	10-51
Relative clast abundance	**Boulders (>63 cm)**	**1**	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0
		3	-	-	-	0	0	-	-	0	0
		4	-	-	-	-	-	-	-	-	0
	Stones (20-63 cm)	**1**	0	*	0	*	*	*	*	0	0
		2	0	0	0	0	0	0	0	*	0
		3	-	-	-	0	0	-	-	0	0
		4	-	-	-	-	-	-	-	-	0
	Cobbles (7.6-20 cm)	**1**	**	*	*	*	*	**	*	0	0
		2	0	0	0	0	0	0	*	*	0
		3	-	-	-	0	0	-	-	*	0
		4	-	-	-	-	-	-	-	-	*
	Gravels (2-76 mm)	**1**	**	***	**	**	**	**	**	**	**
		2	**	**	**	**	**	**	*	**	**
		3	-	-	-	**	**	-	-	**	**
		4	-	-	-	-	-	-	-	-	**

Clast abundance estimates, eg: * slightly gravelly - 15-30%; ** gravelly - 35-60%; *** very gravelly - 60+ %

Table 3.8: Relative clast abundances of Ong Valley site soil horizons.

Soil profile (glacier to leftmost of profile sequence)							
Map unit			E	F	G	H	I
			Ong 2	Ong 1	Ong 5	Ong 6	Ong 4
Distance from ice edge (m)			1500	3600	4800	5500	5700
		Horizon					
Depth (cm)		1	0-1	0-0.5	0-4	0-1	0-4
		2	1-15	0.5-13	4-30	1-4	4-38
		3	-	13-70	30-80+	4-35	38-44
		4	-	-	-	35-80+	44-70+
Relative clast abundance	Boulders (>63 cm)	1	0	*	*	0	*
		2	0	0	0	0	0
		3	-	0	0	0	0
		4	-	-	-	*	*
	Stones (20-63 cm)	1	**	**	0	0	*
		2	0	0	0	0	0
		3	-	0	0	0	0
		4	-	-	-	*	*
	Cobbles (7.6-20 cm)	1	**	**	**	0	*
		2	0	0	0	0	*
		3	-	0	0	0	**
		4	-	-	-	*	*
	Gravels (2-76 mm)	1	**	***	***	***	***
		2	**	**	**	*	**
		3	-	**	*	**	**
		4	-	-	-	***	***

Clast abundance estimates, eg: * slightly gravelly - 15-30%; ** gravelly - 35-60%; *** very gravelly - 60+ %

3.5.3. Patterns of soil depth

Our transect investigating depth to ice, across the Dominion Range lateral moraines, showed a consistent increase in depth to ice (i.e. – amount of soil overlying ice) with distance from the Beardmore glacier (Figure 3.7). Although not quantified statistically, soils at the other sites generally showed the same trend. Observations at Mount Achernar (Figure 3.8) reveal a considerable amount of rock/mineral material within the underlying ice.

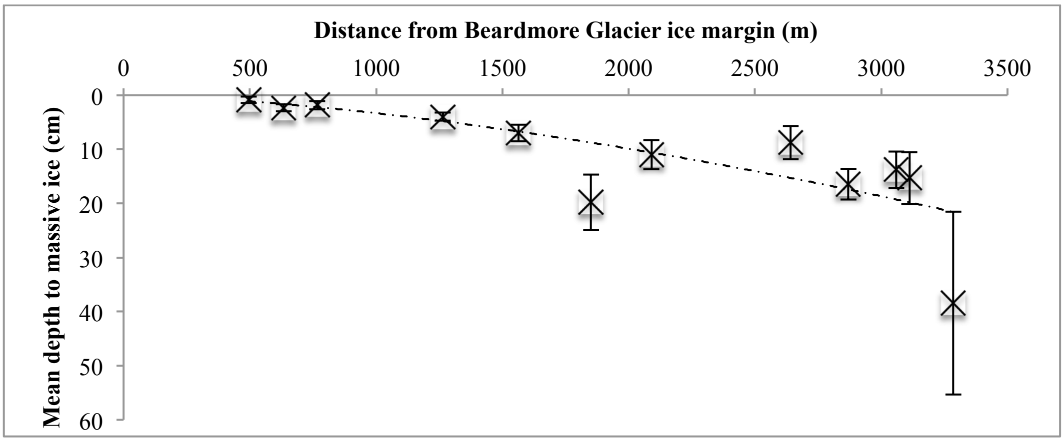


Figure 3.7: Depth to massive ice across Dominion Range site; R^2 0.87. Vertical error bars 1 standard deviation; n = 30 at each site.

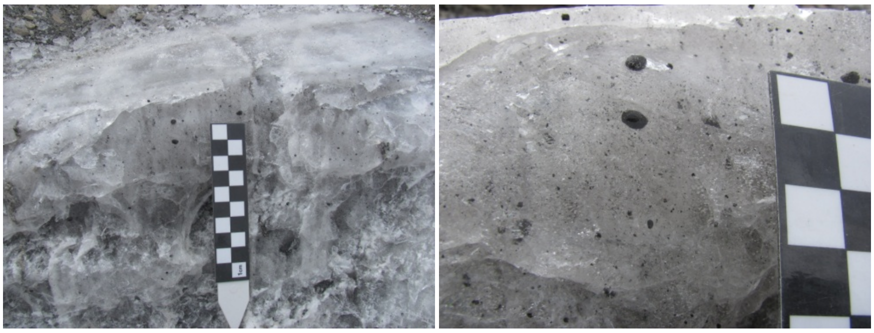


Figure 3.8: Mineral material embedded in massive ice underlying soils at Mount Achernar.

3.6. Discussion

The soils described in this study exemplify, and are perhaps the most extreme example of the statement: *"Antarctic soils are considered to be soils in which the biological factors are reduced to a minimum although they never quite reach zero"* (Claridge & Campbell, 1968). This is in direct contrast to the soils of Cape Hallet at the other end of the LGP, recognized as 'Ornithogenic soils' owing to the profound influence of local Adelie Penguin populations (via guano, other organic matter additions, and stone sorting activities; Hofstee *et al.,* 2006) in a warmer, wetter, coastal environment.

While the same overall soil development pattern was observed along a chronosequence at all three study sites, there are some important differences. Ong Valley differs largely due to its topographic setting; the narrow valley has concentrated the flow of debris-laden ice, and colluviual inputs from the valley walls have a greater influence. The major differences between the Mount Achernar and Dominion Range sites (e.g. – no unit C at Dominion Range; Figure 3.4) is likely due to the amount of debris available to the ice flowing past the site. Taking the Polar Plateau as the arbitrary source of ice flow towards the two sites, it is reasonable to assume that less debris has accumulated in /on the ice by the time it reaches Dominion Range, relative to Mount Achernar. Thus, the amount of soil material is likely a function of the volume of material available 'upstream'.

All the soils could be considered to be weakly developed, showing little in the way of staining, weathering of clasts, or accumulation of salts. According to

Bockheim (1997) the salt stages we recognised (≤2) imply soil ages of less than 18 ka (stage 1, Table 3.1) and between 18-90 ka (stage 2, Table 3.1). The relatively low accumulation of salts (compared to other Antarctic soils) may be due to a short duration of exposure, or a lower salt influx in this region of very low precipitation. The alkaline pH found consistently throughout our soils may also be linked to low levels of salt deposition/precipitation. Claridge and Campbell (1968) found that significant deposition of nitrate and sulfate salts led to soil acidification by formation of nitric and sulfuric acid. A subtle decrease in soil pH with distance from ice edge does, however, support our soil development gradient, with more ice-distal (i.e.- older) soils being more acidic due to greater aerosol accumulation (relative to ice proximal soils); a similar pattern is seen in the salt data.

Our soil investigations in the Beardmore Glacier region of the CTAMs, specifically the high altitude, near-plateau sites, highlight the profound influence of climate on soil development; it must be noted that altitude is far more instrumental in this climatic effect than latitude, as has been previously reported (Bockheim, 2008). The lack of visual evidence of liquid water (both past and present), and soil moisture contents below 5% (Tables 3.4, 3.5, & 3.6), both support an ultraxerous soil-formation climate for all soils investigated in this study. Current temperature data (Figure 3.3) suggests any moisture present will be frozen, even at the height of summer. The occurrence of a vesicular surface crust is indicative of some moisture (Bockheim, 2010). We submit that the patchy occurrence of such a crust is due to spatial heterogeneity of snow melt; the lack of any ice-cemented soil materials, and extremely low soil moisture levels, indicate that any moisture present (intermittently) at the surface has no discernible impact on the underlying soil and its development.

Based on field designations of the weathering and salt stages (Table 3.1), and supported by salt data (Tables 3.4, 3.5 & 3.6), the soils examined at our sites would be expected to be relatively young (i.e. < 24 000 years), if soil formation is assumed to proceed at a similar rate in the Beardmore region as in other, better characterized regions (e.g. – McMurdo Dry Valleys). At the Mount Achernar site, the assumed young age is challenged by two separate estimates of moraine ages based on cosmogenic ^{10}Be and ^{26}Al accumulation in quartz-bearing rocks on the moraines (Faure & Nishiizumi, 1994; Mathieson *et al.,* 2012). Both studies suggest the oldest moraines at Mount Achernar are 300 000 to 500 000 old, and much of the moraine suite is proposed to have been in place over the past two glacial cycles, with only the most ice-proximal material being emplaced since the Last Glacial Maximum (Mathieson *et al.,* 2012). If the cosmogenic exposure ages from Mount Achernar are accepted, rather than the correlated ages obtained from more distant sites where climatic factors likely differ, then soil development in the upper Beardmore Glacier region must be slower, by at least an order of magnitude, than in other regions of Antarctica previously studied (and where the weathering/salt stages were formulated/calibrated). The cosmogenic nuclide exposure ages of Storey *et al.* (2010) in the Darwin Mountains (the second most southern site of the LGP) also point to landscapes being older than past soil development interpretations predict. Although at a lower altitude and further north than our study sites, the climate in the Darwin Mountains is likely similar (i.e. – ultraxerous) to our study sites. Our observations point to the Ong Valley and Dominion Range site soils being of similar age (on the basis of development/weathering, and assuming minimal climatic differences between sites), although no cosmogenic data are available.

We present a model for soil formation/development at the recessional margins of cold-based glaciers near the polar plateau (Figure 3.9). We propose that two main mechanisms contribute material to the developing soil at both the top and bottom of the profile. Weathering of supraglacial clasts provides materials for the upper layer of the soil, which thickens as boulders breakdown by thermally induced splitting, aeolian abrasion and spallation. Independently, the subsoil thickens by residual accumulation of englacial material (Figure 3.8) as glacial ice sublimates. Thus the upper soil horizon thickens by an upbuilding process (Almond & Tonkin, 1999) while the subsoil thickens by lowering of the contact between soil and ice in an analagous way to deepening of soil by *soil production* (Heimsath *et al.*, 1997) into saprolite or rock.

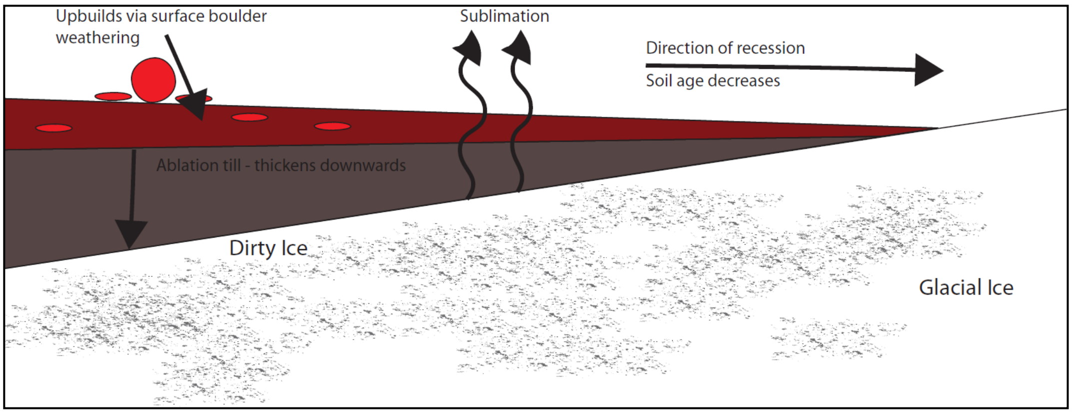


Figure 3.9: Conceptual model of soil formation at recessional margins of cold based glaciers.

Clast abundance data (Tables 3.7 & 3.8) show a thin clast-rich surface layer overlying a thick relatively clast-poor subsoil. The clastic surface layer exhibits fairly constant thickness along the gradient from current ice edge, whereas the underlying finer horizon thickens significantly. This points to a finite contribution of material at the surface (e.g. – the initial supraglacial debris load) and relatively slow coarse-clast comminution, while the subsoil receives continual additions from the underlying ice. The decrease in clay content of the upper horizon with increasing distance from the ice margin probably represents increasing dilution of that fraction by added sand and silt. The presence of larger clasts in lower horizons in the more ice distal soil profiles (Tables 3.7 and 3.8) are likely due to cryoturbation effects; tension cracks were observed to have larger clasts (e.g.- boulders) concentrated in or near them relative to surrounding polygons at the ice distal soil sites. Alternatively the material within the glacier may, on average, be finer further from the sources of rock input on the glacier edges.

The soil of unit I (Ong Valley) is an end-member example of the upbuilding behavior. Here, ongoing rockfall from the valley walls provides a continuous flux of granite clasts, which grussify to supply the upbuilding surface horizon with fine gravel and sand, which then may be redistributed by the wind. The layer of weathered and stained clasts in the soil Ong 4 at 45 cm depth (Table 3.3) is most likely a former desert pavement, buried by accumulating gruss. The hiatus represented by the desert pavement points to an episodic and probably spatially heterogeneous pattern of upbuilding.

Colour and carbon content, in the soils at the Mount Achernar site, also support a two-layer mode of soil formation and development. The bottom-most horizon in all Mount Achernar site soil profiles constitutes the bulk of the soil (i.e. - is the thickest horizon; Table 3.7), and consistently has higher carbon contents (reflected in dark soil colours) than the overlying thin surface horizons. The distinct differences between surface and underlying soil horizons (in the absence of downwards leaching of carbon) indicate different sources of material for the two major soil layers. Quantifying the amount of material within buried ice, and the composition/provenance of it, may support this model in future studies. The relationship between distance from ice edge and depth to buried ice at the Dominion range (Figure 3.7) is also offered in support of this model.

In accordance with our model (Figure 3.9), sublimation rates are an important determinant of the rate of soil thickening. Cosmogenic ^{3}He depth profiles in till over buried ice in the Beacon Valley (McMurdo region) suggest average sublimation rates exceeding 10-100 metres per million years (Ng *et al.,* 2005). Assuming a 3 % wt/wt debris load in the underlying ice, and resultant soil bulk density of 2 g/cm^3, one metre of ice produces 15 mm of sublimation till; thus a 50 cm soil (not including clast rich supraglacial surface horizon) requires 33 m of ice to have sublimed. This gives an estimated time of 300 000 to 3 million years to produce a 50 cm-thick soil, which even at the most conservative end is a lot older than what the salt and weathering stages would suggest, and more within the realms of the cosmogenic exposure ages discussed above (Faure & Nishiizumi, 1994; Mathieson *et al.,* 2012).

It is interesting to ponder the form of a soil 'production' function where sediment released by sublimation is the main soil thickening mechanism, and consider its implications. As soil thickness over ice increases, the water vapour pressure gradient between ice and atmosphere will decrease, thereby slowing the water vapour flux. Thus, like soil production (Heimsath, 1997), the rate of soil thickening by sublimation would be expected to decline with increasing soil thickness. A decreasing rate of ice sublimation beneath a thickening soil cover would feedback to ice dynamics on a glacier's lateral margin, where ablation unloading is an important driver of ice advection; ice advection has been implicated in the development of *blue-ice moraines* in the Heritage Range, West

Antarctica (Fogwill *et al.,* 2012; Figure 8). Reduced sublimation beneath thick soil cover on a glacier margin would act to slow or even stagnate ice flow and shift ice advection inboard to areas of cleaner ice and higher sublimation rate. These areas would then become the focus of enhanced soil thickening. Thus, the growth of soil cover on a glacier margin is likely to be a self-reinforcing process. The development of patterned ground we observed in the drift belts at the Dominion Range and at Mt Achernar is consistent with our inferences. Stagnant ice beneath the ice-distal parts of the moraine belts would accommodate more stable patterns of thermal ice cracking, allowing polygonal patterns of cracks, sand wedges (Levy *et al.,* 2006) and the attendant surface deformation characteristic of patterned ground to develop (Hallet *et al.,* 2011).

3.7. Conclusions

Soils in the ultraxerous climate of the high altitude, ice-free areas in the Central Transantarctic Mountains develop much more slowly (perhaps up to an order of magnitude) than in other continental Antarctic regions. Patterns of soil development across three recessional glacial margin sites include increasing soil thickness, declining soil pH, and increasing salt content. Soil groups mapped include Haplorthels, Haploturbels and Anhyorthels. The fine-scale soil variation we observed could not be effectively represented by mapping soil subgroups, the category currently used in reconnaissance soil maps of Antarctica. We present a conceptual two-mode model of soil development: a thin surface horizon originating as supraglacial till thickens slowly by comminution and aeolian redistribution of sand and silt spalled from surface clasts, while the subsoil thickens more rapidly by release of englacial material by glacial ice sublimation.

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Chapter 4 - The southernmost soil bacterial communities, Central Transantarctic Mountains, Antarctica

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4.1. Abstract

The molecular characterization of bacterial communities in CTAM soils is the southernmost culture-independent soil survey to date. Community fingerprinting (ARISA) and 16S rRNA gene pyrosequencing demonstrated significantly different bacterial communities between eight discrete CTAM locations (5 at low altitude near the Ross Ice Shelf coast, 3 near the polar plateau > 1600 m). Abiotic environmental variables, especially those related to long-term exposure of soils to the atmosphere, correlate well with inter-site community variation. Mount Howe, the southernmost soil on the planet (87° S), harbours an extremely low biomass bacterial community, of a fundamentally different composition to all other sites. It appears that observed DNA sequences at Mount Howe are the result of atmospherically deposited bacteria, the soil being unable to support edaphic life due to extreme local climatic conditions.

4.2. Introduction

The ice-free areas of the Antarctic, covering ~ 0.4% of the continent (Peat *et al.,* 2007), were long considered a lifeless desert, with Captain Scott referring to Taylor Valley in the McMurdo Dry Valleys (MDV), Victoria Land, as "*a valley of the dead*" in 1903 (Scott, 1905). As late as the 1970's, some Antarctic soils were still described as sterile, with any recovered microbes not considered to be indigenous (Horowitz *et al.*, 1972). With the largest year-round animal inhabitants being tiny springtails and mites, and vegetation no more complex than moss and lichens (excluding the Antarctic Peninsula), these ecosystems have a limited trophic structure, with biotic interactions thought to be near-negligible (Hogg *et al.,* 2006). Antarctic desert soils thus offer a unique opportunity to study soil microbial ecology in the absence of a complex biotic interaction network across multiple trophic levels.

The development and application of molecular, rather than culture-dependent, methods revealed a greater microbial abundance and diversity, more widespread than expected in Antarctic soils (Cowan *et al.*, 2002; Barrett *et al.*, 2006; Smith *et al.*, 2006; Yergeau *et al.*, 2007). MDV soil communities are typically dominated by members of the *Actinobacteria, Bacteroidetes* and *Acidobacteria*; compared to temperate soil habitats, *Proteobacteria* are under-represented, and *Deinococcus-Thermus* frequently recovered in the MDV (Cary *et al.,* 2010). Conversely, *Proteobacteria* are relatively abundant community members throughout the Antarctic Peninsula, with members of the *Alpha, Beta, Delta,* and *Gamma Proteobacteria* classes frequently detected (Yergeau *et al.,* 2007). These discoveries prompted further investigations into the ecology of this unique environment, and led to several important insights. Lee *et al.* (2012) found microbial communities to be distinct between disparate locations within the MDV, although phyla-level diversity was relatively constant, and geochemical properties (especially salt content, altitude and copper content) of the soil correlated well with the community heterogeneity. The transplant of a mummified seal carcass in the Miers Valley (MDV) showed the potential for soil microbial community to respond rapidly to changes in the environment (Tiao *et al.*, 2012), thus demonstrating a dynamic and sensitive biota. Similarly, significant shifts in community composition were observed within three years at several sites throughout the Antarctic Peninsula region, under experimentally induced warming (Yergeau *et al.*, 2012). While the aerial redistribution of organic matter is recognised as an important factor in MDV ecosystems (Hopkins *et al.*, 2006)**,** the specific phenomenon of bacterial immigration between distinct communities is unlikely, with little similarity found between Miers Valley soil communities and the bacterial component of the overlying air (Bottos *et al.,* 2013). Sokol *et al.* (2013) recently identified dispersal capability as an important factor for the distribution of cyanobacteria throughout the Transantarctic Mountains, but environmental factors (moisture and pH) determined the coarse (i.e. – Phyla level) structuring of the overall bacterial metacommunity.

The Latitudinal Gradient Project (LGP) prompted and enabled studies both North and South of the MDV along Victoria Land and the Transantarctic Mountains (TAM), with the specific goal to examine changes in ecosystems with respect to environmental/climatic conditions. Latitude along the Victoria Land coast is used as a proxy for a climate gradient (Howard-Williams *et al.*, 2006); latitude has been shown to correlate with bacterial community composition in unvegetated soils throughout the Antarctic Peninsula region (Yergeau *et al.,* 2007). Microbial work south of the MDV has been mainly restricted to the Darwin Mountains (another LGP site). Magalhaes *et al.* (2012) found a decrease in diversity (at multiple trophic levels) in communities examined along a soil development sequence; greater salt accumulations in older soils limiting community complexity. Similar diversity decreases were found by Aislabie *et al.* (2013) at Lake Wellman (Darwin Mountains); clone library sequences revealed communities to be dominated by members of the *Deinococcus-Thermus*, *Actinobacteria* and *Bacteroidetes* phyla. To date, studies further south along the TAM have only been conducted using culture-dependent approaches; Aislabie *et al.* (2006) isolated members of the *Actinobacteria*, *Bacteroidetes* and *Proteobacteria* from the La Gorce Mountains (86°S), and Cameron *et al*. (1971) reported *Arthrobacter* sp. and *Corynebacterium* sp. as well as some yeasts at Mount Howe, the southernmost soil on the planet.

Here, we provide the first molecular-based culture-independent investigation of soil microbial communities south of the Darwin Mountains (~79°S). Soils were sampled at several sites throughout the CTAM region (5 sites at low altitude near the coast, 3 sites > 1600 m at the polar plateau margin; Figure 4.1), including Mount Howe, the southernmost of exposed soils (87°S) on the planet. This study sought to determine whether localised bacterial communities in the Central Transantarctic Mountains (CTAM) region are distinct from site to site as shown in the MDV (Lee *et al.,* 2012), and if similar abiotic factors can explain this between site uniqueness as seen in the MDV. A survey of bacterial diversity throughout the region was also sought, as Antarctic bacterial communities are sensitive to changes in the abiotic environment (Tiao *et al.,* 2012; Yergeau *et al.,* 2012) and baseline data are thus required in order to monitor future change.

4.3. Materials and methods

4.3.1. Sample collection

All samples were collected in December or January of the 2010/2011 austral summer at sites in the Queen Maud Mountains (Figure 4.1). The protocol for sample collection followed that described by Lee *et al.* (2012). Sites along the Ross Ice Shelf 'coast' (i.e. – all sites other than Ong Valley, Mount Achernar, and Mount Howe) were targeted specifically as known locations for lichens, as part of an invertebrate study (Green, Hogg, unpublished data). Site locations were: Gateway Spur, 83°29.6 S 170°46.8 E; Mount Kyffin, 83°47.3 S 171°48.8 E; Mount Harcourt, 83°47.4 S 172°12.0 E; Garden Spur, 84°33.6 S 175°00.3 E; Durham Point, 85°32.2 S 151°11.0 W; Ong Valley, 83°15.0 S 157°47.5 E; Mount Achernar, 84°13.0 S 161°06.5 E; Mount Howe, 87°20.7 S 149°14.8 E.

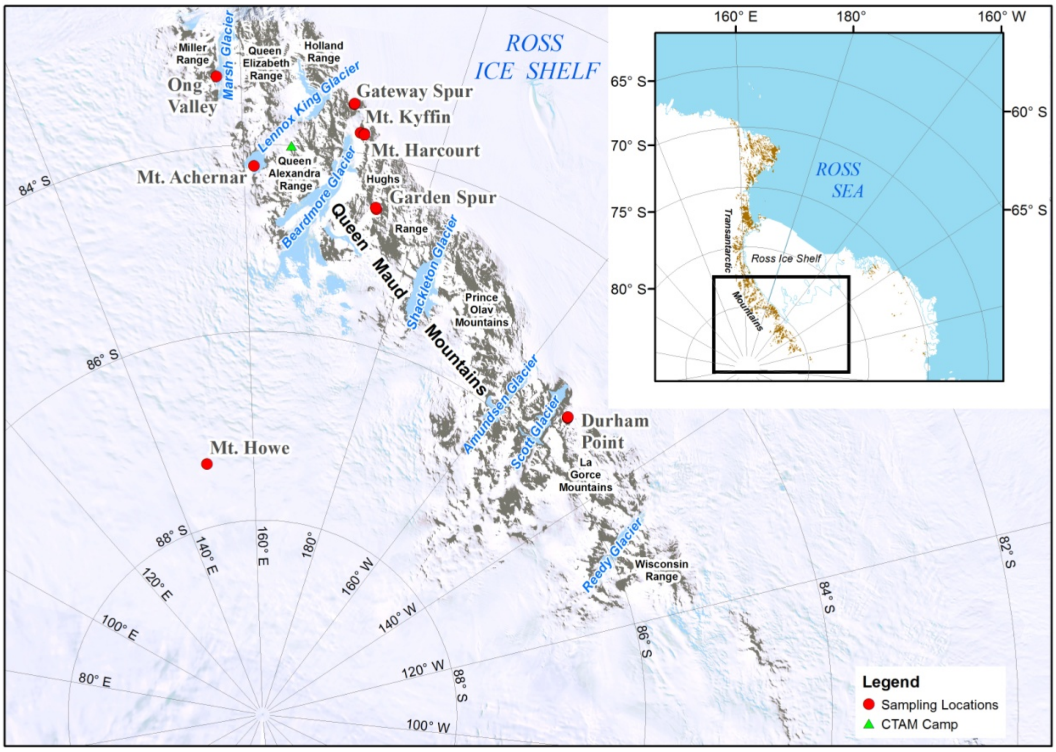

Figure 4.1: Map of sample locations within the Central Transantarctic Mountains; inset greater Ross Sea Region.

Briefly, replicate samples were collected aseptically from the ends of two intersecting 50 m transects, as well as the centre point; each replicate consisted of soil pooled from the top ~2 cm at four corners of a 1 m^2 quadrat. All practical precautions (nitrile gloves, ethanol sterilised trowel) were taken to prevent contamination (both human-induced and inter-site). Separate samples were collected for geochemical and biological analyses, and were transported frozen back to New Zealand at approximately -20 °C.

4.3.2. Geochemistry

At least 5 g of soil was passed through a 2 mm sieve, and air-dried at 35 °C overnight. Moisture content was determined by drying the 5 g to constant weight at 105 °C. pH and electrical conductivity were measured with an Orion 4-star plus benchtop pH/conductivity Meter (Thermo Scientific, Waltham, USA) on a mixture of 2 g of soil mixed with 5 mL deionised water. Particle size was measured on a Malvern Mastersizer 2000 (0.02 – 2000 µm), after digestion of ~ 1g of dry soil with 30% H_2O_2 and dispersion with calgon. 2 g of soil was ground to fine powder with an agate mortar and pestle; ground soil (1 g) was digested according to US EPA Analytical Method 200.2 (Revision 2.8, 1994), for elemental composition analysis via Inductively Coupled Plasma Mass Spectrometry (ICP-MS) in a Perkin-Elmer SCIEX ELAN DRC II. Total carbon and nitrogen were measured by combusting 100-250 mg ground soil in a TruSpec CN analyzer (LECO Corp., St Joseph, MN, USA) at the University of Waikato Stable Isotope Laboratory.

4.3.3. Cell counts

Bacterial cell counts were conducted on each soils sample folowing the methods described by Tiao *et al.* (2012; supplementary information) with the following modification. Cells were fixed with formaldehyde after physical dispersion (rather than before) in a Mini-beadbeater (Glenmills Inc, NJ).

4.3.4. DNA extraction and community fingerprinting (ARISA)

DNA was extracted from 0.6-1.0 g soil using a CTAB bead-beating method (Coyne *et al.,* 2001). Samples yielding unquantifiable DNA (Ong Valley and Mount Howe, presumably due to extremely low biomass) were extracted using a modified version of the MoBio Powersoil megaprep (MoBio, CA, USA) on 20-30 g of soil per sample. Modifications were as follows: soil was aliquoted in 5 g amounts into 50 mL falcon tubes with 9 g of silica-zirconia beads (3 g of 2.5 mm diameter, 6 g of 0.1 mm); 5 mL of phenol:chloroform:isoamyl alcohol (25:24:1; pH 7-8) was added along with 10 mL 'bead solution'and 1 mL of solution C1, before homogenisation on a Vortex-Genie (MoBio, CA, USA). Samples were centrifuged at 2500 x g for 15 minutes, and aqueous layer transferred to a new tube. 1.5 mL of Solution C2 was added mixed by shaking; 1.5 mL of C3 added, mixed and incubated for 5 minutes at 4°C and then centrifuged for 15 minutes at 2500 x g. The supernatant was transferred to a new tube and an equal volume of solution C4 and 100% ethanol added before mixing by shaking. Lysate was loaded onto the spin column, 21 mL at a time (all 5 g soil aliquots pooled through one column), and centrifuged for 6 minutes at 2500 x g; flow-through discarded. The spin column was washed with 20 mL of Solution C5 and centrifuged for 6 minutes at 2500 x g; flow-through discarded. The column was then washed with 20 mL of 100% ethanol and centrifuged for 6 minutes at 2500 x g; flow-through discarded. Column was dried by centrifuging for 20 minutes at 2500 x g. The column was transferred to a new 50 mL tube with the cap off to air dry for 10 minutes. Nucleic acids were eluted in 6 mL TE buffer, and centrifuged for 10 minutes at 2500 x g. 2.5 volumes of 100% ethanol were added, along with NaCl to final concentration of 0.2 M and 20 μL of 5mg/mL linear acrylamide. Tubes were shaken to mix, before overnight precipitation at -20 °C. The next day, DNA was pelleted by centrifuging for 50 minutes at 2500 x g. The pellet was washed with 70% ethanol (5 mL) and then centrifuged again for 20 minutes at 2500 x g to re-pellet. Ethanol was decanted, tube inverted, and air died until traces of ethanol were gone. The pellet was resuspended in 50 μL of TE buffer. All tubes were UV sterilised for 15 minutes prior to use, all equipment (e.g. centrifuge, vortex) cleaned with 70% ethanol, and all transfer steps conducted in a UV sterilised laminar-flow hood, to minimse contamination potential.

Community level fingerprinting was carried out via Automated Ribosomal Intergenic Spacer Analysis (ARISA; Cardinale *et al.,* 2004), using the bacterial primers ITSF (5'-GTCGTAACAAGGTAGCCGTA-3'), and ITSReub (5'-HEX-GCCAAGGCATCCACC-3'). PCR was performed in triplicate for each sample, and pooled after amplification. Each 25 μL reaction contained: 0.75 μL of 50 mM $MgCl_2$, 2.5 μL of 10X PCR buffer, 2.5 μL of 2.0 mM dNTPs, 0.2 μ L of platinum *Taq* polymerase (Life Technologies), 2.5 μL of 0.2 mg/mL BSA, 0.625 μL of each primer, 13.3 μL ultrapure water, and 2 μL of template DNA containing 10 ng total (PCR master mixes were treated with ethidium monoazide (EMA; Rueckert & Morgan, 2007) to inhibit contaminating DNA before template added). Thermal cycling conditions were: 94°C for 2 min, then 30 cycles of 94°C for 45 sec, 55°C for 30 sec, 72°C for 2 min, and a final extension of 72°C for 7 min. Verified PCR products were diluted 1:20, a 1200 bp internal size standard added, and fragment length analysis performed via capillary electrophoresis on a 3130xl Genetic Analyser (Life Technologies) at the University of Waikato DNA Sequencing Facility.

4.3.5. 16S rRNA gene 454-pyrosequencing

Eight samples (MK_a, MH1_a, GS3_b, DP3_b, OV_a, MA_a, HW_a, HW_b;

Table 4.2) were subsequently selected for pyrosequencing of the 16S rRNA gene. The V5-V7 hypervariable region of the 16S rRNA gene was PCR amplified with the primers Tx9 (5-GGATTAGAWACCCBGGTAGTC-3) and 1391R (5-GACGGGCRGTGWGTRCA-3). All amplifications were conducted in triplicate and then pooled prior to sequencing. Each 30 µL reaction contained: 1.2 µL of 50 mM $MgCl_2$, 3.0 µL of 10X PCR buffer, 3.0 µL of 2.0 mM dNTPs, 0.2 µ L of platinum *Taq* polymerase (Life Technologies), 3.0 µL of 0.2 mg/mL BSA, 1.2 µL of each primer, 12.3 µL ultrapure water, and 5 µL of template DNA containing 4-10 ng total (PCR master mixes were treated with EMA to inhibit contaminating DNA before template added). Thermal cycling conditions were: 94°C for 2 min, then 30 cycles of 94°C for 20 sec, 55°C for 10 sec (-0.2° C per cycle), 72°C for 20 sec, and a final extension of 72°C for 3 min. Amplicons were purified and size-selected in a 2% agarose electrophoresis gel, before undergoing a gel extraction (MoBio Ultraclean DNA purification kit) and AMPure purification (Agencourt AMPure XP PCR purification, Beckman Coulter).

Unique MID identifiers were fused to amplicons in a second round of PCR amplification with the primers Tx9 (5-GGATTAGAWACCCBGGTAGTC-3) and 1391R* (5-GACGGGCRGTGWGTRCA-3), the MID being incorporated in the reverse primer. PCR reactions contained the same components as above, although template DNA ranged from 4-20 ng total, and a uniquely MID-labeled reverse primer added to each sample. PCR conditions were same as above, but run for only ten cycles total. PCR products were selected and purified as above, before pyrosequencing on a GS Junior 454 (Roche, Branford, CT, USA) at the University of Waikato DNA Sequencing Facility.

Amplicon pyrosequencing data were processed in AmpliconNoise v1.0 (Quince *et al.,* 2011). Flowgrams with matching primer and MID sequences, with a minimum length of 360 cycles before first noisy signal (0.5-0.7 or no signal for all four bases) were selected. Flowgrams were cut at 360 bases, and clustered, removing sequencing noise in PyroNoise (Quince *et al.,* 2009; Quince *et al.,* 2011). PCR noise was removed using SeqNoise (Quince *et al.,* 2011), and chimeras removed using Perseus (Quince *et al.,* 2011).

Resulting sequences were aligned with prank + F, then analysed via Mothur (version 1.30.0; Schloss *et al*., 2009). OTU$_{0.03}$ (average neighbor clustering at 97% similarity) representative sequences were classified by the RDP classifier (release 10, update 32) on 27/6/2013.

4.3.6. Statistics

Geochemical and spatial data (distance from coast, altitude, pairwise distances between sites) were all log(x+1) transformed (except pH) and imported into Statistica (Statsoft Inc.), pairwise regression analysis was performed on all variables to identify those which co-vary, and thus remove redundant variables from subsequent similarity analyses. Geochemical data were imported into PRIMER 6 (v.6.1.6; PRIMER-E, Plymouth, UK 2006), log(x+1) transformed (except pH) and normalized, and Euclidean distances calculated. Similarities were visualized using non-metric multi-dimensional scaling (MDS), similarity measures (calculated via CLUSTER method) were overlaid on the MDS plots.

ARISA fragment length profiles were imported into Peak Scanner^{TM} v1.0 (Life Technologies), flowgrams were screened for noise/false peaks, and then size-binned, clustered and normalised. Fragment length abundance data were then imported into PRIMER 6, and Bray-Curtis similarities calculated. Similarities were visualized using non-metric multi-dimensional scaling (MDS), similarity measures (calculated via CLUSTER method) were overlaid on the MDS plots.

Biota-Environmental STepwise (BEST – PRIMER 6) analysis was used to link bacterial ARISA profiles to geochemical profiles (ICP-MS data limited to Na, Mg, P, S, K, Ca, Fe and Cu).

4.3.7. Comparison to other libraries

A stringent test for human-introduced contamination was required due to the low biomass of samples, especially Mount Howe. A blast database was constructed from 16S rRNA gene sequences downloaded from the Human Microbiome Project (HMP; http://www.hmpdacc.org/HM16STR). Representative sequences from each OTU$_{0.03}$ were compared to the database, with any matches with an alignment length > 200 bp and an alignment identity > 97% considered as potential human-associated contamination. In order to compare the

CTAM communities with other Antarctic sites and the possible aeolian community, 16S rRNA gene sequences from a study of McMurdo Dry Valley airborne bacteria (Bottos *et al.,* 2013) and Miers Valley soil (Control Site; (Tiao *et al.*, 2012), approximately 650 km to the north (351°) of Mount Kyffin, were also included in the analysis. Sequences from these studies were chosen due to similarity in sequencing protocols allowing direct comparison.

4.4. Results

4.4.1. Geochemistry

Initial analysis of the geochemical data (pH, conductivity, moisture content and clay content) from ≥ 4 replicates per site showed significant variation between each sampling site (one-way ANOSIM, R = 0.604 ; p = 0.001). Two replicates per site were analysed further based on this screening, with replicates chosen to cover the range of pH and conductivity of each site (Table 4.1). One-way ANOSIM of all geochemical data showed a slightly stronger significant difference between sites (R = 0.626; p = 0.001).

Clay content of the > 2 mm fraction of the soil at all sites was lower than 3%, reflecting the coarse sandy nature of all these Antarctic soils. Moisture contents was below 1% w/w except at Mount Howe (1.09%; Table 4.1). Surprisingly, for most samples higher moisture contents was measured from the plateau sites when compared to coastal. Soil pH ranged from 5.95 to 8.35, with no discernible pattern across sites. Conductivity exhibited a strong division between the plateau (> 700 μS/m) and "coastal" sites (< 300 μS/m), by at least an order of magnitude. Total carbon content ranged from 0.05% to 0.41% (Table 4.1). Total nitrogen was very low (0.01-0.04%) across all sites, the highest being at Mount Achernar and Mount Howe. The overall elemental compositions (obtained via ICP-MS) reflect the source geology of the soil, either local bedrock and/or glacially transported materials, with possible contribution from atmospherically deposited salts.

Regression analysis revealed significant correlations between a number of abiotic (geochemical and spatial) variables. Most of the significant correlations were between the various metals, most likely a function of soil source geology. Conductivity correlated with altitude, moisture content, sodium and calcium, with moisture content also correlating with calcium. Distance to coast, pH and clay content all had no significant correlations. Interestingly, total nitrogen correlated with sodium content, and total carbon with arsenic. Co-varying factors were removed from subsequent analyses to minimise redundancy.

Table 4.2: Mean soil physicochemical properties (n = 2).

		Gateway Spur 2	Mt. Kyffin	Mt. Harcourt 1	Mt. Harcourt 2	Garden Spur 2	Garden Spur 3	Durham Point 2	Durham Point 3	Ong Valley	Mt. Achernar	Mt. Howe
Altitude (m asl)		155	1058	502	530	459	340	469	301	1692	1873	2800
Distance to Coast (km)		4.6	7.9	7.9	8.8	55.4	55.6	17.9	16.9	89.3	124	390
Clay (%)*		0.48	0.79	2.76	2.66	1.42	0.44	0.65	1.12	1.02	0.29	1.76
Moisture (% w/w)		0.15	0.14	0.62	0.66	0.38	0.20	0.18	0.20	0.75	0.59	1.09
pH		6.75	6.60	7.43	7.64	5.95	6.05	6.83	8.35	7.49	7.13	6.30
EC (μS/m)		86	265	243	265	151	75	122	289	4192	737	2395
Total C (%)		0.06	0.09	0.41	0.24	0.12	0.05	0.07	0.10	0.35	0.33	0.04
Total N (%)		0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.03	0.04
C:N		6.00	4.50	41.00	23.50	6.00	5.00	7.00	9.50	25.75	12.75	1.17
Elemental concentration (ppm)	B	61	71	57	63	58	58	59	61	64	56	60
	Na	249	510	542	511	622	310	441	695	916	2338	5444
	Mg	2732	21979	14439	29215	11442	4588	5591	4790	6161	4536	10947
	Al	5933	**	25120	**	23437	9236	18607	11617	13359	18256	**
	P	216	1254	779	1176	705	479	505	617	603	505	361
	S	129	609	322	250	406	2516	164	435	2749	764	2210
	K	2787	**	13440	26491	2560	2468	2440	3012	4590	970	925
	Ca	1205	3876	18820	18691	9611	4126	9549	8077	20299	14108	26087
	V	12	85	53	93	62	25	19	19	21	36	42
	Cr	10	69	42	79	17	5	13	8	39	11	15
	Fe	6906	46007	27504	52432	25171	12660	14841	11713	11158	19205	19761
	Mn	134	778	631	815	711	392	386	312	224	396	312
	Co	2	20	12	27	17	9	5	5	8	9	16
	Ni	9	60	27	60	15	4	11	6	14	18	41
	Cu	7	24	22	61	31	8	15	10	16	49	147

Zn	33	123	77	166	77	9088	64	789	3894	131	197
As	1	2	13	1	0	0	***	0	1	2	0
Se	0	1	0	1	0	1	1	1	1	1	1
Sr	6	36	33	75	36	9	28	19	152	57	116
Ag	0	0	0	0	0	0	0	0	0	0	1
Cd	***	***	***	***	***	48	0	6	23	0	1
Ba	28	239	83	171	49	20	20	17	66	44	32
Tl	0	1	1	1	0	0	0	0	0	0	0
Pb	7	11	12	32	12	6	13	10	7	8	3
U	3	3	2	1	3	3	3	7	2	1	0

* Percentage of> 2 mm soil fraction clay sized (> 3.9 µm); ** Above detection limits. *** Below detection limits.

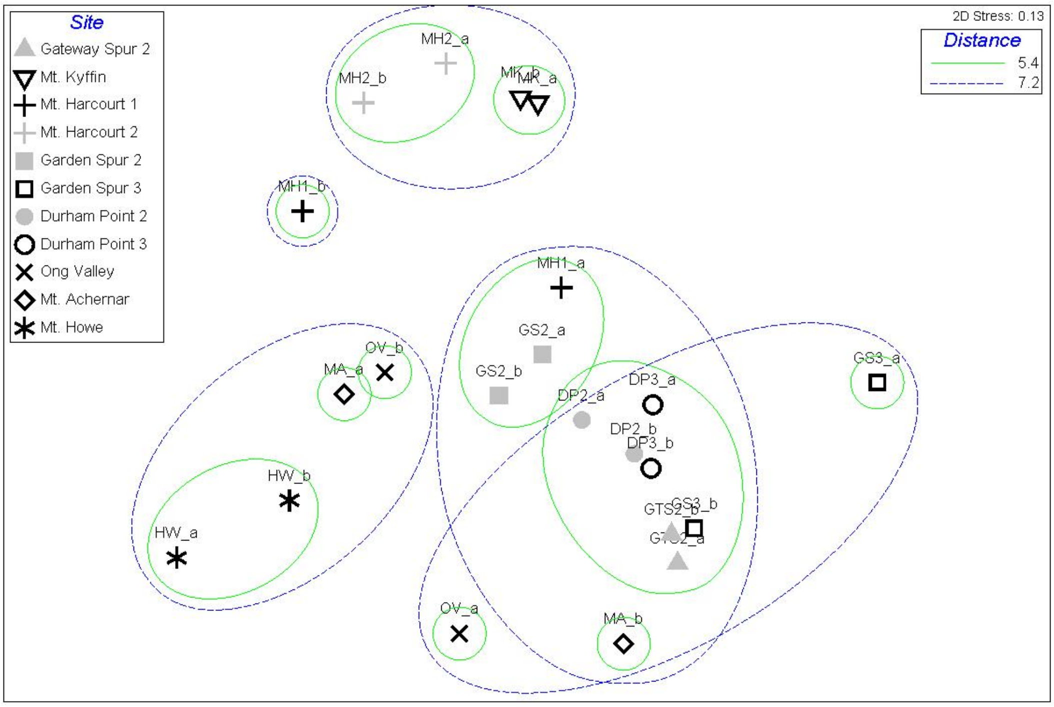

Figure 4.2: MDS plot of soil geochemical profiles; calculated from a Euclidean distance matrix of geochemical data after square-root transformation and normalisation.

4.4.2. Cell counts

The modified soil cell count protocol, as described above, was found to significantly increase observed cell numbers by ~ 25%. Mean cell counts ranged from 2.3 x 10^5 cells/g (Ong Valley) to 2.1 x 10^6 cells/g (Durham Point), with standard deviations of 1.6 x 10^5 and 3.5 x 10^5 respectively. Cell counts were unobtainable from the Mount Howe samples due to extremely low biomass and the high clay particle to cell ratio. No discernible trends in cell abundance were observed between sites, other than Ong Valley having a markedly lower cell count than all others, and Mount Howe being uncountable. These observations were reflected in the efficiency and difficulty of DNA extraction from both of these sites.

4.4.3. Community fingerprinting (ARISA)

Extraction negatives were processed alongside all samples, and confirmed as negative by quantitation (Qubit dsDNA HS Assay Kit and Qubit 2.0 Fluorometer;

Life Technologies Corporation, Carlsbad, CA, USA), gel electrophoresis following ARISA amplification, and subsequent capillary electrophoresis.

Community profiles were found to significantly differ between sites, global ANOSIM reported a R value of 0.431 ($p = 0.001$) when all ARISA profiles ($n \geq 4$ per site) were compared. This dataset was trimmed to $n = 2$ per site in order for comparison with the full suite of physicochemical properties. However, only one Mount Howe sample was analysed via ARISA so as to conserve the minimal DNA extracted. ANOSIM reported a stronger difference between sites ($R = 0.738$; $p = 0.001$) for the limited ARISA profile set with replicate samples tending to cluster by site (Figure 4.3). The MDS plot (Figure 4.3; based on Bray-Curtis similarities calculated from ARISA peak data) indicates a distinct cluster constituting the high altitude, plateau-proximal Ong Valley and Mount Achernar sites separate from the rest of the sampled coastal sites communities ("trimmed dataset" $R = 0.524$, $p = 0.002$; "full dataset" $R = 0.305$, $p = 0.011$). Mount Howe is similarly separate, although ordinated differently in the MDS (Figure 4.3).

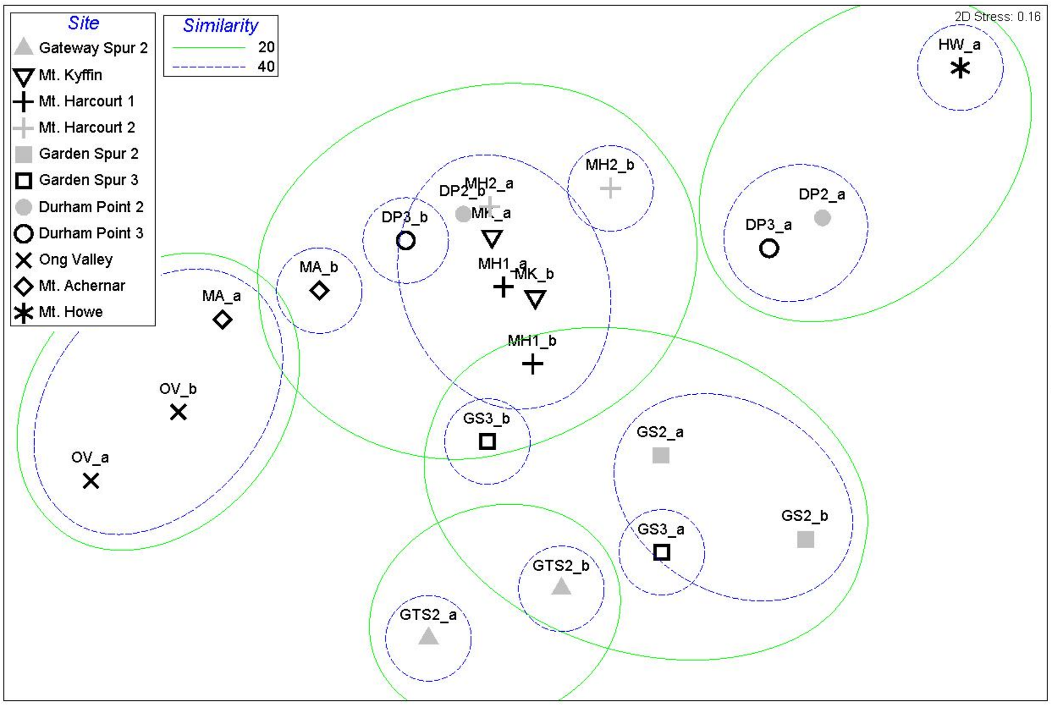

Figure 4.3: MDS plot of soil bacterial community ARISA profiles; calculated from a Bray-Curtis distance matrix of normalised ARISA (abundance) profiles.

4.4.4. 16S rRNA gene amplicon pyrosequencing

The number of sequences per site after denoising, ranged from 1372 to 5430, the exception being Durham Point, from which 10217 high quality reads were recovered (Table 4.2). In total, 2280 $OTUs_{0.03}$ were defined by the Jukes-Cantor average neighbour clustering method using a 0.03 dissimilarity cut-off. A large proportion of these $OTU_{0.03}$ were comprised of only one or two reads (Table 4.2). Mount Howe and Mount Achernar sites had the lowest proportion of these "rare $OTUs_{0.03}$", which does not correlate with total read number. Terminal slopes of rarefaction curves indicate that Mount Kyffin, Mount Harcourt, and Garden Spur communities may not have been sampled fully (Table 4.2), but adequate coverage was achieved for all other sites (slope ≤ 0.05).

Table 4.2: 454 pyrosequencing reads, and $OTU_{0.03}$ distribution, per site

Site	ID	Total reads	Total $OTUs_{0.03}$	1 read $OTUs_{0.03}$	2 read $OTUs_{0.03}$	% rare $OTUs_{0.03}$	Rarefaction terminal slope
Mt. Kyffin	MK_a	1372	293	192	43	80.2	0.16
Mt. Harcourt	MH1_a	3557	756	499	117	81.4	0.15
Garden Spur	GS3_b	2232	498	289	61	70.3	0.14
Durham Point	DP3_b	10217	526	311	82	74.7	0.03
Ong Valley	OV_a	1355	100	55	18	73.0	0.05
Mt. Achernar	MA_a	1750	144	71	29	69.4	0.05
Mt. Howe	HW_a	3115	205	48	35	40.5	0.02
Mt. Howe	HW_b	5340	148	55	25	54.1	0.01

Phylum level (RDP assignment, >75% confidence) diversity varies considerably between sites (ANOSIM: R = 0.625, p = 0.11), although there are some general trends (Figure 4.4). Both samples from Mount Howe are dominated by *Proteobacteria* (> 70%), while these make up less than 10% of any other community. Ong Valley had the only significant *Deinococcus-Thermus* representation (20.6%; all other sites < 1%). All other sites, including Mount Achernar, were dominated by an *Acidobacteria/Actinobacteria/Bacteriodetes* assemblage (> 10% of each phyla), although the relative proportions vary considerably, Acidobacteria were conspicuously underrepresented in the Ong Valley site. Over 10% of coastal site libraries, except for Durham Point, were unclassified to the Phylum level at 75% confidence level; plateau sites had a lower proportion of unclassified reads (Figure 4.4). Less than 10% of each Mount Howe library was identified as potential human-associated contamination, with many of these $\mathrm{OTUs}_{0.03}$ also being represented by environmental entries in the NCBI databases, less than 1% of all other samples were similarly identified (supplementary table S2).

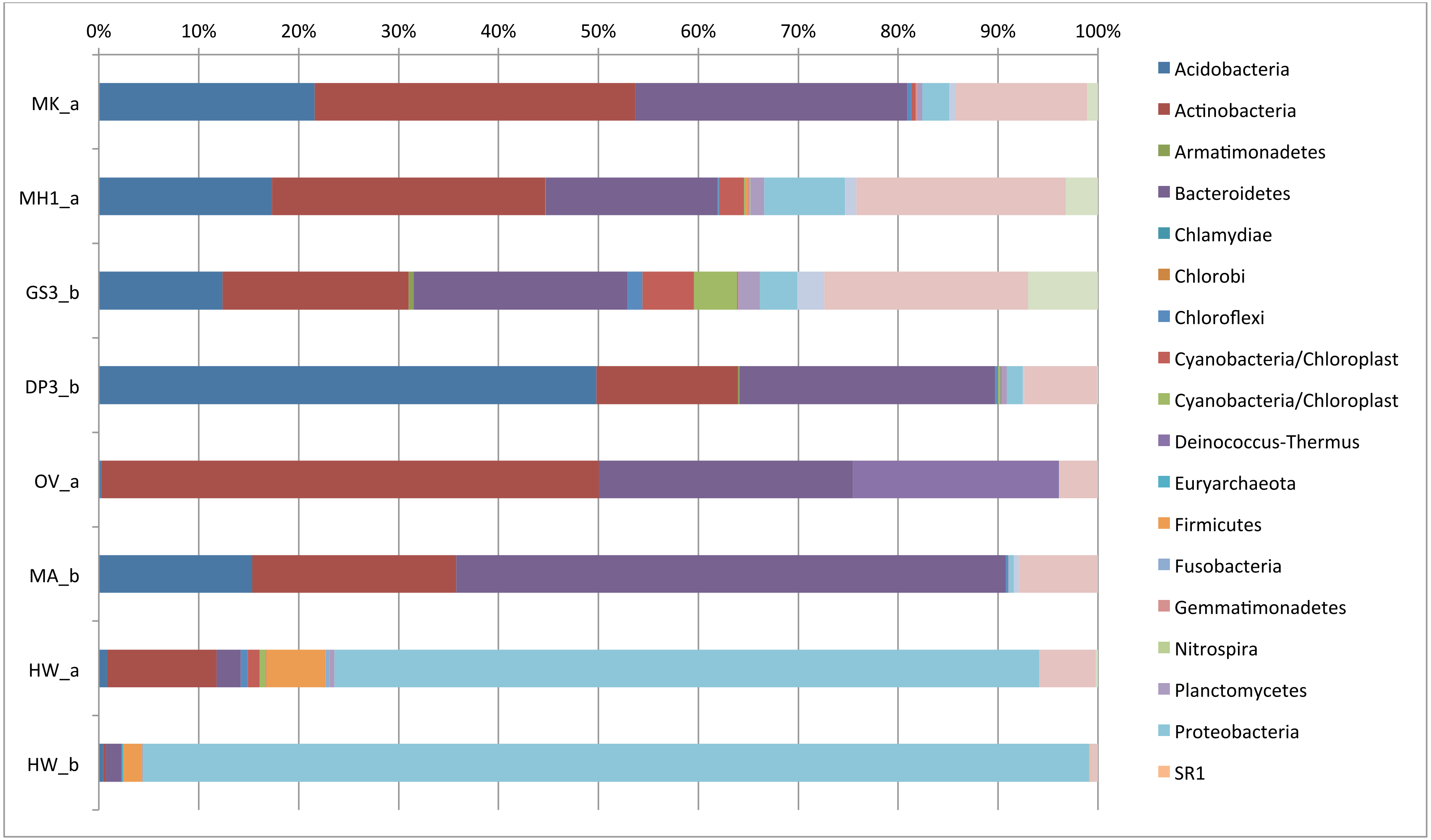

Figure 4.4: Phylum level distribution of bacterial $\text{OTUs}_{0.03}$, based on > 75% confidence assignments from the RDP Classifier.

No $\mathrm{OTU}_{0.03}$ was present in all samples, however shared $\mathrm{OTUs}_{0.03}$ within the two defined groups of sites (plateau and coastal) indicate a higher degree of cosmopolitanism within coastal communities (Figure 4.5). Excluding Mount Howe, each site shared one of its 'top four' $\mathrm{OTUs}_{0.03}$ with one other site (Table 4.3). Over 12% of each coastal site was comprised of the 15 shared $\mathrm{OTUs}_{0.03}$ (supplementary Figure S1), and none of the 15 $\mathrm{OTUs}_{0.03}$ found in all coastal sites were found in the MDV aerosols. The two Mount Howe samples were very similar, with 52 shared $\mathrm{OTUs}_{0.03}$ (Figure 4.5) representing 76% and 94% of HW_a and HW_b respectively (supplementary Table S1).

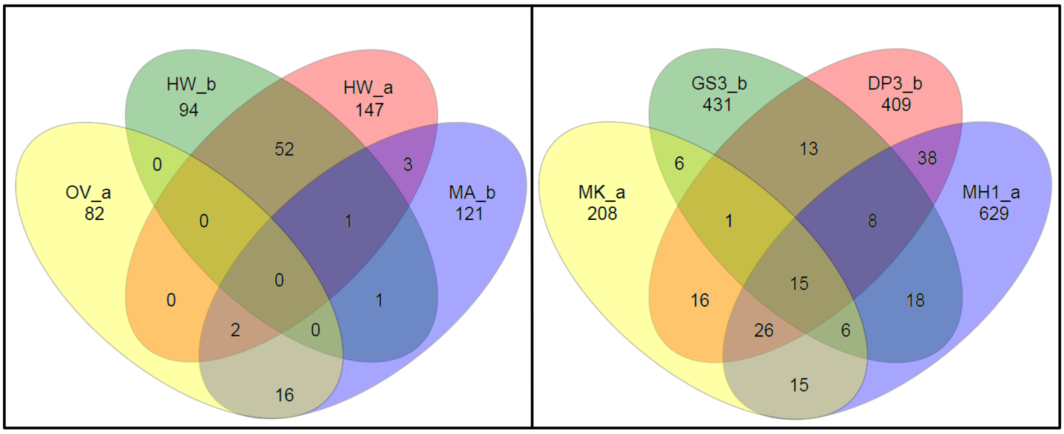

Figure 4.5: Venn diagrams of shared bacterial $\mathrm{OTU}_{0.03}$, between 'plateau sites' (left), and 'coastal sites' (right).

Table 4.3: RDP taxonomy (>80% confidence) of the four most abundant OTUs$_{0.03}$ per site, and their presence in other site libraries. OTUs$_{0.03}$ in bold dominant at more than one site. *Phylum level at 100% confidence unless in brackets.

	OTU$_{0.03}$ number	Proportion of community OTU$_{0.03}$								Phylum*	RDP taxonomy (27/6/2013)	Taxonomic level	Confidence
		MK_a	MH1_a	GS3_b	DP3_b	OV_a	MA_b	HW_a	HW_b				
Mt. Kyffin	29	15.0%	0.3%	-	-	-	-	-	-	Actinobacteria (93)	Rubrobacteridae	Subclass	83%
	14	**10.9%**	**12.1%**	**-**	**1.5%**	**0.3%**	**1.2%**	**-**	**-**	**Bacteroidetes**	**Chitinophagaceae**	**Family**	**100%**
	10	8.0%	3.5%	2.7%	10.9%	-	6.1%	0.1%	-	Acidobacteria (98)	Gp4	Order	98%
	7	7.3%	0.4%	4.2%	15.1%	-	2.5%	-	-	Bacteroidetes	Chitinophagaceae	Family	100%
Mt. Harcourt	**14**	**10.9%**	**12.1%**	**-**	**1.6%**	**0.3%**	**-**	**1.2%**	**-**	**Bacteroidetes**	**Chitinophagaceae**	**Family**	**100%**
	27	0.4%	6.8%	-	0.1%	-	-	-	-	Proteobacteria(36)	Alphaproteobacteria	Class	18%
	15	0.7%	6.2%	-	3.3%	-	0.1%	2.1%	-	Actinobacteria	Solirubrobacterales	Family	100%
	45	-	3.6%	0.3%	-	-	-	-	-	Acidobacteria	Gp4	Order	100%
Garden Spur	56	-	-	4.6%	-	-	-	-	-	Crenarchaeota(89)	Thermoprotei	Class	89%
	7	**7.3%**	**0.4%**	**4.2%**	**15.1%**	**-**	**2.5%**	**-**	**-**	**Bacteroidetes**	**Chitinophagaceae**	**Family**	**100%**
	57	-	0.2%	4.2%	-	-	-	-	-	Bacteroidetes	Ferruginibacter	Genus	88%
	67	-	-	3.4%	-	-	-	-	-	Actinobacteria(84)	Actinobacteria	Class	84%
Durham Point	5	0.2%	0.7%	-	24.1%	0.2%	8.2%	0.3%	-	Acidobacteria(97)	Gp4	Order	97%
	7	**7.3%**	**0.4%**	**4.2%**	**15.1%**	**-**	**2.5%**	**-**	**-**	**Bacteroidetes**	**Chitinophagaceae**	**Family**	**100%**
	11	5.8%	1.2%	-	11.7%	-	0.3%	-	-	Acidobacteria(98)	Gp4	Order	96%
	10	8.0%	3.5%	2.7%	10.9%	-	6.1%	0.1%	-	Acidobacteria(98)	Gp4	Order	98%
Ong Valley	23	0.1%	0.1%	-	0.4%	29.3%	0.1%	-	-	Actinobacteria(99)	Rubrobacterineae	Genus	98%
	28	-	-	-	-	17.5%	0.1%	-	-	Deinococcus-Thermus(99)	Truepera	Genus	99%
	30	-	-	-	-	14.8%	0.9%	-	-	Bacteroidetes	Chitinophagaceae	Family	100%
	25	**-**	**0.3%**	**-**	**0.2%**	**12.1%**	**8.6%**	**-**	**-**	**Actinobacteria**	**Actinomycetales**	**Family**	**97%**
Mt. Achernar	12	0.1%	0.01%	-	3.5%	0.2%	42.8%	-	-	Bacteroidetes	Segetibacter	Genus	76%
	25	**-**	**0.3%**	**-**	**0.2%**	**12.1%**	**8.6%**	**-**	**-**	**Actinobacteria**	**Actinomycetales**	**Family**	**97%**
	5	0.2%	0.7%	-	24.1%	0.2%	8.2%	0.3%	-	Acidobacteria(97)	Gp4	Order	97%
	10	8.0%	3.5%	2.7%	10.9%	-	6.1%	0.1%	-	Acidobacteria(98)	Gp4	Order	98%
Mt. Howe	9	-	-	-	-	-	-	13.6%	21.8%	Proteobacteria	Acetobacteraceae	Family	100%
	8	-	-	-	-	-	-	12.3%	24.8%	Proteobacteria	Xanthomonadaceae	Family	100%
	13	-	-	-	-	-	-	7.2%	10.5%	Proteobacteria	Moraxellaceae	Family	100%
	16	-	-	-	-	-	-	6.8%	6.8%	Proteobacteria	Pseudomonadaceae	Family	89%
	19	-	-	-	-	-	-	3.0%	8.3%	Proteobacteria	Burkholderiaceae	Family	100%

A comparison to soil bacterial community in Miers Valley (Tiao *et al.*, 2012) revealed a considerable amount of similarity, with at least 15% of each site library, excluding Mount Howe, represented in the Miers Valley library at an abundance > 0.1% (cutoff defined due to difference in sequencing depth of an order of magnitude; supplementary table S3). The shared OTUs$_{0.03}$ represent at least 9% of the Miers Valley control library (Supplementary Table S3). The similarity patterns differ from site to site, 7 OTUs$_{0.03}$ represent 11% and 45% of Miers Valley and Ong Valley respectively, while 38 OTUs$_{0.03}$ represent 43% and 20% of the Miers Valley and Mount Harcourt communities. Less than 2% of the Mount Howe libraries are shared with Miers Valley, however up to 10% of the Miers Valley community may be present (in low abundance) at Mount Howe (Supplementary Table S3).

Over 25% of OTUs$_{0.03}$ in Mount Howe samples were shared with aerosol samples from the Miers Valley (Bottos *et al.,* 2013). More of the Mount Howe OTUs$_{0.03}$ were shared with the Miers Valley aerosol samples than with any of the other samples in this current study (Figure 4.5, Table 4.4, Supplementary Table S4); Mount Howe communities consistently cluster (Supplementary Figure S2) with the aerosol samples rather than any other soil communities.

Table 4.4: Number of OTUs$_{0.03}$ shared with aerial samples (Bottos *et al.,* 2013), per site.

Site	MK_a	MH1_a	GS3_b	DP3_b	OV_a	MA_b	HW_a	HW_b
Shared OTUs	2	2	0	2	1	2	41	25
% of library	0.2	2.8	0	0.4	0.2	3.3	38.6	25.8

4.4.5. Biogeochemical analyses

Biota-Environmental STepwise (BEST) analysis was used to link bacterial ARISA profiles to geochemical profiles (ICP-MS data limited to Na, Mg, P, S, K, Ca, Fe and Cu). A global BEST search, run for 999 permutations, returned a ρ value of 0.535 ($p = 0.001$), with altitude, pH, conductivity and Cu being indicated as the significant variables. Inclusion of sulfur to these variables yielded a significant ρ of 0.530.

BEST analyses of geochemistry versus 'all $\mathrm{OTUs}_{0.03}$', 'abundant $\mathrm{OTUs}_{0.03}$' (> 1% abundance in any sample),and 'rare $\mathrm{OTUs}_{0.03}$' (< 0.1% in any sample) consistently returned significant ($p < 0.05$) and strong ($\rho > 0.8$) correlations between abiotic factors and $\mathrm{OTU}_{0.03}$ abundance. These correlations remained strong despite the removal of co-varying abiotic variables and Mount Howe (treated as an outlier) from the analyses. No significant correlations with distance (between sites) with any of the above OTU classes were identified

4.5. Discussion

Molecular investigations of CTAM soil communities reveal several interesting phenomena which have not been observed in other regions of Antarctica. However, fundamental relationships between community structure and abiotic variables appear to resemble those established in the MDV. Soil bacterial communities at several sites throughout the Beardmore Glacier region of the Transantarctic Mountains, over 600 km south of the McMurdo Dry Valleys, are significantly distinct from each other, as shown by ARISA DNA fingerprinting analyses and comprehensive pyrosequencing on replicate soil samples. (Figure 4.4). Lee *et al.* (2012) found phylum level structure to be relatively invariable between 4 sites in the McMurdo Dry Valleys, with all sites being heavily dominated (> 60%) by members of the *Actinobacteria*. Bacterial community structure throughout the CTAM region is much more variable at the phylum level. The *Actinobacteria* appear far less dominant (< 33 % at any one site, excluding Ong Valley) in the CTAM communities than in the MDV. Although there were considerable differences in the sequencing strategy used in each of these studies (different regions of 16S rRNA gene targeted, and sequencing depth/coverage over an order of magnitude different), the predominance of *Actinobacteria* in the MDVs is well supported by several other studies (Aislabie *et al.*, 2006; Zeglin *et al.*, 2011; Tiao *et al.,* 2012), and a recent meta-analysis of 16S rRNA gene sequences reported from across the Antarctic continent reveals the MDV region to be more *Actinobacteria* dominated than any other region (Bottos *et al.*, In Press). The relative proportions/dominance of phyla differ from region to region within Antarctica, the MDV appearing to be anomalous in the magnitude of *Actinobacteria* dominance (Bottos *et al.*, In Press), a higher

Bacteroidetes/Actinobacteria ratio is observed in the Darwin Mountains (Aislabie *et al*., 2013).

This fundamental difference in community dominance maybe due to the environmental conditions, or the glacial history, of the particular sites. The variation in community composition correlates well with the unique physiochemical profiles of each site. Such inter-site variability, seemingly linked to local abiotic factors, has previously been reported in the MDVs (Lee *et al.*, 2012). The geochemical factors most explanatory of community variation were similar in both studies, with altitude, conductivity and copper concentration being the most prominent drivers. pH was also found to be important, this was not the case in the MDV study (Lee *et al.,* 2012), but has been consistently recognised as an important determinant of microbial distributions in other soil habitats (Fierer & Jackson, 2006; Wu *et al.,* 2009). Conductivity and pH can both be influenced by atmospheric deposition of salts (Claridge & Campbell, 1977). Salts deposited atmospherically (i.e.- in snow) accumulate over time as leaching cannot occur in the absence of liquid water. The predominance of sulfates and nitrates, over chlorides, in the salts of soils distant from the coast can lead to more acidic soil conditions (Claridge & Campbell, 1977); interestingly, sulfate was also implicated in the BEST analyses as an important (if less so than those above) geochemical variable.

While all geochemical variables implicated in structuring bacterial community structures above (excepting copper) are linked to atmospheric processes, the influence of time is probably equally as important as local climate in shaping these soils. Historic ice level fluctations vary markedly along the length of the Beardmore Glacier (and other outlet glaciers). During global glaciations, grounding of the Ross Ice Shelf caused ice levels up to 1000 m higher than present levels near Mount Kyffin , while fluctations of < 100 m occurred near the plateau (Denton *et al*., 1989). The higher altitude sites, proximal to the polar plateau, have probably been exposed to the atmosphere (not buried by ice) over a much longer timeframe, allowing the considerable build up of salts. Thus the coastal and plateau sites possibly represent communities of very different ages. Significant differences in bacterial communities (including decreasing diversity) have been linked to deglaciation sequences in several locations (Svalbard -

Kastovska *et al*., 2005; Darwin Mountains - Magalhaes *et al*., 2012; Aislabie *et al*., 2013; Larsemann Hills, East Antarctica - Bajerski & Wagner, 2013), with salt content generally associated with this. In the current study, the plateau sites have considerably less OTUs$_{0.03}$ than the coastal sites (approximately < 200 cf > 300), and it is less likely that our sequencing efforts captured the full diversity of three coastal sites (as indicated by rarefaction analyses; Table 4.2). Of the four sites examined by Lee *et al.* (2012) the saltiest sites (i.e. – oldest sites; > 3000 μS/m c.f. < 400 μS/m), Beacon Valley and Upper Wright Valley, contained the lower diversity communities (less than half the OTUs of the less salty sites).

The distinct structural divide between plateau and coastal site communities is supported by both the ARISA fingerprinting (Figure 4.3) and 16S rRNA gene sequencing. In general, with the exception of Mt Howe, plateau sites appear more typical of MDV soil habitats, rather than the highly productive "hotspots" that harbour significant invertebrate populations. Generally, with the exception of Mt. Howe, the plateau sites are less diverse and less even than coastal sites (Supplementary Table S6). Ong Valley was the saltiest of the sites sampled (~ 4200 μS/m, Table 4.1), but was not outside the conductivity range encountered in the MDVs (100-6000 in the sites examined by Lee *et al.,* 2012), it is also the most *Actinobacteria* rich community surveyed (Figure 4.4). Ong Valley was also the only site containing a significant (20.6%) *Deinococcus-Thermus* representation (a common member prevalent in MDV dry soils; Cary *et al.,* 2010), with one OTU$_{0.03}$ comprising 17.5% of the entire Ong Valley community (OTU$_{0.03}$ 28; Table 4.3), with a 100% RDP assignment to the *Truepera* genus. The most similar sequence to this OTU$_{0.03}$ in the NCBI database was *Truepera radiovictrix* (strain DSM 17093; 94% identity), a thermophilic, halophilic, radiation resistant bacterium isolated from hot spring runoffs in the Azores (Alberquerque *et al.,* 2005; Lucas *et al.,* 2013). These qualities could explain the prevalence of this OTU$_{0.03}$ in Ong Valley (Table 4.1), in less salty soils the halophilic capabilities may be less of an advantage. The difficulties imposed by higher salt contents are likely drivers of lower diversity and unevenness of the plateau sites. The four most dominant OTUs$_{0.03}$ at Ong Valley represented > 75% of the community, while no OTU$_{0.03}$ made up more than 25% of any coastal site or Mount Howe library. Mount Achernar exhibited the most skewed community, dominated by one $OTU_{0.03}$ (42.8% of library), classified by the RDP as belonging to the *Segetibacter* genus (76% confidence). The most similar sequence to this $OTU_{0.03}$ in the NCBI database was *Segetibacter aerophilus* (98% identity; Weon *et al.,* 2010), a novel *Bacteroidetes* isolated from air samples in Korea. The low diversity and relative unevenness of these high altitude sites is likely due to the soil properties (especially salt contents) resultant from the harsher plateau climate, and the glacial history/relative age of the sites (e.g. - Magalhaes *et al*., 2012; Aislabie *et al*., 2013).

The four 'coastal CTAM sites' were targeted specifically as known locations for lichens, as such they are possibly more representative of known high productivity 'biodiversity hotspots' patchily distributed throughout the MDVs. Lichens, nematodes, rotifers, tardigrades and mites were found at all four coastal sites, with springtails (Collembola) only absent from Durham Point (Green, Hogg, unpublished data). No macro-organisms or vegetation were found at Mount Howe. Generally, a certain level of productivity is required to support macro-organism populations; it is reasonable to assume this productivity will support different microbial populations than less productive systems. The four highly productive sites share a considerable amount of microbial diversity. 15 $OTUs_{0.03}$ were common to all four sites, and these made up between 13% and 31% of sequences at each site; these common $OTUs_{0.03}$ are mostly absent from the plateau sites (Supplementary Figure S1). This level of commonality may be due to the environmental factors sustaining productivity of the habitat, although a more direct link may be postulated. The most dominant $OTU_{0.03}$ of this shared group, 'OTU 7' (supplementary table S5), was classified (100%, RDP) as a member of the *Chitinophagaceae*, a genus defined by their ability to metabolise chitin. Similarly, 'OTU 14' (Table 4.3), a shared dominant member of the Mount Kyffin and Mount Harcourt sites was also classified (100% *Chitinophagaceae*), as was another $OTU_{0.03}$ common to all four coastal sites. The possibility of a sub-community of microbes, consistently associated with localised invertebrate populations, and perhaps sustained by invertebrate-derived chitinous debris (for example) is interesting. Burn (1981) demonstrated that one Antarctic collembola species, *Cryptopygus Antarcticus,* may moult every 22-36 days depending on temperature. Where such invertebrates are concentrated, a considerable amount of organic matter may be introduced to the soil and thereby sustain certain microbial populations. However it is generally accepted that biotic (and inter-trophic) interactions are generally unimportant to Antarctic soil microbiota (Hogg *et al.,* 2006; Cary *et al*., 2010), and any such contribution from invertebrate presence may only be one factor influencing the observed similarities between these sites.

Glacially deposited debris, at the foot of Mount Howe, constitutes the southernmost soil on the planet (Cameron *et al.*, 1971), approximately 300 km from the geographic South Pole. At an altitude of ~ 2800 m the climatic conditions are considered some of the most extreme on the continent. Cameron et al. (1971) reported maximum air and soil surface temperatures of -11 °C and -4 °C respectively during the austral summer between 30th December 1970 and 4th January 1971. The extreme incident UV during 24-hour daylight in summer, and lack of liquid water (as exhibited by salt concentrations within the soils; Claridge & Campbell, 1977) are also prohibitive to life in this environment. Extremely low biomass in Mount Howe soils (< 25 microorganisms per gram of soil) reported by Cameron *et al.* (1971) supports our inability to count cells, and explains the extremely low average DNA yield of 0.2 ng per gram of soil from Mount Howe samples.

Here we report the diversity of the bacterial community in the southern-most soil on the planet using molecular genetic approaches. Previous investigations at Mount Howe, using culture-dependent methods, reported *Arthrobacter* sp. and *Corynebacterium* sp., as well as some yeasts (Cameron *et al.,* 1971). In this study five $\text{OTUs}_{0.03}$ from Mount Howe were resolved as *Corynebacteriaceae* (at > 75% confidence by the RDP classifier), no *Arthrobacter* sequences were identified. The community is heavily dominated (70-95%) by members of the *Proteobacteria*, which normally form a small proportion of the bacterial community in similar soil habitats in the Antarctic. The proteobacterial portion of both Mount Howe samples are relatively similar (Supplementary Figure S3), averaging 49% *Gammaproteobacteria*, 30% *Alphaproteobacteria,* and 19% *Betaproteobacteria.* The dominant $\text{OTU}_{0.03}$ at Mount Howe (24.8% in HW_b, 12.3% in HW_b; Table 4.3) shares 99% sequence identity with organisms from a variety of habitats, including South African plant nectar (Alvarez-Perez *et al.*, 2012), and soils (Spain -Caliz *et al.,* 2011; Costa Rica – Pittl *et al.*, 2010). Other dominant proteobacterial sequences from Mount Howe are likewise represented in a variety of global habitats. The low abundance of sequences assigned to the Bacilli (< 6%) and Clostridia (< 1%) classes suggests a lack of spore-forming bacteria in Mount Howe soil. No Mount Howe sequences were assigned to the *Deinococcus-Thermus* phylum, which is interesting given that *Deinococcus* sequences dominated snow samples at the South Pole (Carpenter *et al*., 2000). The dominance of proteobacterial sequences, which are globally distributed yet conspicuously lacking in most Antarctic soils, combined with the relative lack of taxa tolerant of extreme conditions, may suggest no colonisation/survival advantage is conferred by different physiologies at Mount Howe. Mount Howe may represent a soil habitat unable to support bacterial life (likely due to extreme climatic conditions rather than soil properties). A significant component of the recovered DNA may simply represent the low frequency deposition of aerially transported bacterial cells, continually preserved under the local extreme conditions (constant low temperatures and low humidity). Over 25% of Mount Howe $\text{OTUs}_{0.03}$ were also present in air samples in the Miers Valley (Bottos *et al.,* 2013), less than 4% of sequences at any other CTAM site were shared with the air samples. It is interesting to consider long-distance aerial transport of organisms across the continent; perhaps the deposition of such organisms is masked in most instances by a more dominant local community, and it is only where local conditions cannot support edaphic communities that this aerial signal becomes detectable in the soil. All other sites in this study appear able to sustain a local bacterial community, which in some way resembles communities found elsewhere throughout Antarctica. The higher biomass of these soils compared to those of Mount Howe would effectively dilute signatures from aerially deposited microbes to undetectable levels. Although over 60% of each Mount Howe library had no identity to MDV aerosol samples, this in no way precludes their potential atmospheric deposition. The MDV samples were taken at one location > 600 km away, over the course of one summer season. As atmospheric depositon has happened over many thousands of years, as necessary for the accumulation of salts (Table 4.1), the ‘time point’ sampling of Bottos *et al.* (2013) cannot represent the totality of bacteria present in the air over Antarctica. Thus, it is not inconceivable for the vast majority of sequences obtained from Mount Howe soils to also be present in the overlying air mass at some point in time.

Long distance broadcast dispersal (from the MDVs) has been proposed as a mechanism for maintaining the southernmost population of the nematode *Scottnema lindsayae* at the mouth of the Beardmore Glacier (Adams *et al.,* 2007), thus transport and survival of viable organisms over such distances is not inconceivable. Survival and viability are not prerequisites for the recovery of DNA, especially at the low levels reported here. Surveys of aerial microbial populations on the Polar Plateau (rather than the snowpack; Carpenter *et al*., 2000), and perhaps at higher altitudes, may give insight into such dispersal.

With such a low biomass/DNA content in Mount Howe soils, the issue of contamination must be addressed. Stringent checks of extraction negative controls confirmed contamination in-lab to be negligible – no DNA was detected in negatives via both quantification (Qubit 2.0 Fluorometer; Life Technologies Corporation, Carlsbad, CA, USA) and gel electrophoresis following PCR amplification. All practicable precautions were also taken to avoid the introduction of foreign cells/DNA at time of sampling. Less than 10% of each Mount Howe sample had significant identity to bacterial 16S rRNA gene sequences acquired from the Human Microbiome Project, supporting the claim that the majority of the diversity seen in the Mount Howe community is environmental, and not introduced at time of collection.

4.6. Conclusions

Bacterial communities throughout the Central Transantarctic Mountains are spatially distinct, as they are in the McMurdo Dry Valleys over 600 km to the north, although phylum level diversity is more variable in the CTAM region. Community structure variation correlates with local geochemistry, particularly those variables related to atmospheric salt deposition. Soil habitats on the Plateau side of the mountains can be recognised as distinct from coastal habitats, both geochemically and biologically. Mount Howe represents a totally distinct soil habitat, with an extremely low biomass; local climatic conditions limit edaphic bacterial life, and potentially inflate the relative importance of aerially deposited cells.

4.7. References

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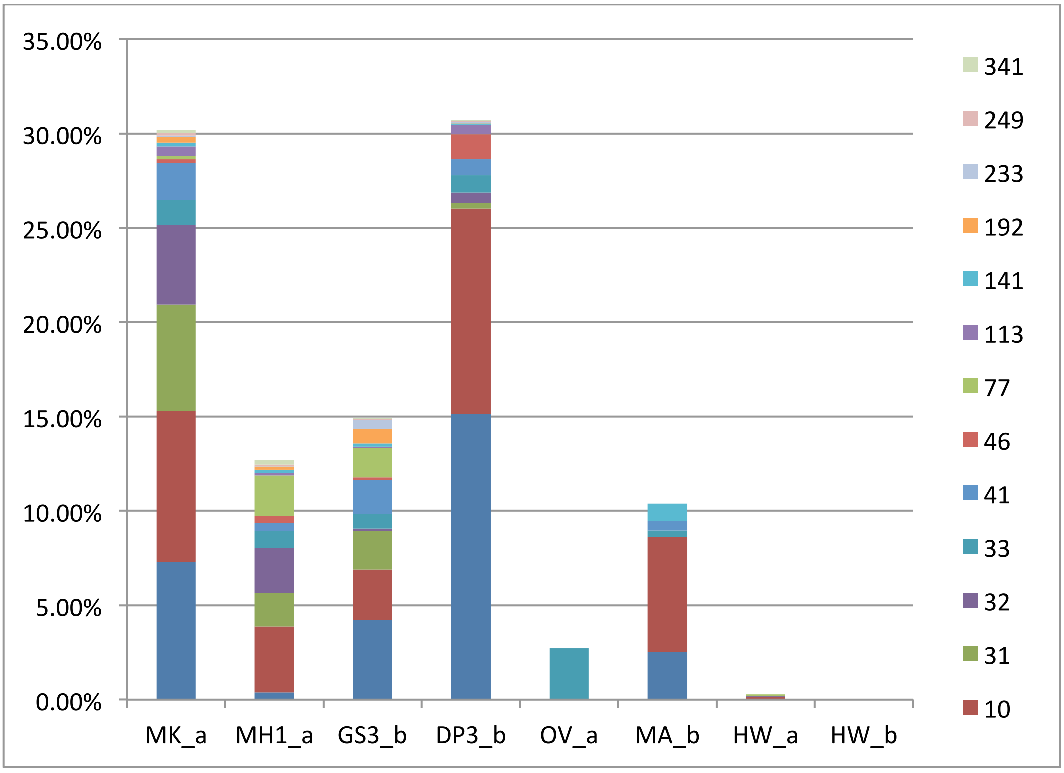
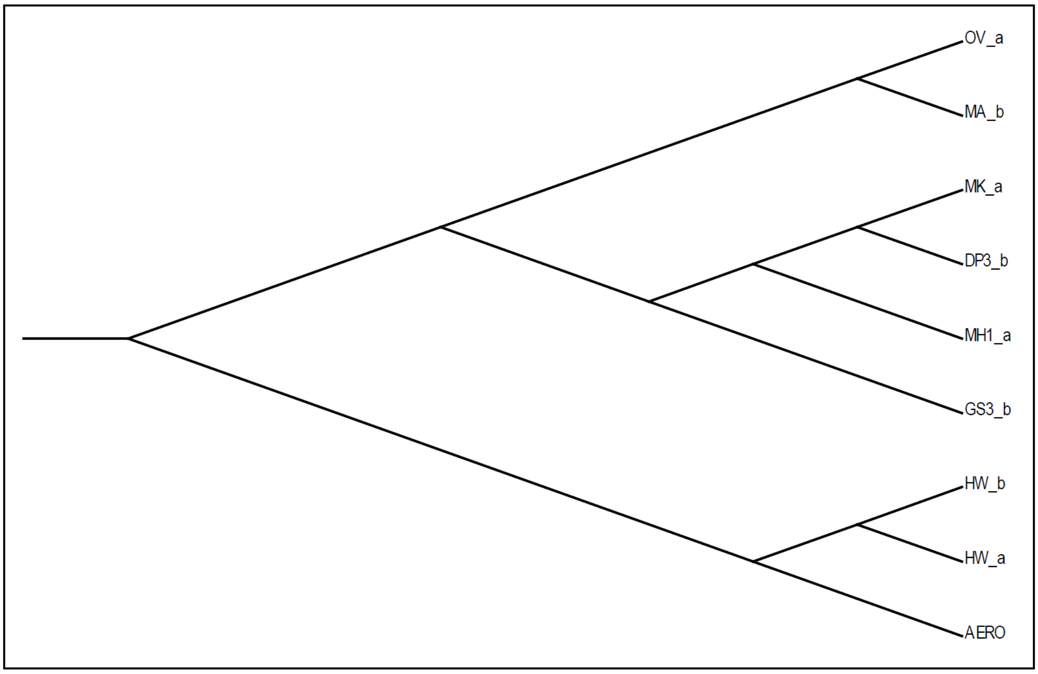
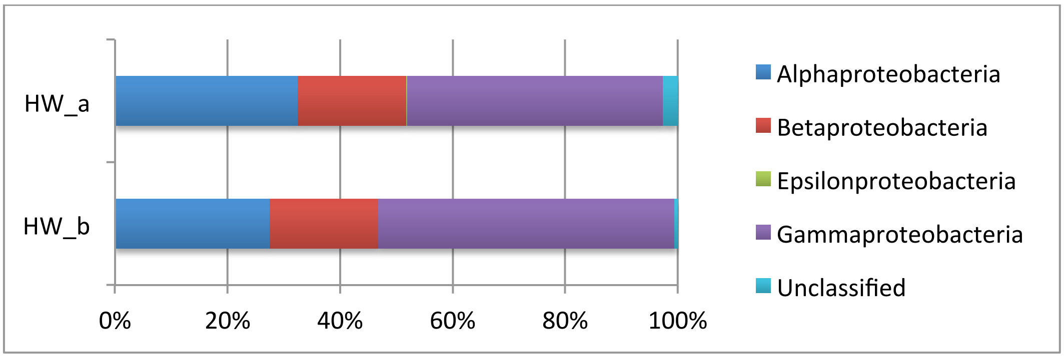
4.8. Supplementary material



Supplementary Figure S1: Abundance of the 15 OTUs$_{0.03}$ common to all coastal sites.



Supplementary Figure S2: Jaccard index tree of community dissimilarity based on OTU$_{0.03}$ abundance.



Supplementary Figure S3: Proteobacteria classes in Mount Howe soil samples. Percentages represent proportion of total Proteobacteria, not of total library.

Supplementary Table S1: OTUs$_{0.03}$ shared between both Mount Howe samples.

OTU$_{0.03}$ number	Percentage of site library								
	MK_a	MH1_a	GS3_b	DP3_b	OV_a	MA_b	HW_a	HW_b	AERO
8	-	-	-	-	-	-	12.33%	24.78%	-
9	-	-	-	-	-	-	13.58%	21.82%	-
10	8.02%	3.49%	2.69%	10.90%	-	6.11%	0.13%	0.04%	-
13	-	-	-	-	-	-	7.19%	10.45%	0.27%
16	-	-	-	-	-	-	6.77%	6.78%	0.06%
19	-	-	-	-	-	-	3.02%	8.30%	-
20	-	-	-	-	-	-	4.56%	0.04%	1.43%
22	-	-	-	-	-	-	3.56%	5.62%	0.21%
24	-	-	-	-	-	-	2.86%	5.36%	-
26	-	-	-	-	-	-	1.96%	1.01%	0.83%
35	-	0.08%	0.13%	1.78%	-	-	0.03%	0.04%	-
37	-	-	-	-	-	-	0.06%	0.06%	0.72%
40	-	-	-	-	-	-	3.47%	0.22%	0.15%
52	-	-	-	-	-	-	0.03%	0.21%	0.41%
55	-	-	-	-	-	-	0.19%	0.04%	0.40%
60	-	-	-	-	-	-	0.10%	1.61%	-
62	-	-	-	-	-	-	1.03%	0.11%	0.21%
68	-	-	-	-	-	-	1.00%	0.81%	-
72	-	-	-	-	-	-	1.48%	0.06%	0.09%
73	0.07%	-	-	-	-	-	2.18%	0.02%	-
83	-	-	-	-	-	-	0.58%	0.75%	-
85	-	-	-	-	-	-	1.44%	0.04%	0.05%
87	-	-	-	-	-	-	0.71%	0.67%	-
95	-	-	-	-	-	-	0.51%	0.58%	-
99	-	-	-	-	-	-	0.06%	0.02%	0.18%
102	-	-	-	-	-	-	0.22%	0.67%	-
111	-	-	-	-	-	-	0.03%	0.67%	-
114	-	-	-	-	-	-	0.13%	0.58%	-
116	-	-	-	-	-	-	0.67%	0.26%	-
130	-	-	-	-	-	-	0.06%	0.04%	0.11%
134	-	-	-	-	-	-	0.83%	0.06%	-
139	-	-	-	-	-	-	0.35%	0.21%	0.03%
144	-	-	-	-	-	-	0.61%	0.15%	-
146	-	-	-	-	-	-	0.19%	0.37%	-
150	-	-	-	-	-	-	0.42%	0.22%	-
151	-	-	-	-	-	-	0.06%	0.43%	-
155	-	-	-	-	-	-	0.13%	0.37%	-
157	-	-	-	-	-	-	0.32%	0.09%	0.04%
158	-	-	-	-	-	-	0.16%	0.02%	0.07%
166	-	-	-	-	-	-	0.55%	0.02%	0.02%
176	-	-	-	-	-	-	0.61%	0.02%	-
187	-	-	-	-	-	-	0.06%	0.02%	0.07%
204	-	-	-	-	-	-	0.06%	0.06%	0.05%
223	-	-	-	-	-	-	0.42%	0.02%	-
226	-	-	-	-	-	-	0.32%	0.07%	-
299	-	-	-	-	-	-	0.22%	0.02%	0.00%
316	-	-	-	-	-	-	0.03%	0.15%	-
415	-	-	-	-	-	-	0.06%	0.07%	-
425	-	-	-	-	-	-	0.16%	0.02%	-
440	-	-	-	-	-	-	0.06%	0.06%	-
442	-	-	-	-	-	-	0.13%	0.02%	-
581	-	-	-	-	-	-	0.06%	0.04%	-
702	-	-	-	-	-	-	0.06%	0.02%	-
Total	8.09%	3.57%	2.82%	12.68%	0.00%	6.11%	75.86%	94.16%	5.41%

Supplementary Table S2: Number of OTUs$_{0.03}$ considered as potential human-associated contamination; > 97% sequence identity and > 200 bp alignment length with HMP 16S rRNA gene database.

Site	MK_a	MH1_a	GS3_b	DP3_b	OV_a	MA_b	HW_a	HW_b
# of OTU	2	2	1	2	0	0	23	13
% of library	0.2	0.6	0.2	<0.1	0	0	9.2	7.4

Supplementary Table S3: Number of OTUs$_{0.03}$ shared with Miers Valley sample (Tiao *et al.,* 2012) per site. Only OTUs$_{0.03}$ with an abundance greater than 0.1% in the Miers Valley library were considered due to differences in sequencing depth. Relative library proportions for shared OTUs$_{0.03}$ are presented.

Site	**MK_a**	**MH1_a**	**GS3_b**	**DP3_b**	**OV_a**	**MA_b**	**HW_a**	**HW_b**
# OTU	23	38	20	27	7	15	11	5
% of miers	23.4	42.6	9.1	26.1	11.1	13.6	10.5	3.0
% of library	36.6	20.3	15.3	32.9	45.3	20.0	1.9	0.8

Supplementary Table S4: OTUs$_{0.03}$ shared with MDV aerial samples (Bottos *et al,*, 2013)

OTU$_{0.03}$ number	**Percentage of site library**								
	MK_a	**MH1_a**	**GS3_b**	**DP3_b**	**OV_a**	**MA_b**	**HW_a**	**HW_b**	**AERO**
13							7.2	10.5	0.3
16							6.8	6.8	0.06
20							4.6	0.04	1.4
22							3.6	5.6	0.2
26							2	1	0.8
34		2.6		0.4	0.2	3.2			0.03
37							0.06	0.06	0.7
40							3.5	0.2	0.2
47							0.8		0.4
49								0.2	0.5
52							0.03	0.2	0.4
55							0.2	0.04	0.4
61							0.7		0.3
62							1	0.1	0.2
71							1		0.2
72							1.5	0.06	0.1
82							0.13		0.2
85							1.4	0.04	0.05
99							0.06	0.02	0.2
130							0.06	0.04	0.1
135								0.4	0.04
138	0.15			0.03					0.07
139							0.4	0.2	0.03
149		0.2					0.4		0.05
157							0.3	0.1	0.04
158							0.2	0.02	0.07
159									0.02
166							0.6	0.02	0.02
167							0.2		0.06
175							0.5		0.02
178							0.2		0.06
184							0.06		0.07
187							0.06	0.02	0.07
194							0.1		0.06
198								0.04	0.06
204							0.06	0.06	0.05
212							0.1		0.05
251							0.03		0.05
268							0.3		0.01
289									0.04
299							0.2	0.02	<0.01
399								0.04	0.02
469							0.06		0.01
482							0.03		0.02
529							0.03		0.01
542							0.06		0.01
613							0.06		<0.01
680	0.07					0.06			<0.01
Total %	0.22	2.8	0	0.43	0.2	3.26	38.59	25.82	7.75

Supplementary Table S5: 15 OTUs$_{0.03}$ shared between all coastal sites; RDP classification and confidence included.

OTU$_{0.03}$ number	Phylum		Class		Order	
7	Bacteroidetes	100%	Sphingobacteria	100%	Sphingobacteriales	100%
10	Acidobacteria	98%	Acidobacteria_Gp4	98%	Gp4	98%
31	Acidobacteria	100%	Acidobacteria_Gp4	100%	Gp4	100%
32	Actinobacteria	100%	Actinobacteria	100%	Rubrobacteridae	100%
33	Actinobacteria	97%	Actinobacteria	97%	Rubrobacteridae	95%
36	Actinobacteria	100%	Actinobacteria	100%	Actinobacteridae	100%
41	Actinobacteria	100%	Actinobacteria	100%	Actinobacteridae	100%
46	Verrucomicrobia	100%	Spartobacteria	79%	Spartobacteria_genera_incertae_sedis	79%
77	Bacteroidetes	100%	Sphingobacteria	100%	Sphingobacteriales	100%
113	Proteobacteria	54%	Deltaproteobacteria	44%	Syntrophobacterales	34%
141	Proteobacteria	29%	Deltaproteobacteria	16%	Syntrophobacterales	12%
192	Acidobacteria	81%	Acidobacteria_Gp4	81%	Gp4	81%
233	Chloroflexi	80%	Thermomicrobia	78%	Thermomicrobiales	77%
249	Actinobacteria	95%	Actinobacteria	95%	Rubrobacteridae	83%
341	Proteobacteria	55%	Deltaproteobacteria	42%	Syntrophobacterales	24%

Supplementary Table S6: Evenness and diversity indices for 454 sequencing of study sites

	MK_a	MH1_a	GS3_b	DP3_b	MA_b	OV_a	HW_a	HW_b
Pielou's evenness	0.70	0.74	0.83	0.51	0.54	0.53	0.72	0.52
Shannon's diversity	3.96	4.89	5.16	3.20	2.71	2.46	3.86	2.61

Chapter 5 - Further discussion, synthesis and conclusions

This chapter further discusses the linkages between the preceding manuscripts, and explores options for further microbial community investigations in the Central Transantarctic Mountains, and Antarctica in general.

5.1. Soil formation and development

5.1.1. Summary of finding

Soil development along the Plateau margin of the CTAM region apparently proceeds at a much slower rate than other regions of Antarctica. Soil properties, consistent with differing soil ages/development, were measured at a finer scale than previous work in the region. The soil variation observed is not captured by the Soil Taxonomy subgroups (USDA; Soil Survey Staff, 2010), commonly used to map Antarctic soils. A conceptual model of soil development at receding glacial margins in this region was developed, with supraglacial and englacial debris both contributing to the resultant soils.

5.1.2. Limitations of study

A major limitation of this investigation was the loss/misplacement of some samples in transit from Antarctica to the University of Waikato. This meant that only the surface soil samples from the Dominion Range site were able to be analysed, hence the lack of sub-surface data in Chapter 3. Inclusion of these analyses would benefit the robustness of our proposed two-mode model of soil development as described above.

The description and sampling of multiple soil pits/profiles at each location, providing replication for each mapped soil unit, would strengthen the findings of our soil-landscape study. However, due to time and logistical constraints, it was decided to attempt to cover the full soil-development sequence at each of three sites, rather than describe in detail the sequence at one site. The similarities in general soil property patterns across three disparate locations (Ong Valley, Mount Achernar, and Dominion Range) supports our generalised findings.

In order to fully characterise the soil-landscape relationships at each location of the study, investigations of soils on the hill slopes and ridges would be necessary. Due to the constraints in the field, it was decided to focus on the glacial deposits across the majority of the landscape, and thus gain a full understanding of soil development related to the historical deglaciation of the area.

Initially, the Dominion Range site was not one of our three targeted study sites; the Otway Massif (85°24.602'S; 171°20.471'E) was our preferred site, as this landscape has the potential to contain much older/more developed soils, and would allow a comparison to soils of the Roberts Massif in the Shackleton Glacier region (Claridge & Campbell, 1968). Unfortunately, camping at Otway Massif was deemed logistically untenable, thus a detailed multi-day survey of the soils therein was impossible. The Dominion Range site was chosen as a substitute; the Otway Massif was visited for about four hours however, and one soil profile described (appendix) and sampled (discussed below). Another site, Mount Kyffin (83°46.140’S; 171°55.605’E), was also visited in order to obtain a soil sample representative of the low altitude ‘coastal’ environment of the CTAM region. This sample (appendix), along with the Otway Massif sample, was excluded from the study in Chapter 3, as we focused on soil properties within the context of a development sequence; sole soil sites could not contribute to the discussion.

5.1.3. Future directions

A major feature of the soil development model proposed in Chapter 3 is the considerable contribution of material to the bottom of the soil profile from englacial debris via sublimation of sub-surface ice. In order to validate this mechanism, and allow some degree of time/accumulation calibration, the quantity and nature of englacial material underlying the soils (and also in the uncovered glacier) must be examined. The distribution of englacial debris is probably not homogenous throughout the glacier as observed by Fogwill *et al.* (2012) in the Heritage Range, West Antarctica. A transect along the soil chronosequence (as implemented in Chapter 3), but also extended some distance (≤ 1 km) out onto the uncovered ice, collecting a known volume of ice at defined intervals along the transect, would be ideal for examining this. Upon melting the ice samples, the leftover debris could be weighed and geochemically analysed (perhaps via ICP-MS; see Chapter 4) to obtain a quantity and a chemical fingerprint to link it to (or differentiate it from) the overlying soil. Sampling ice at multiple depths at each interval would also be of interest, to gain a three-dimensional distribution of englacial debris. Ideally, cosmogenic ^{3}He depth profiles of the overlying till (as in Ng *et al.,* 2005) would also be collected, in order to link sublimation rates to the quantified debris load.

One of the assumptions in Chapter 3, that soils at the different sites are of similar age (based on similar development stages) and influenced by the same climatic conditions, needs to be addressed. At present the Mount Achernar site is the only one with defined cosmogenic exposure ages (Faure & Nishiizumi, 1994; Mathieson *et al.,* 2012). The application of this dating technique to moraines/boulders at various points along the chronosequence at both Ong Valley and the Dominion Range site should validate this assumption. If exposure ages diverge between similarly developed soils at each of the three sites, a mechanism for differential soil development rates must be proposed. Local micro-climatic conditions may explain divergent development/weathering rates; conversely, differences in the lithologies of the glacial deposits may allow development to progress at different rates, or indeed progress via different pathways.

As mentioned above, the Otway Massif was briefly visited, and one soil profile sampled. This soil was within a landscape vastly different to the other three sites (Figure 5.1), and evidence (degree of staining and desert polish, salt accumulation) suggests a much longer exposure history. The Otway Massif soil samples have been analysed by collaborators at Victoria University (Wellington, New Zealand; Renee DeLisle and Warren Dickinson), including meteoric ^{10}Be analysis, used to understand atmospheric processes influencing soil properties over long time scales (Schiller *et al*., 2009). This work is still in progress at the time of submitting this thesis, but is planned for publication in the future. The Otway Massif would be a place of interest for future studies in the CTAM region, as landscape features observed (from helicopter fly-over) suggest a relatively complex glaciation/deglaciation history, and we were unable to access the highest altitude (thus potentially oldest) soils on the massif, given the time and flying conditions available.

Figure 5.1: Landscape visited and sampled at the Otway Massif, inset exhibits degree of staining and desert polish.

5.2. Bacterial communities

5.2.1. Summary of findings

The paradigm of distinct bacterial communities within geographically disparate Antarctic soil habitats, as established in the MDV (Lee *et al.*, 2012), is corroborated by several locations throughout the CTAM region; abiotic factors being explanatory for much of this variation. Communities on the plateau side of the TAM differ significantly from coastal communities, and generally appear to be less diverse and less even than those at lower altitudes. Differences in salt concentrations and composition within the soil, a function of both local climate and exposure age of the soil, appear important to this differentiation. Mount Howe may represent a habitat where soils are unable to support life, and a "rain" of atmospheric bacteria potentially the primary source of DNA recovered from the site.

5.2.2. Limitations of study

While utilizing the 16S rRNA gene to examine community structure offers both diversity and phylogenetic information, it provides no indication into the activity and functioning of organisms present in the soils. Putative physiologies may be inferred from positioning of 16S rRNA gene sequences within phylogenetic trees, but activity assessment (i.e. - thymidine uptake), transcriptomic and proteomic approaches are necessary to reliably assess functionality in the environment. Additionally, the presence of DNA itself does not prove the presence of live, viable or active organisms. The soils (high salt) and environment (low temperature and relative humidity) are conducive to the long-term preservation of DNA (Cary *et al.,* 2010). The use of side-by-side 16S rRNA and rDNA (Jones & Lennon, 2010) approaches would allow differentiation between dormant and active community members. Dormancy is probably a common strategy for microbes in antarctic soils, due to the long periods of extreme cold and darkness throughout winter. A caveat to such a distinction is the fact that it will only capture the active members at the particular time of sampling. A time series analysis, where soil samples are collected from the same spot over a number of hours or days would be interesting. As most soils are severely moisture limited, the brief influx of moisture to surface soils between a snowfall and the subsequent sublimation may significantly alter the 'activity profile' of a given community. Linking active community members to the moisture status of the soil at time of collection may reveal a stronger association between abiotic factors and the microbial community. In-lab experimentation can be achieved, facilitated by *Dry Valley Simulating Chambers* (International Center for Terrestrial Antarctic Research, University of Waikato, Hamilton). This will allow testing of provable hypotheses into community dynamics and functioning, in the absence of the specific restrictions imposed by the Antarctic winter and environmental protection protocols as necessitated by the Antarctic Treaty.

All sites in the study (Chapter 4), excluding Mount Achernar and Ong Valley, were examined for invertebrates (nematodes, rotifers, tardigrades, mites and springtails; TGA Green and ID Hogg, unpubl. data); the only site lacking any invertebrates was Mount Howe. The Mount Achernar and Ong Valley samples must be similarly analysed prior to submitting the manuscript for publication, in order to determine if/what invertebrates may be present at the higher altitude sites. This is necessary in order to determine the full extent to which the plateau sites and coastal sites may differ. Although inter-trophic biotic interactions are suggested to be relatively unimportant to soil microorganisms (Hogg *et al.,* 2006), the presence of invertebrates may serve as a proxy to identify a more productive system and/or more amenable environmental conditions, as discussed in Chapter 4. While not specifically looked for, no vegetation (lichen, moss, or cyanobacterial mat) was observed in any area visited within the Ong Valley or Mount Achernar sites. Vegetation was observed to some degree at all of the coastal sites (TGA Green and ID Hogg, unpubl. data).

Cell counts were conducted using DAPI (4',6-diamidino-2-phenylindole) stain and UV-excited fluorescent microscopy (as in: Tiao *et al.*, 2012). In some cases difficulties in differentiating between clay particles and cells were experienced, and some samples had to be re-processed and counted. In addition, several trials were conducted with an Accuri C6 Flow Cytometer (BD Biosciences), and different stains (e.g. – syto 13, and propidium iodide). No combinations trialed were reliably able to discriminate between bacterial cells and clay particles. It is expected that a flow cytometer equipped with a UV laser, and thus able to discriminate between clays and cells via DAPI, would perform much better in this function. Such facilities were unavailable during the course of this thesis. It is expected that such techniques may recover some level of cell abundance in Mount Howe samples (where we were unable to count any cells), as Cameron *et al*. (1971) reported 5-25 cells per gram of soil. However it must be noted that these cell counts relied on culture dependent methods, thus media introduced biases/contamination may have been an issue, especially at such a low biomass.

5.2.3. Future directions

This study was designed as a comparative investigation between discrete locations, and was strictly limited to the bacterial abundance of the soil communities; archaeal and fungal PCR primers were not employed. Thus the entire microbial community has not been examined, as both fungi and archaea are often found in Antarctic soils (Ruisi *et al.*, 2007; Yergeau *et al.,* 2009; Cary *et al.*, 2010). Interrogation of the soils examined in chapter 4 (and many other sites throughout the CTAM region), using primers specific to these organisms, would greatly improve understanding of the ecology of the CTAM region. A survey of microbes associated with the Otway Massif (discussed above, section 5.1) would be extremely valuable, as this landscape represents a much longer exposure history than our other plateau sites (Ong Valley and Mount Achernar). As factors associated with landscape age (specifically salt concentration and composition) appear important to structuring bacterial communities in the CTAM region, examination of sites at the extreme end of the spectrum is required.

Given that aerially transported bacteria may be an important component of the community observed at Mount Howe, a survey of bacteria in polar plateau air (similar to that conducted by Bottos *et al.*, 2013) would be extremely valuable. Researchers stationed at the Amundsen-Scott South Pole station could perhaps facilitate this. Additionally, surveys at higher altitudes, and across other regions of the Antarctic continent, could be undertaken via balloon-mounted sampling rigs (e.g. - Wainwright *et al.*, 2004). The degree to which ice-free habitats in Antarctica are connected to each other, and indeed other soil habitats globally, is an interesting and fundamental ecological question. More thorough inventories of the bacterial load in Antarctic (especially Polar Plateau) air could validate our claim of edaphic life being restricted at Mount Howe.

Salt content of the soils in this study has been discussed as a proxy for relative exposure age between the sites. The soil study in Chapter 3 illustrates that simple correlation of salt concentrations may not provide accurate estimates of numerical ages in the CTAM region, relative to the better studied MDV. Acquisition of cosmogenic exposure ages for each site sampled would vastly aid our discussion of community structures in relation to landscape age. Cosmogenic ^{10}Be exposure dating generally relies on the presence of erratic boulders (glacially emplaced on top of the landscape) with sufficient quartz content. This may not be the case for all sites studied; additionally the methods used tend to be expensive, thus such an approach may not be feasible for all sites. Dating of a few representative sites may be a compromise, however this is well outside the scope of the current study.

A comparative analysis between 'open soil' communities and soils underneath boulders would increase understanding of the differences/similarities between the CTAM (especially plateau sites) and the better charcterised MDV communities. The transplant of a mummified seal in the Miers Valley (Tiao *et al.*, 2012) not only revealed the ability of Antarctic soil communities to respond relatively quickly to environmental changes, but that these changes were largely effected through physical stabilisation of temperature and humidity (rather than biomass inputs to the soil). It is suggested that such effects may also occur under large/heavy boulders. Significant differences between boulder and open soil communities would indicate a potential for CTAM biota to respond rapidly to future environmental change, as subtle differences in the physiochemical environment drive profound changes in community structure and function.

5.3. Synthesis

The Plateau sites of both studies (Ong Valley, Mount Achernar, Dominion Range, Mount Howe) offer some unique opportunities to investigate the potential turnover and retention of ancient carbon in an essentially closed ecosystem. If the soils examined in Chapter 3 are up to 500,000 years old, and the microbial communities therein are predominantly heterotrophic (as suggested by the lack of

Cyanobacteria etc; Chapter 4), then any biological activity in the soils may be supported by relatively ancient carbon stocks (in the absence of heterotrophic fixation; Niederberger *et al.*, 2012). It is fair to assume these communities do not receive carbon subsidies from aeolian dispersed cyanobacterial mats (as in the MDV), as there is a distinct lack of pond systems at these high altitude sites, and the prevailing katabatic wind directions (Campbell & Claridge, 1987) would preclude material being transported from the coastal regions. The paucity of cyanobacterial sequences in the plateau soils examined would appear to confirm this assumption. Using stable carbon isotopic ratios, heterotrophic communities in recently deglaciated soils in the Austrian Alps have been shown to depend on ancient carbon stocks (Bardgett *et al.*, 2007). Examination of the isotopic ratios of microbial carbon in the Plateau site soils would be very difficult given the extremely low biomass. However, if possible, such a study could yield insights into an ecosystem essentially isolated from contemporary primary production. One potential approach to circumvent the low-biomass issue is high resolution ion microprobe examination of single cells (NanoSIMS; Li *et al.*, 2008). An analysis of the isotopic signature of the coal deposits present at some of the sites (Chapter 3) could be used to evaluate a hypothesis where contemporary microbial communities are sustained by carbon sources derived from coal-derived material within the soils.

The possibility of microbes associated with the englacial debris which contributes to soil development (Chapter 3) would also be worth investigating. Bacteria have been isolated, and 16S rRNA gene sequences recovered, from glacial ice before (Christner *et al.*, 2003; Xiang *et al.*, 2005). Extracting DNA from the ice underlying soils at the Plateau sites, and amplifying 16S rRNA gene sequences, would provide a window into the bacteria present in the past. Seperation of ice-associated and debris-associated sequences/bacteria would be a challenge. Comparing sequence libraries of very "dirty" and very "clean" ice may address this issue. Comparison of sequences in ice underlying soils to those within the surface soils could explore the possibility of sub-surface seeding of soil communities in addition to the aerial component. Upward migration of moisture and solutes from permafrost to soil surface is a common phenomenon in Antarctic soils, perhaps providing a mechanism for such upward seeding.

5.4. Value of research

The research presented in this thesis is essentially exploratory "blue-skies" science, extending current understanding of soil development and distribution, and microbial ecology, to previously uninvestigated areas. However, both studies serve to highlight the heterogeneity of local climate across the continent. The differences in soils and bacterial communities in these studies, in relation to other Antarctic sites (e.g.- McMurdo Dry Valleys), can largely be attributed to local climatic factors. The microenvironmental distribution of vegetation south of 72° S (Green *et al.*, 2011) may be reflected in the soil microbial communities; the linkages between the fundamental ecology of micro and macro organisms is an ongoing focus of current research. The disparate warming rates between the Antarctic Peninsula and the rest of continent further illustrate the climatic variability across Antarctica. The research in this thesis may thus serve as baseline data for future monitoring of the changes in the CTAM region in response to changing climate.

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Appendix – Profile descriptions and photographs

Profile descriptions of all soil sites discussed in Chapter 3 are presented here. Profiles are numbered in order of sampling time, not position in landscape. Soil pit positions are indicated in soil maps included in Chapter 3. Profiles from Otway Massif and Mount Kyffin, the two auxiliary sites, are also included. Samples designated as "Micro" are stored at Landcare Research, Hamilton.

ONG1

Date: 23/12/2010 *Time*: 1200
Weather: Partly cloudy, slight "up valley" wind
Location: S 83°15.027
E 157°43.701
Elevation: 1681 m
Location description: Centre of Ong Valley floor, halfway up the valley.
Slope: 2°
Aspect: NNW
Profile shape: Linear
Contour: Linear
Landform: Ground moraine.
Microtopography: High centered polygons; 1.5-2 m high, 5-8 m across, 6-10 sided, roughly equant. Boulders concentrated in inter-polygon cracks.
Geology: 1% dolerite, 15 % granite, 2-3% sandstone; remainder igneous, metamorphics and fines.
Weathering stage: 2
Salt stage: 1
Depth of coherence: 13 cm
Temperatures (°C):

Air	Surface	5 cm	10 cm	15 cm	20 cm	30 cm	40 cm	50 cm
- 1.0	1.9	1.0	-0.5	-1.7	-3.0	-4.6	-7.1	-9.3

Samples taken:

	Depth/horizon	
Ong1.1	Dp	Chem/phys
Ong1.2	Cox1	"
Ong1.3	Cox2	"
Ong1.A	0-2 cm	Micro
Ong1.B	2-5 cm	"

Horizon	Dp	Cox1	Cox2
Base (cm)	0.5	13	70 (ice)
Thickness (cm)	0.5	12.5	57
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Gradual	Very abrupt
Boundary shape	**???**	**???**	**???**
Colour	2.5Y 7/3	2.5Y 7/3	2.5Y 7/3
Texture	Slightly bouldery, stony, cobbley, very gravelly medium sand.	Fine to coarse gravelly, fine and medium sand.	Fine to coarse gravelly, fine and medium sand.
Structure	Single grained	Single grained	Single grained
Consistence	Loose	Soft	Loose
Other features	ST (HCl)	ST (HCl)	ST (HCl)

Ong 1
m
0·2
0·4
0·6

ONG2

Date: 24/12/2010 *Time*: 1100
Weather: Overcast, slight "up valley" wind
Location: S 83°13.995
E 157°40.213
Elevation: 1555 m
Location description: Centre of Ong Valley floor, on lowest/youngest drift.
Slope: 2°
Aspect: NNW
Profile shape: Convex
Contour: Concave
Landform: Ground moraine.
Microtopography: Elongated/rectangular high centered polygons; 1-2.5 m high, 1-3 m wide, 4-5 m long, long axis orientation variable. Sharp crested cross valley ridges, 2-3 m high. Isolated mounds 2-2.5 m high.
Geology: 30% dolerite, 2% granite, 3% sandstone; remainder metamorphics, tillites, and fines (30% - some surface crusting).
Weathering stage: 2
Salt stage: 1
Temperatures (°C):

Air	Surface	2 cm	5 cm	10 cm	15 cm
- 5.7	-0.9	-2.0	-2.1	-3.3	-4.8

Samples taken:

	Depth/horizon	
Ong2.1	Av	Chem/phys
Ong2.2	Cox	"
Ong2.A	0-2 cm	Micro
Ong2.B	2-5 cm	"

Horizon	Av	Cox
Base (cm)	1	15 (ice)
Thickness (cm)	1	14
Field moisture	Dry	Dry
Boundary distinctness	Abrupt	Very abrupt
Boundary shape	Smooth	Smooth
Voids	10-15% (1 mm, vesicular)	-
Colour	5Y 6/2	2.5Y 6/3
Texture	Stony, cobbley, gravelly, slightly silty fine to coarse sand.	Gravelly, silty fine sand.
Structure	Weak, very thin platey	Single grained
Consistence	Slightly hard, brittle	Soft
Other features	ST (HCl)	ST (HCl)


Ong 2

ONG3

Date: 24/12/2010 *Time*: 1530
Weather: Overcast, slight "up valley" wind
Location: S 83°14.171
E 157°40.962
Elevation: 1577 m
Location description: Centre of Ong Valley floor, glacier side of youngest terminal moraine.
Slope: 10°
Aspect: NNW
Profile shape: Linear
Contour: Concave
Landform: Ice marginal edge of terminal moraine.
Microtopography: Fissures and ridges; maximum relief 1.5 m.
Geology: 30% dolerite, 2% granite, 3% sandstone; remainder metamorphics and fines (30% - some surface crusting).
Surface clasts: Sub-angular and sub-round, unstained.
Weathering stage: 1
Salt stage: 1
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm	20 cm	30 cm	40 cm
-4.0	-0.8	-1.2	-3.4	-5.0	-6.8	-10.1	-11.4

Samples taken: nil

Horizon	Av	-	-
Base (cm)	1	20	45 (ice)
Thickness (cm)	1	19	25
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Clear	Very abrupt
Boundary shape	Smooth	Wavy, inclined	Wavy
Voids	15-20% (1 mm, vesicular)	-	-
Colour	2.5Y 6/2	2.5Y 5/2	2.5Y 7/2
Texture	Cobbley, gravelly, silty fine to coarse sand.	Cobbley, gravelly, silty fine to coarse sand.	Gravelly, silty fine to medium sand
Structure	Weak, very thin platey	Single grained	Single grained
Consistence	Weak, brittle	Loose	Loose
Other features	ST (HCl)	ST (HCl)	ST (HCl)


Ong3
m
0·2
0·4

ONG4

Date: 25/12/2010 *Time*: 1200
Weather: Overcast, slight “down valley” wind
Location: S 83°16.422
E 157°36.107
Elevation: 1709 m
Location description: Centre of Ong Valley floor (narrow, approximately 300 m) at head of valley. Steep, actively eroding rock walls either side. Evidence of landslides.
Slope: 0°
Aspect: N
Profile shape: -
Contour: -
Landform: Colluvial toe slope.
Microtopography: 20-40 cm relief swales, with snow infill
Geology: 1% dolerite, 99% granite.
Surface clasts: Angular and sub-angular, unstained.
Weathering stage: 1
Salt stage: 1
Temperatures (°C):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm	45 cm	50 cm
-4.3	1.2	-0.3	-2.7	-4.4	-5.8	-6.9	-7.4	-8.5	-9.2	-9.9	-11.4

Samples taken:

	Depth/horizon	
Ong4.1	1Dp	Chem/phys
Ong4.2	1Dcum	“
Ong4.3	2bBw	“
Ong4.4	2bCox	“
Ong4.A	0-2 cm	Micro
Ong4.B	2-5 cm	“
Ong4.C	2bBw	“

Horizon	1Dp	1Dcum	2bBw	2bCox
Base (cm)	4	38	44	70+
Thickness (cm)	4	34	6	-
Field moisture	Dry	Dry	Dry	Dry
Boundary distinctness	Very abrupt	Clear	Clear	-
Boundary shape	Smooth	Wavy	Wavy	-
Colour	2.5Y 5/2	2.5Y 7/4	10YR 6/4	2.5Y 6.5/4
Texture	Slightly bouldery, slightly stony, slightly cobbley, very gravelly coarse sand.	Slightly cobbley, gravelly medium to coarse sand.	Cobbley, gravelly fine to coarse sand.	Slightly bouldery, slightly stony, slightly cobbley, very fine gravelly fine to coarse sand
Clasts	Angular and sub-angular, slightly stained, slightly	Angular, fresh; a few clasts grussified.	Sub-angular, stained with oxidation rinds, moderately	

	weathered.		weathered; grussification more common.	
Structure	Single grained	Single grained	Single grained	Single grained
Consistence	Loose	Loose	Soft	Soft
Other features		Mm scale laminations		


Ong 4
m
0·2
0·4
0·6

ONG5

Date: 25/12/2010 *Time*: 1630
Weather: Overcast, slight "up valley" wind
Location: S 83°15.896
E 157°37.947
Elevation: 1690 m
Location description: Centre of Ong Valley floor, on oldest drift.
Slope: 2°
Aspect: N
Profile shape: Linear
Contour: Concave
Landform: Ground moraine.
Microtopography: High centered polygons; 1-1.5 m high, 6-10 m across, 6 sided, roughly equant.
Geology: 5% dolerite, 30% granite, 1% sandstone; remainder metamorphics, igneous and metasedimentary rocks.
Weathering stage: 2
Salt stage: 1
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm
-6.8	1.8	1.0	-0.7	-2.6	-3.6	-4.4	-5.5	-7.3	-8.0

50 cm	60 cm
-9.8	-12.1

Samples taken:

	Depth/horizon	
Ong5.1	Dp	Chem/phys
Ong5.2	Cox	"
Ong5.3	2Cox	"
Ong5.A	0-2 cm	Micro
Ong5.B	2-5 cm	"

Horizon	Dp	Cox	2Cox
Base (cm)	4	30	80+
Thickness (cm)	4	26	-
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Clear	-
Boundary shape	Smooth	Wavy, inclined	-
Colour	2.5Y 6/2	2.5Y 6/3.5	2.5Y 6/3
Texture	Slightly bouldery, cobbley, very gravelly medium to coarse sand.	Gravelly fine to coarse sand.	Slightly gravelly fine to medium sand, with minor coarse sand.
Clasts	Sub-angular, minmal staining, fresh.	Angular, some staining and oxidation.	Tabular, long axis aligned with bedding.
Structure	Single grained	Single grained	Single grained
Consistence	Loose	Soft	Soft
Other features	NE (HCl)	NE (HCl)	NE (HCl) cm scale lenses; 2.5Y 6/3.5, fine to medium sand, sub-horizontal.


Ong5
m
0·2
0·4
0·6
0·8

ONG6

Date: 26/12/2010 *Time*: 1100
Weather: Overcast, slight “up valley” wind, light snow
Location: S 83°16.263
E 157°37.493
Elevation: 1728 m
Location description: Centre of Ong Valley on top of terminal moraine ridge.
Slope: 0°
Aspect: N
Profile shape: -
Contour: -
Landform: Terminal moraine.
Microtopography: Terminal moraine ridge; 2 m wide, minimal relief.
Geology: 10% dolerite, 40% granite, 1% sandstone; remainder metamorphics and fines.
Weathering stage: 2
Salt stage: 1
Temperatures (°C):

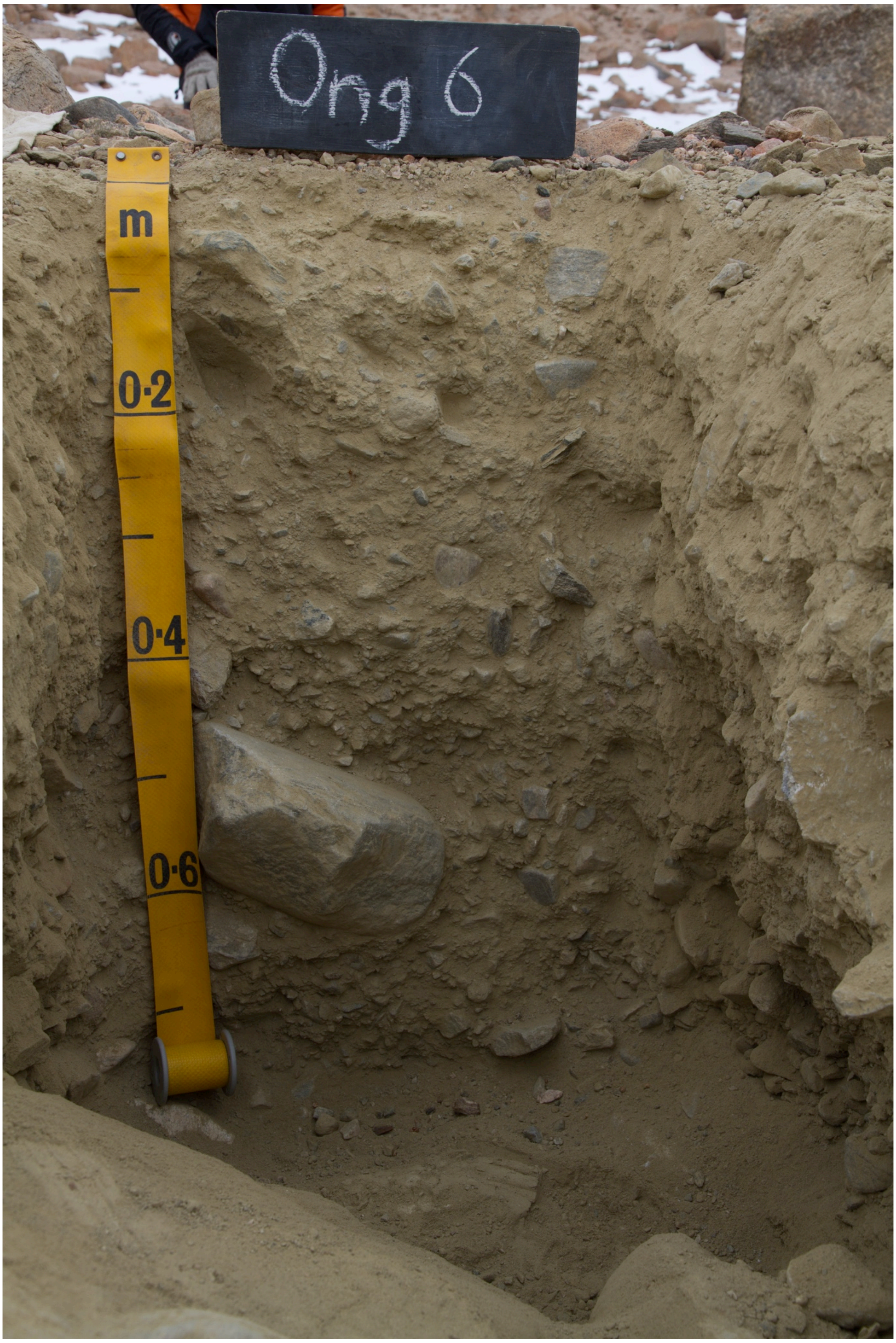
Air	Surface	4 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm	45 cm	50 cm
-8.4	-2.1	-4.3	-4.4	-4.6	-5.0	-5.4	-5.8	-6.4	-6.8	-7.0	-7.3

Samples taken:

	Depth/horizon	
Ong6.1	Dp	Chem/phys
Ong6.2	Bw1	“
Ong6.3	Bw2	“
Ong6.4	Cox	“
Ong6.A	0-2 cm	Micro
Ong6.B	2-5 cm	“

Horizon	Dp	Bw1	Bw2	Cox
Base (cm)	1	4	35	80+
Thickness (cm)	1	3	31	-
Field moisture	Dry	Dry	Dry	Dry
Boundary distinctness	Very abrupt	Abrupt	Clear	-
Boundary shape	Wavy	Wavy	Wavy	-
Colour	2.5Y 6/3	2.5Y 7/4	2.5Y 7/4	2.5Y 6/3
Texture	Very gravelly coarse sand.	Slightly gravelly silt.	Gravelly, silty fine sand.	Slightly bouldery, slightly stony, slightly cobbley, very gravelly, silty fine sand.
Clasts	Red-stained fine gravels.	Sub-angular, unstained, fresh.	Sub-angular, unstained, fresh.	Sub-angular, unstained, fresh.
Structure	Single grained	Massive	Massive	Single grained
Consistence	Loose	Soft	Soft	Soft
Other features	SE (HCl)	SE (HCl)	SE (HCl) Coherent, tightly packed; fine and medium nuts,	ST (HCl) Less coherent than Bw2.

moderate ped strength.



DOM1

Date: 29/12/2010 *Time*: 1830
Weather: Fine, minimal southerly breeze
Location: S 85°16.018
E 164°50.670
Elevation: 2182 m
Location description: Within grey/mudstone belt of drift sheet
Slope: 0°
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet.
Microtopography: High centered polygons; 1 m high, 6-10 m long, 2-5 m wide. New generation cracks present/forming.
Geology: 10% dolerite, 2% sandstone; remainder sedimentary (40% mudstone, some conglomerates) and fines.
Weathering stage: 2
Salt stage: 1
Depth of coherence: 6 cm
Temperatures (℃):

Air	Surface	3 cm	6 cm	14 cm
-9.7		-4.3	-4.6	-6.7

Samples taken:

	Depth/horizon	
Dom1.1	Av	Chem/phys
Dom1.2	Cox	“
Dom1.A	0-2 cm	Micro
Dom1.B	2-5 cm	“

Horizon	Av	Cox
Base (cm)	6	14 (ice)
Thickness (cm)	6	8
Field moisture	Dry	Dry
Boundary distinctness	Very Abrupt	Very Abrupt
Boundary shape	Wavy	Smooth
Voids	5% (1 mm, vesicular)	-
Colour	2.5Y 7/2	2.5Y 7/2
Texture	Gravelly fine sand.	Gravelly fine sand.
Clasts	Un-stained, fresh, sub-angular.	Un-stained, fresh, sub-angular.
Structure	Weak, very thin platy	Single grained
Consistence	Slightly hard, brittle	Loose
Other features	ST (HCl)	ST (HCl)


Dom 1

DOM2

Date: 30/12/2010 *Time*: 1400
Weather: Fine, moderate southerly breeze
Location: S 85°16.084
E 164°35.696
Elevation: 2182 m
Location description: Ice proximal side of ridge within young drift sheet
Slope: 4°
Aspect: WSW
Profile shape: Concave
Contour: Linear
Landform: Drift sheet.
Microtopography: Wavy terracette-like undulations; 0.5 m high, 2 m wide, aligned cross-slope.
Geology: 30% dolerite, 5% sandstone; remainder sedimentary (mudstone, conglomerates) and fines.
Surface description: Approximately 5% surface clasts slightly oxidized and varnished, boulders commonly striated.
Weathering stage: 1
Salt stage: 0
Temperatures (℃):

Air	Surface	2 cm
-10.0		-3.8

Samples taken:

	Depth/horizon	
Dom2.1	Cn	Chem/phys
Dom2.A	0-2 cm	Micro

Horizon	Surface	Cn
Base (cm)	-	2 (ice)
Thickness (cm)	-	2
Field moisture	Dry	Dry
Boundary distinctness	-	Very Abrupt
Boundary shape	-	Smooth
Colour	-	2.5Y 7/2
Texture	Slightly bouldery, slightly stony, cobbley gravel.	Slightly gravelly fine and medium sand.
Clasts	Un-stained, fresh, sub-angular and angular.	Un-stained, fresh, sub-angular and angular.
Structure	-	40% Single grained, 60% coarse nutty aggregates with vesicular porosity.
Consistence	-	Soft and loose
Other features	-	-


Dom 2

DOM3

Date: 30/12/2010 *Time*: 1630
Weather: Fine, moderate southerly breeze
Location: S 85°16.091
E 164°39.510
Elevation: 2169 m
Location description: Ice proximal side of ridge within drift sheet
Slope: 7°
Aspect: WSW
Profile shape: Linear
Contour: Linear
Landform: Drift sheet.
Microtopography: Thermokarst depressions and small mounds, mirrored in ice surface; 20 cm relief, 1-2 m wavelength.
Geology: 5% dolerite, <1% sandstone; remainder sedimentary (10% mudstone, conglomerates) and 70% fines.
Surface description: Cobbley, stony, and bouldery. Dolerite boulders commonly striated. Surface clasts angular and sub-angular.
Weathering stage: 2
Salt stage: 1
Temperatures (℃):

Air	Surface	2 cm	4 cm
-9.8		-6.3	-7.2

Samples taken:

	Depth/horizon	
Dom3.1	Av	Chem/phys
Dom3.A	0-2 cm	Micro
Dom3.B	2-4 cm	“

Horizon	Av
Base (cm)	4 (ice)
Thickness (cm)	4
Field moisture	Dry
Boundary distinctness	Very abrupt
Boundary shape	Wavy
Voids	5-10% (1 mm, vesicular)
Colour	2.5Y 6/3
Texture	Slightly gravelly, silty fine to coarse sand.
Clasts	Un-stained, fresh, sub-angular and angular.
Structure	Strong, very thick platy.
Consistence	Moderately hard and brittle
Other features	SE(HCl)


Dom 3

DOM4

Date: 30/12/2010 *Time*: 1745
Weather: Fine, moderate easterly breeze
Location: S 85°16.046
E 164°41.385
Elevation: 2168 m
Location description: Ice proximal side of ridge within drift sheet
Slope: 4°
Aspect: WSW
Profile shape: Concave
Contour: Linear
Landform: Drift sheet.
Microtopography: Irregular high centered polygons; 4 sided, 0.6 m high, 2-3 m across.
Geology: 10% dolerite, <1% sandstone; remainder sedimentary (30% shale, 30% conglomerates) and 30% fines.
Surface description: Cobbley, stony, and bouldery. Dolerites with chipped varnish. Rare salts under surface clasts.
Weathering stage: 1
Salt stage: 1
Temperatures (℃):

Air	Surface	2 cm	4 cm	8 cm
-10.7		-5.1	-5.3	-6.7

Samples taken:

	Depth/horizon	
Dom4.1	Av	Chem/phys
Dom4.A	0-2 cm	Micro
Dom4.B	2-5 cm	“

Horizon	Av
Base (cm)	8 (ice)
Thickness (cm)	8
Field moisture	Dry
Boundary distinctness	Very abrupt
Boundary shape	Wavy
Voids	10% (1 mm, vesicular)
Colour	2.5Y 6/2
Texture	Fine gravelly, silty very fine to medium sand.
Clasts	Stained (inherited), fresh, sub-angular and angular. Slate platy.
Structure	Moderately developed coarse nutty.
Consistence	Moderately hard and brittle
Other features	SE(HCl)


Dom 4

DOM5

Date: 1/1/2011 *Time*: 1320
Weather: Fine, slight breeze
Location: S 85°16.045
E 164°43.340
Elevation: 2167 m
Location description: Ice proximal side of ridge within young drift sheet
Slope: 5°
Aspect: SW
Profile shape: Linear
Contour: Linear
Landform: Drift sheet.
Microtopography: Rectangular high centered polygons; 0.5 m high, 5-7 m high, 2 m wide, long axis aligned down slope.
Geology: 10% dolerite, 2% sandstone; remainder sedimentary (10% shale, 10% conglomerates, and others) and 40% fines.
Surface description: Slightly stony, cobbley, gravelly. Clasts subround-angular, commonly striated. Fines often occur as vesicular crust.
Weathering stage: 1
Salt stage: 0
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm
-9.0	1.3	-0.9	-5.3	-8.1	-9.0	-9.6

Samples taken:

	Depth/horizon	
Dom5.1	Crust/Av	Chem/phys
Dom5.2	Cox	“
Dom5.3	2Cox	“
Dom5.A	0-2 cm	Micro
Dom5.B	2-5 cm	“

Horizon	Crust/Av	Cox	2Cox
Base (cm)	0.5	10	25
Thickness (cm)	0.5	9.5	15.5
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Clear	Very abrupt
Boundary shape	Wavy	Wavy	Smooth
Voids	5% (1 mm, vesicular)	-	-
Colour	2.5Y 7/3	2.5Y 6/2-3	2.5Y 7/2-3
Texture	Slightly stony, slightly cobbley, gravelly fine to coarse sand.	Slightly cobbley, very gravelly, very fine to medium sand.	Slightly fine gravelly, very fine to coarse sand.
Clasts	Stained, fresh, subround-subangular.	Un-stained, fresh, subround-subangular.	Un-stained, fresh, angular-subangular.
Structure	Moderately developed, thin platy.	Single grained	Single grained
Consistence	Slightly hard and brittle	Soft	Loose
Other features	ST (HCl)	ST (HCl)	


Dom 5
m
0·2
1cm

DOM6

Date: 1/1/2011 *Time*: 1700
Weather: Fine, slight easterly breeze
Location: S 85°15.992
E 164°44.748
Elevation: 2175 m
Location description: Dolerite-dominated "belt" within drift sheet
Slope: 1°
Aspect: SW
Profile shape: Linear
Contour: Linear
Landform: Drift sheet.
Microtopography: Small high centered polygons, triangular, rectangular and wedge shaped; 0.5 m high, 2-4 m long, 1-3 m wide.
Geology: 70% dolerite, 5% sandstone; remainder sedimentary (mudstone, conglomerates) and 15% fines (often crusty).
Surface description: Chipped desert varnish, probably inherited. Striations common. Some sandstones spalling and pitting *in situ*. Clasts subangular to round. Salt efflorescences on sides of polygon cracks.
Weathering stage: 1-2
Salt stage: 0-1
Depth of coherence: 4 cm
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm
-7.1	-2.2	-4.5	-7.4	-8.8

Samples taken:

	Depth/horizon	
Dom6.1	Av	Chem/phys
Dom6.2	Cox	"
Dom6.A	0-2 cm	Micro
Dom6.B	2-4 cm	"

Horizon	Av	Cox
Base (cm)	4	15 (ice)
Thickness (cm)	4	11
Field moisture	Dry	Dry
Boundary distinctness	Abrupt	Very abrupt
Boundary shape	Wavy	Wavy
Voids	5% (1 mm, vesicular)	-
Colour	2.5Y 6/2	2.5Y 7/3
Texture	Gravelly, very fine to coarse sand.	Gravelly, slightly silty, very fine to medium sand.
Clasts	Few stained, slightly weathered, subangular.	Un-stained, fresh, angular-subangular.
Structure	Moderately developed, thin platy.	Single grained
Consistence	Slightly hard and brittle	Loose
Other features	ST (HCl)	VE (HCl)


Dom 6

DOM7

Date: 1/1/2011 *Time*: 1830
Weather: Fine, slight easterly breeze
Location: S 85°15.933
E 164°46.477
Elevation: 2183 m
Location description: Ice proximal slope of ridge within drift sheet
Slope: 3°
Aspect: SW
Profile shape: Linear
Contour: Linear
Landform: Drift sheet.
Microtopography: High centered polygons, rectangular and trapezoidal; 1 m high, 4 m across, roughly equant.
Geology: <1% dolerite; remainder 80% mudstone, 20% fines (often crusty).
Surface description: Gravels, stones and cobbles; clasts subangular to subround. No staining. Mudstones often have carbonaceous accumulations in fissures. Striations common. Crustal fines eroding to mini "badland" topography.
Weathering stage: 1-2
Salt stage: 0-1
Depth of coherence: 3 cm
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm	17 cm
-8.3	-1.4	-2.5	-4.3	-4.4	-7.4

Samples taken:

	Depth/horizon	
Dom7.1	Av	Chem/phys
Dom7.2	C	"
Dom7.A	0-2 cm	Micro
Dom7.B	2-5 cm	"

Horizon	Av	C
Base (cm)	3	17 (ice)
Thickness (cm)	3	14
Field moisture	Dry	Dry
Boundary distinctness	Abrupt	Very abrupt
Boundary shape	Wavy	Wavy
Voids	5% (1-2 mm, vesicular)	-
Colour	2.5Y 7/2	2.5Y 7/3
Texture	Slightly stony, slightly cobbley, very gravelly medium to coarse sand (with minor fine sand).	Gravelly medium to very coarse sand (with minor fine sand).
Clasts	Unstained, fresh, subangular.	Unstained, fresh, angular-subangular.
Structure	Massive	Single grained
Consistence	Slightly hard	Loose
Other features	VE (HCl)	VE (HCl)


Dom 7
1cm

DOM8

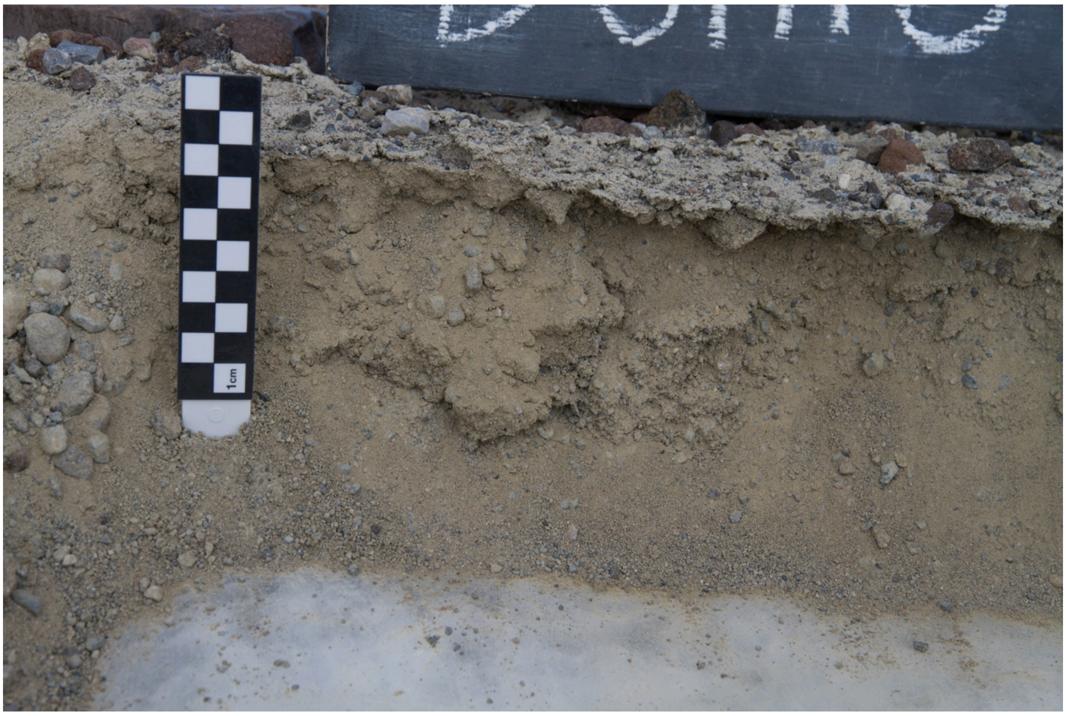
Date: 2/1/2011 *Time*: 1210
Weather: Partly overcast, slight breeze and light snow
Location: S 85°15.983
E 164°48.430
Elevation: 2178 m
Location description: Ice proximal side of ridge within drift sheet
Slope: -
Aspect: SW
Profile shape: Linear
Contour: Linear
Landform: Drift sheet.
Microtopography: Irregular medium and small high centered polygons; 0.5 m high, 1-4m across.
Geology: 20% dolerite, 2%sandstone; remainder 40% conglomerate, 30% fines (often crusty), other sedimentary rocks.
Surface description: Bouldery, slightly cobbley, gravelly. Sandstones commonly spalling and lightly stained. Dolerites with chipped (inherited) varnish. Clasts subangular-subround.
Weathering stage: **???**
Salt stage: **???**
Depth of coherence: 9 cm
Temperatures (℃):

Air	Surface	5 cm	10 cm
-11.0	-3.5	-6.1	-6.7

Samples taken:

	Depth/horizon	
Dom8.1	Av	Chem/phys
Dom8.2	Cox	“
Dom8.3	2Cox	“
Dom8.A	0-2 cm	Micro
Dom8.B	2-5 cm	“

Horizon	Av	Cox	2Cox
Base (cm)	1	9	12 (ice)
Thickness (cm)	1	8	3
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Clear	Very abrupt
Boundary shape	Wavy	Wavy	Wavy
Voids	5% (1 mm, vesicular)	2% (1 mm, vesicular)	-
Colour	2.5Y 7/2	2.5Y 7/3	2.5Y 6/2
Texture	Slightly cobbley, gravelly, fine to coarse sand.	Fine gravelly, very fine to coarse sand.	Gravelly, very fine to coarse sand.
Clasts	Some slightly stained, fresh, subround and subangular.	Unstained, fresh, angular-subangular.	Unstained, fresh, angular-subangular.
Structure	Weak thin platy	Fine-medium blocky	Single grained
Consistence	Slightly hard	Slightly hard	Loose
Other features			


1cm

DOM9

Date: 2/1/2011 *Time*: 1600
Weather: Low cloud and snow, light-moderate breeze
Location: S 85°15.989
E 164°53.703
Elevation: 2183 m
Location description: Dolerite-dominated "belt" within drift sheet
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet.
Microtopography: High centered polygons; 1-1.5m high, 3-6 m across, 3-5 sided.
Geology: 35% dolerite, <1% sandstone; remainder 10% conglomerate, 10% mudstone, other sedimentary rocks, 30% fines (often crusty).
Surface description: Slightly bouldery, slightly cobbley, very gravelly. Dolerites stained, with chipped varnish and striations. Some spalling evident.
Weathering stage: 2
Salt stage: 1
Depth of coherence: 1 cm
Temperatures (°C):

Air	Surface	5 cm	10 cm	15 cm	20 cm	30 cm	40 cm	50 cm	60 cm
-11.8	-5.8	-4.8	-4.5	-4.7	-5.6	-7.4	-11.0	-13.5	-14.6

Samples taken:

	Depth/horizon	
Dom9.1	Av	Chem/phys
Dom9.2	Cox	"
Dom9.3	2Cox	"
Dom9.A	0-2 cm	Micro
Dom9.B	2-5 cm	"

Horizon	Av	Cox	2Cox
Base (cm)	1	11	60 (ice)
Thickness (cm)	1	10	49
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Clear	Very abrupt
Boundary shape	Wavy	Wavy	Wavy
Voids	5% (1 mm, vesicular)	-	-
Colour	2.5Y 7/2	2.5Y 7/2-3	2.5Y 6/2
Texture	Slightly cobbley, very gravelly fine to coarse sand.	Slightly cobbley, gravelly fine to coarse sand.	Slightly fine gravelly, silty, very fine to medium sand.
Clasts	Slightly stained, fresh, subround and subangular.	Unstained, fresh, subangular.	-
Structure	Weak, thin platy	Single grained	Single grained
Consistence	Slightly hard	Soft	Loose
Other features			


Dom 9
m
0·2
0·4
0·6

ACH1

Date: 5/1/2011 *Time*: 1400
Weather: Overcast, slight breeze
Location: S 84°13.870
E 161°11.014
Elevation: 1851 m
Location description: Middle of oldest band of Law Glacier lateral moraine/drift sheet, adjacent to oldest terminal moraine of small glacier to the South.
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet.
Microtopography: High centered polygons; 1-1.5m high, 2-6 m across. Some big, equant, 4-5 sides; others small, elongated, 3-4 sides.
Geology: 50% dolerite, 10% sandstone; remainder conglomerate, mudstone, other sedimentary rocks, 20% fines (often crusty).
Surface description: Bouldery, many fine gravels. Staining/varnish present; spalling evident in both dolerites and sandstones, some pitting. Most clasts subround-round. Discontinuous salt pan (5 mm thick) under larger clasts.
Weathering stage: 2-3
Salt stage: 1-2
Depth of coherence: 4 cm
Depth of staining: 4 cm
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	40 cm	50 cm	60 cm
-5.8	-2.9	-3.6	-5.5	-6.3	-7.9	-8.4	-9.1	-11.2	-13.2	-14.6

Samples taken:

	Depth/horizon	
Ach1.1	Dp	Chem/phys
Ach1.2	Av/Bw	“
Ach1.3	C	“
Ach1.A	0-2 cm	Micro
Ach1.B	2-5 cm	“

Horizon	Dp	Av/Bw	C
Base (cm)	0.5	4	65 (ice)
Thickness (cm)	0.5	3.5	61
Field moisture	Dry	Dry	Dry
Boundary distinctness	Discontinuous, abrupt	Abrupt	Very abrupt
Boundary shape	Smooth	Irregular*	Smooth
Voids	-	Up to 30% (1-4 mm, vesicular)	-
Colour	7.5YR 5/2	10YR 7/3	4Y 6/1 (5% - N4)
Texture	Very fine gravelly and coarse sand.	Slightly stony, slightly cobbley, very fine-coarse gravelly, silty very fine sand.	Slightly cobbley, fine gravelly, very fine sand.

Clasts	Strongly stained	Some strongly stained, some fresh, subround and subangular.	Unstained.
Structure	Single grained	Massive	Single grained
Consistence	Loose	Slightly-moderately hard, brittle	Soft
Other features	No (HCl)	Forms crust in places, salt pan under larger clasts. SE (HCl)	SE (HCl)

*Irregularities occur as wedge shaped inclusions approximately 15 cm into lower horizon; greater gravel content, some with varnish and staining.


ACH 1
m
0·2
0·4
0·6

ACH2

Date: 5/1/2011 *Time*: 1745
Weather: Slightly overcast, still
Location: S 84°13.980
E 161°11.298
Elevation: 1856 m
Location description: Oldest terminal moraine of small southern glacier, adjacent to oldest band of Law Glacier lateral moraine.
Slope: 1°
Aspect: NNW
Profile shape: Linear
Contour: Linear
Landform: Drift sheet.
Microtopography: Large high centered polygons; 1.5-2.5m high, 7-10 m across, 10-15 m long, 5 sided, relatively equant.
Geology: 70% dolerite, 2% sandstone; remainder conglomerate, mudstone, 15% fines (often crusty).
Surface description: Bouldery, many fine gravels; boulders concentrated in cracks. Sandstones strongly weathered, strong varnish on dolerites, spalling prevalent. Most clasts subround to round; patches of fine desert pavement.
Weathering stage: **???**
Salt stage: **???**
Depth of coherence: 6 cm
Depth of staining: 10 cm
Temperatures (°C):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm	50 cm
-8.3	-2.7	-1.9	-3.9	-5.1	-6.5	-8.0	-9.2	-10.6	-12.1	-14.2

Samples taken:

	Depth/horizon	
Ach2.1	D	Chem/phys
Ach2.2	Av	"
Ach2.3	Bw	"
Ach2.4	C	"
Ach1.A	0-2 cm	Micro
Ach1.B	2-5 cm	"

Horizon	D	Av	Bw	C
Base (cm)	0.5	5	10	51 (ice)
Thickness (cm)	0.5	5	5	41
Field moisture	Dry	Dry	Dry	Dry
Boundary distinctness	Abrupt	Abrupt	Clear	Very abrupt
Boundary shape	Smooth	Wavy	Wavy	Smooth
Salts	Coatings under clasts; 2 mm thick, white.	-	-	-
Voids	-	20% (1-2 mm, vesicular)	-	-

Colour	7.5YR 4/2	10YR 7/3	2.5Y 7/3	N4
Texture	Fine gravelly coarse sand.	Fine gravelly, fine to medium sand.	Fine gravelly, fine to medium sand.	Slightly cobbley, gravelly silt.
Clasts	Strongly stained and weathered, subround-subangular.	Stained and unstained, unweathered.	Few stained, unweathered.	Unstained, unweathered, subround and round.
Structure	Single grained	Moderately thin platy	Single grained	Single grained
Consistence	Loose	Slightly-moderately hard	Loose	Loose
Other features	Patchy/inconsistent horizon. Some dolerites spalling in D and Av, leaving 5YR 4/6 flakes.	Structure strongest in top 2 cm; weakens with depth. ST (HCl)	Wedges of gravelly fine to medium sand penetrate this horizon; evidence of cryoturbation. ST (HCl)	SE (HCl)


ACH2
m
0·2
0·4

ACH3

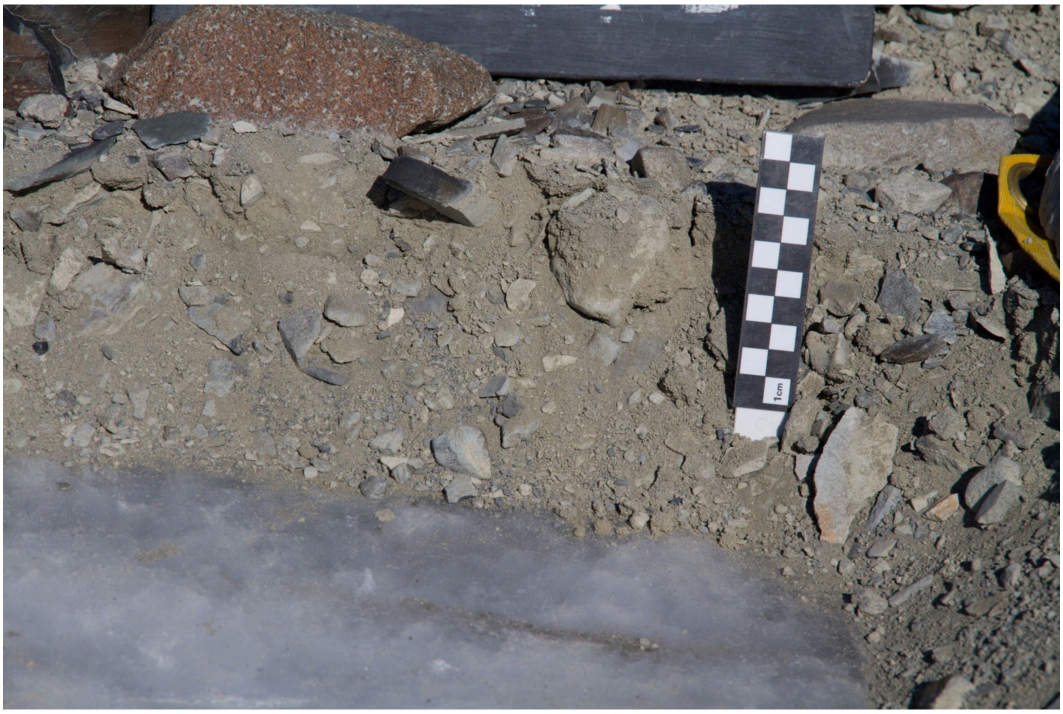
Date: 6/1/2011 *Time*: 1230
Weather: Fine, moderate breeze
Location: S 84°11.238
E 161°09.809
Elevation: 1887 m
Location description: Ice proximal side of ridge within lateral moraine/drift sheet
Slope: 12°
Aspect: NNE
Profile shape: Linear
Contour: Linear
Landform: Lateral moraine
Microtopography: Small high centered polygons; 0.5m high, 1-2 m across, 3-4 m long, long axis orientated downslope.
Geology: 25% dolerite, 15% sandstone; remainder shales, mudstone, 40% fines (some crusting).
Surface description: Cobbles, stones and gravels; Clasts subangular to subround and angular. Moderate staining on sandstones, minimal-moderate staining on dolerites. Some spalling. Carbonate films present on underside of clasts.
Weathering stage: 2
Salt stage: 1
Temperatures (℃):

Air	Surface	5 cm	8.5 cm
-5.0	1.8	-1.3	-5.0

Samples taken:

	Depth/horizon	
Ach3.1	Av	Chem/phys
Ach3.2	C	“
Ach3.A	0-2 cm	Micro
Ach3.B	2-5 cm	“

Horizon	Av	C
Base (cm)	2.5	8.5 (ice)
Thickness (cm)	2.5	6
Field moisture	Dry	Dry
Boundary distinctness	Abrupt	Very abrupt
Boundary shape	Wavy	Wavy
Voids	5% (1 mm, vesicular)	-
Colour	2.5Y 7/2	2.5Y 6/1
Texture	Cobbley, gravelly, very fine to medium sand.	Fine gravelly, very fine to coarse sand.
Clasts	Unstained, fresh, angular.	Unstained, fresh, angular.
Structure	Weak, fine nutty	Single grained
Consistence	Soft	Soft
Other features	SE (HCl)	NE (HCl)


1cm

ACH4

Date: 6/1/2011 *Time*: 1600
Weather: Fine, few clouds, moderate breeze
Location: S 84°11.358
E 161°09.666
Elevation: 1883 m
Location description: Ice proximal toe of ridge within drift sheet
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet
Microtopography: Small high centered polygons; 0.5m high, 1-2 m across, 4 sided, many square shaped.
Geology: 5% dolerite, 75% sandstone; remainder shales, slates, mudstone, 10% fines (some crusting).
Surface description: Cobbles, stones and gravels; Clasts angular to. Moderate and light-unstained sandstones, minimal-moderate staining on dolerites. Some spalling, striations evident.Some carbonate films present on underside of clasts.
Weathering stage: 1-2
Salt stage: 0-1
Temperatures (℃):

Air	Surface	5 cm	8 cm
-5.4	-1.3	-2.6	-5.6

Samples taken:

	Depth/horizon	
Ach4.1	A(v)	Chem/phys
Ach4.2	C	“
Ach4.A	0-2 cm	Micro
Ach4.B	2-5 cm	“

Horizon	A(v)	C
Base (cm)	1	8 (ice)
Thickness (cm)	1	7
Field moisture	Dry	Dry
Boundary distinctness	Abrupt	Very abrupt
Boundary shape	Wavy	Wavy
Voids	5% (1 mm, vesicular)	-
Colour	2.5Y 7/1	N4
Texture	Slightly stony, slightly cobbley, very gravelly fine to coarse sand.	Gravelly, very fine to coarse sand.
Clasts	Weak to moderate staining and weathering.	Unstained, weak-moderate weathering, subround and subangular.
Structure	Single grained, patches of weak crust	Single grained and some weak very fine blocks
Consistence	Loose-soft	Soft
Other features	NE; SE on some clasts (HCl)	NE (HCl)


ACH 4

ACH5

Date: 7/1/2011 *Time*: 1130
Weather: Fine, moderate southerly katabatic breeze
Location: S 84°13.199
E 161°11.861
Elevation: 1838 m
Location description: Middle of drift sheet, approximately 100 m south of higher tongue of drift sheet
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet
Microtopography: High centered polygons; 1-2 m high, 4-6 m across, 5-10 m long 4-5 sided.
Geology: 15% dolerite, 40% sandstone; remainder shales, other sedimentary, 30% fines (often crusty).
Surface description: Sandstones unstained to strongly stained, some with severe weathering (spalling). Dolerites unstained to moderately stained, less weathered. Clasts subangular to round (with minor angular). Boulders (5%) concentrated in/near cracks.
Weathering stage: 2-3
Salt stage: 0
Depth of coherence: 5 cm
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm	20 cm	30 cm	40 cm	50 cm
-8.0	-2.8	-5.0	-6.9	-8.0	-9.0	-9.7	-12.1	-14.5

Samples taken:

	Depth/horizon	
Ach5.1	Av	Chem/phys
Ach5.2	Cox	“
Ach5.A	0-2 cm	Micro
Ach5.B	2-5 cm	“

Horizon	Av	Cox	
Base (cm)	5	60 (ice)	
Thickness (cm)	5	55	
Field moisture	Dry	Dry	
Boundary distinctness	Abrupt	Very abrupt	
Boundary shape	Wavy	Smooth	
Voids	<5% (1 mm, vesicular)	-	
Colour	2.5Y 7/3	2.5Y 7/3	
Texture	Slightly stony, slightly cobbley, gravelly, very fine to coarse sand.	Slightly cobbley, slightly fine gravelly, very fine to medium sand.	
Clasts	Weak-moderately stained, fresh-moderately weathered, subangular-round.	Unstained, fresh, angular-subangular.	*Slightly cobbley, very gravelly wedges down to 50 cm, cross pit corner to corner (cryoturbation).
Structure	Massive	Single grained	
Consistence	Moderately hard	Loose	
Other features	NE (HCl)	NE (HCl)*	


ACH 5
m
0·2
0·4

ACH6

Date: 7/1/2011 *Time*: 1500
Weather: Fine, few clouds, moderate breeze
Location: S 84°12.926
E 161°12.642
Elevation: 1881 m
Location description: Centre of drift belt**.**
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet
Microtopography: High centered polygons; 1-2 m high, large 10-15 m across, small 3-5 m across, 4-5 sided, equant and elongated. Older infilled cracks intersect current polygons.
Geology: 50% dolerite, 20% sandstone; remainder shales, other sedimentary, 25% fines (often crusty).
Surface description: Boulders, cobbles, stones and gravels. Unstained to strongly stained sandstones with spalling. Dolerites stained, some with (inherited) varnish). Some dolerites spalling and pitting, some striated. Clasts subangular to round.
Weathering stage: 2
Salt stage: 0
Depth of coherence: 5 cm
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	40 cm	50 cm	60 cm
-9.5	-3.4	-3.2	-4.1	-5.6	-6.5	-8.2	-8.8	-10.9	-13.1	-14.2

Samples taken:

	Depth/horizon	
Ach6.1	Av	Chem/phys
Ach6.2	Cox	“
Ach6.A	0-2 cm	Micro
Ach6.B	2-5 cm	“

Horizon	Av	Cox	Cox’ (East wall)
Base (cm)	5	70 (ice)	70 (ice)
Thickness (cm)	5	65	65
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Very abrupt	
Boundary shape	Wavy	Wavy	Wavy
Voids	<5% (1 mm, vesicular)	-	-
Colour	2.5Y 7/3	2.5Y7/2	2.5Y7/2
Texture	Slightly stony, cobbley, very fine gravelly, fine to coarse sand.	Fine gravelly, very fine to coarse sand.	Stony, cobbley, very fine gravel.
Clasts	Moderate to strongly stained, weak-	Unstained, fresh to weakly weathered,	Moderate-strongly stained (some varnish),

	moderately weathered, subangular-subround	subangular.	moderately weathered sandstones (others weak), subangular-subround.
Structure	Moderate thin platy	Single grained	Single grained
Consistence	Slightly hard	Loose	Loose
Other features	SE (HCl)	SE (HCl)	SE (HCl) Infilled crack


ACH6
m
0·2
0·4
0·6

ACH7

Date: 7/1/2011 *Time*: 1745
Weather: Fine, steady southerly breeze
Location: S 84°12.525
E 161°14.117
Elevation: 1845 m
Location description: Dominantly red-coloured/dolerite belt of drift sheet
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet
Microtopography: Rectangular high centered polygons; 5 m wide, 20 m long.
Geology: 60% dolerite, 25% sandstone; remainder sedimentary rocks, 30% fines (some crusting).
Surface description: Moderate-strongly stained dolerite boulders stones and cobbles; exfoliation and spalling evident, strong varnish (chipped). Sandstone stained and spalling
Weathering stage: 2
Salt stage: 1
Depth of coherence: 30 cm
Temperatures (°C):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	40 cm	50 cm	60 cm
-6.5	-0.3	-2.2	-3.9	-5.0	-5.5	-6.1	-6.8	-8.5	-9.9	-11.7

Samples taken:

	Depth/horizon	
Ach7.1	Av	Chem/phys
Ach7.2	Cox1	“
Ach7.3	Cox2	“
Ach7.A	0-2 cm	Micro
Ach7.B	2-5 cm	“

Horizon	Av	Cox1	Cox2
Base (cm)	4	30	100+
Thickness (cm)	4	26	74+
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Clear	-
Boundary shape	Wavy	Wavy	-
Voids	10% (1 mm, vesicular)	-	-
Colour	2.5Y 7/3	2.5Y 6/2	2.5Y 6/2
Texture	Slightly stony, slightly cobbley, gravelly very fine sand.	Fine and medium gravelly, very fine to coarse sand.	Fine gravelly, silty, very fine to medium sand.
Clasts	Unstained to modearately stained, fresh-moderately weathered, suubangular and	Unstained (except few dolerites), fresh-weakly weathered, subangular.	Unstained, fresh, subangular.

	subround.		
Structure	Moderate thin platy	Weak very coarse prisms	Single grained
Consistence	Moderately hard	Very hard	Loose
Other features	ST (HCl) One side with stony, cobbley, gravelly infilled crack.	SE (HCl) Fine gravels in inclined lamina. Free-flowing fine to coarse sand between prisms.	NE (HCl)

ACH7
m
0·2
0·4
0·6

ACH8

Date:8/1/2011 *Time*: 1445
Weather: Fine, slight breeze
Location: S 84°11.773
E 161°13.394
Elevation: 1838 m
Location description: Dominantly grey-coloured/sandstone belt of drift sheet
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet
Microtopography: Rectangular high centered polygons; 0.5 m high, 1-2 m wide, 3-4 m long.
Geology: 20% dolerite, 60% sandstone; remainder shale and carbonaceous mudstone, 15% fines.
Surface description: Boulders, stones, cobbles, gravels. Most sandstones moderately to strongly stained and weathered, spalling common. Some dolerites spalling, weak-moderately stained. Most clasts subangular to subround, some round
Weathering stage: 2
Salt stage: 1
Depth of staining: 2 cm
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm
-5.8	-3.4	-5.9	-7.8	-9.1

Samples taken:

	Depth/horizon	
Ach8.1	Bw/Cox	Chem/phys
Ach8.2	C	“
Ach8.3	Ice	“
Ach8.A	0-2 cm	Micro
Ach8.B	2-5 cm	“

Horizon	Bw/Cox	C
Base (cm)	2	15 (ice)
Thickness (cm)	2	13
Field moisture	Dry	Dry
Boundary distinctness	Abrupt	Very abrupt
Boundary shape	Wavy	Wavy
Voids	-	-
Colour	2.5Y 7/2	2.5Y 6/1
Texture	Slightly cobbley, gravelly, fine to medium sand.	Very fine gravelly, slightly silty, very fine to medium sand.
Clasts	Unstained to moderately stained, fresh, subangular-subround.	Unstained, fresh, subangular.
Structure	Single grained	Single grained
Consistence	Loose	Loose
Other features	NE (HCl)	NE (HCl)


ACH8

ACH9

Date: 8/1/2011 *Time*: 1700
Weather: Fine, slight-moderate breeze
Location: S 84°12.158
E 161°11.351
Elevation: 1849 m
Location description: Dominantly red-coloured/dolerite belt of drift sheet
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Drift sheet
Microtopography: Rectangular high centered polygons; 1 m high, 2-5 m wide, 5-15 m long, long axis orientation varies. Older infilled cracks intersecting current polygons.
Geology: 50% dolerite, 25% sandstone; remainder shale and carbonaceous mudstone, 20% fines (some crusting).
Surface description: Boulders, some stones, cobbles, gravels. Most sandstones moderately to strongly stained and spalling common. Dolerites moderately stained, some varnish, some spalling and pitting. Clasts subangular to round, with few angular. Boulders concentrated in/near cracks.
Weathering stage: 2
Salt stage: 1
Depth of staining: 8 cm
Depth of coherence: 2 cm
Temperatures (°C):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm
-7.0	-5.5	-5.3	-5.4	-5.7	-6.7	-7.3	-7.9

Samples taken:

	Depth/horizon	
Ach9.1	Av	Chem/phys
Ach9.2	Cox	"
Ach9.3	C	"
Ach9.A	0-2 cm	Micro
Ach9.B	2-5 cm	"

Horizon	Av	Cox	C
Base (cm)	2	8	65 (ice)
Thickness (cm)	2	6	57
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Abrupt	Very abrupt
Boundary shape	Wavy	Wavy	Wavy
Voids	10-20% (1 mm, vesicular)	-	-
Colour	2.5Y 7/2	2.5Y 7/2	2.5Y 5/2 (2% N3)
Texture	Slightly stony, slightly cobbley, fine gravelly, very fine to coarse sand.	Gravelly, slightly silty, fine to coarse sand.	Fine gravelly, fine to medium sand.
Clasts	Moderate-strongly stained, weak-moderately	Weakly stained, fresh, subangular.	Unstained, fresh, angular.

	weathered, subangular to round.		
Structure	Weak massive	Single grained	Single grained
Consistence	Slightly hard	Loose	Loose
Other features	NE (HCl) Infilled crack/wedge to 40 cm with stained clasts, cobbley, slightly stony, very gravelly.	NE (HCl)	


ACH9

KYF1

Date: 11/1/2011 *Time*: 1530
Weather: Thin high cloud, slight breeze
Location: S 83°46.140
E 171°55.605
Elevation: 222 m
Location description: Centre of lateral moraine beside northeastern flank of Mount Kyffin
Slope: -
Aspect: -
Profile shape: -
Contour: -
Landform: Lateral moraine
Microtopography: Slight undulations; 30 cm relief, 2-3 m wavelength.
Geology: <1% granite, 99% Greywacke.
Surface description: Clasts angular, few subangular. Stones, cobbles, gravels. No staining evident.
Weathering stage: 1
Salt stage: 0
Depth to ICP: 20 cm
Depth of coherence: 20 cm (wet)
Temperatures (℃):

Air	Surface	5 cm	10 cm	15 cm	20 cm
6.0	6.9	5.1	3.3	2.1	0.1

Samples taken:

	Depth/horizon	
Kyf1.1	C	Chem/phys
Kyf1.A	0-2 cm	Micro
Kyf1.B	2-5 cm	“

Horizon	Surface	C
Base (cm)	-	20 (ICP)
Thickness (cm)	-	20
Field moisture	Moist	Moist
Boundary distinctness	Clear	Abrupt
Boundary shape	Wavy	Wavy
Voids	-	-
Colour	N5-6 (lithochromic)	2.5Y 4/2
Texture	Slightly stony, cobbley, gravel.	Very fine gravelly, silty, fine to coarse sand.
Clasts	Unstained, fresh, angular.	Unstained, fresh, angular.
Structure	Single grained	Single grained
Consistence	Loose	Slightly friable
Other features		NE (HCl)


KYF 1
1cm

OTW1

Date: 31/12/2010 *Time*: 1400
Weather: Fine, slight breeze
Location: S 85°24.602
E 171°20.471
Elevation: 2165 m
Location description: Shallow basin above ice level on slopes of Otway Massif; areas of patterned ground and stable desert pavement. Midway down a 60 m slope within basin.
Slope: 4°
Aspect: SSW
Profile shape: Linear
Contour: Linear
Landform: **???**
Microtopography: Slight undulations; 0.5 m maximum relief. Stable desert pavement.
Geology: 95% dolerite, <1% granite; remainder fines and some diabase.
Surface description: Strong well developed varnish. Most clasts ventifacted; spalling and cavernous weathering present..
Weathering stage: 4-5
Salt stage: 4-5
Depth of staining: 45 cm
Depth of coherence: 45 cm
Depth of visible salts: 7 cm
Temperatures (°C):

Air	Surface	5 cm	10 cm	15 cm	20 cm	25 cm	32 cm	40 cm	50 cm	60 cm	70 cm
-10.0	1.4	-1.1	-2.4	-3.2	-4.7	-4.7	-4.4	-5.6	-7.7	-9.6	-9.7

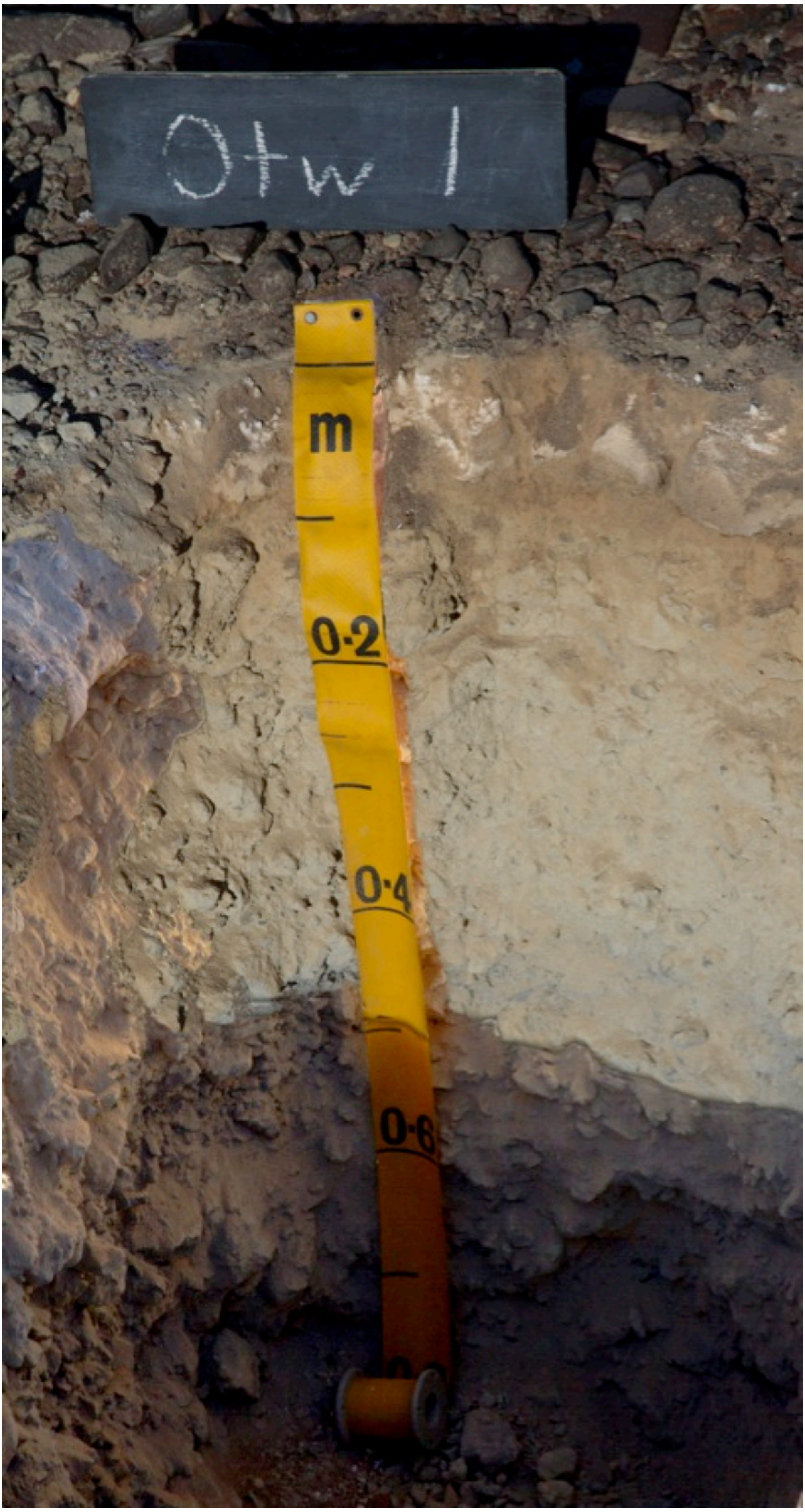
Samples taken:

	Depth/horizon	
Otw1.1	Dp	Chem/phys
Otw1.2	Bz(m)	“
Otw1.3	Bw	“
Otw1.4	Cox (12-22 cm)	“
Otw1.5	Cox (22-32 cm)	“
Otw1.6	Cox (32-45 cm)	“
Otw1.7	C (45-60 cm)	“
Otw1.A	0-2 cm	Micro
Otw1.B	2-5 cm	“

Horizon	Dp	Bz(m)	Bw
Base (cm)	1	7	12
Thickness (cm)	1	6	5
Field moisture	Dry	Dry	Dry
Boundary distinctness	Abrupt	Abrupt	Clear
Boundary shape	Wavy	Wavy	Wavy
Salts	10% (10-20 mm, soft nodules)	-	2% (10 mm, concentrations)
Pan type/cementation	-	Salt pan; ranging from 100% at top of horizon, to 30% at bottom.	-

Voids	-	30% (1-2 mm, vesicular)	-
Colour	7.5YR 5/3-4	20% White; 40% 2.5Y 8/1-2; 40% 10YR 4/4	10YR 5/4
Texture	Slightly cobbley, gravelly fine to coarse sand.	Very fine to medium sand (applies to 10YR 4/4 material)	Gravelly, silty fine to medium sand.
Clasts	Strongly stained and varnished, subround-subangular. Salt encrustation > 1 cm thick under clasts.	-	Unstained, fresh, subround and subangular.
Structure	Single grained	Massive	Single grained
Consistence	Loose	Hard	Soft
Other features	No (HCl)	No (HCl)	No (HCl)

Horizon	Cox	C
Base (cm)	45	80+
Thickness (cm)	33	35+
Field moisture	Dry	Dry
Boundary distinctness	Clear	Clear
Boundary shape	Wavy	Wavy
Salts	-	-
Pan type/cementation	-	-
Voids	15% (1 mm, packing voids round clasts)	-
Colour	2.5Y 8/2	5Y 8/1
Texture	Very gravelly, silty, very fine sand.	Gravelly silt
Clasts	Unstained, fresh, subround and subangular.	Unstained, fresh, subround and subangular.
Structure	Single grained	Very coarse blocks
Consistence	Soft	Extremely hard
Other features	No (HCl)	ST (HCl) Some blocks and clasts with polished faces.


Otw 1
m
0·2
0·4
0·6