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Soil Characteristics and Pedogenesis on Sub-Antarctic Marion Island

by

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Submitted in partial fulfilment of the requirements for the degree
Master of Science (Geography)
In the Faculty of Natural and Agricultural Sciences
University of Pretoria
Pretoria

April 2010

Declaration

I, Natalie Lubbe, declare that the dissertation, which I hereby submit for the degree Master of Science (Geography) at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNITURE:

DATE: 30 April 2010

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Abstract

Marion Island is a sub-Antarctic volcanic island with a cold, wet climate. Much of the interior of the island is bare, with vegetation only found at lower altitudes. No soil classification has yet been undertaken for the Island, and literature on its soils and pedogenesis is sparse. As part of a broader research project on Geomorphology and Climate Change the morphological, physical, chemical, mineralogical and biological properties of soils from seven terrestrial habitats on Marion Island were analysed. It was determined that pedogenesis has taken place on Marion Island. A relationship was observed between soils and terrestrial habitats. Soils were classified according to the World Reference Base (WRB) soil classification system as Histosols, Histic Andosols, Andosols and Regosols. Generalised soil profiles were constructed for each of the seven terrestrial habitats. The spatial distributions of soil types for the Island were predicted with the use of a GIS model and are presented, together with the implications of climate change for pedogenesis and soil distribution on Marion Island.

Acknowledgements

"*Ask, and you will receive. Search, and you will find. Knock, and the door will be opened for you*" Matthew 7:7. I would like to thank the Lord, for the opportunity that was provided to me to conduct this research project.

Funding was provided by the National Research Foundation (NRF) research project on Geomorphology and Climate Change, as part of the South African National Antarctic Programme (SANAP). Logistical support was provided by the Directorate: Antarctica and Islands, Department of Environmental Affairs and Tourism.

Ian Meiklejohn, and Johan van der Waals are thanked for their advice, supervision of the project and continued support.

Valdon Smith is thanked for help with background information, identification of habitat types and fieldwork. Jan Boelhouwers is thanked for fieldwork help and advice. Werner Nel, Jacqui Davis, Barend van der Merwe and Jonas Boström are thanked for their help in the field and continued support.

Phil Harris and Beth Taylor are thanked for their assistance with obtaining reflectance infrared data and Linda Prinsloo is thanked for her assistance with obtaining transmittance infrared spectra and Raman spectra. John Barry and Niel Malan are thanked for their assistance with understanding of chemical and mineralogical data.

Thank you also to my family, especially to Johan and my parents, for their continuous assistance, encouragement and support.

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Abbreviations

ARC	Agricultural Research Council
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
FTIR	Fourier Transform Infra-Red
GIS	Geographic Information System
GPS	Global Positioning System
IR	Infra-Red
ISCW	Institute for Soil Climate and Water
IUSS	International Union of Soil Sciences
LOI	Loss on Ignition
mamsl	Meters above mean sea level
NRF	National Research Foundation
SANAP	South African National Antarctic Programme
SSSA	Soil Science Society of America
USDA	United States Department of Agriculture
WRB	World Reference Base
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

Symbols

%	Percent
Ø	Phi
g	Gram
G	Gravitational acceleration
µm	Micrometer
mm	Millimetre
cm	Centimetre
ρb	Bulk density
ms	mass of oven dried soil
V	Volume / Velocity (where relevant, refer to specific definitions with equations)
r	Radius
ppm	Parts per million
ρs	Particle density
ρw	Fluid density
H	Viscosity of fluid

Definitions

It is noted that the terms below have been interpreted differently by different scientists, fields of science and at different times. The definitions as given below will be used for the purposes of this study.

Clay: “*a particle size term in which the size fraction is less than 0.002mm*” (Whittow, 2000).

Clay Mineral: “*naturally occurring material composed primarily of fine-grained minerals which is generally plastic at appropriate water contents and will harden when dried or fired*” (Klein, 2002).

Pedogenesis: the formation of the solum as a result of the soil forming factors, which are parent material, climate, topography, time, and living organisms (van der Watt & van Rooyen, 1995).

Primary Mineral: “*A mineral that has remained unchanged from the time it was formed out of molten rock*” (van der Watt & van Rooyen, 1995).

Regolith: All loose material lying above the undecomposed bedrock, including any soil horizons (Whittow, 2000).

Saprolite: Weathered or ‘rotted’ bedrock; may still contain the original parent rock structure (Whittow, 2000).

Secondary Mineral: “*A mineral resulting from the decomposition of another mineral or from the reprecipitation of the products of decomposition of another mineral*” (van der Watt & van Rooyen, 1995).

Sediment: Solid particles that have been transported from one place to another and deposited there (Whittow, 2000).

Soil: Unconsolidated material on the surface of the earth which has been altered by the five soil forming factors, which are parent material, climate, topography, time and living organisms (van der Watt & van Rooyen, 1995; Whittow, 2000).

Solum: The true soil consisting of A- and B- horizons; and not including any other horizons (Whittow, 2000).

Weathering: “*The physical and chemical breakdown of particles*” (Brady & Weil, 1999).

1 Introduction

The Prince Edward Islands are found approximately 1770km south east of Port Elizabeth, in the roaring forties of the southern Indian Ocean (Hänel & Chown, 1998) (Figure 1). They are located approximately 370km southeast of the mid-Indian oceanic ridge (Verwoerd, 1971). The Prince Edward Island group comprises two Islands, namely Prince Edward Island and Marion Island. These two Islands lie 22km apart (Verwoerd, 1971). Marion Island, the larger of the two (with an area of ±290km^2) lies to the south west of Prince Edward Island (45km^2) (Verwoerd, 1971). Mascarin Peak (previously known as State President Swart Peak) is the highest peak on Marion Island, rising to 1240mamsl (McDougall *et al*., 2001). The closest landfall to the Prince Edward Islands is the French Crozet Island group, 950km to the east (Chown & Fronemann, 2008).

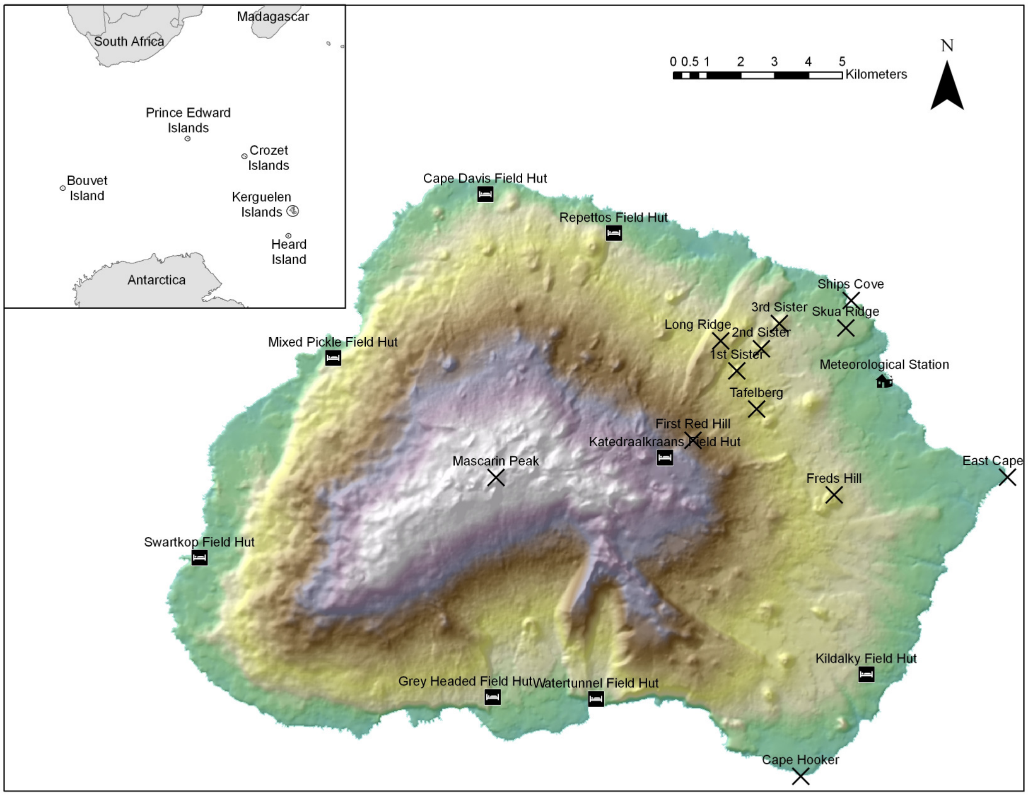


Figure 1: Location of Marion Island (after Chief Directorate of Surveys and Mapping, 2002).

The Prince Edward Islands were created by a shield volcano resulting from a mantle plume, similar to that of Hawaii (Verwoerd, 1971; McDougall, *et al.,* 2001; Boelhouwers *et al.*, 2008). The Islands were formed during the Quaternary Period, and are still volcanically active (Verwoerd *et al.*, 1981; Meiklejohn & Hedding, 2005; Boelhouwers *et al.*, 2008).

The Prince Edward Islands were first discovered in 1663. Their location was accurately recorded in 1772, and they were annexed by South Africa in 1947 (Marsh, 1948; Cooper, 2008). Marion Island now has a permanent base and forms part of a special nature reserve along with Prince Edward Island. The Prince Edward Islands are home to many birds, seals and invertebrates. These Islands form an important habitat for breeding of sub-Antarctic plant and animal species.

Soil research on Marion Island to date has focused predominantly on soil as a growth medium for plants. Little previous research has been conducted on the soils of Marion Island and this project was, therefore, conceived to investigate the characteristics, pedogenesis and distribution the soils found there.

2 Literature review

2.1 Climate

Marion Island, being surrounded by the Southern Ocean, has a hyper-oceanic climate, with low daily and seasonal variability in temperature (Le Roux, 2008a). Even though temperatures are buffered by the ocean, they regularly drop below 0°C at any time during the year (Le Roux, 2008a). The mean monthly air temperature as measured at the meteorological station (Figure 1) varies from approximately 4°C in winter to approximately 8.5°C in the summer months (Le Roux, 2008a). The meteorological station is on the eastern shore of Marion Island and intra-island scale variability is acknowledged, but poorly documented (Le Roux, 2008a).

Marion Island has a high degree of cloud cover, with a low incidence of sunshine, and a high precipitation (an average of 1975mm of precipitation per year in the 1990's). Precipitation falls predominantly as rain, but also as snow, hail, mist, and graupel (Le Roux, 2008a). The Island is situated in the roaring forties, with predominantly westerly winds that reach gale force on more than 100 days during each year (Le Roux, 2008a).

Temperatures on Marion Island have increased steadily since the 1950's, with a 1.2ºC overall increase between 1969 and 1999 (Smith, 2002). Other research using Marion Island's meteorological dataset from 1960 to 2001 indicates that weather on the island is warming and drying, with an increase in sunshine hours, non-rainy days, pressure, minimum and maximum temperatures (Rouault, *et al*., 2005). It is also noted from analysis of Antarctic ice core data that global temperatures have risen in the last 10000 to 15000 years, since the last ice age (McCarthy & Rubidge, 2005). Temperatures decreased slightly during the "little ice age" that occurred between about 1500 and 1700AD, but since then, temperatures have risen steadily (McCarthy & Rubidge, 2005).

2.2 Geology and geomorphology

The Prince Edward Islands were formed in geologically recent times (Quaternary Period) with lavas that originate from a mantle plume or 'hotspot', which lead to the formation of a shield volcano (Verwoerd, 1971). This volcano is still active today, with the most recent lava flow in the 1980's, and gaseous volcanic activity in 2004 (Verwoerd *et al.*, 1981; McDougall *et al.*, 2001, Meiklejohn & Hedding, 2005; Boelhouwers *et al.*, 2008). K-Ar dating suggests that rocks occurring above the sea surface on Marion Island are all less than one million years old, with the oldest calculated rock age being 454000 years before present (McDougall *et al.*, 2001). Volcanism on Marion Island is episodic, with eight identified periods of volcanism, and at least five, but up to eight cold periods in which glaciation occurred (McDougall *et al.*, 2001; Boelhouwers *et al.*, 2008).

Marion Island's surface geology was laid down as pahoehoe, aa and block flows, with aa being the most common (Verwoerd, 1971). The Island's rocks are characteristic of oceanic island basalt with 45 to 55% consisting of SiO_2 (McDougall *et al.*, 2001). The lavas on Marion Island can be divided into two main periods, the older grey lavas and the newer black lavas along with associated ash and scoria cones (Verwoerd, 1971) (Figure 2).

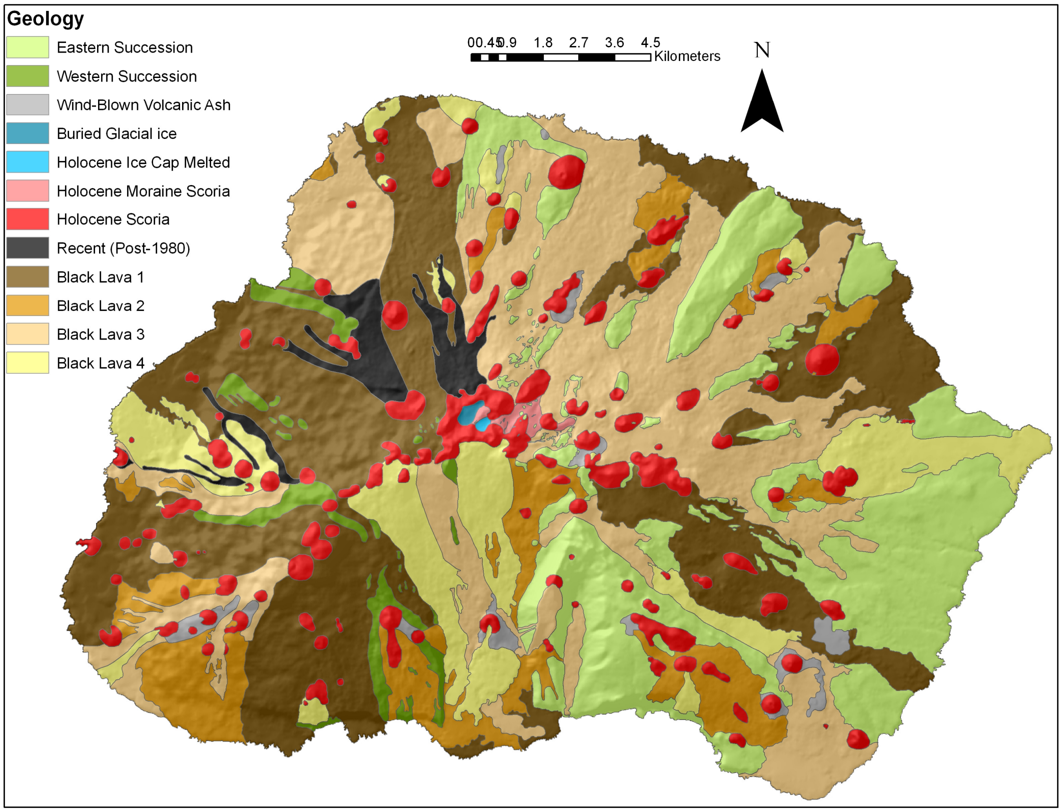


Figure 2: Geology of Marion Island (after Hedding, 2006).

The grey basalts were laid down in the first volcanic stage during the Pleistocene Epoch (McDougall *et al.*, 2001). They are fine grained, platy, compact, and massive. The grey lavas have been glaciated, as indicated by the resulting landforms (McDougall *et al.*, 2001). An analysis of autochthonous blockfields on Marion Island concluded that grey lavas were most likely weathered by release of pressure with deglaciation, and by some subsequent granular scale weathering (Sumner & Meiklejohn, 2004).

The black lavas, as well as the associated scoria cones, are basaltic in composition and were laid down during the second volcanic stage, which occurred during the Holocene Epoch (McDougall *et al.*, 2001). They usually contain visible vesicles and may contain phenocrysts of plagioclase, pyroxene and / or olivine (Verwoerd, 1971). These lavas do not show evidence of glaciation (McDougall *et al.*, 2001). It has been shown that the black lava weathers considerably faster than the older grey lavas (Sumner, 2004; Boelhouwers *et al.*, 2008).

In coastal areas, wild animals frequenting Marion Island play a role in the weathering and erosion of sediment. Three penguin species, four burrowing bird species (petrels and prions) as well as two of the seal species have been identified as animals having a significant effect on the geomorphology of the Island (Boelhouwers *et al.*, 2008).

It was previously noted by researchers that an ice cap existed in the centre of the island (Verwoerd, 1971), which is now a fraction of its originally documented size (Sumner *et al.*, 2004). Permafrost was also documented on Marion Island in recent years (Sumner & Meiklejohn, 2004). It is now recognised that most, if not all of the ice in these areas is rapidly degrading or has disappeared altogether (Boelhouwers *et al.*, 2008).

2.3 Vegetation

Wielgolaski (1997) places Marion Island within the Tundra Biome. Plants within this biome (and those found at high latitudes) are generally adapted to colder temperatures, having amongst others, a shorter, more rapid growing season (Wielgolaski, 1997). The annual net primary production of all plant communities on Marion Island is high (Smith, 2008). Nitrogen nutrient pools are low , but in line with other sub-antarctic areas (Smith, 2008). Herbivores (in the case of Marion Island, indigenous herbivores are invertebrates) consume approximately 3-5% of the primary production of vegetation on Marion Island, however, the introduced house mouse is likely to consume at a much higher rate (Kanda & Komárková, 1997). The deposition of washed up seaweed and manure by seabirds and seals will add to the organic matter production on the Island (Kanda & Komárková, 1997). Plant production in tundra regions becomes dead organic matter, which feeds detritivores, or decomposes at a very slow rate due to the low temperatures (Kanda & Komárková, 1997). Detritivores play an important role in the breakdown of dead organic matter in order to release the nutrients therein (Kanda & Komárková, 1997). It has been shown that soil microfauna are crucial for the nitrogen mineralization on Marion Island (Smith & Steenkamp, 1992a; Smith, 2008).

Marion Island has 23 vascular plant species, and at least 90 moss, 44 liverwort and 108 lichen species (Gremmen & Smith, 2008). It is estimated that approximately 5% of these species are endemic to the Prince Edward Islands, while about 20% are endemic to Southern Indian Ocean Islands (Gremmen & Smith, 2008). Humans have introduced 18 species of vascular plants to Marion Island, 12 of which still remain (Gremmen & Smith, 2008).

Eight major habitat types have been identified on Marion Island (Gremmen & Smith, 2004). These are salt-spray, biotic, drainage line, mire, fernbrake, fellfield, polar desert and aquatic habitats (rivers, stagnant lakes and ponds). Several minor habitat types also exist; these cover only a small portion of the Island (for example, lava tunnels and cliff faces). The seven terrestrial habitats as described by Gremmen & Smith (2004) are detailed in Table 1.

Table 1: Key plant species and characteristics of the seven terrestrial habitat types considered Gremmen & Smith, 2004; Smith[i]).

Habitat	Key plant species	Other characteristics
Biotic	• *Poa cookii* • *Cotula plumosa* • *Marchantia berteroana* • *Callitriche antarctica* • *Poa annua*	• Strong influence of animals, such as seals, penguins, albatrosses, prions, and petrels. • Enriched with nutrients as a result of animal activity.
Saltspray	• *Crassula moschata* • *Cotula plumosa*	• Near the coast, in areas receiving sea spray. • Presence of kelp on the land surface.
Mire	• *Sanionia uncinata* • *Agrostis magellanica* • *Juncus scheuchzerioides* • *Blepharidophyllum densifolium* • *Clasmatocolea humilis*	• Very wet, with groundwater levels very close to or at the surface. • Peat deposits.
Drainage line	• *Acaena magellanica* • *Agrostis stolonifera*	• Linear feature, characterised by pronounced water flow (may be subsurface).
Fernbrake	• *Blechnum penna-marina*	• Well drained lowland slopes.
Fellfield	• *Azorella selago*	• Windswept areas. • The surface is partially covered with stones and patchy vegetation.
Polar desert	• None	• Lack of plants. • Lichens and mosses present.

In order to gain a better understanding of plant succession on Marion Island, the succession of vegetation on the 1980 lava flow has been monitored (Gremmen & Smith, 2008). Within the first year *Bryum* moss species were found to be growing on the newly deposited rocks (Gremmen & Smith, 2008). Thirteen years later a lush growth of bryophytes and lichens were observed, and 18 years after the eruption, four vascular plants and 10 other plants were identified (Gremmen & Smith, 2008). Twenty three years after the eruption, the lava flow was almost covered by vegetation (mostly bryophytes) (Gremmen & Smith, 2008). Gremmen & Smith (2008) suggest that the establishment of vegetation at this monitored site was aided by the low altitude (less than 100m), and mention that floral succession is most likely initiated by the vascular *Azorella selago* rather than the mosses observed on the 1980 lava flow due to the differences in relative availability of moisture. *Azorella selago* plants are crucial to soil formation and the succession of vegetation as they accumulate organic matter and fine volcanic particles, and other plant species establish themselves on the *Azorella selago* cushions (Gremmen & Smith, 2008). It was however found in a study of plant succession on a glacial foreland in the Kerguelen Islands that *Azorella selago* plants were late-colonising species while *Poa kerguelensis, Poa annua, Ceratium fontanum* and *Colobanthus kerguelensis* were the pioneering plants there (Frenot *et al*, 1998). Of these species all except *Poa kerguelensis* are also found on Marion Island (Gremmen & Smith, 2004).

2.4 Fauna

Marion Island is home to three indigenous seal species and 28 bird species, consisting mainly of penguins, albatrosses and petrels (Ryan & Bester, 2008). The common house mouse was introduced to the Island, and is the only naturalised vertebrate remaining (cats were introduced, but have been successfully eradicated) (Ryan & Bester, 2008). Several invertebrate species are also found on the Island. These are generally adapted for their environment. ‘Flying’ invertebrates have lost or reduced wings (Hänel & Chown, 1998).

Seals which breed and moult on Marion Island are the Elephant seal, Sub-Antarctic fur seal and Antarctic fur seal (Ryan & Bester, 2008). Other species of seal have been sighted on occasion, but do not breed or moult at the Island (Ryan & Bester, 2008). The biomass of these three seal populations on Marion Island is approximately 15000t (Ryan & Bester, 2008). Seals bring nutrients to the Island in the form of faeces, placentas, corpses and moulted skin and hair (Ryan & Bester, 2008).

Four species of penguins are found on Marion Island. These are the king, gentoo, macaroni and southern rockhopper penguins (Ryan & Bester, 2008). Penguins contribute 8900t of biomass, which is 97% of the total biomass of breeding birds at Marion Island (Ryan & Bester, 2008). King and macaroni penguins breed in dense colonies and erode much of the substrate on which they breed as a result (Boelhowers *et al*, 2008). Many of the nutrients brought onto the Island by the penguins (e.g. nitrogen) are washed back out to sea, or volatilised (Smith & Froneman, 2008).

Four species of albatross (wandering, grey-headed, light mantled sooty, and dark mantled sooty) breed on Marion Island (Ryan & Bester, 2008). Albatrosses account for approximately 100t of biomass on Marion Island (Ryan & Bester, 2008). Wandering albatrosses breed in coastal plain areas, and build nests from peat and vegetation, increasing the nutrients of the immediate vicinity thereof (Ryan & Bester, 2008). The other albatross species make nests of tall cones of muddy peat on cliff faces (Ryan & Bester, 2008).

Other bird species that breed on Marion Island include petrels, skuas, kelp gulls, terns, prions and Crozet shags (Ryan & Bester, 2008). The lesser sheathbill is the only terrestrial bird species, and scavenges mostly within penguin colonies to obtain its food (Ryan & Bester, 2008).

Seals and birds influence Marion Island by acting as erosion agents, trampling surfaces and transporting propagules (Ryan & Bester, 2008). It is estimated that penguins bring 30000t of guano, feathers, carcasses and eggs onto Marion Island each year (Ryan & Bester, 2008).

2.5 Soil

Several authors have investigated soils as a growth medium for plant on Marion Island (Huntley, 1971; Smith, 1976; 1978; Smith & Steenkamp, 1992a; 1992b; Smith, 2003; 2005; Smith & Mucina, 2006). Soils were previously classified as Highmoor peats, Lowmoor peats and Rawmark based on their moisture content, pH, organic content, and ion content (Huntley, 1971). Peat formation is common in the cold, wet, poorly drained lowlands (Smith, 1976). Soils on well drained slopes are dominated by a greater mineral component, and within the Fellfield habitat, little pedogenesis has taken place (Smith, 1976). Gribnitz *et al.* (1986) found abundant glass fragments, plagioclase, and augite in the 'soil' sediments they analysed. They found no signs of mineral alteration, and could not find any clay minerals (Gribnitz *et al*,. 1986). No biotite or olivine where found in the samples analysed (Gribnitz *et al.*, 1986), contradicting Verwoerd's (1971) previous findings. Gribnitz *et al.* (1986) considered the only possible parent material of 'soils' to be ash, and described a generalised 'soil' profile to contain a few centimetres of humic accumulation overlying up to three different layers of ashy deposits, under which a completely un-weathered scoria, black or grey lava could be found. They also attributed all 'soil-formation' to three processes only, namely: accumulation of organic matter, percolation of humic acids, and precipitation of iron minerals at the water table surface (Gribnitz *et al.*, 1986).

Soil research on Marion Island has focused predominantly on soil as a growth medium for plants (Huntley, 1971; Smith, 1976; 1978; Smith & Steenkamp, 1992a; 1992b; Smith, 2003; 2005; Smith & Mucina, 2006). Smith (1978) showed that soils on Marion Island are acidic with pH varying between 3.2 and 5.9, and have a cation exchange capacity which increases with increasing organic matter content. Little research has been undertaken on soils of Marion Island with regard to their pedogenesis, classification and distribution.

2.5.1 Soils in the sub-Antarctic

Six soil zones have been identified within the sub-Antarctic region as a whole (Bockheim & Ugolini, 1990). These are: sub-Antarctic forest; sub-Antarctic low tundra; sub-Antarctic high tundra; Antarctic subpolar desert; Antarctic polar desert and Antarctic cold desert. Due to the sparse data the boundaries of these zones have not been fully mapped, but Marion Island falls within the sub-Antarctic tundra zone, where dominant soils are likely to be peat accumulations and 'Sub-Antarctic brown soils' (soils with a litter layer, a humified, brown A horizon, and a weakly developed B horizon) (Bockheim & Ugolini, 1990). While acknowledging that soil formation is the result of several interactive processes, Bockheim & Ugolini (1990) highlighted several key processes that are specific to the formation of soil in the Antarctic and Sub-Antarctic regions; these being: salinisation (salt accumulation), carbonation / decarbonation (accumulation / dissolution of carbonates), rubification (reddening of soil), pervection (migration of silt & clay), peat accumulation (accumulation of organic matter), melanisation (formation of a deep, black surface horizon), and podzolisation (mobilisation & movement of organic matter and / or sesquioxides).

2.5.2 Soils of volcanic origin

Soils which form as a result of the weathering of volcanic ejecta generally have distinctive andic properties, including variable charge characteristic, high water retention, and high phosphate absorption (Arnalds & Stahr, 2003). Volcanic soils typically have low bulk densities, and it is noted that only highly organic soils have a lower bulk density (Nanzyo, 2002; Arnalds & Stahr, 2003). Volcanic ash soils are characteristically rich in humus and dark in colour (Nanzyo, 2002). These unique properties of volcanic soils are attributed to accumulation of organic matter and the formation of noncrystalline materials (Dahlgren *et al.*, 2004). Soils of volcanic origin may be classified as Andosols in the WRB Soil Classification System (Dreissen *et al.*, 2001).

Andosols can be divided into two distinct groups, namely allophanic Andosols and nonallophanic Andosols (Dahlgren *et al.*, 2004). Allophanic Andosols are dominated by the presence of allophane and imogolite, and generally form in environments with higher pH (5-7), lower rainfall (<1000mm) with basaltic type parent material having coloured volcanic glass (Dahlgren *et al.*, 2004). Nonallophanic Andosols are dominated by Al humus complexes and 2:1 layer silicates and form preferentially were pH is lower (<5), rainfall is higher (>100mm) and parent material is base poor (as in ryolite or andesite) with noncoloured volcanic glass (Dahlgren *et al.*, 2004).

The mineralogical content of basalt at various stages of weathering was analysed by Moon & Jayawardane (2004), and showed that the diversity of clay minerals found increased over time. They found that moderately weathered basalt (discoloured rock with some soil material) contained clay minerals such as smectite, illite and kaolinite. In highly weathered samples (predominantly soil with some corestones), kaolinite, illite, halloysite, beidellite and montmorillonite were found (Moon & Jayawardane, 2004). In completely weathered basalt (soil material containing relict rock structure), saporite, vermiculite, goethite and hematite were found in addition to the clay minerals occurring at other stages of weathering (Moon & Jayawardane, 2004).

Some soils in various regions of Ecuador have been classified as Andosols (Buytaert *et al.*, 2006). The occurrence of Holocene volcanic deposits, a cold, wet climate and steep topography (Buytaert *et al.*, 2006) make this part of Ecuador comparable with Marion Island. Soils in the Ningar and Huagrauma regions were formed in an area that was built up by volcanic deposits and covered by ash falls during the Holocene (Buytaert *et al.*, 2006). These soils were all classified as Andosols and are dark in colour with a high organic matter content (up to 68%) (Buytaert *et al.*, 2006). They have a low pH (4.4-5.6), a low bulk density (0.13-0.72g.cm-^{1}) and are at an advanced stage of weathering (shown by the presence of vermiculite and kaolinite) (Buytaert *et al.*, 2006). Soils in the Rio Paute basin of Ecuador, also classified as Andosols, exhibit a large abundance of volcanic glass (24-49%), an Al+½Fe ratio of 2.4-4.0%, and a lower (but still high in terms of soil classification) organic carbon content of 17-20% (Buytaert, *et al.*, 2006).

A soil profile on the western side of the Piton des Neiges shield volcano in La Réunion, that has been influenced by recent volcanic deposits was classified as a Spodosol (United States Department of Agriculture (USDA) Soil Classification System; equivalent to a Podzol in the WRB Soil Classification System) (Driessen *et al.*, 2001; Basile-Doelsch *et al.*, 2005). The organic carbon content of the soil profile analysed was high in all the horizons and loss on ignition values varied from 11.8% - 62.3% (Basile-Doelsch *et al.*, 2005).

Young soils studied in the White River Tephra in Canada were affected by the deposition of volcanic material (ash and tephra) at two different times in their formation (Smith *et al.*, 1999). After each volcanic deposit, organic matter accumulated as a forest floor developed (Smith *et al.*, 1999). Based on the evidence available from the profiles studied, the authors concluded that the soils were not yet sufficiently developed to be classified as Andisols (USDA Soil Classification system, equivalent to the Andosol in the WRB Soil Classification System) (Smith *et al.*, 1999). Soils were therefore classified as Cryosols due to the presence of permafrost (at a depth of 2m) (Smith *et al.*, 1999). Smith *et al.* (1999) also concluded that it would take at least 4000 to 5000 years of soil development in the White River Tephra area of Canada to meet the criteria of an Andisol.

Iceland is a large volcanic island formed of predominantly basaltic lavas on a mid-ocean ridge. Iceland is still volcanically active with eruptions occurring every 4 to 5 years (Arnalds, 2004). The most recent volcanic eruption in Iceland occurred during April 2010. The large clouds of ash that spewed from the Eyjafjallajokull volcano will impact on the future soil formation in the area. Most soils in Iceland (86%) are classified as Andosols (Arnalds, 2004). These soils have a low bulk density ($0.17\text{-}0.4 g.cm^{-3}$) and a low pH (4.9-7 in H_2O) (Arnalds, 2004). Arnalds (2004) points out that soils other than Andosols in Iceland include Histosols, Leptosols and Cryosols.

Marion Island, along with Prince Edward Island was created by a shield volcano resulting from a mantle plume, similar to that of Hawaii, which formed during the Quaternary Period (Verwoerd, 1971; McDougall *et al.,* 2001; Boelhouwers *et al.*, 2008). Studies in Hawaii indicate that the basalts there have weathered into Gibbsite or Goethite (depending on the environmental conditions) as well as montmorilonite (from olivine and pyroxene) and Kaolinite (from plagioclase). Gibbsite is formed in a continuously wet environment as the iron is leached out, while Goethite is formed in an area where there is a seasonal change in wet and dry climatic conditions (Chorley et al, 1984).

2.5.3 Pedogenesis

Pedogenesis is defined as the formation of the solum as a result of the five soil forming factors (van der Watt & van Rooyen, 1995). Soil can be defined as unconsolidated material on the surface of the earth which has been altered by these soil forming factors (van der Watt & van Rooyen, 1995; Whittow, 2000).

2.5.3.1 Independent soil forming factors

Jenny (1941) determined that five independent variables exist which define the soil system. These five independent variables, or soil forming factors, are climate, organisms, topography, parent material, and time. All other soil variables or characteristics (such as clay content, porosity, pH, etc) are dependent on these five soil forming factors, therefore it can be said that soil is a function of these factors (Equation 1) (Jenny, 1941). Should all five of these factors be fixed, only one type of resulting soil can exist (Jenny, 1941).

$$s = f(cl, o, r, p, t)$$

s = Soil
f = Function of
cl = Climate
o = Organisms
r = Topography
p = Parent material
t = Time

Equation 1: The soil system (Jenny, 1941).

2.5.3.1.1 Climate

Climate can be defined as "*the average weather conditions at a specific place*" (Whittow, 2000). Climate influences the nature and intensity of weathering processes (Brady & Weil, 1999). Jenny (1941) stresses the complexity of quantifying climate as a soil formatting factor, and divides climate into its most important two factors, namely moisture and temperature. Some weathering process can only occur at certain temperatures or moisture levels.

Chadwick *et al.* (2003) analysed a series of soil profiles along a climatic gradient, and found that weathering, mineralogy and soil exchange properties differed along the rainfall gradient studied. They also showed trends along the rainfall gradient of various soil properties (organic matter content, pH, cation exchange capacity etc) (Chadwick *et al.*, 2003).

Generally, chemical reactions double or even triple for every 10ºC rise in temperature (Jenny, 1941; Brady & Weil, 1999; Dahlgren *et al.*, 2004). As previously mentioned, the mean annual air temperature on Marion Island is 5.7°C (Le Roux, 2008a). The low temperatures may result in slowed biochemical reactions, and allow for the accumulation rather than the disintegration of organic matter (Brady & Weil, 1999). Hall & André (2001), however, indicate that the factor limiting chemical weathering in cold regions may be the availability of water, as apposed to the colder temperatures. The temperature on Marion Island may regularly fall below the 0°C threshold (Le Roux, 2008a). This may allow the soil and parent material to be altered by cryogenic processes. A study of the differences in temperature within different microhabitats on Marion Island was conducted by Chown & Crafford (1992), and it was found that the mean temperature in adjacent microhabitats varied by as much as 5.2°C. Temperature differences, even over such a small scale may influence the weathering process active at any point in time.

The availability of water is an important factor for many chemical reactions. Marion Island receives an average of 1975mm of precipitation per year in several forms (Le Roux, 2008a). Water is, therefore, available for uptake by plants and for chemical reactions on Marion Island. Water is, however, not necessarily readily available in the polar desert regions, as it may be frozen for some parts of the year. Marion Island experiences strong westerly winds, often reaching gale force (Le Roux, 2008a). This increases the chances of physical weathering by means of wind action.

2.5.3.1.2 Living organisms

From the point of view of soil formation, living organisms can be divided into four main groups. These are: microbes, vegetation, animals and man (Jenny, 1941). Microbes (including lichens and mosses) will play a role in the early stages of soil formation before vegetation has become established in colder / relatively drier areas. Even though plants and animals do not live in the polar desert regions, lichens and mosses will have an effect on weathering and soil formation on Marion Island.

Vegetation minimises erosion rates and assists weathering within the profile. Plant roots may aid physical weathering by penetrating the soil. Plants assist chemical weathering by releasing organic acids which result in complexation and other chemical reactions within the soil profile. Plants also add organic matter to the soils when residue (plant litter) is deposited on the soils.

Animals play a role in soil formation. Indigenous fauna on Marion Island is, however, limited to seals, penguins and other birds and insects. Mice (alien invasive fauna) may also play a significant role in the formation of soils. Humans impact on the soils by constructing structures, compacting soil (along footpaths) and altering soil structure and functioning by working the soil.

2.5.3.1.3 Topography

Topography refers to "*the surface features of the earth's surface*" (Whittow, 2000). Steep slopes generally prevent the infiltration of water, and encourage erosion, thus limiting soil formation in these areas (Brady & Weil, 1999). Depressions are likely to receive more infiltration than slopes, as the water from precipitation as well as water from runoff of surrounding areas will be allowed to infiltrate, thus making them locally wetter, and the slopes locally drier (Jenny, 1941).

2.5.3.1.4 Parent material

Parent material is "*the material from which soil is formed*" (Whittow, 2000). Parent material may be considered the C-horizon of the soil profile, however this assumption is not always correct and the soil may have formed from other parent material which has since weathered in its entirety (Jenny, 1941). The grain size of the parent rock will influence the texture of the resulting soil (Brady & Weil, 1999). It is suggested by Jenny (1941) that if climate, organisms, topography and time are constant, then the parent material can be differentiated by the soil texture. The chemical and mineralogical properties of the parent material will affect the properties of the resultant soil (Brady & Weil, 1999).

Organic parent materials are formed in areas where the rate of plant growth exceeds the rate of residue decomposition (Brady & Weil, 1999). This commonly occurs in very wet areas as a result of a lack of oxygen (Brady & Weil, 1999).

2.5.3.1.5 Time

Time is "*the period through which an action, condition or state continues*" (Whittow, 2002). Soil forming processes all take time. The longer the time passed, the more weathering will have taken place and the greater the degree of soil formation (Brady & Weil, 1999). Over time, sediment will evolve into a young soil, and this in turn will evolve into a more mature soil. The rate of soil formation may differ from one place to another and will be dependent on environmental factors as discussed above such as temperature, moisture, degree of plant and animal activity, etc. The more horizons that exist within a profile, and the greater their thickness, the more mature the soil is considered to be (Jenny, 1941).

2.5.3.2 Dependent soil forming factors

Weathering is the alteration or disintegration of rocks and minerals (primary and secondary) at or near the earth's surface as a result of their not being in equilibrium with the surrounding environment in order to produce more stable forms (Boul *et al.*, 1989). Weathering processes are dependent variables of soil formation and none of them can take place independently. They are influenced by parent material, climate, living organisms and time. Weathering processes have been briefly discussed below. It should, however, be noted that these processes operate in conjunction with one another, simultaneously, and / or assist one another. Marion Island has a periglacial environment that favours conditions for mechanical weathering processes (Sumner & Meiklejohn, 2004).

2.5.3.2.1 Physical / mechanical weathering processes

Physical weathering processes refer to all weathering process that come about as a result of physical stresses placed on rocks, such as:

- Cryogenic process: occurs when water freezes and ice melts as the temperature fluctuates around freezing point (Driessen *et al.*, 2001).
- Granular disintegration: the dislodgement of particles or disintegration of grains as a result of the freezing of pore water and / or the expansion and contraction of rocks caused by insolation (Whittow, 2000).

- Weathering caused by the precipitation of or hydration of salts: causes physical stresses on particles (Whittow, 2000, Goudie, 1993).
- Unloading: pressure release as a result of the removal of overlying layers (Whittow, 2000).
- Insolation weathering: the weathering of rocks as a result of large daily temperature changes (Goudie, 1993).

2.5.3.2.2 Chemical weathering processes

Chemical weathering processes involve chemical reactions which alter the composition of rocks or parts thereof. Chemical weathering produces solutes (such as sodium, potassium, magnesium, calcium, strontium, etc), clays (complex hydrous aluminosilicates) and mineral residua (as yet unweathered components) (Chorley *et al.*, 1984). Chemical weathering processes including:

- Carbonation: the accumulation of carbonates in solution. Weak carbonic acid dissolves basic oxides to produce bicarbonate. (Bockheim & Ugolini, 1990; Whittow, 2000). Decarbonation is the dissolution of carbonates in solution.
- Hydrolysis: occurs when water combines with a salt, to form in soluble precipitates or clays (van der Watt & van Rooyen, 1995; Whittow, 2000).
- Oxidation and reduction reactions: occur when minerals are exposed to air or water. Oxidation and reduction reactions result in an alteration of the chemical makeup of the mineral. For example, the oxidation of Fe(II) oxide will result in the occurrence of FeOOH (rust) (Brady & Weil, 1999).
- Rubification: reddening of soil as Fe^{2+} or Fe^{3+} is oxidised during chemical weathering of minerals containing iron (Fe) (Bockheim & Ugolini, 1990).
- Solution: particles within a rock dissolve in water or carbonic acid (water combined with carbon dioxide) (Goudie, 1993).
- Hydration: the uptake of water by certain minerals that causes them to expand or swell, which may in turn cause disintegration (Goudie, 1993).
- Salinisation: the accumulation of salt within a profile or solution (Bockheim & Ugolini, 1990; van der Watt & van Rooyen, 1995; Whittow, 2000).

2.5.3.2.3 Biological weathering processes

Plant roots produce organic acids (such as oxalic, citric, tartaric, fulvic and humic acids). These acids react with minerals to form organic complexes (chelates) with metal ions, altering the chemical composition of minerals and releasing other ions for uptake by plants (Brady & Weil, 1999; van der Watt & van Rooyen, 1995; Whittow, 2000). This process can also be referred to as complexation or chelation. The resulting chelate is a heterocyclic ring compound containing at least one metal cation (van der Watt & van Rooyen, 1995; Sinclair, 2001). Laboratory experiments considering the effects of the presence of humus (and therefore humic acid) on the weathering of rocks indicated that basic rocks (such as basalts) are more heavily affected by the presence of humus than acidic rocks (Chorley *et al*., 1984). It is however also noted that the humic acid content of tundra soils is generally low (Chorley *et al*., 1984). Biological weathering processes include:

- Melanization: the formation of a deep, black surface horizon as a result of the incorporation of humus into a mineral soil (Bockheim & Ugolini, 1990; van der Watt & van Rooyen, 1995).
- Peat accumulation: the build up of organic matter, especially in soils with poor drainage, but receiving high rainfall (Bockheim & Ugolini, 1990).

2.5.4 Soil classification

Due to the geological history of Marion Island, and the relative age of rocks found there, it is expected that soils will be poorly developed, or volcanic in nature. It is well known that organic or fertile soils are associated with volcanic regions.

2.5.4.1 South African Soil Classification System

Based on the South African Soil Classification system (Soil Classification Working Group, 1991) it is expected that organic soils would fall within the Champagne soil form (organic topsoil with unspecified subsoil), while remaining (volcanic) soils may fall anywhere within the system. No provision is made for typically volcanic soils, or soils from cold regions as these are not found on the South African mainland.

2.5.4.2 World Reference Base (WRB)

According to the WRB Soil Classification System, soils that have developed from volcanic materials are most likely to fit into the Andosol soil group (Driessen *et al*., 2001). Andosols are dark soils that may be rich in allophones (highly reactive aluminium-humus complexes) or volcanic glass (Driessen *et al*., 2001). The soils formed are affected by factors such as the crystal size, character of the volcanic parent material, and the weathering regime.

In lower lying areas on the Island, organic soils predominate. Previous research (e.g. Smith, 1978) indicates that some soils in coastal areas of Marion Island have an organic matter content of as much as 46%. In the WRB classification system such soils may be classified as Histosols (Driessen *et al*., 2001). It is thus possible that Histosols may occur at lower altitudes of the Island.

In permafrost regions where soils are frost-affected, Cryosols may be present (Driessen *et al.*, 2001). It has however been shown that permafrost no longer exists on Marion Island (Hedding, 2006, Boelhouwers *et al.*, 2008).

3 Academic problem

3.1 Rationale

Soils as a medium for plant growth on Marion Island have been researched by Huntley (1971), Smith (1976; 1978; 2003; 2005), Smith & Mucina (2006) and Smith & Steenkamp (1992a; 1992b). Gribnitz *et al.* (1986), concentrated on the weathering of parent rocks to what they termed '*ash soils*'. Gribnitz *et al.* (1986) even suggested in their paper that true soils do not exist on Marion Island and described a generalised profile that contained a few centimetres of plant growth in humus, overlying several layers of varying ash. Little soil science research has been undertaken on Marion Island, especially with regard to the pedogenesis and classification of these soils and the relationships between plant communities and soils and altitude.

3.2 Aim

Given the scarcity of research relating to pedogenesis and soil classification on Marion Island, the aim of this study is to determine whether or not pedogenesis has taken place on Marion Island. If it is found that soil formation has taken place on Marion Island, soils will be described, classified, and their spatial distribution estimated.

3.3 Research questions

In order to achieve the aim, a set of research questions have been proposed as indicated below:

1. Has pedogenesis has taken place on Marion Island?
    a. Have soils been influenced by climate, topography, and living organisms?
    b. What is the parent material of the soils?
    c. Over what period of time have the soils formed?
2. Can it be shown that the vegetation habitats are related to soils on Marion Island?
3. Has altitude influenced the formation of soils on Marion Island?
4. What soil forms can be found on Marion Island?
5. What is the spatial distribution of soils on Marion Island?
6. Is climate change likely to have an effect on the soils found on Marion Island and their spatial distribution?

3.4 Method

In order to fulfil the aim of the project, and to answer the various research questions, soil samples were collected from Marion Island. Soil samples collected were analysed in order to determine their properties and characteristics.

3.4.1 Delimitations

Based on the nature of the research program currently taking place on Marion Island as well as the amount of specialised analysis required in order to determine certain soil properties, the fieldwork for this research project was conducted over two annual relief voyages to Marion Island. Fieldwork was therefore conducted during April and May of 2006 and 2007, and was limited to approximately 8 weeks in the field in total.

Fieldwork consisted of becoming acquainted with the general environment of the Island, selecting appropriate sample sites, collecting samples and describing soils *in situ*. Bulk densities of the soil were determined on the Island, whilst the majority of soil analyses were conducted during the months following the site visit in laboratories at the University of Pretoria.

This study concerns only the soil of Marion Island; however the geographical proximity of Prince Edward Island to Marion Islands as well as the similarity in their geological formation and climatological setting implies that results of the research may also be applicable to Prince Edward Island to some extent. A description of Prince Edward Island and its soils is, however, specifically excluded from this study.

3.4.2 Fieldwork

A total of 96 soil samples were collected from 47 sites during the annual relief voyages to Marion Island in April and May of 2006 and 2007 (Figure 3). Smith *et al.* (2001) noted that the impoverished flora on Marion Island, along with the harsh environment result in a link between plant communities, biotic and abiotic factors. Sites were therefore selected based on this observation, and sites were chosen where typical characteristics of each of the seven terrestrial habitat types (as defined by Gremmen & Smith (2004)) were identified. It was ensured that several samples were collected from each habitat in order to allow for comparison of soils from these habitats.

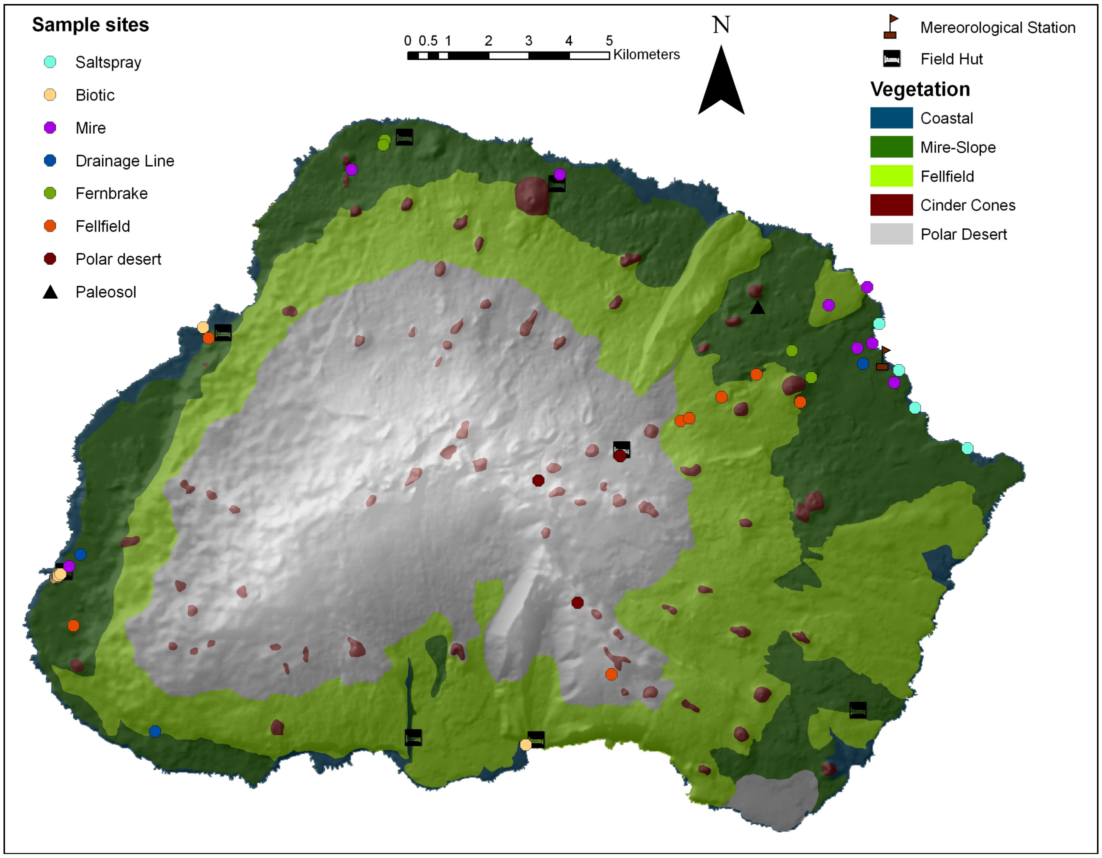


Figure 3: **Sample sites on Marion Island.**

Sample sites were selected using the judgement sampling technique which requires the sampler to use the knowledge and information available to determine where a suitable sample site exists (Petersen & Calvin, 1996). Samples were therefore collected from sites showing 'typical' habitat characteristics (key plant species, and characteristics) that best represented the population as a whole (Table 1). The judgement sampling technique is, by definition, biased since samples are selected based on the judgement of the sampler. However, with only short periods of fieldwork time on the Island, this technique was deemed to be the most appropriate.

Samples were collected from various Island aspects (Figure 3). The habitat of the sample sites may vary from that of the vegetation map on which they are plotted. This can be explained by the fact that small areas of a habitat may occur in many places (Smith & Mucina, 2006). The vegetation as depicted by the map has therefore been generalised and only the major habitat groups mapped (Smith & Mucina, 2006). Note also that on the vegetation map available for the Island (Mucina & Rutherford, 2006), the habitat types differ from the seven described by Gremmen & Smith (2004). On the vegetation map, (Mucina & Rutherford, 2006) the coastal vegetation class encompasses both the biotic and saltspray habitat types. The mire slope complex includes mires, drainage lines and fernbrake habitats, and cinder cones have been differentiated from the rest of the polar desert habitat. This also means that within any of the habitats depicted on the vegetation map, there may be small areas of another habitat.

At least three sample sites were selected within each habitat (Table 2). Samples taken at each site represented different identifiable soil horizons. In a few instances, where slope failures were found, a clear profile of the soil, unaffected by the slope movement was cut and fully analysed, in all other cases, samples were extracted with the use of an hand auger, and horizons were assumed to start and end where a visible change could be identified. While conducting fieldwork, a possible palaeosol was found, and additional soil samples were also collected at this site.

Table 2: **Number of sites and samples collected from each habitat type.**

Habitat	No of sites	No of samples collected
Biotic	15	21
Saltspray	4	10
Mire	8	15
Drainage line	3	6
Fernbrake	4	16
Fellfield	8	11
Polar desert	4	8
Palaeosol*	1	9

* The site where a possible palaeosol was found is not considered to represent a distinct habitat, however, it is included here to indicate the number of samples collected from the site.

An altitudinal transect starting at Skua Ridge, and ending at Tafelberg (Figure 3) was sampled to establish altitudinal variation in soil properties. This transect was chosen to closely follow that conducted by McDougall *et al.* (2001). Sample sites were chosen at approximately 100mamsl altitudinal intervals (Table 3). This was determined with the use of a handheld GPS. Sea cliffs at the start of the transect prevented low altitude sampling, and the first sample was taken at 43mamsl, and the transect ended at 458mamsl, where the gradient abruptly increased, and vegetation was no longer found. Other samples, not along the altitudinal profile, were taken at altitudes as low as 3mamsl, and as high as 947mamsl (Appendix A).

Table 3: **Altitudes of samples along the transect from Squa Ridge to Tafelberg.**

mamsl (GPS)	Habitat	Site number
43	Mire	26
103	Mire	27
201	Fellfield	33
299	Fellfield	32
401	Fellfield	29
458	Fellfield	28

3.4.3 Laboratory work

Laboratory work was conducted in order to determine the characteristics of the soil samples collected from Marion Island. The extent of this work was determined by soil properties that can be used to aid in fulfilling the aim of the study, soil properties that will be useful in the classification of the soils into soil forms in the WRB soil classification system and soil properties that will be useful in describing the general soil characteristics. Therefore, the following soil analyses were proposed:

1) Morphological properties:
    a) Soil colour.
    b) Observations of other pedological features.
2) Physical properties:
    a) Coarse particle size distribution.
    b) Fine particle size distribution.
    c) Bulk density.
3) Chemical properties:
    a) pH.
    b) Aluminium and iron ratio.
4) Mineralogical properties:
    a) X-Ray Fluorescence (XRF) to determine elemental composition of soils.
    b) X-Ray Diffraction (XRD) to determine mineral composition of soils.
5) Biological properties:
    a) Organic carbon content.
    b) Characterisation of biological soil composition (infrared analysis).

All soil samples were air dried before analysis. A sub-sample of approximately 50ml was taken out for mineralogical and infrared analyses. Sub-samples of approximately 100g were sieved (dry) for particle size analysis. All particles larger than 2mm were then discarded, and the remaining material was kept for further analysis. The <2mm fraction was used for fine sediment analysis, and the determination of all chemical parameters.

To determine whether or not clay minerals exist in some of the soils found on Marion Island, five samples were analysed further. These samples were sent to the Institute for Soil, Climate and Water (ISCW) at the Agricultural Research Council (ARC) for the determination of clay mineralogy as well as iron and aluminium content. Additional infra-red analyses were also performed on these samples in order to determine which portions of the soil medium were lost during loss on ignition analysis. Only five samples were chosen due to the cost and time requirements of the analysis. The results of these analyses while useful to fully describe the soil characteristics were not required in order to determine answers for the proposed research questions.

Of the five samples, four were chosen from the habitats that comprised mineral soils (fernbrake, fellfield and polar desert habitats) and one from an organic soil (mire habitat) for comparison. Two fernbrake samples were included in the mineral analysis as these soils are considered to be the best developed (field observation). Sub-surface samples were sent for clay mineralogy analysis, while surface samples were used for all other analyses.

Where applicable, results obtained for any single soil property analysed were compared with the specific requirements of soil horizons within the WRB Soil Classification System (Driessen, *et al.*, 2001). All horizons with fixed values within their criteria where considered, though not all were applicable to soils on Marion Island. Soil horizons were later considered holistically, taking earlier findings into account.

Details pertaining to the methods followed for the determination of each soil characteristic as described above are included in Chapters 4 to 8 along with the results (also refer to Appendices) and interpretation of each analysis. Descriptions of all samples taken at each sample site (soil colour, depth *etc*.) as well as basic site description (habitat, location, altitude) are tabulated in Appendix A. Detailed descriptions of typical profiles for each habitat are further discussed in Chapter 9.

4 Morphological soil properties

While conducting the fieldwork and collecting soil samples, several morphological soil properties were noted. These field observations are described below.

4.1 *Soil colour and texture*

Differences in colour and texture occurred from one soil horizon to the next (Appendix A.) Distinct colour differences were identified moving downwards in the saltspray and mire soil profiles. The surface horizon is lighter in colour than the subsurface horizon (Figure 4). Visible plant matter is found in the surface horizon, while plant material cannot be discerned in the subsurface horizon. The texture of the soil is smoother in the subsurface horizon than in the surface horizon (Figure 4).

Figure 4: Saltspray soil sample (sample site no 5). The surface horizon is on the left, with the subsurface horizon on the right.

The changes in colour in the fernbrake profile are clear. Fernbrake profiles have a dark brown surface horizon (Figure 5). Subsurface horizons are various shades of browns and reds, and the base of the profile is a darker colour (Figure 5). The texture also changed throughout the profile, and a coarser layer containing some scoria was noted in the middle of the profile as well as at the base. The scoria rich horizon in the middle of the profile may be attributed to a volcanic scoria deposit (possibly Island-wide); alternatively, it may have been deposited there by wind or water.

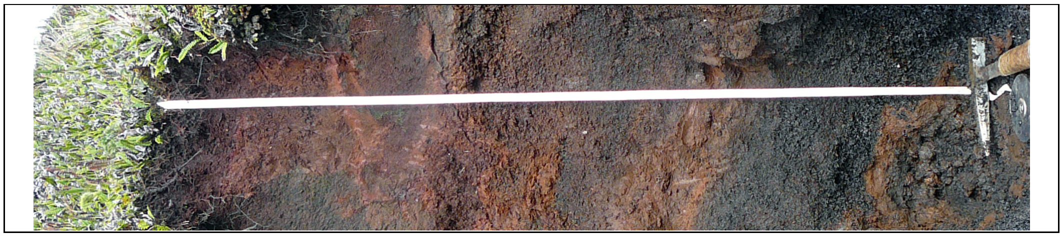


Figure 5: Fernbrake soil sample (sample site no 37). The surface horizon is on the left, with the subsurface horizon on the right.

4.2 *Ironpans / manganese nodules*

Within the fernbrake habitat there were accumulations of redder material at several depths within the soil profile (Figure 6). These layers were usually thin and of a different texture to that of the surrounding horizons. In some cases the accumulation was slightly harder than the surrounding horizons as well. These layers have been described as ironpans as they have the characteristics expected of ironpans (hardened accumulation of iron / manganese / organic compounds).

Figure 6: **Ironpan (fernbrake habitat; sample site no 1).**

Manganese nodules were identified in one case (Figure 7). Black hardened nodules were found, and were notably different from the black lava and scoria. The presence of several ironpans and manganese nodules within profiles is suggestive of a fluctuating water table, as well as active weathering and erosion processes.

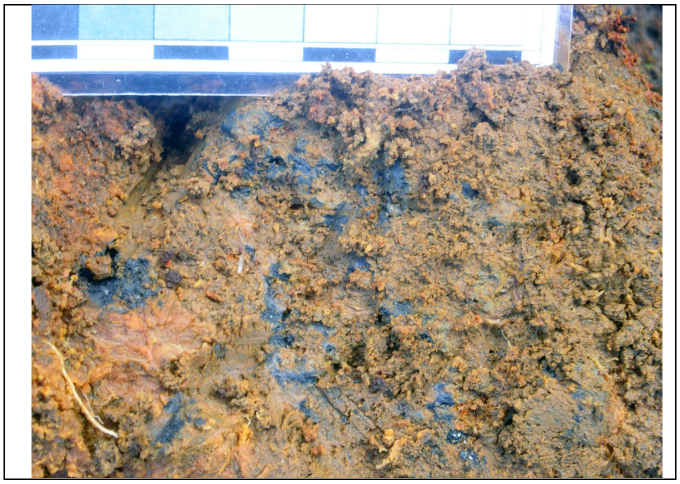


Figure 7: **Manganese nodules (fernbrake habitat; sample site no 19).**

4.3 Organic matter accumulation

Organic matter accumulation within soil profiles is particularly evident in mire, saltspray, drainage line, fernbrake and biotic habitats. In all cases plant material was recognisable near the surface, and became less recognisable lower in the profile (Figure 4). Humus enriched the organic content of the soils (Chapter 8) and also darkened the soil colour;

this is particularly noticeable in the surface horizons of profiles within the fernbrake habitat (Figure 8).

Figure 8: Organic horizon of a soil profile on Marion Island (fernbrake habitat; sample site no 1).

4.4 A palaeosol

A soil profile was identified below a thick layer of scoria south of third sister (Figure 1; Figure 3) that possibly represents a palaeosol. The profile was exposed by fluvial incision, with a river bed of an ephemeral stream below (Figure 9). The profile was poorly developed but a firmly cemented iron pan was found (Figure 10). Differences in textural properties were also noted during laboratory textural analysis. It is assumed that this is a palaeosol that developed before being covered by a scoria eruption. The scoria deposit buried the soil and prevented further soil formation there. The firmly cemented ironpan (Figure 10) was noted in several different locations in close vicinity to each other at a similar level, and continued deep within the river bank, beyond the point at which the surface scoria layer had been eroded, suggesting that it formed previously as a part of a soil profile.

Scott & Hall (1983) noted that palaeosols had developed near Kildalkey (Figure 1) on Marion Island during at least two of the interglacial periods that occurred. These palaeosols were old peat deposits, and pollen evidence indicated that vegetation including *Azorella* sp., *Cotula* sp., *Acaena* sp. and several other species were present during the interglacial periods (Scott & Hall, 1983). The palaeosols described by Scott & Hall (1983) are some distance from the one observed in this study, suggesting that others may exist on the island as well.

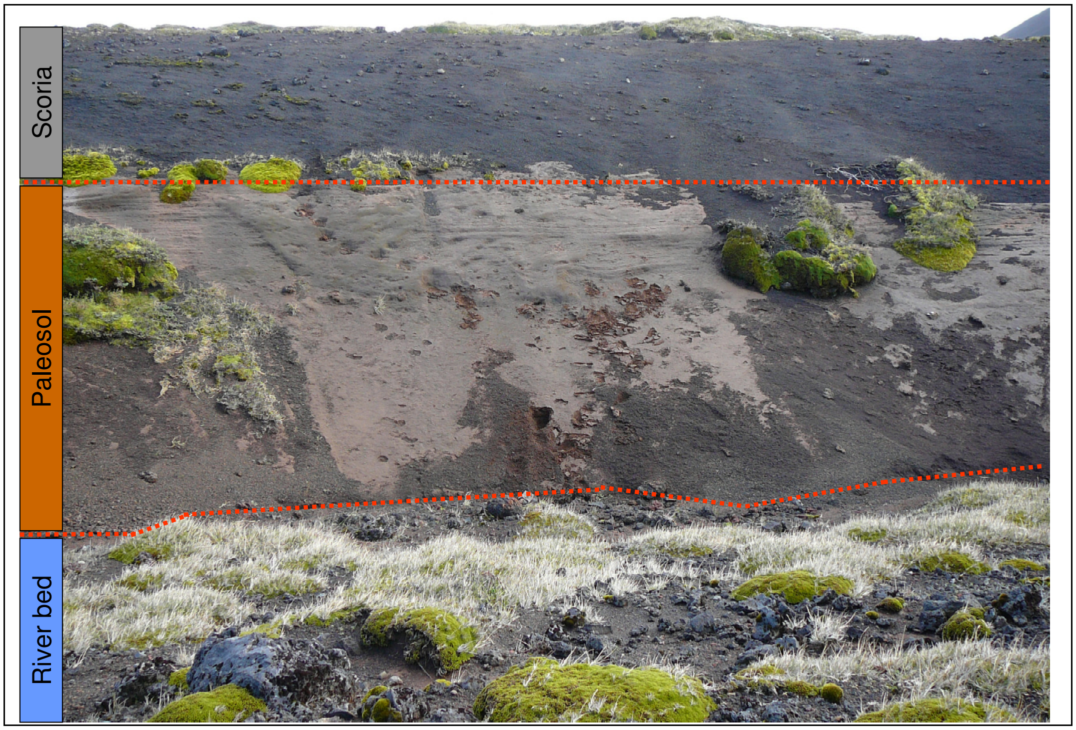


Figure 9: **Palaeosol found along a drainage line.**

Figure 10: **Palaeosol showing the firmly cemented ironpan.**

5 Physical soil properties

Bulk density and textural analyses were conducted on selected soil samples from Marion Island. The Island's General Purpose Laboratory was utilised for the determination of bulk density, and textural analyses were performed in the Geomorphology Laboratory at the University of Pretoria.

5.1 Bulk density

Bulk density is defined as the mass of the dry solid particles in a standard volume of field soil (Brady & Weil, 1999) and is a diagnostic criterion for two horizons in the WRB Soil Classification system (Andic and Vitric horizons) (IUSS Working Group WRB, 2006). The Andic horizon is generally found in areas of volcanic origin, as with Marion Island. Bulk density was determined on selected samples in the laboratory on Marion Island.

5.1.1 Method

Bulk density was only determined in areas where a profile could be exposed, or where the gouge auger (long, cylindrical auger, specifically designed for minimal disturbance) could be used, so that a known *in situ* volume of soil could be collected. The other clay and sand augers utilised in this study could not be used to collect soils for bulk density as it is very difficult to extract a known *in situ* volume of undisturbed soil using such an auger. In wet, marshy areas where the gauge auger was used, 10cm of the cylindrical sample was collected for bulk density determination. In drier areas where a profile could be cut, a square bulk density sampling box was used. The volumes of both the cylindrical and square samplers were determined and used appropriately for calculations. The samples were weighed, dried and re-weighed and the bulk density was determined (Equation 2). Bulk density determination can be very sensitive to sampling errors, therefore, three samples were taken from each site analysed, and the results averaged (IUSS Working Group WRB, 2006).

$$D_b = \frac{m_s}{V}$$

$D_b =$ Bulk density
$m_s =$ mass of oven dried soil
$V =$ Volume of in situ soil (pores & solids)

Equation 2: Soil bulk density (Brady & Weil, 1999).

5.1.2 Results

Average bulk density values were determined for 24 samples from 15 of the sample sites on Marion Island (Table 4). Bulk density values ranged from 0.07g.cm^{-1} to 1.29g.cm^{-1}.

Table 4: Percentage water content and bulk density of samples analysed.

Site (Sample)*	Habitat	Horizon	Water content (%)	Average bulk density (g/cm^3)
05 (O)	Saltspray	Surface	90.93	0.13
21 (O)	Saltspray	Surface	84.31	0.19
05 (A)	Saltspray	Subsurface	79.74	0.21
21 (A)	Saltspray	Subsurface	79.26	0.22
06 (O)	Mire	Surface	93.82	0.07
18 (O)	Mire	Surface	93.26	0.07
22 (O)	Mire	Surface	93.38	0.08
06 (A)	Mire	Subsurface	84.79	0.16
22 (A)	Mire	Subsurface	83.34	0.18
26 (1)	Mire	Surface	93.69	0.29
18 (A)	Mire	Subsurface	67.39	0.41
27 (O)	Mire	Surface	85.00	0.71
27 (A)	Mire	Subsurface	75.38	1.29
20 (A)	Biotic	Subsurface	78.10	0.26
20 (O)	Biotic	Surface	76.86	0.28
25 (1)	Drainage line	Surface	84.31	0.16
19 (O)	Fernbrake	Surface	75.00	0.27
19 (A/B1)	Fernbrake	Subsurface	73.12	0.28
19 (B2)	Fernbrake	Subsurface	65.73	0.38
24 (1)	Fellfield	Surface	73.78	0.28
33 (1)	Fellfield	Surface	48.59	0.67
32 (1)	Fellfield	Surface	50.38	0.71
28 (1)	Fellfield	Surface	31.46	0.82
29 (1)	Fellfield	Surface	30.16	1.04

**Refer to Appendix A for descriptions of samples.*

5.1.3 Interpretation

Bulk densities analysed were generally low (Table 4). Histosols typically have bulk densities of between 0.1g.cm^{-3} and 0.7g.cm^{-3} (Brady & Weil, 1999). Of the 24 samples analysed, 19 would fit into this category. Andosols generally have bulk densities between 0.6g.cm^{-3} and 0.9 g.cm^{-3} (Brady & Weil, 1999), and four of the calculated values would fit into this class. The WRB Soil Classification system (IUSS Working Group, 2006) defines bulk density as a diagnostic criterion of two different horizons; the results obtained were compared to these criteria (Table 5).

Table 5: **Frequency of occurrence of diagnostic criteria for bulk density in soils according to the WRB Soil Classification System (Driessen *et al.*, 2001).**

	Andic	**Vitric**
WRB bulk density requirement	**<0.9** g.cm^{-3}	**>0.9** g.cm^{-3}
Saltspray	4	0
Biotic	2	0
Mire	8	1
Drainage Line	1	0
Fernbrake	3	0
Fellfield	4	1
Polar Desert	NA	NA
Palaeosol	NA	NA
Total	**22**	**2**

5.2 Particle size analysis of course material

Particle size analysis was performed to differentiate between the coarser particle size fractions (sand, gravel, and coarser) of the soil. Soil texture or particle size distribution influences the physical and mechanical behaviour of the soil (Pansu & Gautheyrou, 2006). Particle size analysis was performed in the Geomorphology Laboratory at the University of Pretoria.

5.2.1 Method

Particle size analysis was undertaken using the sieve method (Briggs, 1977). A set of eight sieves (8mm; 4mm; 2mm; 1mm; 0.5mm; 0.25mm; 0.125mm; 0.063mm) were arranged according to size, decreasing from top to bottom. Approximately 100g of soil was dry sieved from each sample for 10 minutes on a shaker. This method allows the sand and gravel fractions to be separated into gravel (>8mm), fine gravel (2-8mm), coarse sand (0.5-2mm), medium sand (0.25-0.5mm) and fine sand (0.063-0.25mm). The silt and clay fractions gather in the pan at the base of the stack.

Ludwick & Henderson (1968) noted that there are many sources of error in sieving sediments to determine particle size distribution. While standards are set for the accuracy of sieving screens, it is accepted that they can only be manufactured to a certain degree of accuracy, and therefore, within any one sieve, some holes will be larger, while others are smaller (Ludwick & Henderson, 1968). Particle shape and the particles interaction with each sieve influences whether or not the particle will pass through a sieve (Ludwick & Henderson, 1968). An ellipsoid may or may not pass through a sieve (where the aperture is less than the length but greater and the width) depending on the angle at which it reaches the sieving mesh as well as how much it is agitated / shaken (Ludwick & Henderson, 1968). Sieves may also become clogged if lots of material gathers in any particular sieve, or if particles become lodged within the wire mesh (Ludwick & Henderson, 1968). Samples were all analysed in the same manner to limit the influences of potential error on the final interpretation of the results.

The median, mean, skewness, sorting and kurtosis (Equation 3) of samples were determined. The mean value represents the average of the dataset, and the median is the middle value (Briggs, 1977); these values will typically be close to each other, but are not necessarily the same.

a.	$Median = \phi 50$	$\phi Y =$ The size value (on the phi scale) read off the X-axis of the cumulative percentage graph corresponding to the percentage Y value given. *i.e.* $\phi 50 =$ the x-value at cumulative percentage of 50%.
b.	$Mean = \dfrac{\phi 90 + \phi 80 + \phi 70 + \phi 60 + \phi 50 + \phi 40 + \phi 30 + \phi 20 + \phi 10}{9}$	
c.	$Skewness = \dfrac{\phi 84 - \phi 50}{\phi 84 - \phi 16} - \dfrac{\phi 50 - \phi 5}{\phi 95 - \phi 5}$	
d.	$Sorting = \dfrac{\phi 90 + \phi 80 + \phi 70 - \phi 30 - \phi 20 - \phi 10}{5.3}$	
e.	$Kurtosis = \dfrac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$	

Equation 3: Parameters for statistical analysis of particle size. (a) Median. (b) Mean. (c) Skewness. (d) Sorting. (e) Kurtosis. (Briggs, 1977).

Skewness (Table 6) shows the symmetry or asymmetry of the data; the closer the skewness is to zero, the more symmetrical the dataset (Briggs, 1977). Sorting (Table 6) is an expression of the standard deviation of the sample; the lower the number; the better sorted the sample, or the less size classes that dominate (Briggs, 1977). Kurtosis (Table 6) is the peakedness of the distribution; the lower the value, the flatter the distribution curve (Briggs, 1977). These three parameters essentially describe the character of the distribution curve and can also be referred to as the moment measures (Whittow, 2000).

Table 6: Descriptions for results of skewness, sorting and kurtosis (Briggs, 1977).

Skewness		**Sorting**		**Kurtosis**	
Very negatively skewed	-1.0→-0.3	Very well sorted	<0.35	Very platykurtic	<0.67
Negatively skewed	-0.3→-0.1	Well sorted	0.35→0.50	Platykurtic (less peaked)	0.67→0.90
Symmetrical	-0.1→0.1	Moderately well sorted	0.50→0.70	Mesokurtic	0.90→1.11
Positively skewed	0.1→0.3	Moderately sorted	0.70→1.00	Leptokurtic (more peaked)	1.11→1.50
Very positively skewed	0.3→1.0	Poorly sorted	1.00→2.00	Very leptokurtic	1.50→3.00
		Very poorly sorted	2.00→4.00	Extremely leptokurtic	>3.00
		Extremely poorly sorted	>4.00		

Many different definitions and classifications exist for the size classes. These were developed for different countries or classification systems. For the purposes of this study soil classes used are defined by the Wentworth scale as described by Briggs (1977) (Appendix B).

5.2.2 Results

Results of the particle size distribution analysis were plotted on histograms (Figure 11), and cumulative percentage plots against the phi scale (Appendix C). The results were also plotted on a gravel:sand:mud ternary diagram with the aid of Gradistat (Blott, 2000) (Figure 12). A gravel:sand:mud ternary diagram is used as the samples were generally course. The samples all plot as ‘sand’ or ‘silty sand’ in a sand:clay:silt ternary diagram (Appendix C).

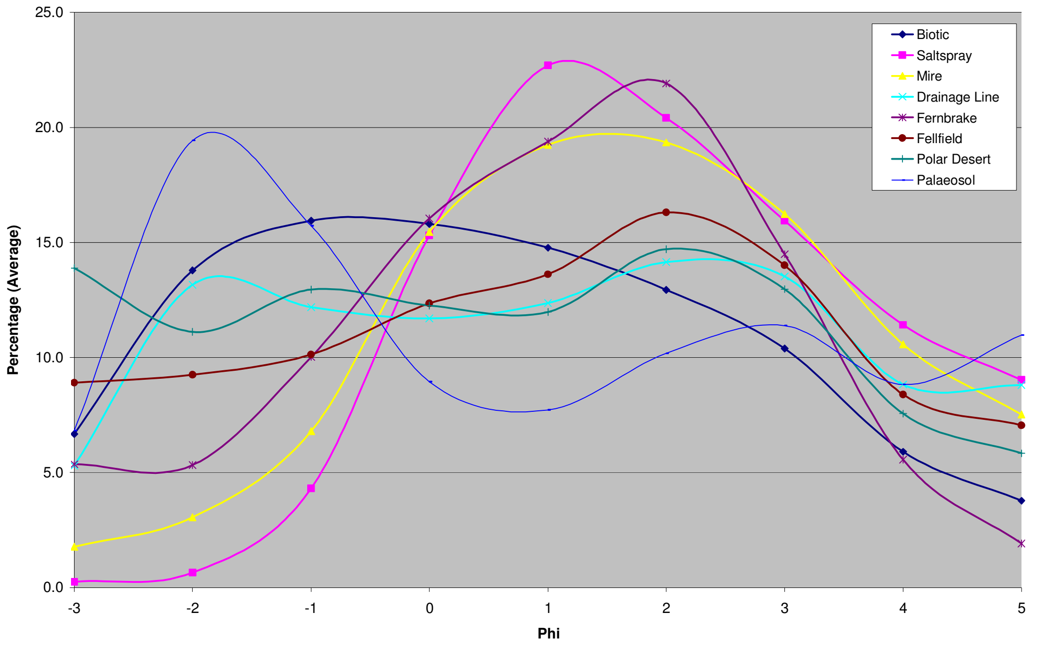


Figure 11: Average particle size distribution curves for each habitat.

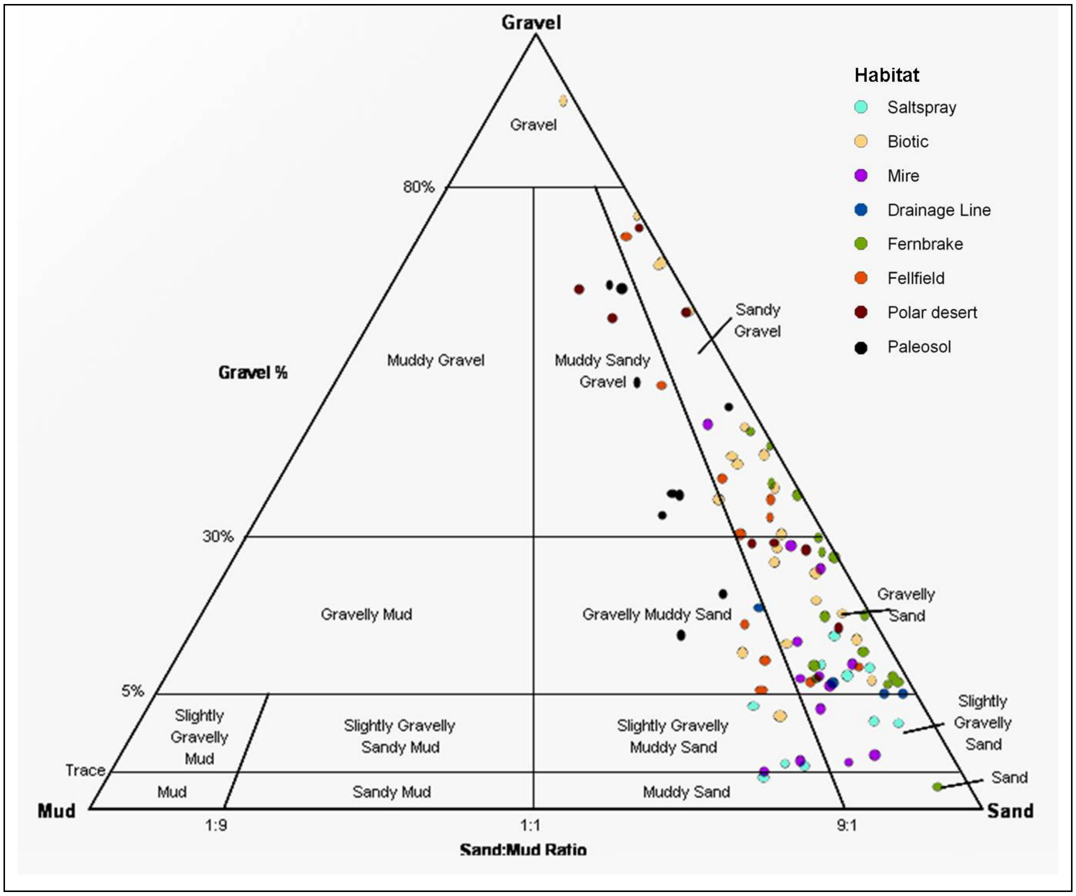


Figure 12: Particle size analysis of soil samples drawn using Gradistat (Blott, 2000).

5.2.3 Interpretation

The soil samples from Marion Island were found to be generally coarse. Most samples fit either into the gravely sand or sandy gravel classes (Figure 12). The coarse texture of the soil can be attributed to the parent material from which it is derived, the youth of the Island, as well as potentially slowed weathering rates (Sumner, 2004). Bearing in mind that the parent material on Marion Island is limited to that of basaltic origin only, it follows that no distinction can be made from one habitat to another in terms of particle size distribution of soils.

The data had a high variance and no trends were found within the dataset (Figure 13; Appendix C). In order to illustrate this, box plots were constructed for each habitat to indicate the variance of the mean particle sizes of samples (Figure 13). The variance in the mean particle size ranged from 0.3 – 1.7 for the different habitats (Figure 13). This means that in some habitats (saltspray, mire, drainage line and fernbrake) the data within the habitat did not vary a lot, however in other habitats (biotic, fellfield, polar desert and the palaeosol) data varied to a larger degree. The variance between the data from the different habitats was small (0.405). This indicates that the mean particle sizes of the various habitats are similar, i.*e.* the data is too similar in nature to be able to differentiate between habitats. The same was found when comparing soils of different altitudes and depth of soil. The similarity in data can be explained by the limited parent material. Since rocks on Marion Island are all young and basaltic in nature there is little variety in terms of parent material.

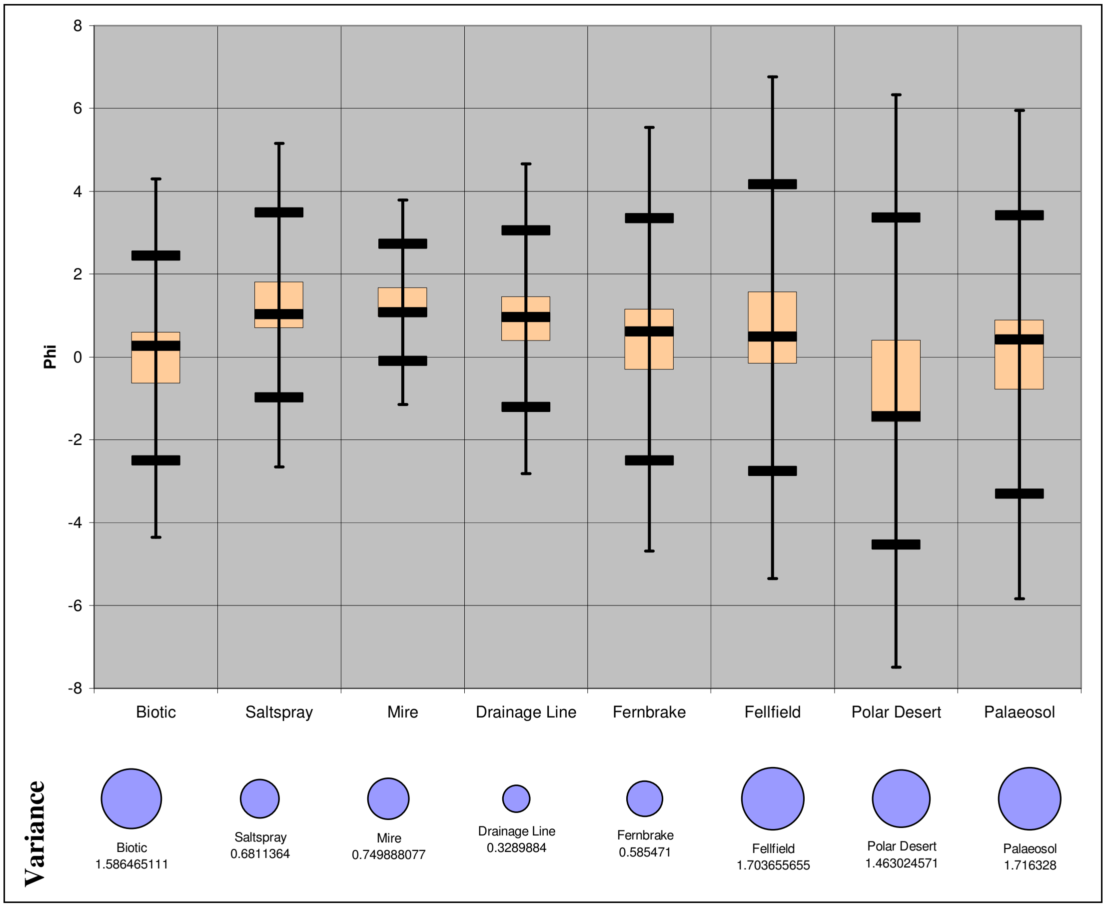


Figure 13: Statistical analysis of sample means.

More than 80% of the data was symmetrical or positively skewed (Table 7). A symmetrical dataset has a normal distribution; the more skewed the dataset, the more it deviates from a normal distribution. A positively skewed dataset indicates that there is more fine sediment than is expected in a normal distribution, or there is a lack of coarse sediment. Only a small proportion of the data analysed is negatively skewed (having a greater proportion of coarse material and less fines than expected with a normal distribution) (Table 7). All samples, except one, are poorly or very poorly sorted meaning that there was a wide range of particle sizes present in the samples (Table 7). Since the samples were poorly sorted, it was expected that they should also be less peaked than a normal distribution (platykurtic). The bulk of the sample set fitted into the mesokurtic or platykurtic categories, indicating that the data plotted either close to a normal distribution, or flatter (Table 7).

Table 7: Frequency of occurrence of skewness, sorting and kurtosis data, by habitat.

Habitat	Skewness					Sorting			Kurtosis				
	v-	-	Sym	+	v+	Mod	Poor	V Poor	V Plat.	Plat.	Meso.	Lept.	V Lept.
Biotic		1	10	11	1	1	13	9		6	14	3	
Saltspray		1	2	7			10			3	7		
Mire			8	5			12	1		4	8	1	
Drainage Line		1	4	1			4	2			6		
Fernbrake	2	3	8	3			12	4	1	4	9	2	
Fellfield		2	4	3	2		5	6		4	5	2	
Polar Desert		2	1	2	3		3	5	1	4	2		1
Palaeosol	1	2	1	2	3			9	1	5	2	1	
Total	**3**	**12**	**38**	**34**	**9**	**1**	**59**	**36**	**3**	**30**	**53**	**9**	**1**

The WRB Soil Classification system (IUSS Working Group, 2006) defines soil texture as a diagnostic criterion of four different horizons. In each case, the texture is defined as a sandy loam or finer (Driessen, *et al.*, 2001). As noted from the results of this study, soils on Marion Island are all coarser than this requirement.

5.3 Particle size analysis of fine material

Fine sediment analysis was performed to differentiate the clay from the silt and sand fractions. Clay content is a criterion for several of the WRB Soil Classification System's diagnostic horizons (Andic, Argic, Cambic, Ferralic, Natric, Nitic, and Vertic). The determination of particle size distribution of the fine portion of the soil samples was performed in the Geomorphology Laboratory at the University of Pretoria.

5.3.1 Method

Fine sediment analysis was performed by means of sedimentation (Briggs, 1977). Sub samples of the size fraction less than 2mm were used. Twenty grams of each sample was placed in a 500ml cylinder and 0.5g of Calgon (sodium hexametaphosphate) was added to deflocculate (break down aggregates) the sample. Cylinders were then filled up to the 500ml mark with distilled water, and shaken well. Three samples, of 10ml each, were pipetted from this suspension at a depth of 10cm from the surface. One sample was taken from each cylinder immediately (A), another after 3 minutes and 50 seconds (B), and the third after 8 hours and 10 minutes (C). Equation 4 was used to calculate the sand, silt and clay fractions of these samples.

a.	Clay $= \frac{50\times C}{W}\times 100$	$A =$ Weight of dry soil A. $B =$ Weight of dry soil B. $C =$ Weight of dry soil C. $W =$ Weight of dry, initial sample. Clay, fine and medium silt, coarse silt and sand are all expressed as percentages.
b.	Fine & medium silt $= \frac{50\times (B-C)}{W}\times 100$	
c.	Coarse silt $= \frac{50\times (A-B)}{W}\times 100$	
d.	Sand = 100 – coarse silt – fine & medium silt - clay	

Equation 4: Equations for calculation of percentages of fine sediments; (a) Percentage clay; (b) Percentage fine and medium silt; (c) Percentage coarse silt; (d) Percentage sand (Briggs 1977).

The method is based on Stoke's law which states that the velocity with which a particle falls through a viscous medium is directly proportional to its diameter (Briggs, 1977) as described by Equation 5. Stoke's law has five basic assumptions, which are:

1. Particles are spherical.
2. Particles reach terminal velocity.
3. Flow is laminar.
4. There is no Brownian motion.
5. There is differential settling.

These assumptions, however, open this experiment to errors. Particles are never truly spherical (Taylor, 1948), especially in the geologically young environment of Marion Island where weathering is limited (Sumner, 2004). Brownian motion in reality cannot be excluded; and it will affect particles smaller than 0.0002m (Taylor, 1948). Differential settling is also unlikely as high volume of particles will interact both with each other and with the edges of the cylinder (Taylor, 1948). However it has been shown that where less than 50g soil per litre is used, this affect is negligible (Taylor, 1948). In this study, the equivalent of 40g of soil per litre was used. The composition of particles will also vary, and while average particle density can be assumed for a soil, it will vary from grain to grain, and from sample to sample. However the effects of these parameters will be small and each sample is treated in the same manner, therefore, this equation and method are still well suited for calculation of fines in sediment, and will allow for results to be compared.

$V = \frac{2gr^2\rho_s - \rho_w}{9\eta}$	$V =$ Velocity of falling particle (cm.sec^{-1}) $g =$ Gravitational acceleration $r =$ Radius of particle $\rho_s =$ Particle density $\rho_w =$ Fluid density $\eta =$ Viscosity of fluid

Equation 5: Stokes Law (Whittow, 2000).

It is important that temperature and pressure are kept constant when determining fine particle size distribution with the method described above. If temperature and pressure are allowed to vary, the viscosity of the water may be altered. Viscosity of a liquid decreases with a rise in temperature and increases with a rise in pressure (Gillam & King, 1971). The particle size determination was therefore undertaken in a room with a constant temperature of 20°C. Air pressure, however, could not be controlled.

There are many other potential sources of error when carrying out the sedimentation method in the laboratory, including errors or inconsistencies in timing and depth of sampling, or placing the pipette too rapidly into the solution (Pansu & Gautheyrou, 2006). Therefore, careful attention was paid to ensuring conditions were kept as constant as possible so as to eliminate errors, and keep results comparable.

It should be noted that, in the context of this experiment, clay refers to the size fraction of the soil particles smaller than 0.002mm; and may include clay minerals, as well as other substances smaller than this size threshold (Pansu & Gautheyrou, 2006). Furthermore, sand and fines proportions may differ from those presented in the coarse particle size analysis, which could be attributed to several factors.

1. Only the portions of the soil less than 2mm were used for this analysis.
2. The calgon may have disaggregated particles to a greater extent than they were in the coarse particle size analysis.
3. Experimental errors such as those relating to Stoke's law as well as the laboratory method may affect the final results.

5.3.2 Results

All samples analyzed are classified as "silt" on a sand / silt / clay ternary diagram that was determined with the aid of Gradistat (Blott, 2000). The relative average percentages of sand, coarse silt, medium and fine silt, and clay were determined for each habitat (Figure 14). Graphs showing the relative percentages of sand, coarse silt, medium and fine silt, and clay were constructed for each horizon within each habitat type and are also presented in Appendix D.

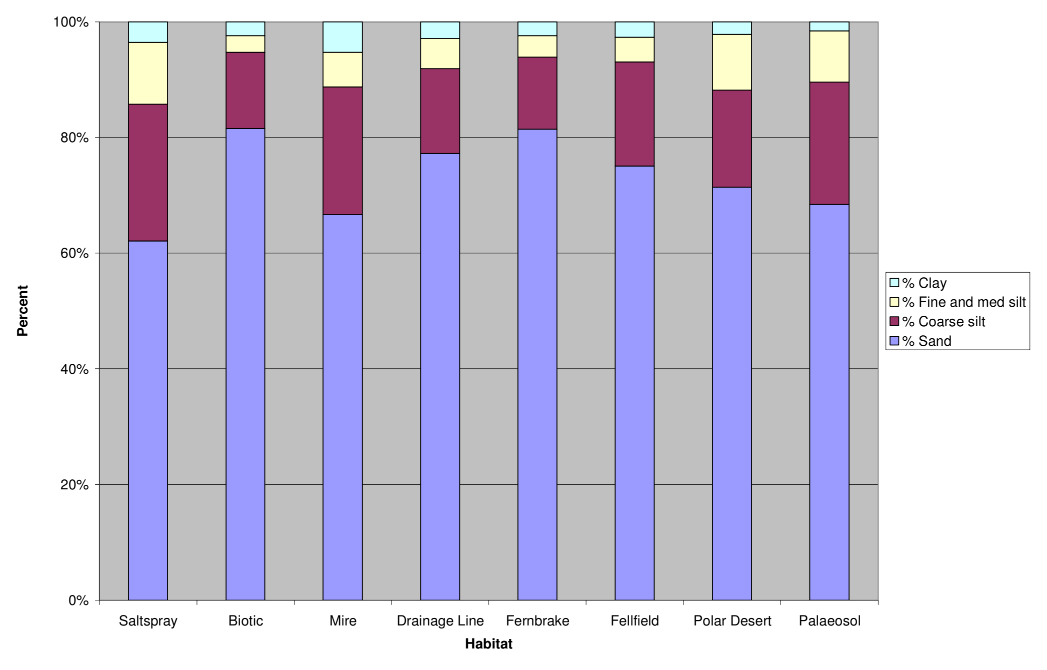


Figure 14: **Differences in fine texture results between habitat types (averages).**

5.3.3 Interpretation

The relative percentages of the sand, coarse silt, fine and medium silt and clay fractions of the samples from each habitat had a high variance. The variance between habitats was also high (Appendix D). While the values within and between habitats varied widely, they varied over similar ranges (Appendix D) and therefore no distinction could be made from one habitat to the next, or along altitudinal lines. Clay content is a diagnostic criteria in seven different horizons in the WRB Soil Classification System. The diagnostic clay contents were therefore compared to the results obtained to establish whether the criteria for clay content for any horizon was met (Table 8). The clay content of 96% of the soils analysed would fit into the requirements of the Ferralic horizon (Table 8).

Table 8: **Frequency of occurrence of diagnostic criteria for clay content in soils according to the WRB Soil Classification System (Driessen *et al.*, 2001).**

	Andic / Cambic	**Argic / Natric**	**Ferralic**	**Nitic / Vertic**
WRB clay requirement	>10%	>8%	<10%	>30%
Saltspray			10	
Biotic			23	
Mire	1	3	10	
Drainage Line			6	
Fernbrake			16	
Fellfield		1	10	
Polar Desert			8	
Palaeosol			9	
Total	**1**	**4**	**92**	

6 Chemical soil properties

Chemical soil properties were determined from sub samples of the soils finer than 2mm. pH was determined in the laboratory in the Department of Soil Science at the University of Pretoria. A selection of soil samples were sent to the Institute for Soil, Climate and Water (ISCW) in Pretoria for analysis of their iron and aluminium content.

6.1 Soil pH

pH refers to the presence of hydrogen ions in solution, and is a measure of the acidity or alkalinity of a soil (Whittow, 2000). Soil pH can be determined in water, calcium chloride or potassium chloride. To ensure results are comparable to others presented in literature, all three methods were used in this study.

6.1.1 Method

pH was determined in deionised water (H_20), calcium chloride ($CaCl_2$ 0.01M solution) and potassium chloride (KCl 1M solution), as described in Blakemore *et al.* (1987). Soils were air dried; 10g was weighed into a beaker and 25ml of reagent (H_20, 0.01M $CaCl_2$, or 1M KCl) was added in each case. The solution was stirred and allowed to stand for one hour, it was then stirred again before the pH was determined with the use of a pH meter.

Thomas (1996) notes that the most important aspect of taking pH measurements is that they are carried out in a consistent way, as pH values vary slightly depending on where in the solution the pH meter is placed, and whether or not the solution is stirred during determination. Care was therefore taken to ensure that samples were stirred just prior to taking the pH reading, and that the pH mater was submersed just as much as required in order to take a reading, in each case.

6.1.2 Results

pH values in all cases varied slightly between 4 and 7 (Table 9 and Table 10). These values are correspond to the values previously measured by Smith (1976; 1978), Smith & Steenkamp (1992b) and Smith *et al.* (20011) that ranged from 3.2-5.9 (0.01M CaCl) (Smith, 1976; 1978) or between 4.2 and 6.2 as determined in water (Smith, *et al.*, 2001; Smith & Steenkamp, 1992).

Table 9: **Average pH per habitat.**

Habitat	pH (H_20)	pH ($CaCl_2$)	pH (KCl)
Biotic	4.26	5.25	4.59
Saltspray	4.43	4.08	4.10
Mire	4.72	4.22	4.05
Drainage line	5.01	4.58	4.41
Fernbrake	5.62	4.76	4.80
Fellfield	5.70	5.17	5.38
Polar desert	5.85	5.89	5.74
Palaeosol	6.28	5.66	5.66

Table 10: **Average pH at the surface and below the surface.**

	pH (H_20)	pH ($CaCl_2$)	pH (KCl)
Surface	4.93	4.68	5.10
Subsurface	5.91	5.36	5.15

6.1.3 Interpretation

It was found that generally the lower lying, more organic habitats (biotic, saltspray; mire; drainage line and fernbrake (refer also to Chapter 9)) had lower pH values of between 4.05 and 5.62 (Table 9). Less developed soils, generally found at higher altitudes (fellfield and polar desert) had higher pH values (5.17 to 5.89; Table 9). The palaeosol had pH values slightly higher (more basic) than that of the rest of the soils (5.66 to 6.28; Table 9). This could be attributed to the fact that there was no visible organic activity impacting on the profile as it was still covered with a thick layer of unvegetated scoria. It was also found that the pH generally increased in subsurface horizons as compared to surface horizons (Table 10).

6.2 Iron aluminium ratio

The sum of iron and aluminium content as determined by acid ammonium oxalate extraction is used as a requirement in three horizons in the WRB soil classification system. These are the Vitric, Spodic and Andic horizons, (Driessen, *et al.*, 2001) some of which may occur on Marion Island.

6.2.1 Method

Extractable iron (Fe) and aluminium (Al) were determined using acid ammonium oxalate extraction as described by the Soil Classification Working Group (1991). Five surface soil samples were sent to the ISCW laboratory for them to perform this analysis. The ISCW provided the results presented for interpretation.

6.2.2 Results

The iron and aluminium contents as determined (Table 11) were added together (Al content + ½ Fe content). The resultant value may aid in the classification of these soils as per the requirements of the WRB Classification system (Driessen, *et al.*, 2001).

Table 11: Iron and aluminium contents of soils (ISCW).

Sample no	Habitat	%Al	%Fe	Al+½Fe (%)
38	Mire	0.8	1.48	1.54
19	Fernbrake	2.33	3.29	3.98
37	Fernbrake	1.99	2.83	3.41
32	Fellfield	2.3	3.31	3.96
34	Polar desert	4.04	5.31	6.70

6.2.3 Interpretation

A Vitric horizon requires an Al+½Fe value greater than 0.4%; a Spodic horizon requires a value greater than 0.5% and an Andic horizon requires a value greater than 2% (Driessen, *et al.*, 2001). According to these analyses, all the soils except that of the mire habitat fulfil the iron and aluminium criteria for any three of these horizons (Table 11). The mire soil could, by virtue of its lower iron and aluminium contents fit into either the Spodic or Vitric horizon. However due to other criteria it does not fit appropriately in either of these (Chapter 9).

7 Mineralogical soil properties

Mineralogical analyses were carried out in the Geology and Physics Departments at the University of Pretoria, as well as by the Institute for Soil, Climate and Water (ISCW) in Pretoria. Analyses were carried out on a smaller selection of samples. Samples were selected from different habitats, and the horizon used in each case was dependent on the purpose and expected result of the test.

7.1 X-ray fluorescence

X-Ray Fluorescence (XRF) was used to determine the basic elemental composition of a sample. All samples from 4 sites on Marion Island were analysed by this method.

7.1.1 Method

Soil sub-samples were milled in a tungsten carbide crucible to a fine powder. Moviol (polyvinyl alcohol binder) was added to a few grams of sample which was pressed under pressure into a pellet and dried for analysis. A further 3g sample was dried and weighed; it was then ashed overnight at 1000ºC to remove all combustible (organic) components and cooled. One gram of this sample was melted with 6g of flux to form a fused bead for analysis. The fused beads were used to determine the major elements, while the pressed pellets were used to determine trace elements (Karathanasis & Hajek, 1996). Once the samples were prepared they were submitted to the Geology Department at the University of Pretoria for analysis, and results were returned for interpretation.

7.1.2 Results

The elemental compositions of samples analyzed are tabulated (Appendix E). Fourteen major elements were determined and the remaining composition was made up by loss on ignition (Appendix E). Twenty six trace elements were determined and reported as parts per million (ppm) (Appendix E).

7.1.3 Interpretation

The results of the XRF analyses are typical of soils of basaltic origin, and are similar to those reported by Winter (2001) for mid-ocean ridge basalts as well as those for basalts found more specifically in the Indian Ocean ridge (Winter, 2001). The most noticeable difference in the data collected from soils on Marion Island and that presented by Winter (2001) was that there was less (average 9% difference) SiO_2 in the soil samples from Marion Island, and slightly more of all the other major elements. The data obtained in this study was also very similar to that obtained from rocks on Marion Island by Abbot (1963) and by Lacroix (1940, cited in Abbot, 1963:92).

7.2 X-ray diffraction

X-Ray Diffraction (XRD) was used to determine the basic mineralogical composition of a sample. All samples from 4 sites on Marion Island were analysed by this method (as with XRF).

7.2.1 Method

After the determination of the elemental composition (XRF) the pressed pellets were analysed to determine the mineralogical composition of the soils (XRD). The method of preparation of the pressed pellets was described earlier in this chapter (XRF). The XRD analysis was performed by the staff of the Geology Department at the University of Pretoria and results were returned for interpretation.

7.2.2 Results

The following minerals were found in the samples analysed: diopside ($CaMgSi_2O_6$); forsterite (Mg_2SiO_4); hematite (Fe_2O_3); magnetite (Fe_3O_4); and plagioclase ($Ab_{100}An_0$ – Ab_0An_{100}) (Figure 15; Appendix F). Plagioclase refers to minerals with a composition of pure albite (Ab) ($NaAlSi_3O_8$) to pure anorthite (An) ($CaAl_2Si_2O_8$) or any layered combination of the two (Klein, 2002).

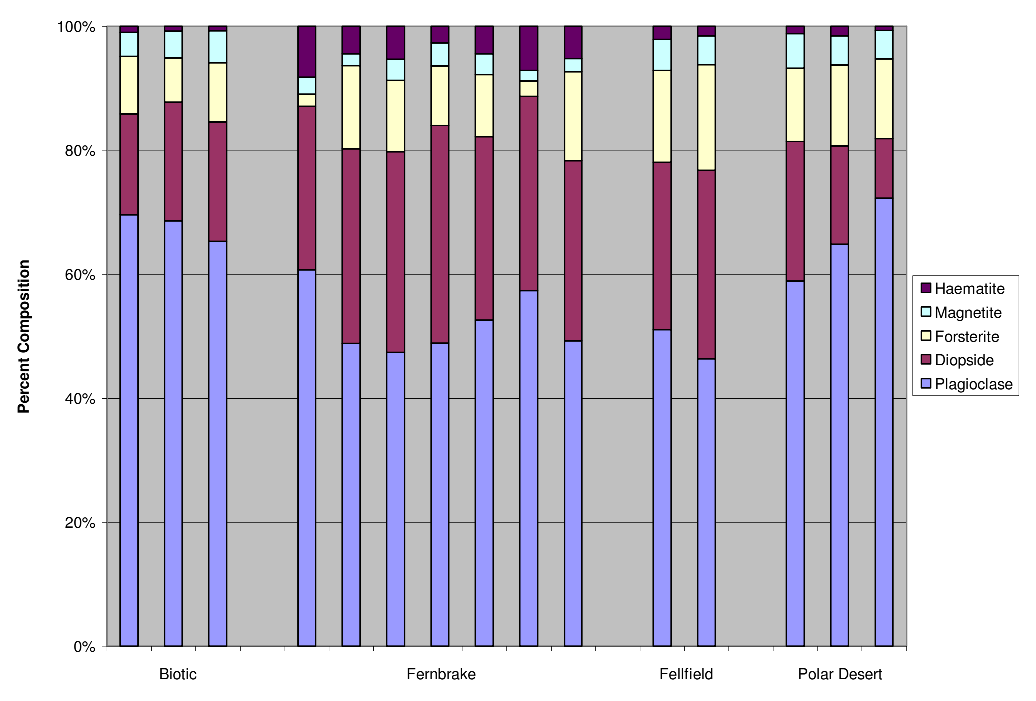


Figure 15: X-Ray diffraction results.

7.2.3 Interpretation

The average results for each site on Marion Island were compared with the average composition of basalts of the mid-ocean ridge and the Indian Ocean ridge (Winter, 2000) as well as previous analyses obtained from rocks on Marion Island (Abbot, 1963) (Appendix F). Results obtained for soils during this study correspond to those for rocks presented by Abbot (1963) and Winter (2000). The quantities of diopside and magnetite were higher in the soil samples analysed in this study than the compared rocks (Abbot, 1963; Winter, 2000). This implies that the diopside and magnetite are likely to weather faster than the remaining minerals from the parent material. This observation is confirmed by the fact that pyroxenes (including diopside) are susceptible to weathering (Skinner & Porter, 2000). No alteration or secondary minerals were found from the XRD analysis.

As indicated in Chapter 8, loss on ignition values for some of the soil samples were high. A high loss on ignition value could be caused by the presence of hydrous or carbonate minerals, or a high organic matter content. Since no hydrous or carbonate minerals were found during the XRD analysis, it is assumed that the loss on ignition (Chapter 8) can be used as a representation of organic matter content.

7.3 Clay mineralogy (XRD)

Five samples were sent to the ISCW for XRD analysis of minerals within the clay fraction. Should secondary minerals be found, a clear indication exists that alteration and, therefore, pedogenesis has taken place. The same five samples were analysed in more detail for their iron and aluminium content (See Chapter 6).

7.3.1 Method

As mentioned in Chapter 4, signs of a fluctuating water table were noted in some profiles, indicating that clays may be washed out of surface horizons and deposited in lower horizons by illuviation. Therefore subsurface horizons were used for clay mineralogy analysis. In order to determine the mineralogy of the clay fraction of soils, clays from soil sub samples are concentrated and then precipitated onto a glass plate in order to analyse them by XRD. Samples were prepared and analysed by the ISCW, and results returned for interpretation.

7.3.2 Results

The percentage mineral compositions of clay fraction of soils were provided by the ISCW. Quartz (SiO_2), feldspar ($MAlSi_3O_8$), smectite (layered clay mineral group) and gibbsite ($Al(OH)_3$) were found in soil sub-samples (Figure 16; Appendix G).

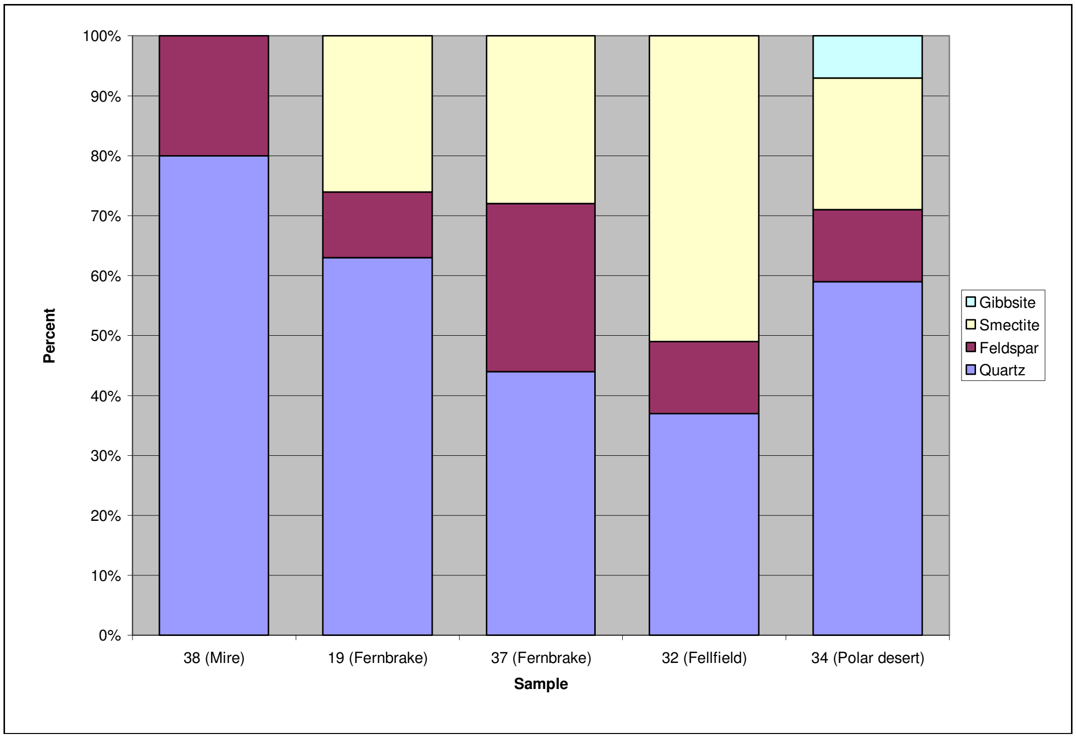


Figure 16: **X-Ray diffraction results of minerals within the clay fraction of selected soils.**

7.3.3 Interpretation

Of the four minerals identified within the clay fraction of the soil samples analysed, two are primary minerals (quartz and feldspar), and two are secondary minerals (smectite and gibbsite) (Sparks, 2003) (Figure 16; Appendix G). Quartz and feldspar are the most commonly occurring rock-forming minerals on earth (van der Watt & van Rooyen, 1995). Quartz is often the most dominant constituent of a soil (van der Watt & van Rooyen, 1995). Feldspars are aluminosilicates of linked SiO_4 and AlO_4 tetrahedra with cavities that may contain Ca^{2+}, Na^+, K^+ or Ba^{2+}.

Smectite is a group of clay minerals consisting of 2:1 unit layers (two silicon–oxygen tetrahedral sheets and one aluminium–oxygen octahedral sheet) (van der Watt & van Rooyen, 1995). Smectites are able to absorb water and other polar molecules between clay sheets and swell upon wetting (van der Watt & van Rooyen, 1995; Klein, 2002; Sparks, 2003). Clay minerals within the smectite group are: montmorillonite, beidellite, nontronite, saponite and hectorite (Klein, 2002). These clays are differentiated by whether or not they are di- or tri-octahedral and where isomorphous substitution has taken place (Sparks, 2003). Smectite is the initial and main clay product that results from the weathering of volcanic ash (Press & Siever, 1986; Dahlgren *et al.*, 2004). Smectites have high surface areas and high absorptive properties, swelling when wet and shrinking on drying (Schulze, 1989).

Gibbsite is an aluminium hydroxide mineral which is often found in highly weathered soils (Sparks, 2003). Gibbsite can become concentrated in soils by one of two processes. The first is the slow weathering of kaolinite (Buol *et al.*, 1989). Since kaolinite was not found in any of the samples analysed it was not expected that gibbsite would be found on Marion Island. Gibbsite may, however, also be formed by rapid weathering of primary minerals where there is rapid movement of water through a profile (Buol *et al.*, 1989). Intense weathering results in the accumulation of an aluminium rich residue for conversion to gibbsite or possibly the formation of allophone (Buol *et al.*, 1989). In this case, the presence of gibbsite is contrary to expectation, since it was found in the polar desert region only, the area expected to have the least weathering and soil formation. The presence of gibbsite in the polar desert sample can be explained by one of three possibilities:

1. Soils may have weathered during a previous interglacial period; this possibility would be supported by the presence of a palaeosol (Chapter 4).
2. Gibbsite may exist over the whole Island, but in very small quantities that might not be detectable by the methods employed in this study. The gibbsite may be allowed to gather more effectively in the polar desert as this region is protected for large portions of the year by snow cover. This limits the movement of water through the profile, and may allow the clay minerals to accumulate there. Throughout the remaining habitats the gibbsite may be too dispersed to be detected, or washed out too rapidly.
3. Since a very small soil sub-sample is used for clay mineralogy analysis, it may not have been representative of the whole sample, and therefore a portion not containing gibbsite may have been selected for analysis.

It is noted that there is no smectite or gibbsite in the mire habitat. This can be attributed to the fact that the mires are permanently wet, and water will be moving laterally through them preventing clay minerals from accumulating. The parent materials of these soils are mostly decomposed plant matter and while particles may be small in size the mineral fraction of the soil is very small and the organic content is greater than 80% in some cases (Chapter 8). This suggests that only very small quantities of clay minerals may be produced in these areas.

Secondary minerals are the weathered products of primary minerals (refer to the definitions above). Therefore, the presence of secondary minerals (smectite and gibbsite) is a clear indication of the beginning of the weathering of particles and therefore soil formation.

Gribnitz *et al.* (1986) found no signs of chemical weathering on black lavas and found no clay minerals in any of their samples. They also stated "*even the finest products of disintegration appear to be free of clay minerals*" (Gribnitz, *et al.*, 1986). As noted above, the conditions on Marion Island are conducive to chemical weathering. Sumner (2004) found that weathering of both grey and black lavas occurred at a granular scale on Marion Island. He also found that black lavas disintegrated more rapidly than grey lavas. However his results did not indicate which weathering process were active in the disintegration of rocks on Marion Island.

8 Biological soil properties

All biological soil properties were determined from sub samples of the soils, finer than 2mm. Analyses were performed in the laboratories in the Soil Science, Geography, Geoinformatics and Meteorology, and Physics Departments at the University of Pretoria, as well as at Anglo American in Johannesburg.

8.1 Organic carbon and loss on ignition

Soil organic carbon is defined as the organic portion of soil including fresh or decomposing microbial, animal or plant residues, as well as soil humus (Soil Science Society of America, 1979, cited in Nelson & Sommers, 1996:962). Only particles smaller than 2mm should be taken into consideration when determining soil organic matter content (Nelson & Sommers, 1996).

8.1.1 Method

Organic carbon content was determined on 43 samples using the Walkley-Black method (Non-Affiliated Soil Analysis Work Committee, 1990); however, it was found that this method was not appropriate for the soil samples from Marion Island due to their exceptionally high organic matter content (and possibly interference of other components). It was, therefore, decided to make use of the loss on ignition method. Nelson & Sommers (1996) report that neither the chemical treatment of a sample nor the ignition at a high temperature, is accurate in the determination of organic carbon content. They suggest the former does not quantitatively remove organic matter, while the latter overestimates it. It was also noted that the combustion of organic soil components has been used specifically in the determination of organic carbon of soils of volcanic origin (Chadwick *et al.*, 2003; Arnalds, 2004; Basile-Doelsch *et al.*, 2005; Buytaert, *et al.*, 2006).

8.1.1.1 Walkley-Black method

The Walkley-Black method was followed as described by the Soil Classification Working Group (1991). One gram of soil is measured, ground, sieved (through a 0.5mm sieve) and placed in an Erlenmeyer flask. 10cm^3 of 0.167M $K_2Cr_2O_7$ solution is added to the soil. Rapidly, 20cm^3 concentrated H_2SO_4 is added and swirled vigorously for 1 minute. The solution is allowed to stand for 30 minutes, while being shaken intermittently. A volume of 200cm^3 of water and a further 10cm^3 of H_3PO_4 is added to the solution. To allow for titration, 0.5cm^3 of sodium diphenylaminesulphonate indicator is added and $FeSO_4$ is added drop by drop until the light green endpoint. It is noted that should more than 6cm^3 of the $K_2Cr_2O_7$ solution be titrated, the organic carbon determination should be repeated with less soil (Soil Classification Working Group, 1991). Once the results have been gathered and a standard determined, the molarity of the $FeSO_4$ is determined from the standards (Equation 6), and the organic carbon can be calculated (Equation 7).

$$\boxed{Molarity(FeSO_4) = \frac{10cm^3 K_2Cr_2O_7 \times 0.167 \times 6}{cm^3 FeSO_4}}$$

Equation 6: Determining the molarity of the $FeSO_4$ (Soil classification working group, 1991).

$$\boxed{\%C = \frac{\left[cm^3 FeSO_4 blank - cm^3 FeSo_4 sample\right] \times molarity(FeSO_4) \times 0.3}{g(sample) \times 0.77}}$$

Equation 7: Percent organic carbon (Soil classification working group, 1991).

8.1.1.2 Loss on ignition

The loss on ignition method used was adapted from the method described by Heiri *et al.* (2001). Sub-samples of 10g of each soil were weighed into crucibles, and dried overnight at 105°C. The samples were then weighed and placed into a cold furnace. The furnace was turned on to 550°C and samples were left to combust for 10 hours. After this time, samples were removed from the furnace and put back into the oven at 105°C overnight. They were then weighed again the following morning, and loss on ignition values were calculated (Equation 8).

$$LOI_{550} = \frac{(DW_{105} - DW_{550})}{DW_{105}} \times 100$$

LOI_{550} = Loss on ignition at 550°C (%).
DW_{105} = Dry weight of sample after heating at 105°C overnight.
DW_{550} = Dry weight of sample after combusting at 550°C for 10 hours.

Equation 8: Loss on ignition (Heiri *et al.*, 2001).

It was noted above that loss on ignition can overestimate organic matter content of soils. Ball (1964, cited in Heiri *et al.*, 2001:104) found that up to 20% of the weight loss resulting from combustion at 500°C may be the loss of structural water from clays and hydrated minerals. However, since high clay contents were not expected (field observation, confirmed by results noted in Chapter 5), this was not considered as a significant constraint.

Heiri *et al.* (2001) pointed out that while 4hours exposure to 550°C should be sufficient for most samples, the required time to burn off all organic matter content will vary depending on the sample. It was noted after some experimentation that samples from Marion Island (especially those with high organic matter contents) were not fully combusted after 5 hours in the furnace at 550°C. Therefore, the methodology was adapted and all samples were placed in the furnace for 10 hours to ensure full organic matter combustion.

8.1.2 Results

Loss on ignition values were obtained (Appendix H) and plotted against habitat (Figure 17). Loss on ignition values varied widely with values ranging from 0.4% to 96.8%.

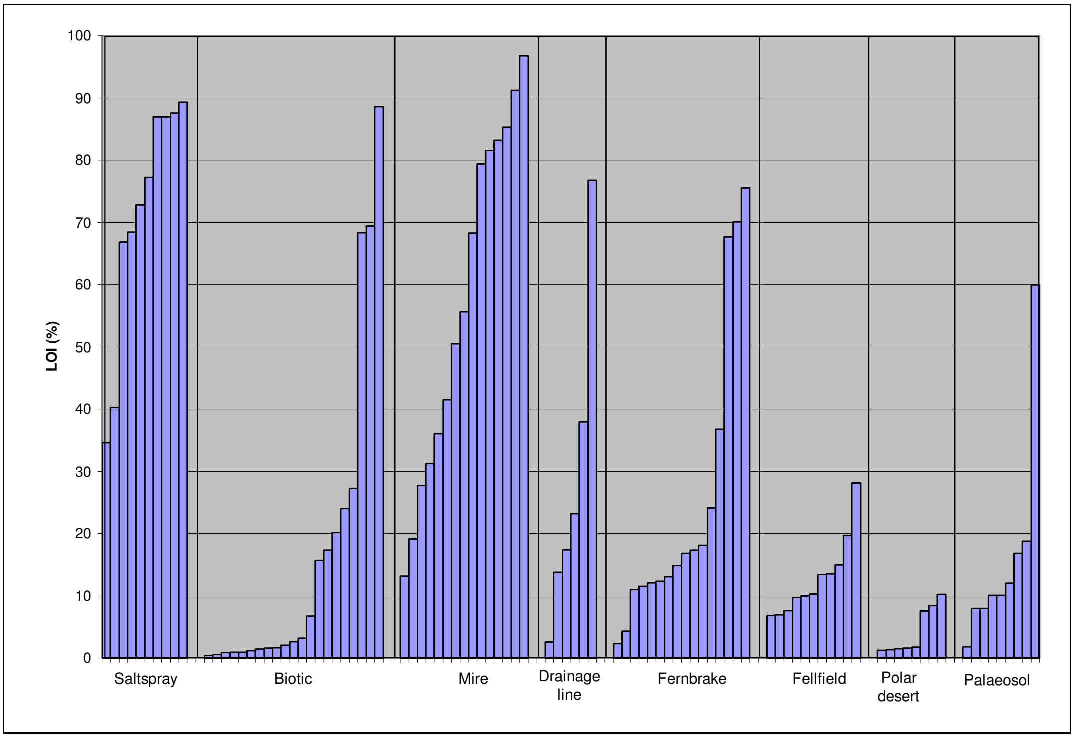


Figure 17: **Loss on ignition results of soil samples.**

In the majority of the samples analysed by the Walkley-Black method (36 out of 42), more than 6cm^3 of the $K_2Cr_2O_7$ solution was titrated, and these results are therefore not acceptable. It was determined that very small amounts of soil would be required for the accurate determination of high organic matter content by means of this method, which would result in experimental error from deriving small sub samples. These results were therefore discarded, and are not considered further.

8.1.3 Interpretation

An organic matter content of 20% is a qualifier for an organic soil in the WRB Soil Classification System (Driessen, *et al.*, 2001). As noted from the results, some samples from the saltspray, biotic, mire, drainage line, fernbrake and fellfield habitats would be considered high in organic matter. The loss on ignition values determined in this study are in some cases higher than those obtained by Smith *et al.* (2001) for soils on Marion Island. They found that organic carbon content varied from 6.3%-43.5% (Smith *et al.*, 2001).

As indicated above, the effect of structural lattice water was considered to be negligible in this study. Ball (1964, cited in Heiri *et al.*, 2001:104) suggested that the estimated maximum expected loss as a result of lattice water is 20% of the loss on ignition value. If 20% is subtracted from the calculated loss on ignition values of all samples, only four samples that previously were considered to have a high organic matter content (more than 20%) would no longer be classified as such (Appendix H). Results from the XRD (Chapter 7) showed no hydrous or carbonate minerals in the samples analysed and this suggests that mass loss on ignition will be a good indicator of the organic matter content. Therefore, loss on ignition has been used in this study as a proxy for organic carbon content.

It was noted that loss on ignition values were generally higher in some habitats and lower in others (Figure 18). Mire and saltspray habitats have very high LOI values (up to 92%) (Figure 17). Drainage line, fellfield, and fernbrake habitats also have high loss on ignition values (in terms of WRB Soil Classification System, 20% or more organic matter content can be considered high) but considerably less than the mire and saltspray habitats.

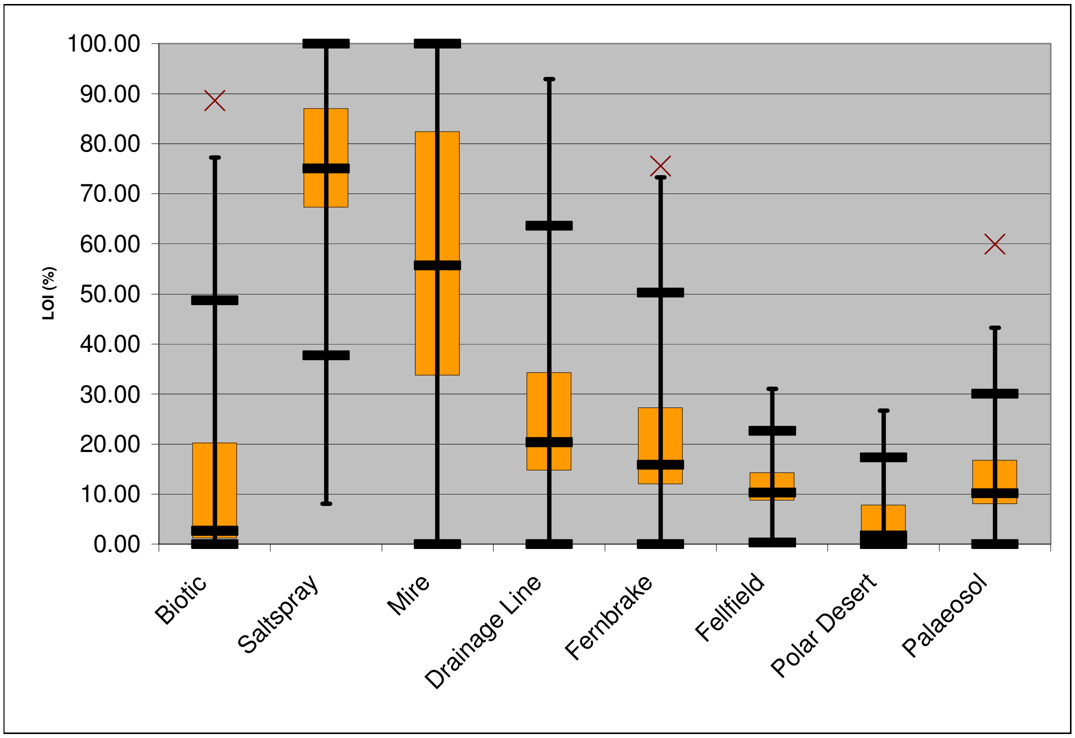


Figure 18: Box plot of loss on ignition results.

Biotic habitats have varying loss on ignition values. This can be attributed to the nature of the biotic habitat sampled. Where vegetation cover was prolific the organic matter content was higher. This is a result of vegetation thriving on the nutrients added to the soil by the fauna. However in other areas, vegetation is not given the opportunity to grow due to excessive faunal activity. In these areas, nutrients will rapidly move through and out of the soil profile. This observation is confirmed by similar findings in the Antarctic, where it was shown that abandoned penguin nests had very low loss on ignition values (2.7%) (Campbell & Claridge, 1966). Smith & Froneman (2008) noted that nutrients deposited near to the shore, within penguin colonies (where some biotic soils were sampled) are rapidly washed out to sea or volatilised. Uric acid is insoluble, and 80% of the nitrogen in the faeces of king and macaroni penguins on Marion Island is made up of uric acid (Smith & Froneman, 2008). Uric acid breaks down into ammonia, which is easily volatilized (Smith & Froneman, 2008). This further explains why the loss on ignition values in some of the biotic soils analysed were measured to be low (Figure 18).

Penguins moult on the land and, as a result, deposit most of their old feathers within the rookery, increasing the nutrients available in the surrounding soils (Kanda & Komárková, 1997). Samples used for this study were all collected during relief voyages to Marion Island in the months of April and May in 2006 and 2007. This is just after the macaroni penguins have left the land and gone back to sea, leaving behind vast volumes of feather material (refer also to Chapter 2). The nutrients from these feathers will not yet have broken down.

There is also a visible relationship between estimated loss on ignition values and altitude. There is a distinct decrease in organic matter content at higher altitudes. This correlation is considered statistically significant. A Spearman's rank correlation test was performed on the data. For a students *t*-test; one-tailed; significance level of 0.01, the critical value is 2.64 (Briggs, 1977). The calculated *t* value is 6.61, which far exceeds this critical value. The correlation is inversely proportional, meaning that as the altitude increases, the organic matter will decrease.

In most cases, the loss on ignition values decreased consistently throughout the profile. This is logical since organic matter input will be at the surface of profiles. Loss on ignition values were also compared with the requirements of WRB Soil Classification System for criteria of diagnostic horizons (Table 12).

Table 12: Frequency of occurrence of diagnostic criteria for organic matter content in soils according to the WRB Soil Classification System (Driessen *et al.*, 2001).

	Fragic / Ochric / Petroplinthic / Plinthic	**Mollic / Spodic / Umbric**	**Chernic**	**Fulvic / Melanic**	**Histic**	**Folic**
WRB clay requirement	<1	>1	>2.5	>6	>20	>35
Saltspray	0	10	10	10	10	9
Biotic	5	16	11	9	6	3
Mire	0	15	15	15	13	13
Drainage Line	0	6	6	5	3	2
Fernbrake	0	16	16	14	5	4
Fellfield	0	11	11	11	1	0
Polar Desert	0	8	3	3	0	0
Palaeosol	0	9	8	8	1	1
Total	**5**	**91**	**80**	**75**	**39**	**32**

8.2 Organic matter characterisation

Infra red spectroscopy was used to aid the quantification of the organic fraction of the soil samples collected. The term "infra red" refers to the range of the electromagnetic energy spectrum between the wavenumbers of 10cm^{-1} and 10000cm^{-1} (Johnston & Aochi, 1996). Infra-red analysis techniques rely on the oscillating or moving of molecules. Spectra were obtained only in the mid-infrared range of between 400cm^{-1} and 4000cm^{-1}. The relationship between wavenumber and wavelength is illustrated in Equation 9.

$$\boxed{Wavenumber = \frac{1}{Wavelength}}$$

Equation 9: Relationship between wavelength and wavenumber (Johnston & Aochi, 1996).

Only certain molecules can be identified with the use of infra-red spectroscopy, while other elements will remain hidden. Each species will have a characteristic spectrum, however, when more than one type of molecule is present in the same mixture, interference occurs making it more difficult to recognise individual components.

Several problems exist when analysing soil by this method. Soil is not homogeneous (Peterson & Calvin, 1996) and due to the small sub sample used, sampling may not be representative of the whole. Furthermore due to the heterogeneity of the samples, interference makes the identification of specific components difficult as bands of one component may overlap with those of another, making the resultant spectra more complex to interpret. Mixtures of varying sized particles are usually dominated by smaller particles, and therefore, the analysed sample will be biased by particle size (Johnston & Aochi, 1996). Identification of particular humic substances is not possible, due to the fact that the peaks are broad and there is a mixture of too many compounds to single out specific substances (Swift, 1996). As previously indicated (Chapter 5), samples comprise a range of particle sizes. Differing surface areas may influence the resulting infra-red spectrum. Despite this, useful information can still be gained from infra-red spectra by comparing different samples, or comparing spectra before and after chemically altering the sample (Swift, 1996).

8.2.1 Method

Seventy four samples, from 34 sample sites, were analysed using both reflectance and transmittance infra-red techniques. To determine the transmittance spectra, a sub sample of 2mg of soil was combined with 100mg potassium bromide (KBr) and pressed under 8t of pressure to form a pressed pellet (Johnston & Aochi, 1996; Swift, 1996). These pellets were placed in a Bruker 113v FTIR spectrometer and mid-infra-red spectra (400-4000cm^{-1}) were recorded in the infra-red laboratory at the Department of Physics, University of Pretoria. The resolution was set to 2cm^{-1} and 32scans were signal-averaged in each interferogram. Transmittance spectra are determined by collecting the spectra that are transmitted through the sample. Spectra were read and manipulated using OPUS software. The potassium bromide is “transparent” over the 4000-400 cm^{-1} region (Swift, 1996), but is hygroscopic (attracting water) (Pouchert, 1981 & Swift, 1996) and could cause additional water to be detected in the sample.

Infra-red spectra were compared visually against one another to determine whether any noticeable pattern existed. Infra-red spectra were analysed and interpreted as described by Smith (1999) (Appendix I).

8.2.2 Results

Seventy four individual infra-red spectra were obtained during the infra-red analysis; therefore, not all of these data have been included either in this Chapter or in Appendix I due to the size of the dataset. Some graphs are attached hereto in Appendix I as described in the interpretation of results below.

8.2.3 Interpretation

Some of the spectra obtained were very noisy, with many sharp peaks throughout the spectrum. Such data may be caused by interference and were discarded from the analysis. Seven of the 74 spectra were discarded for this reason (9% of the sample) and not further considered in the interpretation process. It is also noted that since soils are a heterogeneous medium, infra-red spectra represent a range of materials and the precise identification of certain materials may be limited. Intense bands within the samples were noted and identified (Table 13).

Table 13: Intense wave group numbers found in samples analysed (band position and function group description adapted from Johnston & Aochi (1996) and Smith (1999).

Band position in cm^{-1}	Functional group	Presence *^{1}	Habitats *^{2}	E.g. *^{3}
3500 – 3200	N-H, or O-H stretching of carboxylic acids, phenols, alcohols	100%	All	5
3200 – 2800	C-H	34%	Saltspray, biotic, mire, drainage line, fernbrake.	4
2970 – 2820	Aliphatic C-H stretching	34%	Saltspray, biotic, mire, drainage line, fernbrake.	4
2250 – 2000	C≡N, C≡C	None	N/A	N/A
1800 – 1600	C=O stretching of carboxylic acids, amides, ketones	100%	All	6
1650 – 1540 *and* 1450 – 1350	Asymmetric and symmetric COO^- stretching of carboxylic acid salts	89%	All	3
1250 – 1200	C-O stretching & O-H bending of –COOH	8%	Saltspray, mire, fernbrake	1
1170 – 950	C-O stretching of polysaccharides	100%	All	2
<1000	C=C, Benzene rings	100%	All	7

Note
*^{1} *Presence: refers to the % of the samples collected in which the particular functional group was present.*
*^{2} *Habitats: refers to which habitats showed presence of the functional group described.*
*^{3} *E.g.: refers to number of the figure found in Appendix I that clearly shows the particular IR-band.*

Swift (1996) differentiates between the "*fingerprint region*" (1250-400cm-1) showing the molecular structure and the "*characteristic group frequency region*" (4000-1250cm-1) which indicates the presence of organic functional groups. The presence of the aliphatic C-H stretch (Table 13) indicates that simple, standard organic carbon chains were found in samples, (as apposed to those with double bonds, aromatic rings *etc.*, this does not however exclude the possible presence of more complex molecules). Note that aliphatic C-H stretches were not noted in the fellfield or polar desert habitats, *i.e.* simple organic compounds were not found. As indicated above (Figure 17), the fellfield or polar desert habitats have lower organic content than the others. The lack of the aliphatic C-H stretch may be due to the limited organic matter within the sample.

The presence of polysaccharides in all the samples can be attributed to the degradation of plant material. Plant material is made up of amongst others starch, glycogen, and cellulose, and these are the building blocks for polysaccharides (many sugars joined together) (Mader, 1998).

One sample from each of the seven terrestrial habitats (saltspray, biotic, mire, drainage line, fernbrake, fellfield, and polar desert) was analysed in detail using the steps described by Smith (1999) (Appendix I). The spectra from each habitat were visually compared and a spectrum chosen which represented most peaks present within a habitat's samples (graphs 8 -14 in Appendix I). Major peaks were identified (Table 14).

Table 14: Organic infra-red bands identified (Pouchert, 1981; Johnston & Aochi, 1996; Swift, 1996; Smith, 1999).

Description	Range	Biotic	Saltspray	Mire	Drainage line	Fernbrake	Fellfield	Polar desert
O-H stretch	3350±50	3412	3397	3394	3371	3409	3383	3454
CH_2 Asymmetric stretch	2926±10		2922	2923	2928	2924		
CH_2 Symmetric stretch	2855±10		2853	2852		2853		
C=O stretch(es)	1630-1750	1647	1732 1651	1652	1683	1649	1629	1635
NO_2 asymmetric stretch	1550-1500		1517	1514				
N-H in-plane bend	±1505							
NO_2 symmetric stretch	1390-1330	1384	1375	1375	1388	1376	1397	1372
O-H in-plane bend	1350±50							
C-C-O stretch or C-O stretch	1230±30		1255	1267		1229		
C-N stretch	1020-1250	1147 1083	1059	1071	1149 1091	1157 1087	1134 1077	1145 1080
C-O stretch	880-1210	974			974	979	973	974
NH_2 out-of-plane bend	750-850			813				
O-H out-of-plane bend	650±50	624	668	610	668 & 628	629	622	621
Refer to Appendix I	Example	Graph 8	Graph 9	Graph 10	Graph 11	Graph 12	Graph 13	Graph 14

Water (O-H stretch at ±3500-3000 & O-H scissors at ±1630) (Pouchert, 1981; Swift, 1996) was found in each of the samples analysed. Air dried samples were used for analysis and interstitial water can be detected by the infra-red techniques. KBr, a hygroscopic substance, was however used to make the IR pellets to be analysed. Therefore, KBr pellets are likely to attract water from the atmosphere; making it unclear whether or not water found in samples was present before analyses or as the result of the method applied (Pouchert, 1981). The presence of water was therefore ignored, and not used for the comparison of samples.

Since soil samples are, by definition, mixtures, the compounds present cannot be fully characterised, and further investigation is required before organic substances can be interpreted. It appears that phenols are present in the saltspray, mire, and fernbrake habitats (bands at ±3350; ±1350 and ±1230). Phenolic functional groups are major contributors to the negative charges found in soils (Sparks, 2003). A CH_2 functional group was present in the saltspray, mire, and fernbrake habitats. The organic matter present in the saltspray, mire, and fernbrake habitats is either more complex or more diverse than that found in other habitats. It is likely that organic compounds don't accumulate as much in the other habitats for the following reasons:

1. Biotic habitats are found near the coast, and may be barren in places due to biotic activity.
2. Organic components in the biotic habitat are likely to be easily washed through the soil and out of the profile.
3. Drainage line habitats are permanently wet, with water moving through the profile downstream, thereby washing particles out of the profile.
4. Fellfield and polar desert habitats are characterised by patchy occurrences of pioneer plants, where vegetation is present, thereby reducing the organic signal.

The Aldrich Library of infra red spectra (Pouchert, 1981) was consulted to determine whether or not uric acid, a major component of penguin excreta, (Figure 19) existed in any of the samples analysed. The major peaks of this spectrum were compared with the peaks found in the infra-red spectra of all the soils analysed in this study. It was found that 25 of the 74 samples analysed showed characteristics of the uric acid spectrum. Since the samples analysed are not pure, broader ranges were considered to account for interference. Of the 25 spectra noted here, 19 were from the saltspray, mire and biotic habitats (these habitats are singled out as they are likely to be occupied by penguins, or are likely to be adjacent to areas occupied by penguins).

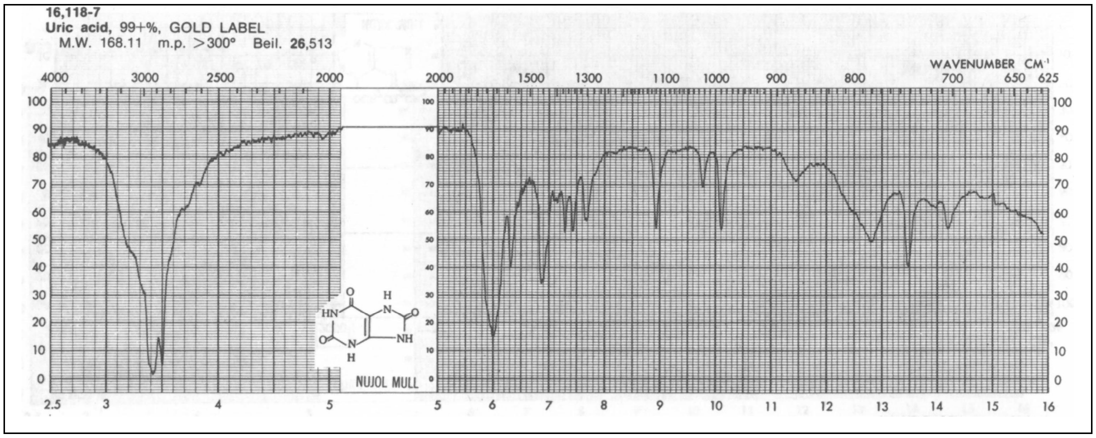


Figure 19: **Infra-red spectrum of uric acid (Pouchert, 1981).**

8.2.4 Infra-red before and after loss on ignition

Four soils were analysed by transmittance infra-red techniques before and after loss on ignition analysis to determine what portions of the soil sample were removed during loss on ignition, and to determine whether or not the results from the analysis of loss on ignition could indeed be used as a measure of organic matter content. Should only organic bands be affected, it can be assumed that the loss on ignition value is analogous to the organic matter content of the soil. Alternatively, if the mineral bands are affected then mineral alteration may have taken place, and the loss on ignition value cannot be used as an indication of organic matter content. KBr pellets were made as described above from unmilled, dried samples before and after having been in the furnace at 550°C for 10 hours. The sample after loss on ignition will have changed from the original sample. Components may have been lost or changed, and the relative quantities of the remaining components will, therefore, be altered. The graphs were equalised on the curve in the vicinity of $1000cm^{-1}$ (*i.e.* the graphs were stretched or shrunk along the y-axis in order to ensure that the before and after loss on ignition graphs are equal at one peak along the curve, to allow for easier comparison of remaining peaks).

The four resulting spectra (graphs 15-18 in Appendix I) each had three very prominent peaks ($3400cm^{-1}$ – OH stretch; $1630cm^{-1}$ – C=O stretch & $1080cm^{-1}$ – C-N stretch / C-O stretch), and a further 2 less prominent peaks ($2900cm^{-1}$ – CH_2 asymmetric stretch & $1390cm^{-1}$ – O-H in-plane bend / NO_2 symmetric stretch). It was noticed that the peaks around $3400cm^{-1}$ (O-H stretch), $2900cm^{-1}$ (CH_2 asymmetric stretch), $1630cm^{-1}$ (C=O stretch) and $1390cm^{-1}$ (NO_2 symmetric stretch / O-H in-plane bend) decreased after loss on ignition in all cases. In some cases they decreased more dramatically than others, or they disappeared completely (such as with the peaks at $2900 cm^{-1}$ (CH_2 asymmetric stretch) and $1390cm^{-1}$ (NO_2 symmetric stretch / O-H in-plane bend) in most samples)). The disappearance of peaks after loss on ignition indicates that the components of the soil creating these peaks were lost on ignition.

The peaks around $460cm^{-1}$ (the fingerprint region) were almost unaffected in all the samples analysed (Appendix I). Therefore since altered peaks were from the characteristic group frequency region, it is concluded that material lost during ignition of samples was predominantly organic material. This also means that loss on ignition values can be used as a proxy for organic matter content.

9 Soil genesis

Pedogenesis can be defined as the formation of the solum as a result of the five soil forming factors (van der Watt & van Rooyen, 1995). These five independent soil forming factors are climate, organisms, topography, parent material, and time (Jenny, 1941; van der Watt & van Rooyen, 1995; Whittow, 2000).

Contrary to the findings of Gribnitz *et al.* (1986), several characteristics of soils on Marion Island that have been visually observed (Chapter 4) or tested in a laboratory (Chapters 5 - 8) indicate that pedogenesis has taken place on the Island. There is evidence that each of the soil forming factors have played a role in the development of soils on Marion Island.

9.1 Independent soil forming factors

Climate has allowed for the availability of water and fluctuations in temperature, affecting both weathering and erosive processes. The accumulation of organic matter within soil profiles is illustrated in Chapter 8, and can be attributed to the influence of living organisms. Topography has resulted in the formation of deeper soils in valleys, and the lack of soil formation on steep slopes. Parent material has influenced the mineralogical makeup of the soil, and time has allowed the soil forming processes to continue to further develop the soil profiles.

9.1.1 Climate

As noted in Chapter 2, the climatic conditions on Marion Island are cold and wet. Meteorological records over the last 60 years indicate that the climate on the Island is warming and drying (Smith, 2002; Rouault, *et al.*, 2005). It has also been shown that Marion Island experienced between five and eight glaciations during the Quaternary Period (Boelhouwers, *et al.*, 2008), indicating that Marion Island has been subjected to a variety of climatic conditions over that period.

Temperature and moisture availability, which are governed by climatic conditions will impact on the nature and rate of weathering and erosive process active on Marion Island, therefore impacting on soil formation. Low temperatures may inhibit chemical reactions, or induce freezing of water. Wind speed and direction will influence whether or not particles are removed or deposited. It has been shown that wind ripple marks on Marion Island are deflated (Callaghan, 2005). Bearing in mind that gale force winds occur on Marion Island for nearly one third of the year (Le Roux, 2008a), it is likely that strong winds carry sediment with them from the island. Windswept areas are common on Marion Island and may be dominated by *Azorella selago* plants and grasses (*Agrostis megallanica*) (Figure 20).

Figure 20: Windswept plain with scattered *Azorella selago* and *Agrostis megallanica* plants.

9.1.2 Organisms

Human impacts on Marion Island are likely to be localised since it is a Special Nature Reserve (de Villiers & Cooper, 2008). It is however noted that in the 1950's, attempts were made to grow trees on the Island (King, 1954). Sheep, pigs and fowls were also taken to the island to use for fresh meat, and cats were introduced in an attempt to rid the island of the accidentally introduced house mouse (King, 1954; Cooper, 2008). One of the largest human influences on Marion Island's soils is probably as a result of sealing activities, which took place from about 1800 to 1930 (Cooper, 2008).

While humans almost certainly have impacted on soils on Marion Island, this will not be considered in detail in this study as this influence on pedogenesis is considered minimal, and currently fairly stringent management rules disallow further influence to a large degree (de Villiers & Cooper, 2008). The meteorological station is situated on the east of Marion Island, and as many as eight field huts have existed around the Island, with another in the interior. Humans have travelled around the Island by helicopter and on foot. Footpaths are quite distinct in some places, while almost absent in others (field observation).

Plants have an impact on soils on Marion Island. The cut soil profile (Figure 21) and the cross section of the *Azorella selago* cushion plant (Figure 22) clearly show how organic matter and fine particles have accumulated. *Azorella selago* plants are pioneer plants on Marion Island and succession is likely to begin with grasses growing on or around these plants (le Roux, 2008b).

Figure 21: *Blechnum penna-marina* plants impacting on the underlying soil.

Figure 22: Cross section of an *Azorella selago* plant (Photo courtesy of Prof. M. A. McGeoch).

Seals bring organic matter onto the Island by dropping their faeces and shedding their skins on land through moulting. They also make wallows, which fill with water and organic matter. Penguins impact on soils on Marion Island by adding nutrients, and trampling ground, specifically in penguin breeding colonies; one excellent example is that of the macaroni penguin colony at the Amphitheatre, near the Swartkops field hut (Figure 1; Figure 23) which houses approximately 14000 breeding pairs (average over seasons between 1994 and 2003) (Crawford *et al.*, 2003). Terraces have been trampled and carved out by the weathering and erosion effects of these penguins. The vegetation on top of the uneroded pedestals is thick and lush, a result of the rich nutrients available (Figure 23).

Figure 23: Soils affected by macaroni penguins at the Swartkop penguin colony (Amphitheatre).

Albatrosses build up nests on the ground surface or on cliff faces (Figure 24). Some petrels burrow to make nests, taking nutrients to below the surface with them. The effects of fauna (except for invertebrates) on Marion Island's soils are mostly limited to low-lying coastal areas to which the penguins and seals have access. Invertebrates will also play an important role in soil formation on Marion Island by increasing organic matter decomposition rates, and promoting nutrient mineralization (Smith, 2008).

Figure 24: Wandering Albatross nest.

9.1.3 Topography

Marion Island's Topography is governed by the more recent black lava flows and scoria cones (Boelhouwers *et al.*, 2008). The topography of Marion Island varies from flat mires, to steep cliffs (Figure 25). The highest peak (Mascarin Peak) rises to 1231mamsl, and therefore some very steep areas are found on the Island.

Figure 25: Varying topography on Marion Island, with steep slopes to the left, a scoria cone in the foreground and flatter areas to the right.

Topographical effects have aided in the transportation of particles. Steep slopes (such as those of scoria cones (Figure 25) appear to be at or close to their angle of repose (field observation.) with particles sliding down slope with every step taken. It was also noted that vegetation was generally only present on the lower slopes of scoria cones (field observation). This may also be as a result of less water availability (due to steep slope angles) or possibly the geologically young age of the parent material. Slope failures were also noted at several locations on Marion Island (Figure 26). Slope failures will transport material down slope and expose previously buried particles to the elements, potentially allowing further weathering and erosion.

Figure 26: Slope failure.

9.1.4 Parent material

Marion Island is a volcanic Island with typical oceanic basalt rocks (Chapter 7; Winter, 2001). Geologically, Marion Island consists of grey lava (Figure 20), black lava (Figure 27) and scoria (Figure 25), all of which are similar in chemical composition (Abbot, 1963; Verwoerd, 1971). In this study it was assumed that the soil is a function of the parent material over which it lies (C-horizon).

Figure 27: Basaltic parent material; foreground - black lava; background - red scoria - note the encircled person and backpack at the bottom of the figure for scale.

The mire habitat on Marion Island is very wet, and has very high loss on ignition values (up to 92% - refer to Chapter 8). Organic parent materials are likely to develop in this habitat as long as moisture remains available.

9.1.5 Time

The oldest rocks on Marion Island (above the surface of the ocean) are approximately 450000years old, with the most recent lava flow occurring in 1980 (McDougall *et al.*, 2000). Therefore soils in different areas around Marion Island have had varying times over which to develop. As previously mentioned (Chapter 2), vegetation has already become established on the most recent lava flow on Marion Island (Gremmen & Smith, 2008).

9.2 Active weathering processes

The five soil forming factors described above will influence weathering and erosive processes, which will in turn influence the development and characteristic of soils on Marion Island. Some potential weathering processes that may occur on the island have therefore been identified, and are listed below. It should however, be kept in mind that other processes may also be active, and interactions between processes may also occur. Due to the environmental conditions on Marion Island, as well as general field observations, it is anticipated that the following weathering processes may be active on Marion Island (refer also to Chapter 2):

- Chemical Weathering:
    - Hydrolysis - due to the abundance of water on Marion Island.
    - Oxidation and reduction reactions – due to the availability of water; the rates of reactions are likely to be affected by low temperatures.
    - Rubification - red coloured iron accumulations (iron pans) were observed in several profiles, especially within the fernbrake habitat (Figure 6).
    - Salinisation – likely to occur in saltspray habitats where sea salt is added to the profile on a regular basis (Gremmen & Smith, 2004).
- Physical weathering:
    - Cryogenic processes – the climate on Marion Island is cold, and temperatures regularly cross 0ºC (le Roux, 2008a). This suggests that water on Marion Island may freeze and thaw, which in turn may place physical stresses on particles.
    - Precipitation of salts - likely to occur in saltspray habitats where sea salt is added to the profile on a regular basis (Gremmen & Smith, 2004).
    - Unloading – Marion Island has had at least five glaciations within its history, and therefore the five deglaciations will have allowed for pressure release. Boelhouwers *et al.* (2008) note the presence of dilatation shattering, suggesting that unloading has occurred on Marion Island.
- Biological weathering:
    - Melanization - dark coloured surface horizons high in organic matter were found on Marion Island (Figure 8), suggesting that this process may be active.
    - Peat accumulation - Marion Island receives much rain (Chapter 2). Mire and drainage line habitats are generally waterlogged with organic matter contents as high as 92%. Mire, drainage line and most saltspray habitats are essentially peat fields of up to three meters in depth (Figure 4).

The weathering processes are unlikely to occur in isolation, and a combination of weathering processes will have occurred on Marion Island. Other weathering processes not mentioned above may also be active on Marion Island.

10 Soil-habitat relationships

Initial field observations suggesting that a relationship exists between habitat type and underlying soils was confirmed by analysis of soil samples collected. Soils are discussed below in relation to the seven habitats within which soils were sampled. Pictures of the habitat are shown and a generalised profile for each habitat has been compiled.

10.1 Saltspray habitat

Saltspray habitats (Figure 28a) occur only near the coast where sea spray heavily affects both soils and plant growth (Gremmen & Smith, 2004). Plants in this habitat are usually dwarfed, by the high content of sea salt. These soils are regularly affected by the sea spray, and the kelp washed up can be clearly seen (Figure 28a). Saltspray habitats are commonly found at the edges of sea cliffs.

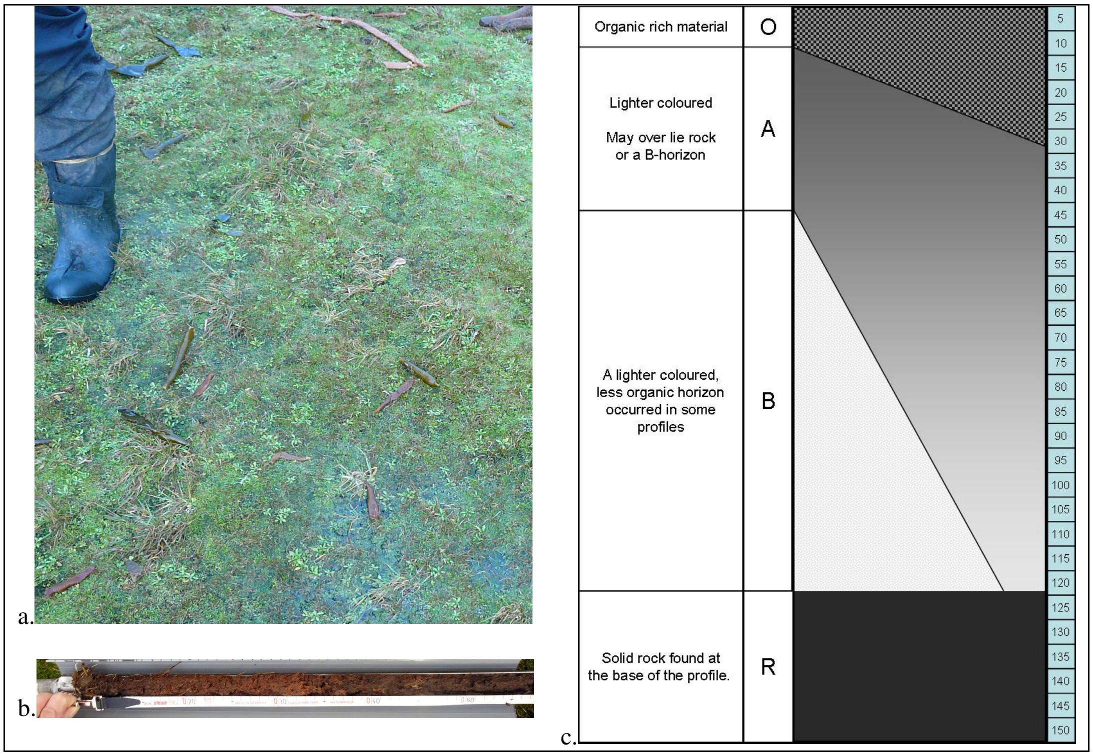


Figure 28: Saltspray habitat (a) Typical saltspray habitat; (b) Soil sample from a saltspray habitat; (c) Generalised soil profile for saltspray habitat.

Two or three horizons were found in the saltspray habitats. The depth of the horizons and profile, varied considerably between samples (Figure 28c). The depth of profile is assumed to be affected more by topography than by habitat. The deepest soil sampled from a saltspray habitat reached a depth of 220cm. These soils generally had high loss on ignition values (Chapter 8). Transitions between horizons were diffuse, and most easily noticed by colour (Figure 28b). Solid rock was found at the base of most saltspray profiles, but in some cases regolith was present. The sea spray will add salts to the soil profile. This not only affects the soils and plants, but will also increase the likelihood of salt induced weathering to occur within this habitat.

10.2 Biotic habitat

Biotic habitats (Figure 29a) are heavily affected by animals, and are found generally near the coast where both penguins and seals are common, but may also be found where birds nesting inland have had an effect on the soils. Animals will affect the nutrient status of the soils and plant growth is prolific where it has the chance to grow. Plant growth cannot take hold in seal wallows and penguin colonies. Seal wallows are utilised regularly by seals, and often fill with water (Figure 29a).

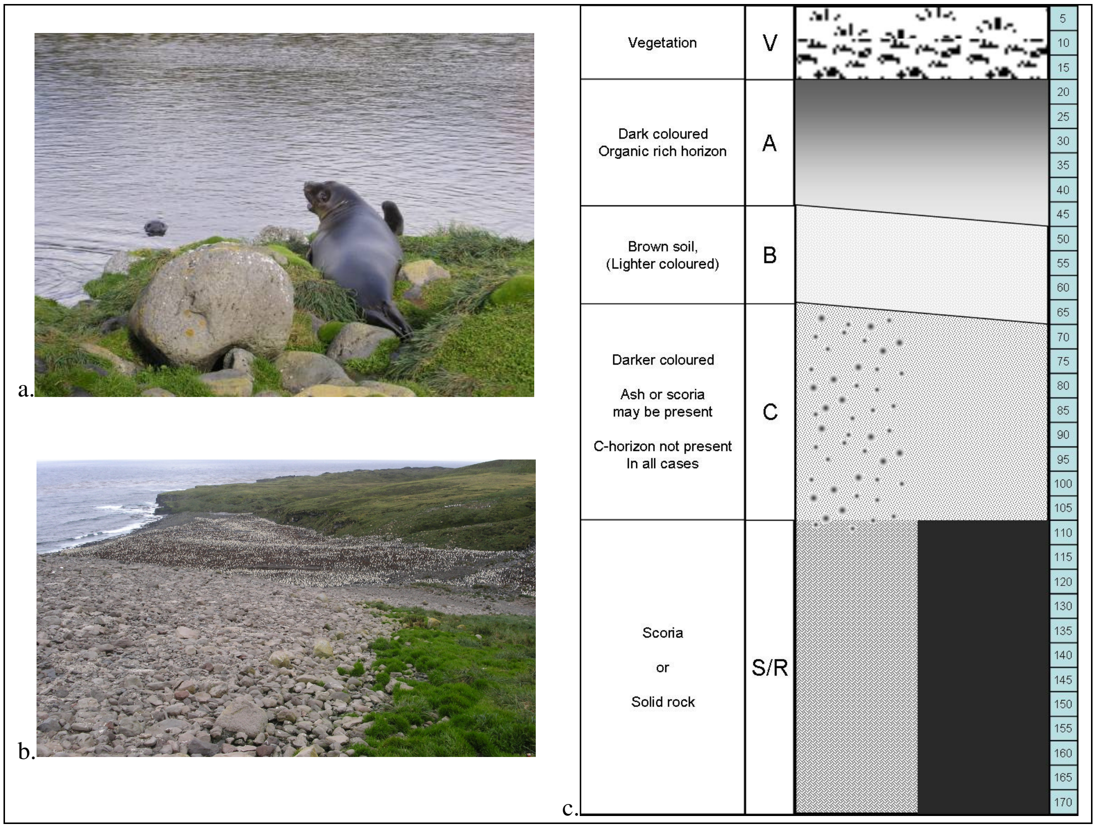


Figure 29: Biotic habitat; (a) Seal in biotic habitat; (b) Kildalky penguin colony; (c) Generalised soil profile for a biotic habitat.

Penguin colonies are only occupied for a few months of the year during the nesting season of the particular penguin species, however the penguins trample the ground and remove topsoil (Figure 29b). Most of the penguins nest in large colonies (Figure 29b and Figure 30), and have a lesser nutrient effect on soils than some of the other fauna. This is due to the fact that their large, bare, nesting sites are found adjacent to the sea resulting in the guano being quickly washed into the sea (Smith, 1976). Nesting birds as well as seals play a very important role in adding important nutrients to the soil (Smith, 1976).

Figure 30: Biotic habitat - the Swartkop macaroni penguin colony.

In the biotic habitat, the vegetation thrives on the additional nutrients available. Where vegetation is prolific, soils are well developed and several horizons occur (Figure 29c). Where vegetation cannot take hold the organic content of soils is very low (Chapter 8) and soils are thin or non-existent, overlying either scoria or solid rock.

10.3 Mire habitat

Mire habitats (Figure 31a) are permanently waterlogged and soils are dark in colour. Loss on ignition values for these soils were very high (up to 96% organic matter; Chapter 8).

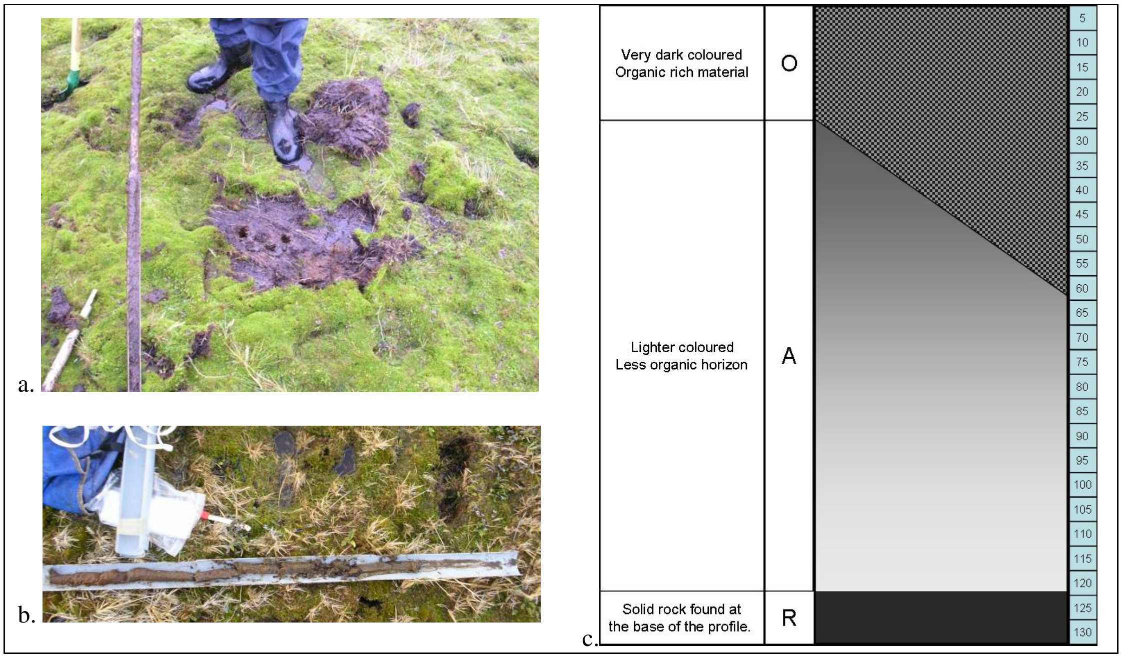


Figure 31: Mire habitat; (a) Typical mire habitat; (b) Soil sample from mire habitat; (c) Generalised mire profile.

Generally two horizons were identified; a lighter peaty horizon above and a darker, smoother horizon below (Figure 31b). In some cases regolith was encountered above the solid rock base of the profile. In most cases the water table is very close to the surface of the soil, and in some cases above the surface, this is illustrated by the ponding of water in footprints (Figure 31b). The vegetation layer, consisting mostly of mosses was removed before soil samples were collected by auger. The depth of horizons and profiles varied considerably, dependent on topography. Depth of the soil profile in the mire habitat varied from 40cm – 230cm.

10.4 Drainage line habitat

Drainage line habitats (Figure 32a) are wetter areas bordered by mire and / or fernbrake habitats, and their characteristics are affected by these adjacent areas. The habitat characteristics are, however, more akin to those of a mire than a fernbrake. *Acaena magellanica* and mosses are species indicative of a drainage line habitat (Gremmen & Smith, 2004). Drainage line habitats, as the name implies, are very wet, and characterised by the movement of water.

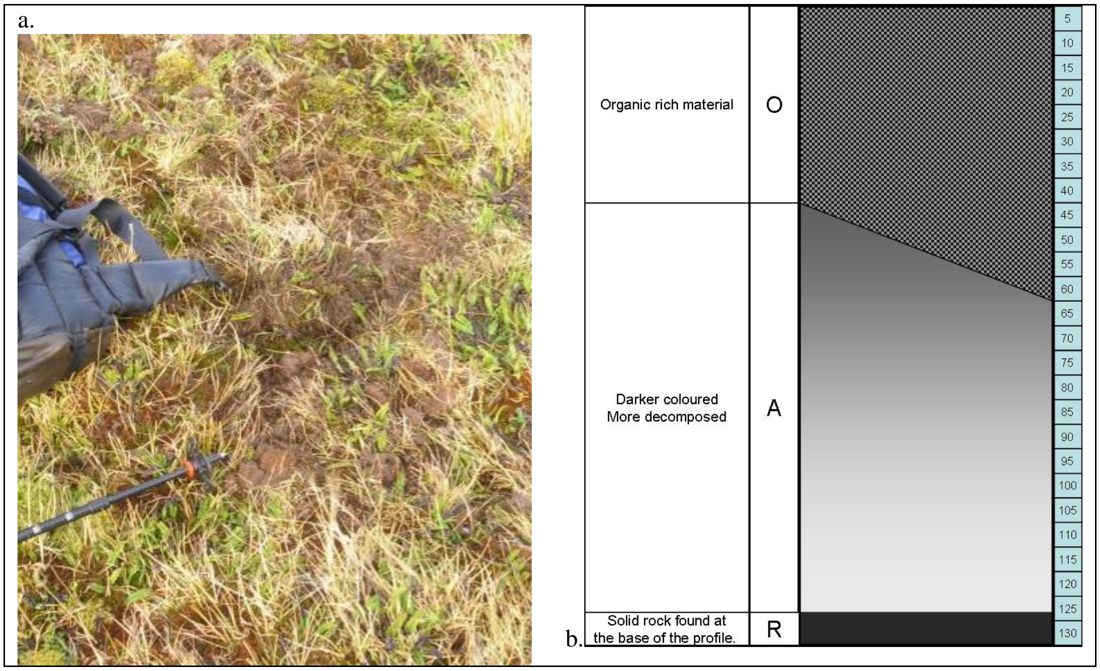


Figure 32: Drainage line habitat; (a) Typical drainage line habitat; (b) Generalised soil profile for a drainage line.

Two horizons were found in all cases and as with mires, depth varied between sites. Sampled profiles varied in depth from 120cm to 210cm. A lighter coloured peaty horizon was found to overly a darker more decomposed subsurface horizon.

10.5 Fernbrake habitat

Fernbrake areas are covered in thick fern vegetation (*Blechnum penna-marina* sp.) sometimes with patches of *Acaena magellanica* (Gremmen & Smith, 2004) (Figure 33a). Soil profiles are well developed with at least three horizons. Iron pans are common, and several of them exist in each profile. The multiple iron pans suggest that there has been a fluctuating water table. Hardened manganese nodules were found one site (Figure 33c).

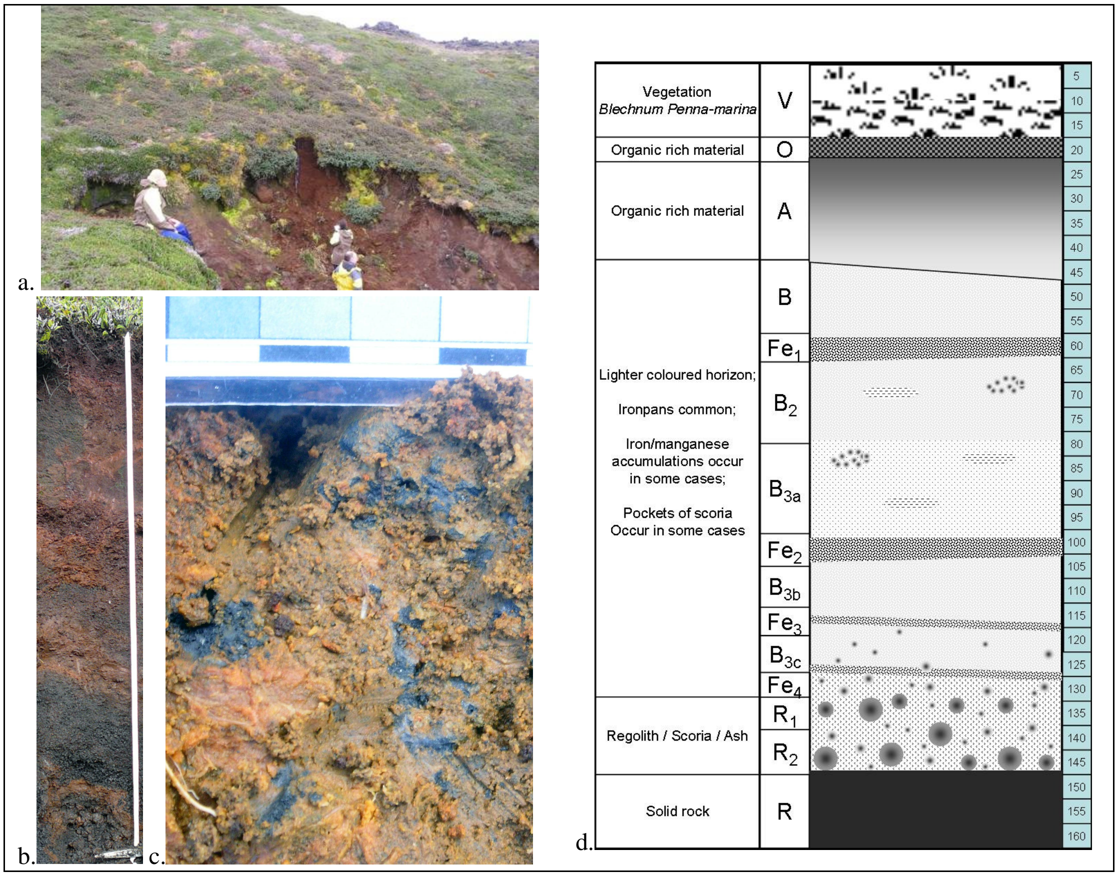


Figure 33: Fernbrake habitat (a) Typical fernbrake habitat; (b) Fernbrake profile; (c) Manganese modules (note centimetre cm marks above) found at site no 19; (d) Generalised soil profile of a fernbrake habitat.

Patches of scoria were found in the B-horizon of one profile and scoria became more and more common moving downwards through the profile (Figure 33b). Below the soils in the fernbrake habitat, either large scoria particles or sold rock were found. Generally, a thin dark organic horizon overlies an A-horizon. The B-horizon is lighter and redder in colour, and several ironpans may occur occasionally with manganese nodules, or scoria accumulations (Figure 33d).

10.6 Fellfield habitat

Fellfield habitats are windswept areas, with sparse *Azorella selago* plants (Gremmen & Smith, 2004). Soils are generally shallow and rocky. The surface of these soils is dominated by large particles or rock (glacial till). No finer particles occur at the surface, these may have been removed by the continuous, strong winds, or surface wash. Organic matter accumulation in this habitat is minimal, mainly due to the sparse vegetation present. *Azorella selago* plants, however, assist soil formation by allowing the accumulation of particles and organic matter and limiting erosion (Figure 22). Sampling in these areas was problematic because of the large number of platy rocks present on the surface (Figure 34a) and within the profile.

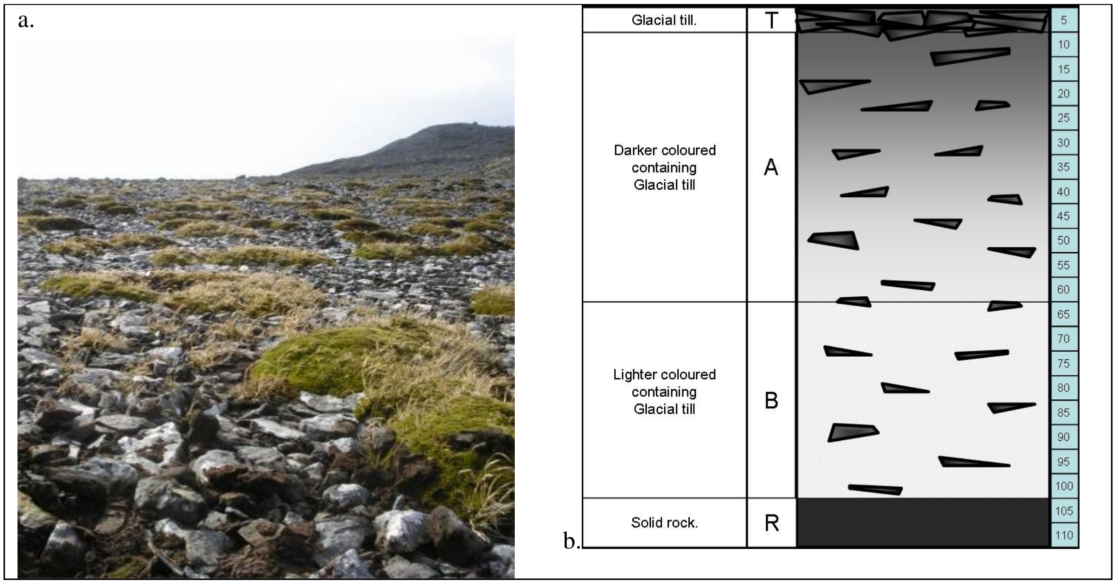


Figure 34: Fellfield habitat; (a) Typical fellfield habitat; (b) Generalised soil profile of a fellfield habitat.

In many cases, only a surface horizon was found, and soils were found to be shallow (20-30cm deep). However, in some cases, soils were found to be as deep as 100cm. It was assumed that the rocks within the profile prevented successful sampling to the full profile depth in some cases (Figure 34b). Surface rocks were removed and soil samples taken from an area in several different places in order to determine the real depth of soil inbetween the rock clasts.

10.7 Polar desert habitat

Polar desert areas (Figure 27; Figure 35a) are barren with the absence of plants; however mosses and lichens do occur (Gremmen & Smith, 2004). Soils in this habitat are very variable, but generally very poorly formed, if found at all. The lack of pedogenesis in this habitat type is attributed mainly to two factors; namely, the distinct lack of biological activity, as well as the fact that the environment is very cold and the surface is often covered with ice or snow, especially during winter months. The surface layer may be frozen for parts of the year, but permafrost no longer exists (Hedding, 2006; Boelhouwers, *et al.*, 2008). In some cases profiles with horizon differentiation were found. This may be the first sign of soil formation. Smectite was found in the polar desert soil sample analysed for clay mineralogy (Chapter 7). This is also an indication of the beginnings of soil formation.

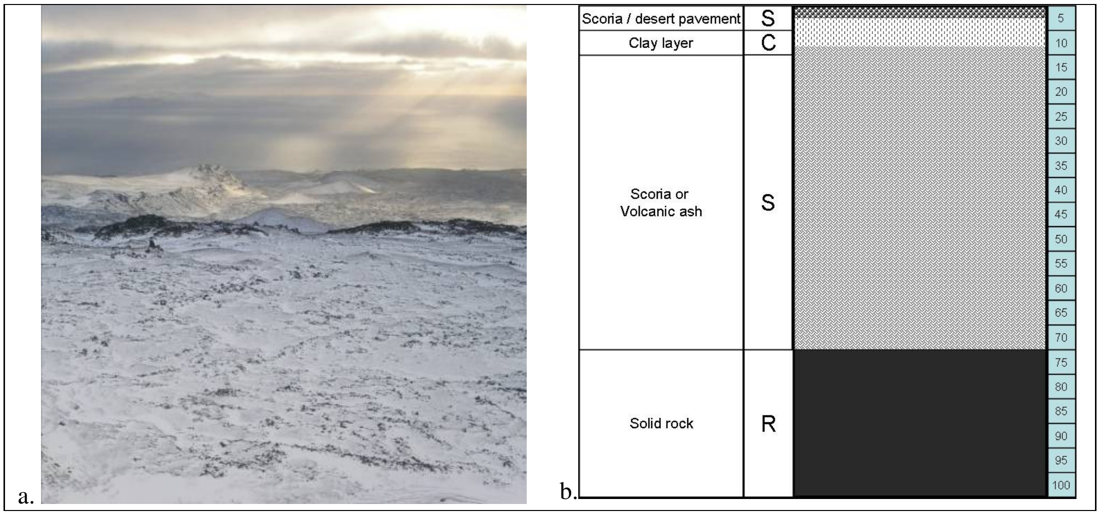


Figure 35: Polar desert habitat (a) Typical polar desert habitat, after snowfall; (b) Generalised soil profile of a polar desert habitat.

It was noted (field observation) that a desert pavement was present in polar desert habitat (Figure 36). A desert pavement is defined by Whittow (2000) as an extensive area of bare pebbles occurring at the surface as a tightly packed crust. The pavement of coarse material is exposed at the surface where finer dust and sand have been blown away. This hard stony layer protects the underlying finer layers from further erosion.

Wind ripple marks observed in the interior of Marion Island indicate that these features have been deflated of finer particles by wind action (Callaghan, 2005). Sorted ground is found in some places and Hall (1979) describes how sorted stripes on Marion Island consist of either coarse or fine material. However, he also notes that even the fine stripes are covered with gravel sized granules. Bockheim & Ugolini (1990) suggested that desert pavements were limited to continental Antarctica, with increasing likelihood of formation at higher latitudes. Their classification is broad, taking into account the entire southern circumpolar region, and is based on climatic and vegetation zones. It is noted that trends found in Bockheim & Ugolini's (1990) research (Chapter 2) for changes with increasing latitude also seem applicable with an increase in altitude on Marion Island. This would certainly make sense in most cases for soil formation on Marion Island.

Figure 36: Polar desert sample site (Site 34).

A generalised soil profile was constructed for the polar desert habitat (Figure 35b), however soils in this habitat varied greatly. A layer of coarse material (scoria/desert pavement/sorted surface) was found at the surface of each profile. A layer consisting of fine particles was found in some cases. Below one or both of these layers, volcanic ash or scoria would be found in one or two differing layers. Solid rock lies at the base of the profile, but the depth of the profile is variable.

11 Soil classification

Soil is a heterogeneous body of material, and can never be considered homogenous, therefore distinct boundaries between different soil units used to classify soils are rare. Rather there is a gradual transition from one soil unit to the next (Peterson and Calvin, 1996). The small scale spatial variation of vegetation on Marion Island is highlighted by Smith & Mucina (2006). They attribute this specifically to topography, which in turn influences insolation, wind, and moisture.

11.1 South African Soil Classification System

The South African classification system divides soils into forms, based on diagnostic horizons identified, then families, based on diagnostic family criteria within a form (Soil Classification Working Group, 1991). Within this system, all the soils sampled on Marion Island would fit into three soil forms.

Most surface horizons on Marion Island would be classified as an organic O horizon. This would suit all soils with an organic matter content of greater than 10% (as was the case with 68% of the samples analysed; Chapter 8). These soils will fit into the Champagne (Ch) form – soils containing an organic O horizon; with unspecified material below (Soil Classification Working Group, 1991).

The remaining soils on the Island are generally more poorly developed, having an orthic A surface horizon. These samples (within penguin colonies or in the polar desert) have either regic sand or hard rock subsurface horizons, placing them in either the Namib (Nb – Orthic over Regic sand) or Mispah (Ms – Orthic over hard rock) soil forms (Soil Classification Working Group, 1991).

11.2 World Reference Base Soil Classification System

Since the soils on Marion Island (organic and volcanic) are very different to those generally found on mainland South Africa, the South African Soil Classification System (Soil Classification Working Group, 1991) does not cater fully for these soils and is not appropriate in this instance. The World Reference Base (WRB) was, therefore utilised to classify soils on Marion Island (Driessen, *et al.*, 2001; IUSS Working Group WRB, 2006).

The WRB Soil Classification System was developed to encompass all soil types that may be found throughout the world in an attempt to make international communication between soil scientists more feasible (IUSS Working Group WRB, 2006). This system also caters for volcanic soils.

Based on general characteristics of the soils found on Marion Island, and the connotations and general definition of soil groups in the WRB system, it was determined that soils from Marion Island would fit into three of the reference soil groups within this system. Other reference soil groups are also discussed below along with the reasons as to why Marion Island's soils do not fit into these reference soil groups.

11.3 Histosols

Histosols characteristically have very high organic matter contents (Driessen, *et al.*, 2001). The soil can contain either a histic or a folic surface horizon. In the case of this study, the folic horizon is excluded as it requires soil not to be saturated for longer than one month of the year (Driessen, *et al.*, 2001) – many soils on Marion Island are saturated all year round.

Histosols are defined as "*soil, having a histic or folic horizon, either 10cm or more thick from the soil surface to a lithic or paralithic contact, or 40cm or more thick and starting within 30cm from the soil surface; and having no andic or vitric horizon starting within 30cm from the soil surface*" (Driessen, *et al.*, 2001). The classification of a histic horizon requires an organic matter content of between 20% and 30% depending on the clay content of the soils (Driessen, *et al.*, 2001). Histic horizons need to be saturated with water for at least one month of the year (Driessen, *et al.*, 2001). Organic soils, especially those from saltspray, mire and drainage line habitats on Marion Island are saturated year round. The histic horizon also needs to be at least 10cm in thickness (Driessen, *et al.*, 2001). Based on the three criteria for the classification of a horizon as histic, the following set of soils were classified as Histosols (Table 15).

Table 15: **Soils classified as Histosols.**

Site no	Organic matter content	Clay content	Thickness of sample	Habitat
WRB requirement	**>20 – 30%**[*1]	**Not defined**[*2]	**>10cm**	**NA**
1	68%	2.5%	25cm	Fernbrake
5	88%	7.5%	35cm	Saltspray
6	85%	8.7%	80cm	Mire
14	20%	1.3%	20cm	Biotic
17	24%	0.6%	20cm	Biotic
18	82%	9.9%	50cm	Mire
19	45%	4.3%	25cm	Fernbrake
20	36%	2.5%	30cm	Mire
21	87%	4.9%	60cm	Saltspray
22	91%	2.5%	50cm	Mire
24	28%	2.6%	27cm	Fellfield
25	38%	5.0%	30cm	Drainage line
26	79%	4.9%	40cm	Mire
27	42%	5.0%	15cm	Mire
35	97%	12.4%	50cm	Mire
36	70%	1.3%	88cm	Fernbrake
38	83%	3.1%	55cm	Mire
39	89%	1.2%	20cm	Biotic
41	77%	5.0%	80cm	Drainage line
44	68%	1.2%	30cm	Biotic
46	89%	1.2%	10cm	Saltspray
47	77%	2.5%	20cm	Saltspray

**1: Organic content must be at least 20% for soils with no clay, and at least 30% for soils with 60% clay content, or a proportionate value in between these two, based on the clay content of the soil. Loss on ignition values were used as a proxy for organic matter content (Chapter 8).*
**2: Clay content is not defined as a horizon criterion, but is included here as it impacts on the required organic matter content.*

11.4 Andosols

It was noted by Smith *et al.* (1999) that Andosols would take at least 4000 to 5000 years to fully develop (using the example of soils in the White River Tephra of Canada). However, Dahlgren *et al.* (2004) point out that Andosols may develop in as little as 200-300 years in humid conditions, if no further volcanic ash is deposited.

Andosols are soils of volcanic origin and characteristically also have high organic matter contents (Driessen, *et al.*, 2001), however, this is not a criterion for their classification. Andosols are defined as "*soils having a vitric or an andic horizon starting within 25cm from the soil surface; and no diagnostic horizons (unless buried deeper than 50cm) other than a histic, fulvic, melanic, mollic, umbric, ochric, duric or cambic horizon*" (Driessen, *et al.*, 2001). An andic horizon requires 10% or more clay. As noted above (Chapter 5), only one soil sampled fits this description. An andic horizon also requires less than 10% volcanic glass. Previous analysis by Abbot (1963) showed that rocks from Marion Island contained up to 50% glass. The presence of glass was confirmed by Raman analysis performed on some soil samples[ii]. The alternative horizon for an Andosol, the vitric horizon, requires 10% or more volcanic glass. The vitric horizon requires a bulk density of greater than 0.9kg.dm^2 or $\text{Al}_{ox}+½\text{Fe}_{ox}>0.4\%$ or a phosphate retention of greater than 25%. The vitric horizon also needs to be 30cm or more thick (Table 16). There is little differentiation between Andosols and Histosols, and so some soils were placed into an intermediary category of Histic Andosols (soils with the characteristics of Andosols, but with high organic matter content). Andosols generally have an average of about 8% organic matter (Driessen, *et al.*, 2001). Soils with a high organic matter (double that of the average or greater than 16%) were labelled as Histic Andosols (Table 16).

Table 16: Soils classified as Andosols and Histic Andosols.

Site no	Organic matter content	$Al_{ox} + ½Fe_{ox}$ *2	Thickness of sample	Histic Andosol or Andosol	Habitat
WRB requirement	**Not defined*1**	**>0.4%**	**>30cm**	**NA**	**NA**
15	16%	1.5	30cm	Histic Andosol	Biotic
16	17%	1.5	30cm	Histic Andosol	Biotic
37	17%	3.7	10cm	Histic Andosol	Fernbrake
4	4%	1.5	40cm	Andosol	Biotic
28	8%	4.0	70cm	Andosol	Fellfield
29	7%	4.0	45cm	Andosol	Fellfield
30	8%	6.7	40cm	Andosol	Polar Desert
31	7%	4.0	30cm	Andosol	Fellfield
32	10%	4.0	70cm	Andosol	Fellfield
33	15%	4.0	25cm	Andosol	Fellfield
34	10%	6.7	44cm	Andosol	Polar Desert
42	9%	4.0	30cm	Andosol	Fellfield
43	2%	3.0	45cm	Andosol	Drainage line

**1: Organic matter content is not defined as a horizon criterion, but is included here as it determines whether soils are classified as Histic Andosols or just Andosols.*
**2: Alox+½Feox values were extrapolated from samples analysed based on habitat.*

As noted in Chapter 2, Andosols can be either allophanic or nonallophanic (Dahlgren *et al.*, 2004). Since neither allophane nor imogilite were found in the samples analysed by XRD, and smectite (2:1 layer silicate) was found, it is assumed that Andosols on Marion Island are nonallophanic. The Andosols on Marion Island fit two of the generalisations concerning nonallophanic Andosols, in that they have a low pH and form in an environment with high rainfall. However, the parent material on Marion Island is basaltic and coloured glass has been found previously (Gribnitz *et al.*, 1986). Therefore, a more detailed study would need to be conducted in order to classify Andosols on Marion Island as either allophanic or non-allophanic.

11.5 Regosols

Little or no soil formation is evident in Regosols, and there is not necessarily clear differentiation into distinct horizons (Driessen, *et al.*, 2001). By definition Regosols refer to soils that do not fit appropriately in any other reference soil group (Driessen, *et al.*, 2001). The remaining soils not yet classified above, were classified as Regosols as they did not fit appropriately into any other group (Table 17). Clay minerals were also found in some of these soils on Marion Island (Chapter 7), indicating the beginnings of soil formation. Other reference soil groups that were considered but rejected are described below.

Table 17: Soils classified as Regosols.

Site no	Habitat	Altitude (mamsl)
2	Polar Desert	753
3	Biotic	62
7	Biotic	60
8	Biotic	61
9	Biotic	62
10	Biotic	62
11	Biotic	63
12	Biotic	63
13	Biotic	63
23	Drainage line	142
40	Fellfield	53
45	Polar Desert	751

11.6 Cryosols

Cryosols are soils found in cold environments, dominated by cryic processes (Cryic processes include freeze-thaw, cryoturbation, frost heave, cryogenic sorting, thermal cracking, and ice segregation) (Driessen, *et al.*, 2001). These soils by definition require a permafrost layer (frozen ground for a period of two or more years) within the profile (Driessen, *et al.*, 2001). Widespread needle ice induced processes noted on Marion Island were described by Boelhouwers, *et al.* (2000, 2008). Needle ice frost heave was also noted during fieldwork conducted in April 2006 (field observation) indicating that cryic or related process may be active on the Island.

Sumner *et al.* (2004) indicated that permafrost could be present above 1000mamsl. However more recent research has shown that permafrost is no longer found on Marion Island, even in the interior regions (Hedding, 2006; Boelhouwers, *et al.*, 2008). Bockheim & Ugolini (1990) also noted that permafrost was lacking in the sub-Antarctic regions, and attributed it to winter temperatures being moderated by the Antarctic convergence. This suggests that while Cryosols may have been present in the past, it is not anticipated that Cryosols are still present on Marion Island.

11.7 Podzols

Since hardened ironpans were found in several profiles, especially those in the fernbrake habitats, the podzol soil reference group was considered. This group requires the presence of a spodic horizon, which has a hardened pan as a possible defining feature. This pan must be 2.5cm or thicker and continuously cemented by a combination of organic matter and aluminium, with or without iron. This group was not used as a defining reference soil group as the ironpans found were considered to be too soft (a hardened concentration of iron, but not solidly cemented) (Driessen, *et al.*, 2001). Smith (1976) suggests that the low temperatures, waterlogged acidic soil, and high leaching rainfall favour podsolisation, and suggests that lowland soils may be podsolised. While no podsolised soils were found during the fieldwork in this study, conditions do appear to be right for their formation, and they may exist on the Island. The soils collected at the sampling sites lacked the illuviated horizon, characteristic of a podzol, therefore the podzol reference group was not used in this study.

11.8 Climate change

Evidence from research conducted on Marion Island since the 1950's suggests that the Island is warming up. The summer snow line rose from 600mamsl in 1954 to 950mamsl in 1971, and has now disappeared completely (Boelhouwers, *et al.*, 2008). While it was shown that permafrost was once present on Marion Island, recent studies have found that it no longer exists there (Boelhouwers, *et al.*, 2008). Average measured air temperatures on Marion Island increased by 1.2ºC between 1969 and 1999 (Smith, 2002). It has also been hypothesised that temperatures may increase by 2-5ºC over the next 50-100 years (Hall & Walton, 1992).

As the climate of Marion Island continues to warm, the whole ecosystem and the way it functions will be affected. Soils will be altered and development and succession of soils will occur. As temperature increases, pioneer plants are likely to establish themselves on now less-developed or undeveloped soils. Higher temperatures will lead to an enhanced rate of chemical reactions affecting both the breakdown of rock and the formation of soil. Based on underlying geology, Andosols are likely to develop from now unconsolidated materials. Slowly, more plants will be able to grow and the soil will develop further perhaps into a Histic Andosol. Current Andosol profiles will also continue to develop at an increased rate, potentially resulting in the formation of soils such as Podzols, Planosols, or Luvisols. It is anticipated that these soil types will develop as they are characteristic of previously cold and glaciated areas, such as Marion Island is becoming. Podzols may develop in current fernbrake habitats where iron accumulations are already noted. Planosols, (eluviated soils typical of seasonally waterlogged flatlands (Driessen, *et al.*, 2001)) may be found in the future in currently waterlogged areas such as mire, saltspray and drainage line habitats. Luvisols require clay accumulations (Driessen, *et al.*, 2001), and while clay isn't currently readily available in soils on Marion Island, it may well develop there at a later stage. Nanzyo (2002) noted that highly weathered and very old soils that were previously Andosols may eventually develop into Ultisols or Oxisols (USDA Soil Classification System) which are equivalent to Ferralsols, Alisols, Nitisols and Acrisols in the WRB Soil Classification System. It is likely that any changes to soils as a result of climate change will take time. Hall & Walton (1992) suggest that Histosols, Andosols and Regosols are resistant to change and may require 1000 years or more to alter.

It has been shown with the use of short term climate change experimentation that *Azorella selago* plants will be adversely affected by predicted warming and drying of the climate on Marion Island (Le Roux *et al.*, 2005). It was also noted that such changes would have significant implications for the structure and functioning of the areas on Marion Island currently considered to be fellfield (Le Roux *et al.*, 2005). Along with the changes to *Azorella selago* plants noted, the microarthropods living within them will also be affected (McGeoch *et al.*, 2006). Such changes would affect the soil as organic matter inputs and the activity of detritivores will differ, which may alter the currently active soil forming processes on Marion Island. Hall & Walton (1992) note that higher temperatures promote floral diversity, and therefore it is assumed that changes in flora will impact on soil formation in the future on Marion Island.

12 Graphical distribution of soils

A raster soils map was predicted in ArcGIS® 9.2 (Environmental Systems Research Institute, 2007) from the existing coastline map, Digital Elevation Model (DEM), geology map and vegetation map, as well as general field observations. These data were used in the model because each of these factors are related to one of the five soils forming factors and will influence the formation of soils on Marion Island.

The geology (Figure 2) of the Island defines the parent material of soils developed there. For the purposes of this model, it is assumed that the underlying geology at any point is the parent material of the overlying soil.

The vegetation data (Figure 37) is a good indicator of the biotic factor. While this layer only takes into account the affects of flora, the most prominent effects of fauna (seals and penguins) are near to the coast, most likely falling into the coastal habitat indicated on this map. It should be noted here that the habitat classes given in the vegetation map differs from that of the habitat classes described in Chapter 2 (on which sampling is based), this is due to the fact that the habitats may be very patchy and occupy very small areas. This makes mapping at an Island scale virtually impossible, as a result, for the purposes of map-making, classes were combined in some cases, or the dominant habitat type was mapped (Smith & Mucina, 2006).

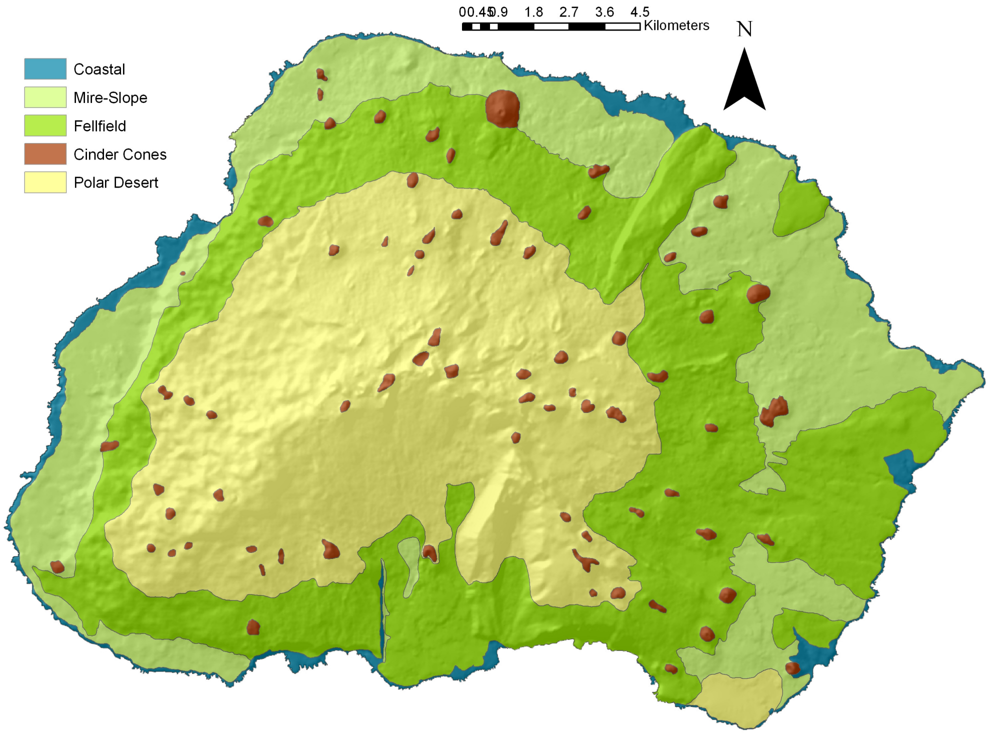


Figure 37: Vegetation of Marion Island (Mucina & Rutherford, 2006).

Climate data are only readily available for areas on Marion Island around the Meteorological Station, however the Island is relatively small, and for purposes of this model it is assumed that the effect of climate does not vary enough to a have a large effect around the Island. Therefore it has been excluded from the model. Microclimatic effects, however, cannot be dismissed and although suitable Island wide data is not available, the DEM (Figure 38) is used so that temperature changes with height are taken into account. At higher altitudes the temperature will generally be lower at any given time (unless an inversion occurs). Vegetation is also limited by altitude, and so the DEM will supplement this dataset. Le Roux & McGeoch (2008) have shown that the upper altitudinal limit of various plants differs on different Island aspects (north, south, east, and west). In order for these data to be taken into account, the coastline map of the Island was used to determine its centroid. From this point, the different Island aspects can be calculated. Using the upper altitudinal limits of vegetation will also be a basic indication of microclimate, as these values differ from one aspect to the next over the Island scale.

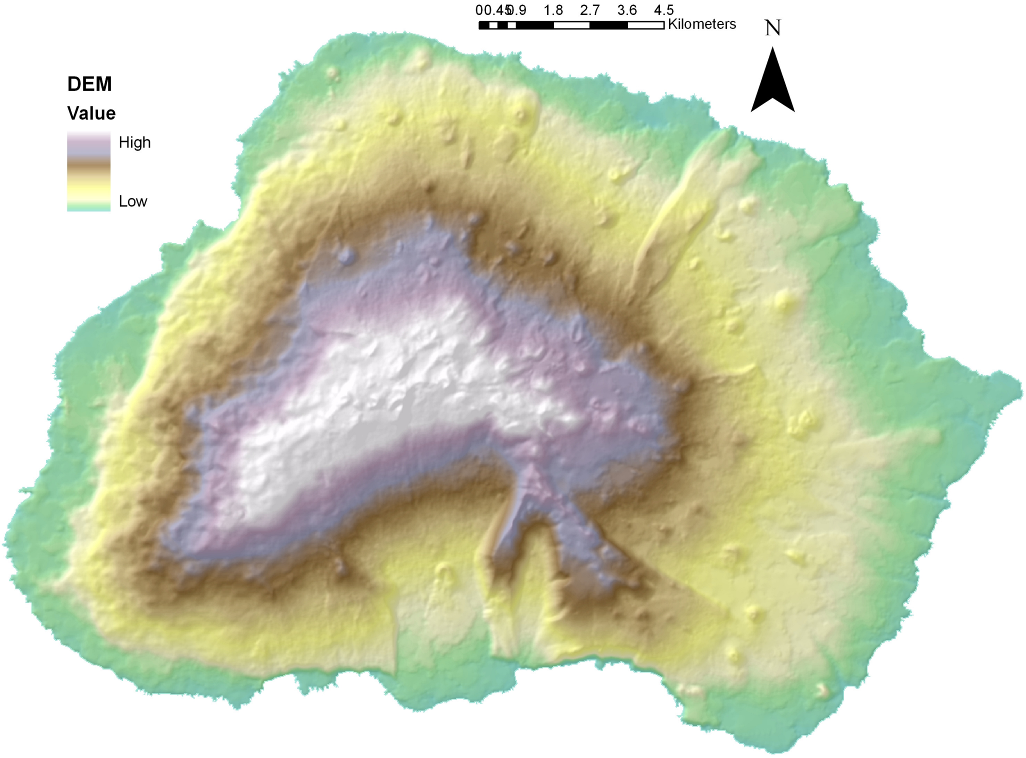
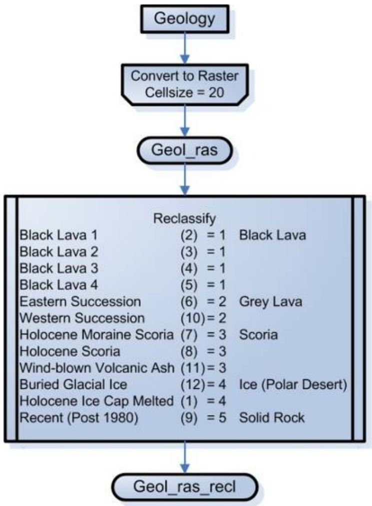


Figure 38: **Hillshaded Digital Elevation Model of Marion Island (Chief Directorate of Surveys & Mapping, 2003).**

A model was built in ArcGIS in order to create a soils map from the input data described above. The model as built in ArcGIS is shown in Appendix J, and has been divided into four sections and described in detail below.

12.1 Geology

The vector based geology layer (Hedding, 2006) was converted to a raster file with a cell size of 20 (20x20m), to match the DEM data (Figure 39). Lithology of Marion Island is typical oceanic island basalts (McDougall *et al.*, 2001; Winter, 2001). The available geology data is fairly detailed and can be more simply described by dividing it into five classes. These classes are: black lava (all black lava classes), grey lava (eastern and western succession grey lavas), scoria (all scoria and ash classes) ice (buried glacial ice and the Holocene ice cap) and solid rock (recent (post 1980) lava flows) (Figure 39). In this reclassification, the main geology types were given single digit values for later use in the construction of the soils map (Figure 39 & Figure 40).



Black Lava 1	(2)	= 1	Black Lava
Black Lava 2	(3)	= 1	
Black Lava 3	(4)	= 1	
Black Lava 4	(5)	= 1	
Eastern Succession	(6)	= 2	Grey Lava
Western Succession	(10)	= 2	
Holocene Moraine Scoria	(7)	= 3	Scoria
Holocene Scoria	(8)	= 3	
Wind-blown Volcanic Ash	(11)	= 3	
Buried Glacial Ice	(12)	= 4	Ice (Polar Desert)
Holocene Ice Cap Melted	(1)	= 4	
Recent (Post 1980)	(9)	= 5	Solid Rock

Figure 39: Process followed to convert and reclassify geology.

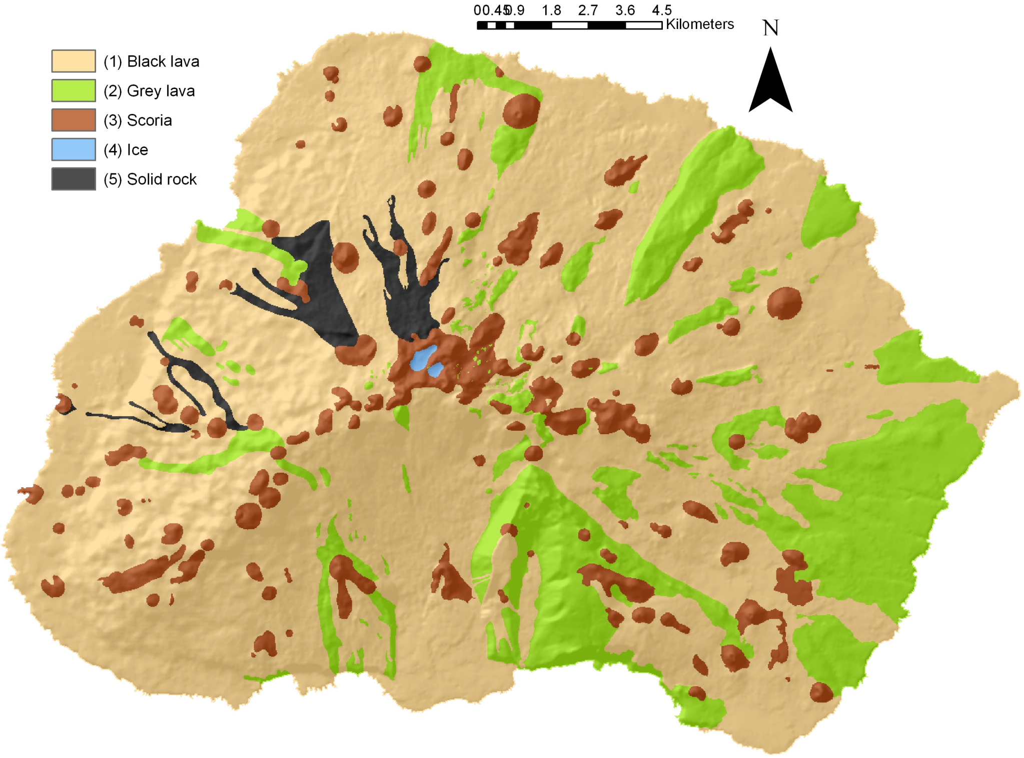


Figure 40: **Raster, reclassified geology of Marion Island (Geol_ras_recl) (based on Hedding, 2006).**

Soils may form from residual parent material (*in situ*) or from transported parent material. Since it is not always clear for every given profile what the parent material origin is, and since the model is to be extrapolated to an Island wide scale, it has been assumed that soils have formed *in situ* from the residual parent material, for the purposes of this study.

12.2 Vegetation

The vegetation layer (Mucina & Rutherford, 2006) originally had five classes, coastal vegetation, cinder cones, mire/slope complexes, fellfield vegetation and polar desert. It was however noted (field observation) that vegetation cover was generally more prolific, and soils further developed at the foot of the cinder cones. The cinder cone class on the vegetation map was therefore divided into two classes: "cinder_out" referring to the lower slopes, and "cinder_in", referring to the inner parts of these cinder cones. This was performed by means of buffering, converting to raster, and multiplying with the original raster vegetation layer (Figure 41). The layer was converted to a raster file and reclassified to have double digit units (Figure 41 & Figure 42).

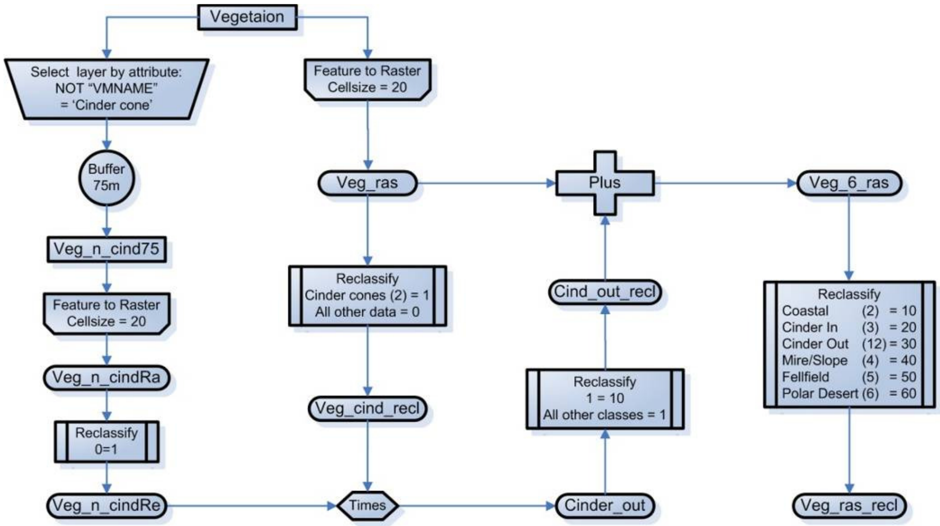


Figure 41: **Process followed to convert and reclassify vegetation.**

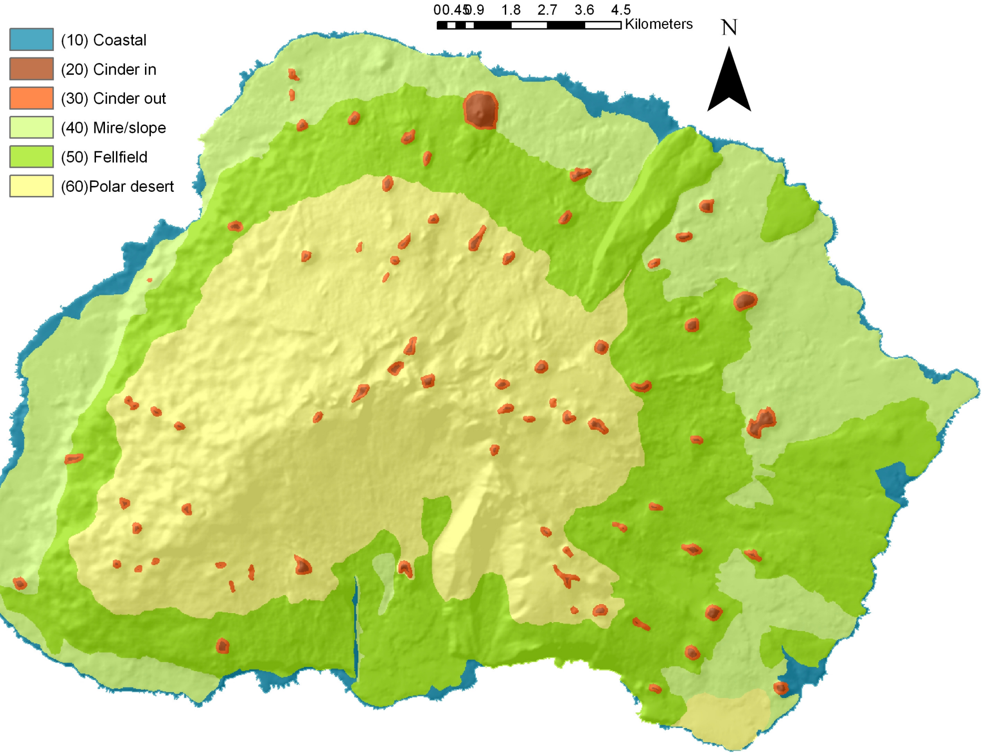


Figure 42: **Raster, reclassified vegetation data set (veg_ras_recl) (based on Mucina & Rutherford, 2006).**

12.3 Digital Elevation Model (DEM)

The centroid of Marion Island was determined from the coastline map (Chief Directorate of Surveys and Mapping, 2003). From this central point, the Island aspects were determined. The DEM (Chief Directorate of Surveys and Mapping, 2003) was reclassified separately for each of the four aspects. The upper altitudinal limits of some vegetation types (as determined by Le Roux & McGeoch (2008)) were used to determine the classes for reclassification for each directional aspect (Table 18). Le Roux & McGeoch (2008) determined upper altitudinal limits of certain plant species. Key species representing certain habitats (see Chapter 2) were picked out as an indicator for that habitat. This allows for interpolation of the species data to a habitat level. Each directional aspect was then reclassified separately to reflect these limits. These four files were added together to create the adjusted DEM, with a three digit number to represent each class (Figure 43 & Figure 44).

Table 18: Reclassification of Digital Elevation Model, by directional aspect (based on le Roux, 2008b and le Roux & McGeoch, 2008).

Habitat	Key species	Directional aspect			
		North	South	East	West
Biotic	*Cotula plumosa*	35	49	16	38
Saltspray	*Crassula moschata &* *Cotula plumosa*	35	49	16	38
Mire	*Juncus scheuchzerioides &* *Uncinia compacta (lower value)*	146	213	421	330
Drainage line	Wetter areas within mire or fernbrake habitats; ∴same upper limits as with fernbrake habitat	358	396	421	330
Fernbrake	*Blechnum penna-marina*	358	396	421	330
Fellfield	*Agrostis magellanica or poa cookii (higher val.)*	583	743	625	642
Fellfield	*Azorella selago*	673	765	667	658
Polar desert	Lack of vegetation	All altitudes above upper limits of Fellfield habitat.			

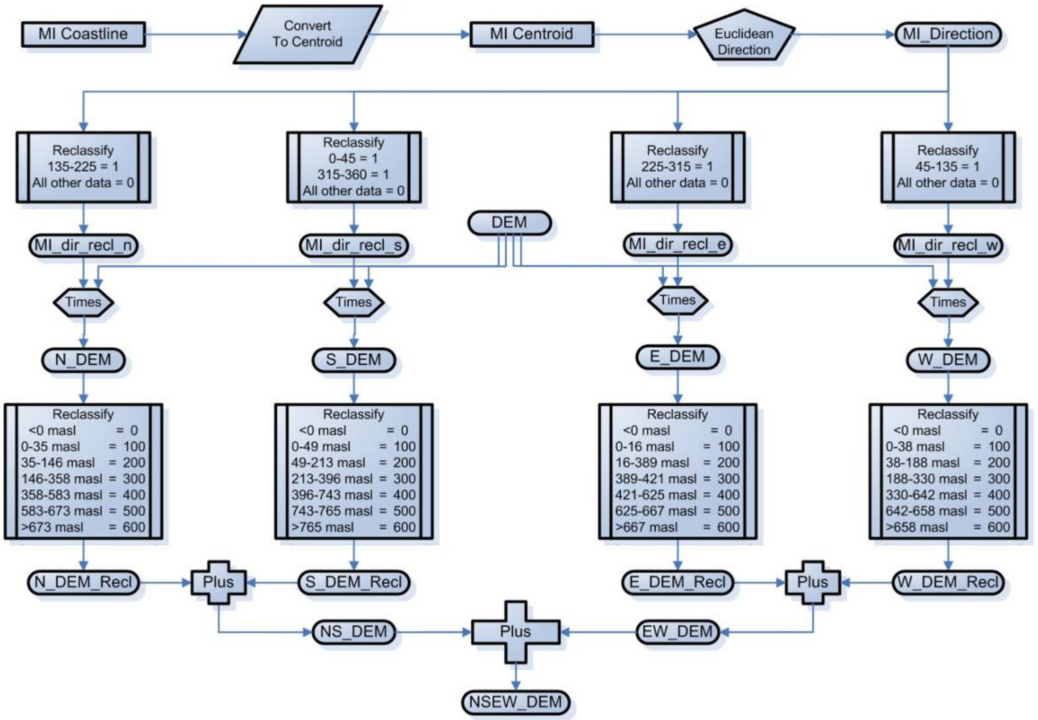


Figure 43: Process followed to reclassify the Digital Elevation Model.

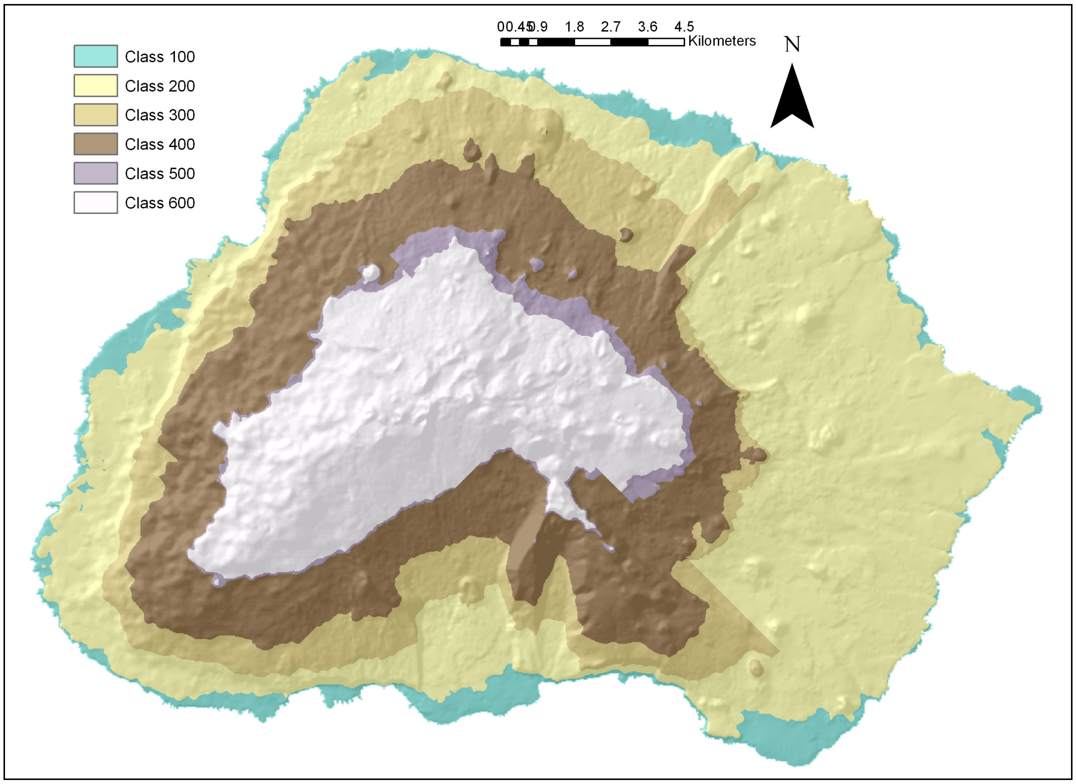


Figure 44: **Raster reclassification of the DEM (NSEW_DEM).**

12.4 Soil map

These three adjusted and reclassified layers (geology (Figure 40), vegetation (Figure 42), and the DEM (Figure 44)) were then added together. The resulting layer (v_g_d) is a composite file, and each class has a three digit value. The hundreds digit indicates the elevation, the tens digit, the vegetation type, and the units represents the geology type. This file was reclassified to form a map with four soil classes namely, Histosols; Histic Andosols; Andosols; and Regosols (Figure 45 and Figure 46). One non-soil class, solid rock, was allocated to the most recent (1980) lava flow. The classification of soils on Marion Island and division into these five classes is discussed in Chapter 11. The table showing the reclassification of the composite soil layer (v_g_d) to obtain the preliminary soils map can be found in Appendix K. The final classification was based on general field observations made while visiting the Island, as well as on results of samples analysed.

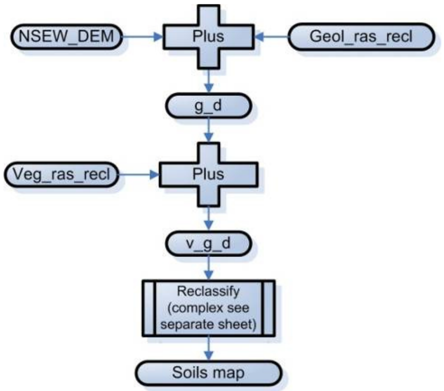


Figure 45: **Process followed to produce the final soils map from vegetation, geology and DEM layers.**

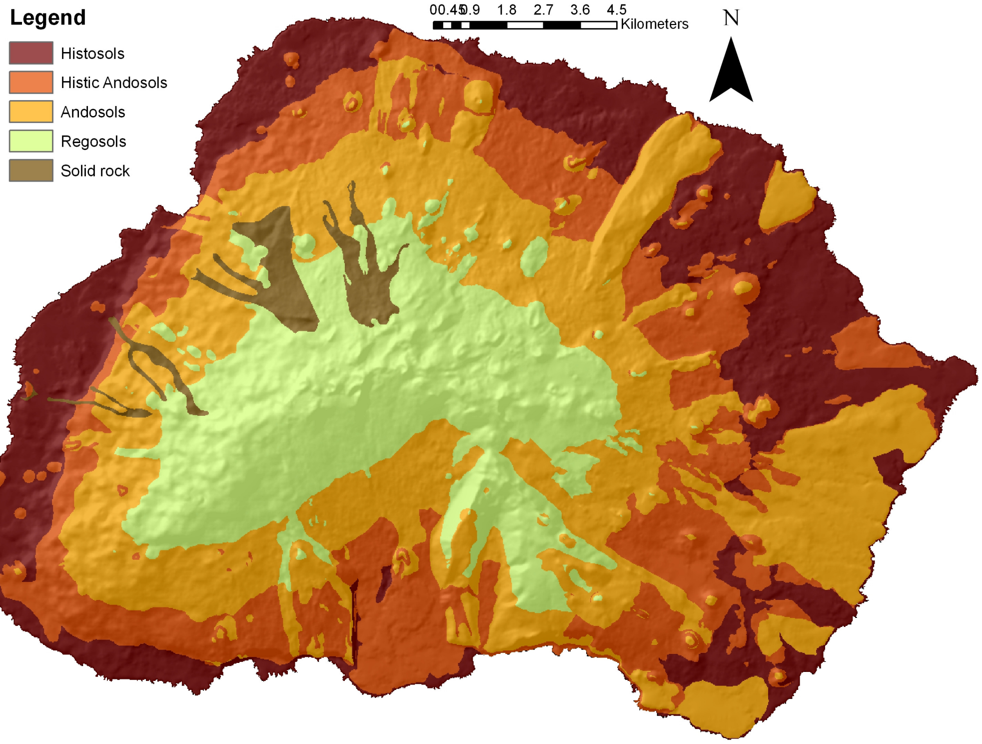


Figure 46: **Soil map for Marion Island.**

While distinct boundaries are demarcated within the classification and therefore on the map as well, it should be noted that while profiles analysed and properties of soils differ distinctly from one area to the next, distinct boundaries between soil units in general are rare, rather there is a gradual variation from one soil type to the next (Peterson & Calvin, 1996). As discussed in Chapter 2 there is great variation in habitat types and often very small areas of a habitat type may be found (Smith & Mucina, 2006). It should be kept in mind that this will also be true for soils on Marion Island. The variation may be great and within any one class depicted on the map, small areas of another class may exist.

The soil map presented above (Figure 46) has many limitations. The data on which it was based is limited, and of a low resolution, and although every attempt has been made by the author not to be biased, the final outcome remains likely to be affected by bias due to the relative backgrounds of the author as well as the other researchers and techniques that have assisted the author in the final reclassification of the soil map. This map can be greatly improved by further research. High resolution remotely sensed images could be used to refine the map. Also more intensive sampling and observations over the whole Island to increase sampling resolution would aid in refining the map. However despite the potential inaccuracies and low resolution the above map can serve as the basis for further research, and give a general impression of soil distribution over an Island scale.

12.5 Extent of soils of Marion Island

Based on the soils map determined above, the extent of each of the soil types as described in Chapter 11 can be determined using ArcGIS. The extent of each soil type as well as the percentage coverage over Marion Island is presented in Table 19 below.

Table 19: Extent of different soil types as determined based on the soil model constructed for Marion Island.

Soil Type	Extent (km^2)	% Coverage
Histosol	62	22
Histic Andosol	64	22
Andosol	98	34
Regosol	58	20
Solid rock	7	2

13 Conclusion

Marion Island is part of the Prince Edward Island group, which formed through the volcanic activity associated with a mantle plume (Verwoerd, 1971). The Island's lithology consists mainly of basalt, scoria and ash of less than 1million years in age (McDougall *et al.,* 2001). Little previous research has been done on the Island to consider the weathering of rocks and formation, classification and distribution of soils there.

Given the scarcity of research relating to pedogenesis and soil classification on Marion Island, the aim of this study was to determine whether or not pedogenesis had taken place on Marion Island. Contrary to the findings of Gribnitz *et al.* (1986), several characteristics of soils on Marion Island that have been visually observed (Chapter 4) or tested in a laboratory (Chapters 5 - 8) indicate that pedogenesis has taken place on the Island. Signs of pedogenesis observed during this study include:

- Differentiation of soil profiles into distinct horizons, with differences in colour and / or texture.
- Presence of ironpans and manganese nodules.
- Accumulation of organic matter.
- Differences in soil properties from one sample to another (particle size distribution, clay content, pH, Al+½Fe ratio, chemical and mineralogical composition).
- The presence of smectite and gibbsite in some soil samples.

Pedogenesis is defined as the formation of the solum as a result of the five soil forming factors (van der Watt & van Rooyen, 1995). Therefore, the five soil forming factors (Jenny, 1941) and their relation to soils on Marion Island were described.

- Climate (strong winds, much precipitation, etc) plays a role in the formation of soils on Marion Island.
- Living organisms (seals, birds, invertebrates and humans) live on Marion Island and will influence the formation of soils, especially in the biotic habitat where birds nest and seals wallow.
- Topography on Marion Island plays an important role in soil formation. Soils are more developed on shallower slopes and in depressions. Soil formation on steep slopes is clearly lacking.
- Parent material on Marion Island consists of both rocks (basalt, scoria and ash deposits) as well as organic matter (where the rate of plant growth exceeds the rate of residue decomposition).
- Time plays a role in soil development on Marion Island. Marion Island is less than 1 million years old (McDougall, et al., 2001). Much of the interior of the Island was

previously covered by glacial ice or snow, limiting the time of exposure of those surfaces to the elements to allow for soil formation. Soils are, therefore, generally more developed in the coastal regions where snow and ice cover have been of less hindrance.

Morphological, physical, chemical, mineralogical and biological characteristics of soils on Marion Island were determined and described. Soil samples from Marion Island have a low bulk density (0.07-1.29g.cm^{-3}), are coarse (sandy gravel or gravely sand) and are poorly sorted. The pH values of samples analysed are acidic (4.26-6.28 in H_2O), and the Al+½Fe ratio vary from 1.5% to 6.7%. The chemical and mineralogical composition of soils are typical of mid-ocean ridge basalts, and some secondary clay minerals were found (smectite and gibbsite). The loss on ignition values were used as a proxy for organic matter content and were found to be generally high (up to 97%).

Soil properties were described, and a generalised soil profile for each of the seven terrestrial habitats highlighting particular characteristics of that habitat were constructed. Characteristics of soils from each habitat are as follows:

- Saltspray habitats are found near the coast and are influenced by additions from sea spray. The soils in these habitats reach up to 2m in depth and are high in organic matter content, despite the fact that vegetation is heavily dwarfed by the salt content.
- Biotic habitats are heavily influenced by seals, penguins and other birds. These soils contain an abundance of nutrients and plant growth is prolific. Several soil horizons occur in this habitat.
- Mire habitats are waterlogged, soils are peaty and dark in colour and high in organic matter content. The bulk density of these soils is very low, and profiles can be as deep as 2m.
- Drainage line habitats are considered to be wetter than mires, and soil properties are similar to those found in the mire habitat.
- Fernbrake habitats are characterised by the presence of *Blechnum penna-marina*. Soils are well developed with at least three distinct horizons visible. Ironpans and manganese nodules are well developed in places.
- Fellfield habitats are windswept areas. Soils were found to be up to 1m in depth, and are poorly developed.
- Polar desert areas are characterised by a lack of vegetation. However, lichens and mosses are present. Soil formation in this habitat is distinctly lacking.

Soil properties were determined for samples collected to classify the soils in terms of the WRB Soil Classification System. Based on the results of analysis performed, soils on Marion Island were classified as Histosols, Histic Andosols, Andosols and Regosols. The possible effects of climate change on these soil types were assessed.

A model was built in ARCGIS to estimate the spatial distribution of soils on Marion Island. Existing GIS data (vegetation, geology and a digital elevation model) were used as input data. The soil distribution model was based on the three input layers as well as the characteristics of soils described and general field observations. A resultant map of likely soil types for Marion Island was produced. It is thought that Andosols are likely to be the most common soil type on Marion Island, with Histosols and Histic Andosols the next most common types.

Several areas where detailed information is still lacking have been identified, and therefore further work is required to create a better understanding of the formation and distribution of soils on Marion Island. Further research that would fill current knowledge gaps relating to soils on Marion Island includes the following:

- Seasonal differences in soil properties: Samples collected for this research project were all collected during the months of April and May (during annual relief voyages to Marion Island). It is suggested that a soil study be conducted where soil samples are collected and analysed year round in order to identify seasonal changes, specifically with relation to organic matter content.
- Seasonal changes in pedogenesis: More knowledge of the seasonal climatic changes at various locations around the island would be useful in delineating areas where pedogenesis is limited during winter months by freezing of soil, or by snow cover.
- Palaeosols: Palaeosols have been identified in the past by Scott & Hall (1983), as well as during this study. A detailed study on palaeosols on Marion Island would lead to a better understanding of the past environment.
- Animal-soil and plant-soil interactions: Detailed work could be conducted to analyse the impacts of certain birds or plants on soil formation at Marion Island. It was noted that penguins have an effect on soils around penguin colonies. Wandering albatrosses build large nests, which may result in a source of organic matter, and *Azorella selago* plants, which are abundant in the fellfield habitats may be vitally important pioneer plants which allow other plants to begin growing in an area, facilitating soil formation. These and other relationships could be further studied in detail.
- Detailed classification of Andosols: Andosols on Marion Island were assumed to be nonallophanic based on the presence of smectite in samples analysed. The soils on

Marion Island, however, do not fully fit the generic criteria of nonallophanic Andosols. Further investigations into soils found on Marion Island may confirm with a greater degree of certainty whether soils are allophanic or nonallophanic.

- Classification of soils: More work could be conducted on the detailed classification of soils. Such work could be used in order to develop relevant classification criteria for possible inclusion into the current South African soil classification system. Marion Island is part of South Africa, yet the South African soil classification system does not fully take into consideration volcanic or organic soils as these are rare (if present) in South Africa.
- Spatial variation of soils: A detailed soil study based on an Island wide grid would allow for a better understanding of the spatial variation of soils on the Island, and would allow for a more accurate soils map to be compiled.

It has been shown in this study that pedogenesis has taken place on Marion Island. Morphological, physical, chemical, mineralogical and biological soil properties were described. Soils were classified as Histosols, Histic Andosols, Andosols and Regosols based on the characteristics determined. A soil map was constructed to indicate the spatial distribution of soils on Marion Island.

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NOTES

i Information from personal communication with Prof. V.R. Smtih, Department of Botony and Zoology, Stellenbosch University, South Africa, 2006.

ii Information from personal communication with Linda Prinsloo, Department of Physics, University of Pretoria, South Africa, 2006.

APPENDIX A:

Brief description of soil samples collected

Table A-1: Soil descriptions.

Site no.	Habitat	Location	mamsl	Soil horizon	Depth (cm)	Colour	Brief description
01	Fernbrake	Juniors Kop	118	A	0-25	10YR 3/2	Organic rich layer.
				Fe	25-30	10YR 3/4	Ironpan (not sampled).
				2	30-85	7.5YR 4/4	Roots present; pockets of scoria.
				Fe	85-90	10YR 3/4	Ironpan with redder colour above and below and almost black in the middle (not sampled).
				3	90-160	10YR 5/6	Still some roots present; Mn nodules.
				Fe	160-165	7.5YR 5/8	Iron accumulation (not sampled).
				4	165-180	10YR 4/6	Overlying rock (some regolith).
02	Polar desert	Katedraalkrans	753	1	0-2	2.5Y 3/2	Scoria desert pavement.
				2	2-7	10YR 3/6	Accumulation of fines.
				3	7-60	10YR 3/4	Black ash overlying rock.
03	Biotic	Swartkop penguin colony	62	1	0-10	2.5Y 2.5/1	Covered with feathers.
				2	10-30	5Y 4/1	Volcanic ash.
				3	30-120	2.5Y 2.5/1	Darker coloured ash.
04	Biotic	Swartkop penguin colony	60	A	0-15	10YR 3/3	Prolific *Cotula plumosa* growth.
				B	15-40	10YR 4/4	Lighter coloured.
				C	40-80	10YR 4/4	Darker, with ash present.
				4	80-170	10YR 4/3	Black ash, as in sample 03(3).
05	Saltspray	Trypot Beach	9	O	0-35	10YR 4/4	Abrupt transition between horizons.
				A	35-120	7.5YR 3/2	Underlain by rock.
06	Mire	Nellie Humps	29	O	0-80	10YR 2/2	Diffuse transitions, varying by 20cm in depth.
				A	80-147	10YR 4/3	Underlain by rock.
07	Biotic	Swartkop penguin colony	60	1	Surface sample	2.5Y 2.5/1	Penguin nesting site.
08	Biotic	Swartkop penguin colony	61	1	Surface sample	2.5YR 2.5/1	Penguin nesting site.
09	Biotic	Swartkop penguin colony	62	1	Surface sample	10YR 3/4	Penguin nesting site.
10	Biotic	Swartkop penguin colony	62	1	Surface sample	2.5YR 3/2	Penguin nesting site.
11	Biotic	Swartkop penguin colony	63	1	Surface sample	10YR 3/2	Penguin walkway, surrounded by thick *Cotula plumosa* patches.
12	Biotic	Swartkop penguin colony	63	1	Surface sample	2.5YR 3/2	Penguin walkway, surrounded by thick *Cotula plumosa* patches.
13	Biotic	Swartkop penguin colony	63	1	Surface sample	2.5Y 2.5/1	Penguin nesting site.
14	Biotic	Swartkop penguin colony	62	1	Surface sample	10YR 3/3	*Cotula plumosa* slope, near penguin colony.
15	Biotic	Swartkop penguin colony	62	1	Surface sample	10YR 3/4	*Cotula plumosa* slope, near penguin colony.
16	Biotic	Swartkop penguin colony	63	1	Surface sample	10YR 3/4	*Cotula plumosa* slope, near penguin colony.
17	Biotic	Swartkop penguin colony	62	1	Surface sample	10YR 3/4	*Cotula plumosa* slope, near penguin colony.
18	Mire	Swartkop	39	O	0-50	10YR 3/3	Mire near to hut.
				A	50-138	10YR 3/6	Underlain by rock.
19	Fernbrake	Van den Boogaard River Valley	120	O	0-5	10YR 3/3	Dark; organic rich.
				A	5-24	10YR 3/6	Diffuse boundary.
				B1	24-42	10YR 4/6	Diffuse boundary.
				Fe	42-50	7.5YR 4/4	Iron accumulation (not sampled).
				B2	50-63	10YR 5/8	
				B3	63-82	10YR 5.8	One horizon, broken in two places by iron accumulations (Iron accumulations not sampled).
				Fe	82-90	7.5YR 4/4	
				B3	90-100	10YR 5/8	
				Fe	100-103	7.5YR 4/4	
				B3	103-110	10YR 5/8	
				Sc	110-120	2.5Y 2.5/1	Scoria, underlain by coarse ash (not sampled).

Site no.	Habitat	Location	mamsl	Soil horizon	Depth (cm)	Colour	Brief description
20	Biotic	Rockhopper Bay	37	O	0-30	10YR 4/4	Prolific *Cotula plumosa* growth.
				A	30-87	10YR 4/6	Underlain by weathering rock (with saprolite).
21	Saltspray	Rockhopper Bay	6	O	0-60	10YR 2/1	Diffuse boundary between horizons.
				A	60-220	5YR 2.5/2	Depth of profile dependant on underlying rocks. At this site, the base of the profile varied from 100-220cm deep.
22	Mire	Rockhopper Bay	14	O	0-50	10YR 2/2	Dry mire habitat.
				A	50-150	7.5YR 3/3	Underlain by rock.
23	Palaeosol	3rd Sister	142masl	1	Surface sample	10YR 3/3	Scoria at surface.
				Fe	50-51	7.5yr 6/8	
				2	51-100	10YR 4/6	Profile believed to be palaeosol; discussed in detail in section 3.6.5 Samples were taken at 1m intervals as horizons were not evident.
				3	100-200	10YR 5/8	
				4	200-300	10YR 4/6	
				5	300-400	10YR 5/8	
				6	400-500	10YR 4/6	
				7	500-600	10YR 5/8	
				8	600-700	10YR 4/6	
				9	700-800	10YR 4/6	
24	Fellfield	Juniors	156masl	1	0-27	10YR 4/6	Underlain by coarse regolith and black lava.
25	Drainage line	Prion Valley	39masl	A	0-30	10YR 4/4	*Acina megelanica; agrostis, blechnum penna-marina* and mosses present.
				B	30-70	10YR 4/6	Diffuse boundaries between horizons.
				C	70--120	10YR 3/6	Underlain by rock.
26	Mire	King Bird Head	24masl	1	0-40	7.5YR 2.5/2	Lowest site of transect.
27	Mire	Skua ridge	91masl	O	0-15	10YR 4/4	Transect.
				A	15-50	10YR 5/8	Red mottling (iron).
28	Fellfield	First Red Hill	437masl	1	0-70	10YR 4/4	Patterned ground prominent Transect.
				2	70-80	10YR 4/6	Underlain by rock.
29	Fellfield	First Red Hill	389masl	1	0-45	10YR 4/4	Transect. underlain by rock.
30	Polar desert	Beret (Feldmark Plateau)	718masl	1	0-10	10YR 4/6	Patterned ground prominent.
				2	10-40	10YR 4/6	Underlain by rock.
31	Fellfield	Snok (Feldmark Plateau)	591masl	1	0-30	10YR 4/4	Patchy *azorella selago* plants; underlain by rock.
32	Fellfield	Tafelberg	230masl	1	0-70	10YR 4/4	Covered by large clasts of glacial till (were removed for sampling). Transect.
				2	70-100	10YR 4/6	Underlain by rock.
33	Fellfield	Van den Boogaard River Valley	181masl	1	0-25	10YR 4/	Transect.
34	Polar desert	No Name Peak	947masl	1	0-44	10YR 4/4	Fine textured. Underlain by rock.
35	Mire	Repetto's Hill	54 mamsl	O	0-50	10YR 3/4	Amorphous aluminum present.
				A	50-230	10YR 3/6	Underlain by rock.
36	Fernbrake	Cape Davis	40 mamsl	1	0-88	10YR 2/2	Open *Blechnum penna-marina* vegetation. No ironpans present. Underlain by rock.

Site no.	Habitat	Location	mamsl	Soil horizon	Depth (cm)	Colour	Brief description
37	Fernbrake	Cape Davis	43 mamsl	O	0-5	10YR 3/4	Rooty, black organic rich.
				A	5-10	10YR 3/6	Browner than above.
				Fe1	10-45	10YR 3/6	Iron rich layer.
				Fe2	45-47	10YR 4/6	Hardened ironpan with Mn concretions.
				(Fe1)	47-58	10YR 3/6	Resembling horizon Fe1 above; sample not collected.
				(Fe2)	58-63	7.5YR 4/4	Resembling horizon Fe2 above; sample not collected.
				(Fe1)	63-82	10YR 3/6	Resembling horizon Fe1 above; sample not collected.
				Sc	82-100	10YR 3/2	Scoria layer.
				Sed	100-108	10YR 3/6	Ash / Sediment layer.
				(Sc)	108-130	10YR 3/2	Resembling horizon Sc above; sample not collected.
				(Sed)	130-133	10YR 3/6	Resembling horizon Sed above; sample not collected.
				(Sc)*	133-140	NA	Rocks / sediment resembling horizon Sc above; however particles were considerably larger and rockier, sample not collected. Horizon / rocks continued below.
38	Mire	Tweeling	68 mamsl	O	0-55	10YR 2/2	Lots of roots present.
				A	55-60	10YR 3/4	Underlain by scoria.
39	Biotic	Mixed pickle	31 mamsl	O	0-20	10YR 2/1	Prolific *Cotula plumosa* growth, amongst seals.
				A	20-30	10YR 2/2	Darker, finer texture than above. Underlain by bedrock.
40	Fellfield	Mixed Pickle	53 mamsl	A	0-5	10YR 3/4	Stony. Amorphous aluminium present.
				B	5-28	10YR 3/4	Underlain by rock.
41	Drainage line	Swartkop	37 mamsl	O	0-80	10YR 3/3	Samples had a strong sea smell Amorphous aluminium present.
				A	80-180	10YR 4/3	The boundary between the horizons was diffuse and varied. Underlain by rock.
42	Fellfield	Kleinkoppie	69 mamsl	1	0-30	10YR 3/6	Volcanic ash within horizon. Amorphous aluminium present.
43	Drainage line	Cape Crozier	101 mamsl	1	0-210+	10YR 3/4	Volcanic ash within horizon. Dark, black colour.
44	Biotic	Devils staircase	11 mamsl	1	0-45	10YR 3/3	Underlain by rock.
45	Polar desert	Katedraalkrans	751 mamsl	1	0-30	2.5Y 3/3	Covered with 30cm of snow when sampled. Amorphous aluminium present.
				2	30-65	10YR 4/6	Coarse scoria continued below.
46	Saltspray	Transvaal Cove	10masl	O	0-10	10YR 2/2	Dwarfed *Cotula plumosa* vegetation.
				A	10-40	10YR 2/2	Horizon boundaries diffuse, varying by 10cm.
				B	40-50	7.5YR 3/1	Underlain by bedrock.
47	Saltspray	Archway Bay	10masl	O	0-20	10YR 2/2	Vegetation: dwarfed *Cotula plumosa*, some grass and *Sagina sp.*
				A	20-55	7.5YR 3/1	Horizon boundaries diffuse, varying by 10cm.
				B	55-146	10YR 3/1	Underlain by bedrock.

APPENDIX B:

Relationships of particle size classes, millimetres, micrometers and the phi scale

Table B-1: Phi scale.

Phi scale (ø)	**Millimeters (mm)**	**Micrometers (µm)**	**Wentworth grade**
-6.0	64	64000	Cobbles
-5.5	44.8	44800	Coarse gravel
-5.0	32	32000	
-4.5	22.4	22400	
-4.0	16	16000	Medium gravel
-3.5	11.2	11200	
-3.0	*8*	*8000*	
-2.5	5.6	5600	Fine gravel
-2.0	*4*	*4000*	
-1.5	2.8	2800	
-1.0	*2*	*2000*	
-0.5	1.4	1400	Coarse sand
0.0	*1*	*1000*	
0.5	0.71	710	
1.0	*0.5*	*500*	Medium sand
1.5	0.355	355	
2.0	*0.25*	*250*	
2.5	0.18	180	Fine sand
3.0	*0.125*	*125*	
3.5	0.090	90	
4.0	*0.063*	*63*	
4.5	0.045	45	Coarse silt
5.0	0.032	32	
5.5	0.023	23	
6.0	0.016	16	Medium silt
6.5	0.011	11.0	
7.0	0.008	8.0	
7.5	0.0055	5.5	Fine silt
8.0	0.004	4.0	
8.5	0.00275	2.75	
9.0	0.002	2.0	Clay
9.5	0.00138	1.38	
10.0	0.001	1.0	

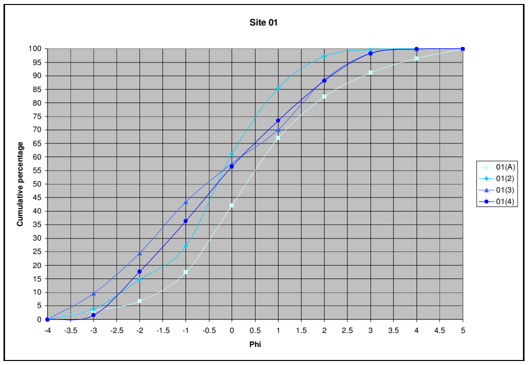
Briggs (1977)

Note: values marked in italics represent sieves used in particle size analysis in this study.

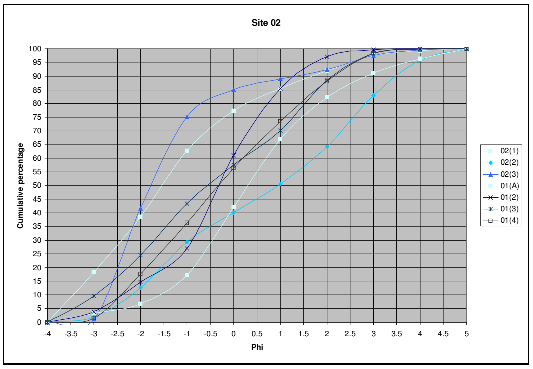
APPENDIX C:

Coarse texture results

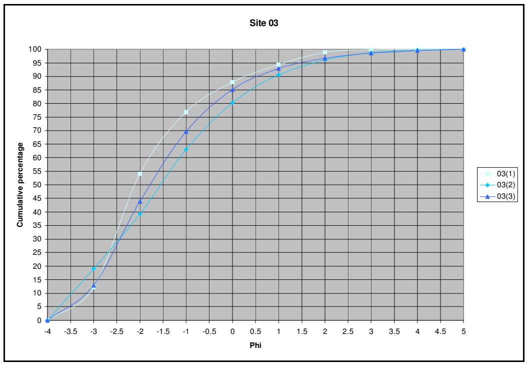
Cumulative percentage particle distribution curves for each sample site individually:



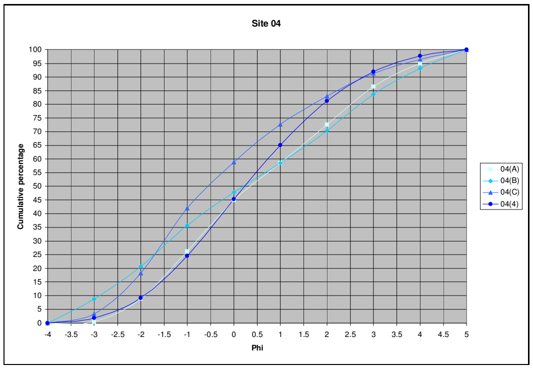
Graph C-1: Site 1.



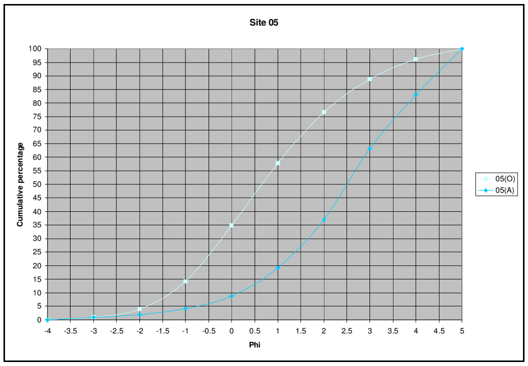
Graph C-2: Site 2.



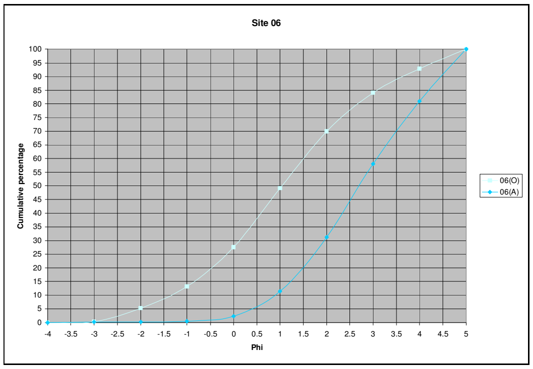
Graph C-3: Site 3.



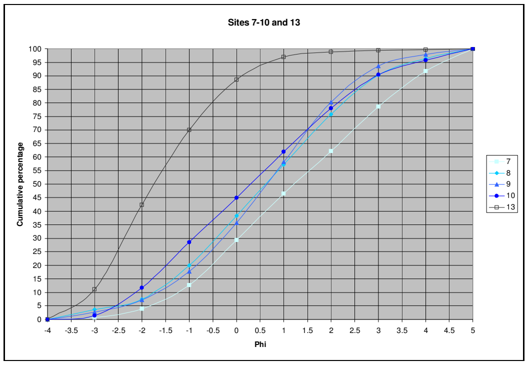
Graph C-4: Site 4.



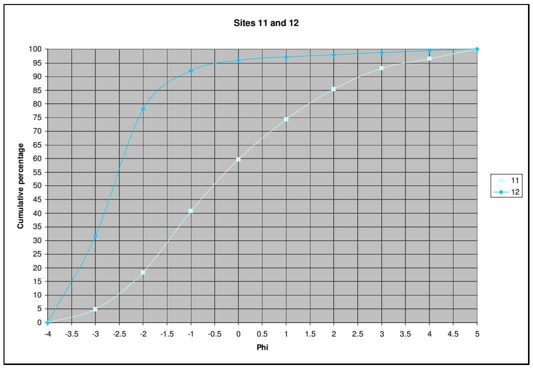
Graph C-5: Site 5.



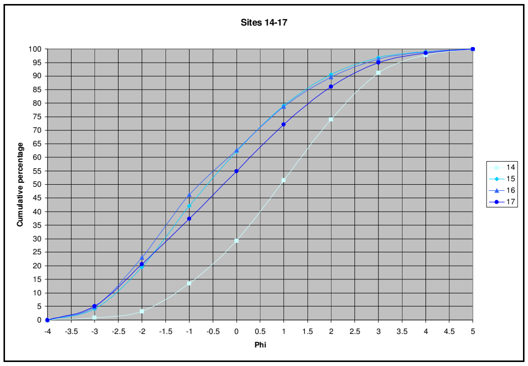
Graph C-6: Site 6.



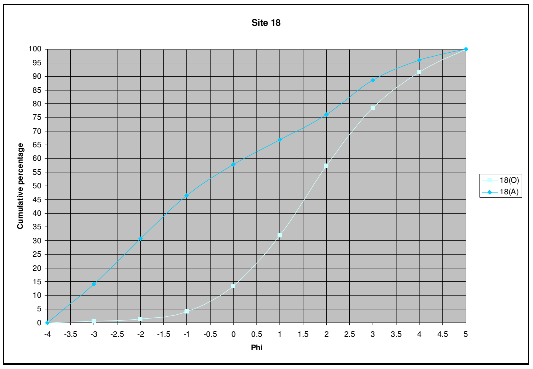
Graph C-7: Sites 7, 8, 9, 10 & 13.



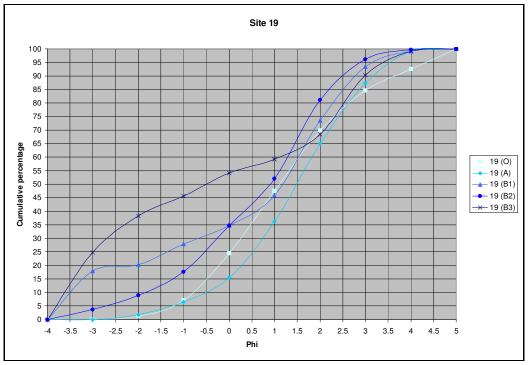
Graph C-8: Sites 11 & 12.



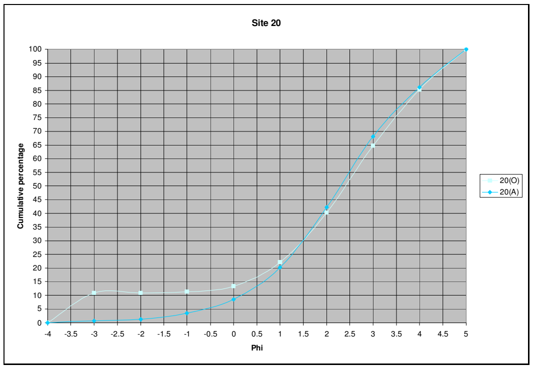
Graph C-9: Sites 14, 15, 16 & 17.



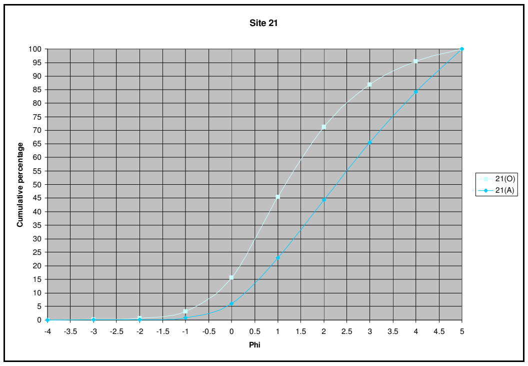
Graph C-10: Site 18.



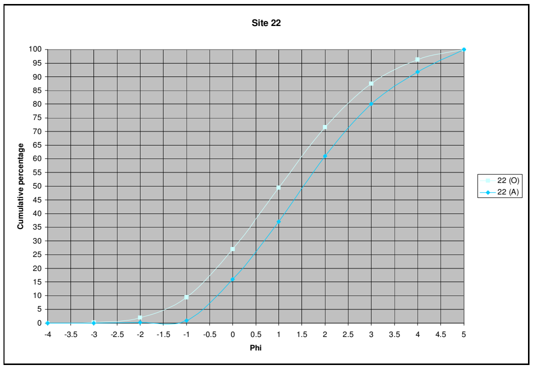
Graph C-11: Site 19.



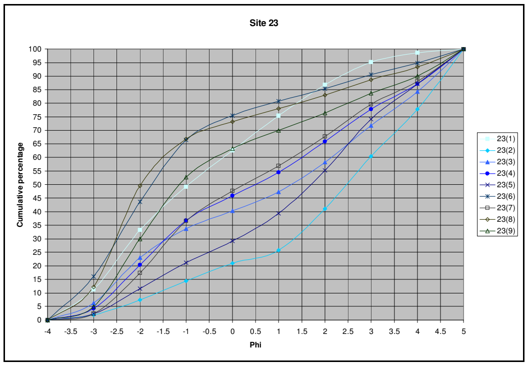
Graph C-12: Site 20.



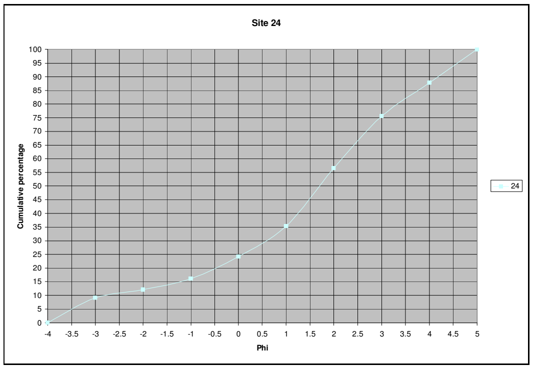
Graph C-13: Site 21.



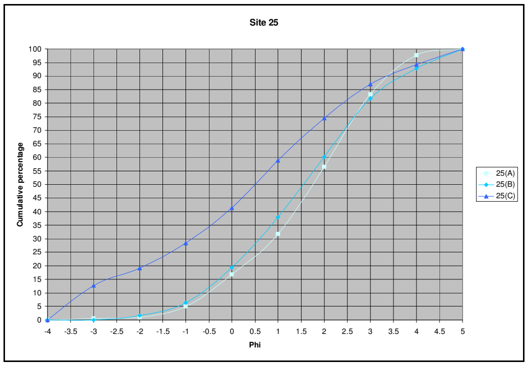
Graph C-14: Site 22.



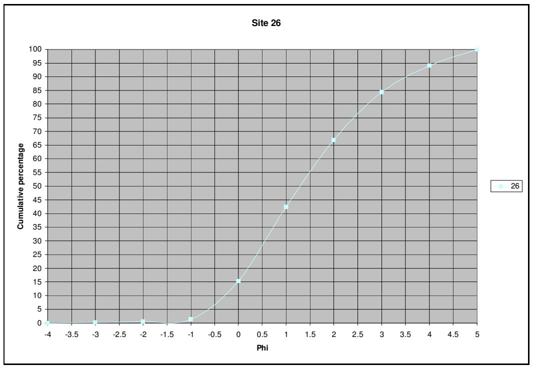
Graph C-15: Site 23.



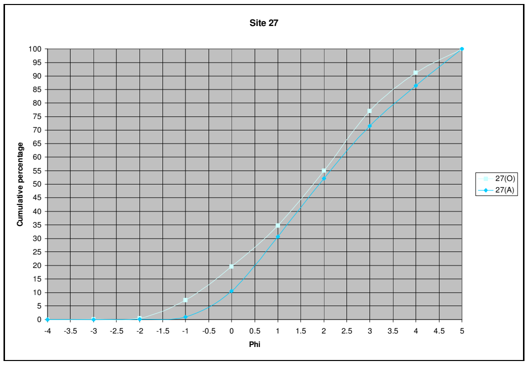
Graph C-16: Site 24.



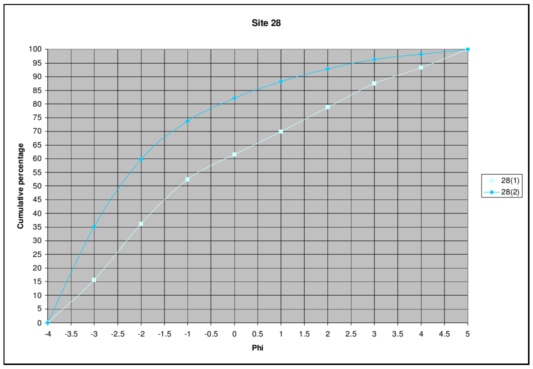
Graph C-17: Site 25.



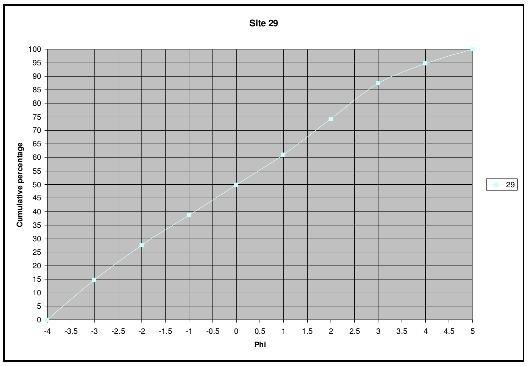
Graph C-18: Site 26.



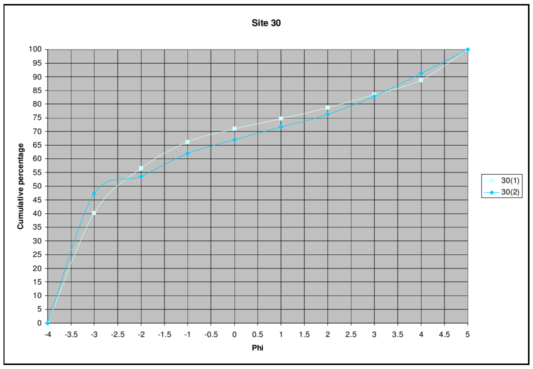
Graph C-19: Site 27.



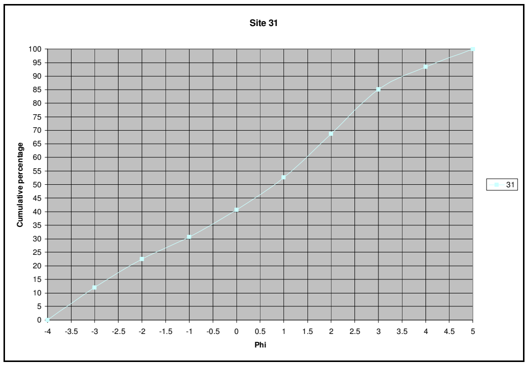
Graph C-20: Site 28.



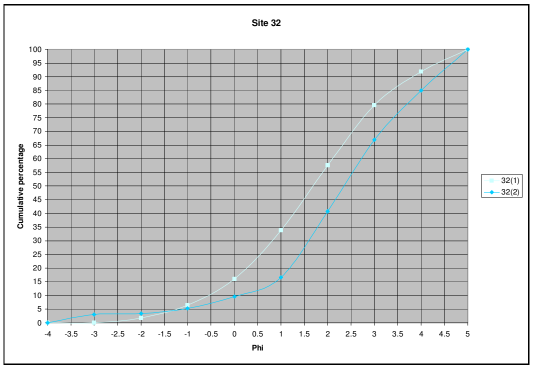
Graph C-21: Site 29.



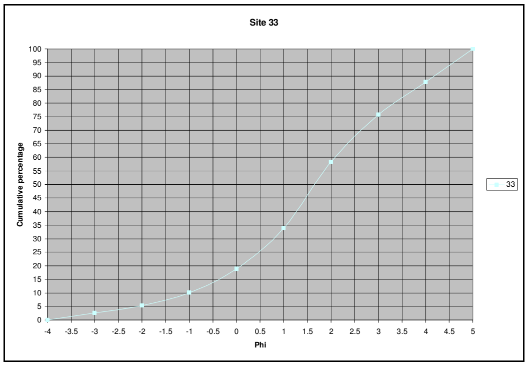
Graph C-22: Site 30.



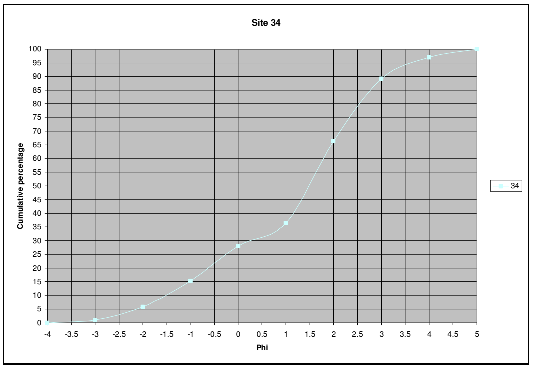
Graph C-23: Site 31.



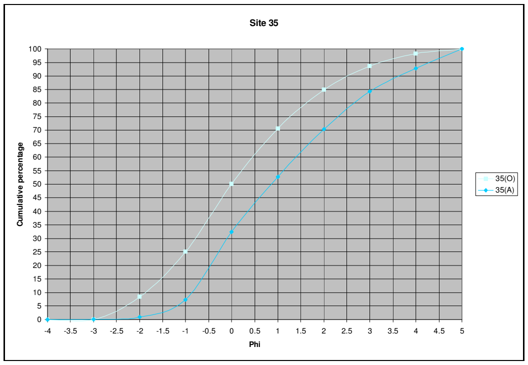
Graph C-24: Site 32.



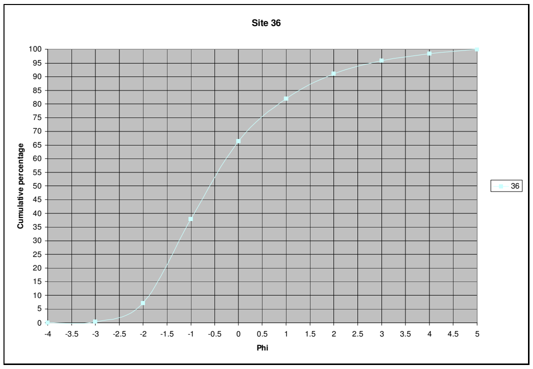
Graph C-25: Site 33.



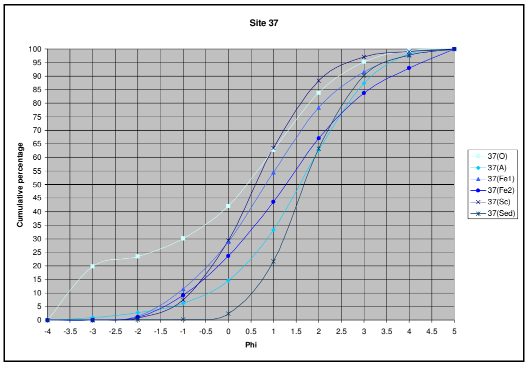
Graph C-25: Site 34.



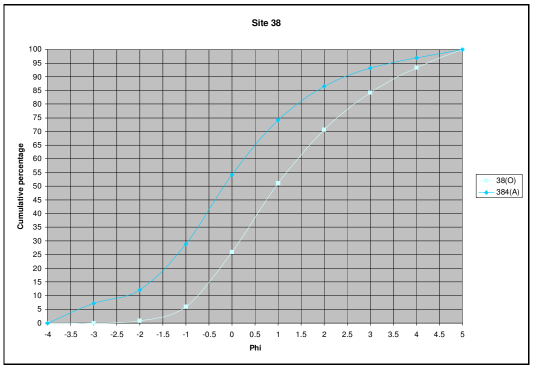
Graph C-27: Site 35.



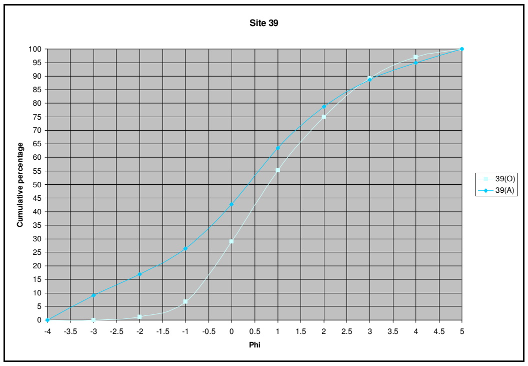
Graph C-28: Site 36.



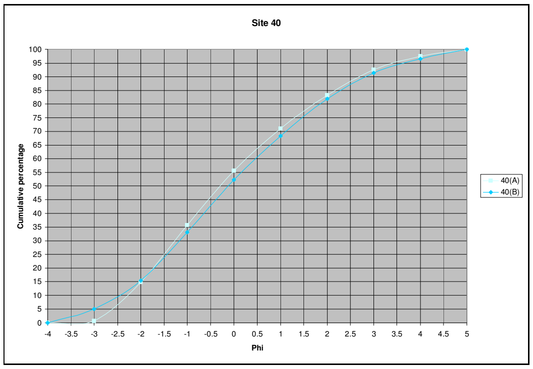
Graph C-29: Site 37



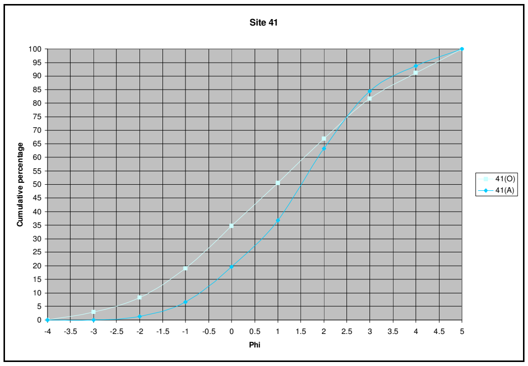
Graph C-30: Site 38



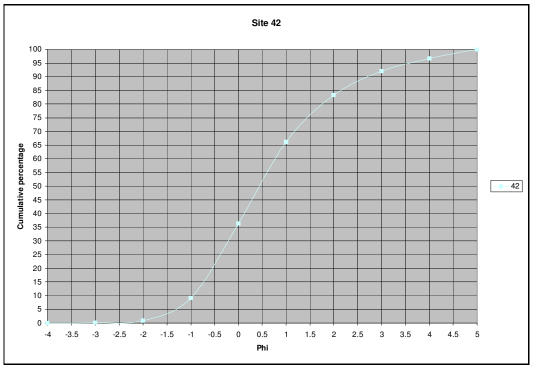
Graph C-31: Site 39.



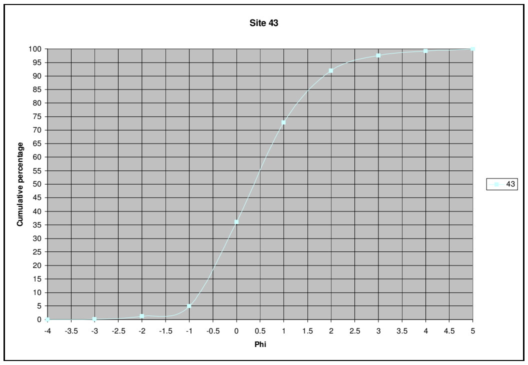
Graph C-32: Site 40.



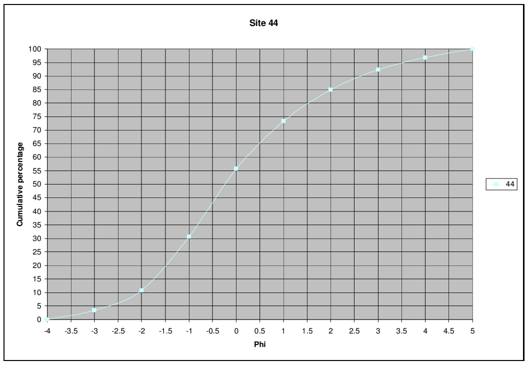
Graph C-33: Site 41.



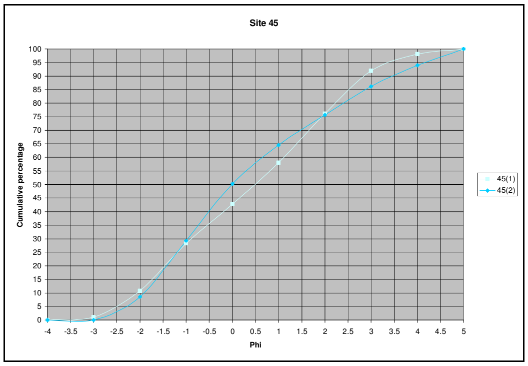
Graph C-34: Site42.



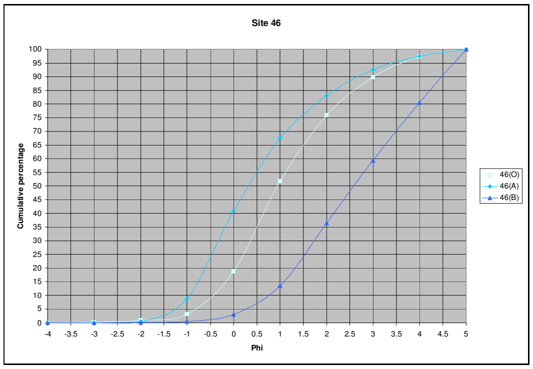
Graph C-35: Site 43.



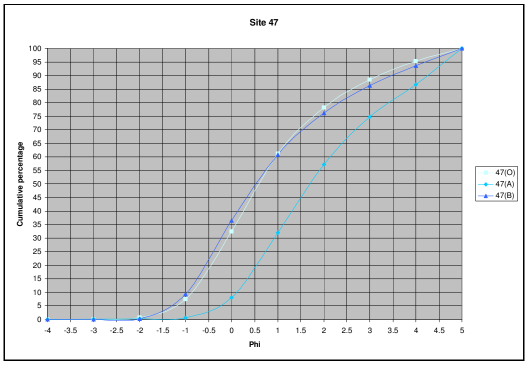
Graph C-36: Site 44.



Graph C-37: Site 45.

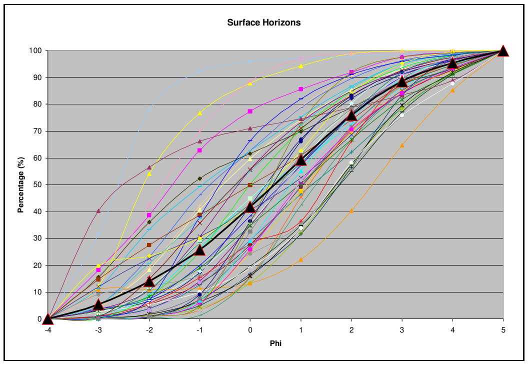


Graph C-38: Site 46.

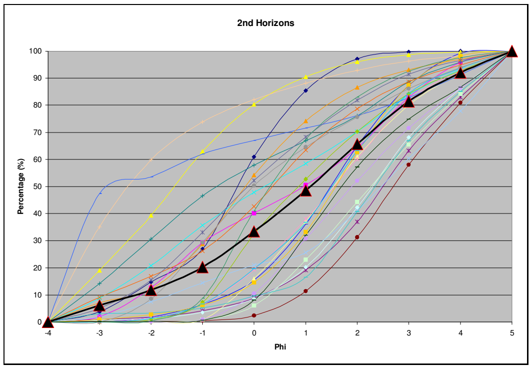


Graph C-39: Site 47.

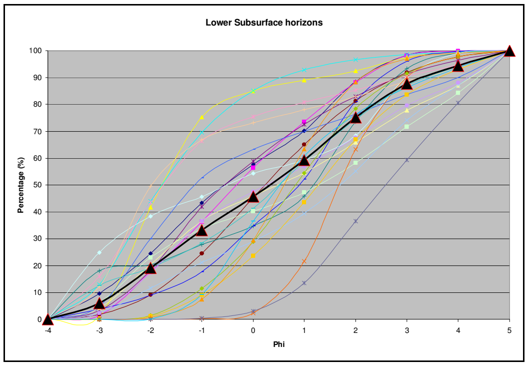
Cumulative percentage particle distribution curves for sites according to depth:



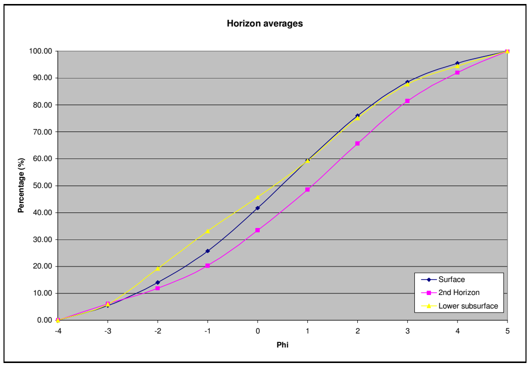
Graph C-40: Surface horizons.



Graph C-41:Second horizon.

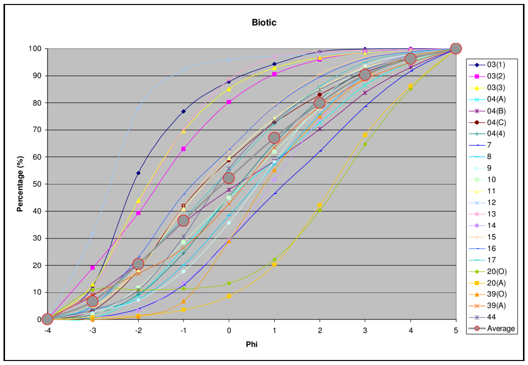


Graph C-42: Subsurface horizons (excluding second horizon).

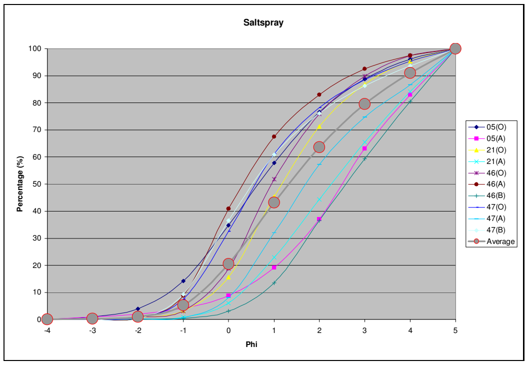


Graph C-43: Comparison of horizon averages.

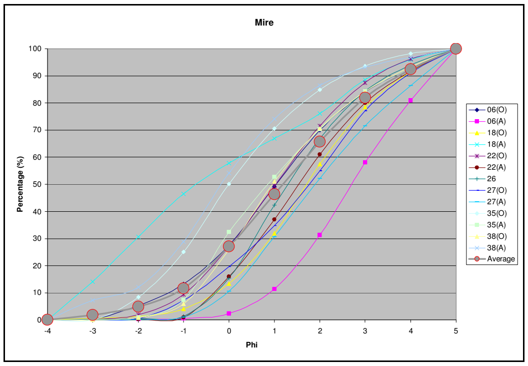
Cumulative percentage particle distribution curves for all sites within each habitat:



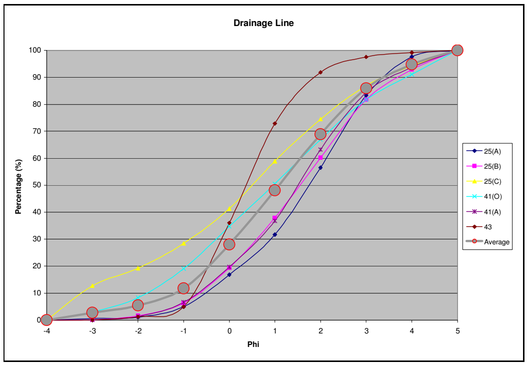
Graph C-44: Biotic habitat average.



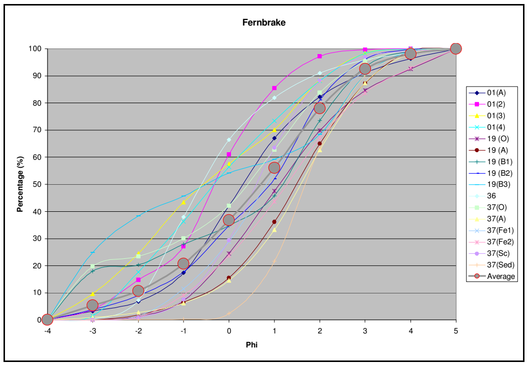
Graph C-45: Saltspray habitat average.



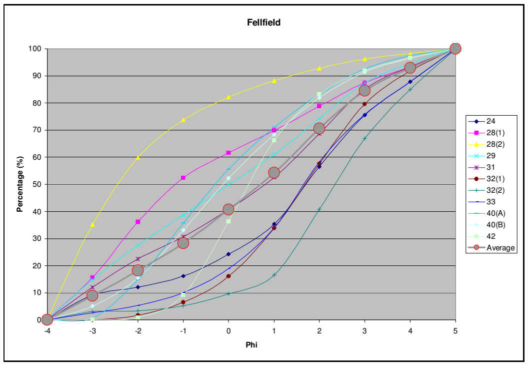
Graph C-46: Mire habitat average.



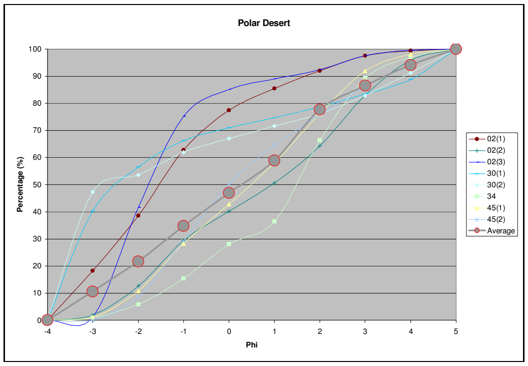
Graph C-47: Drainage line habitat average.



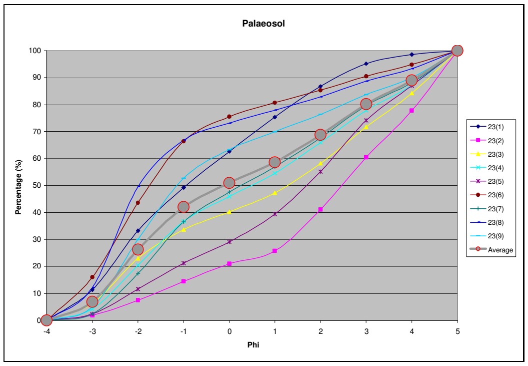
Graph C-48: Fernbrake habitat average.



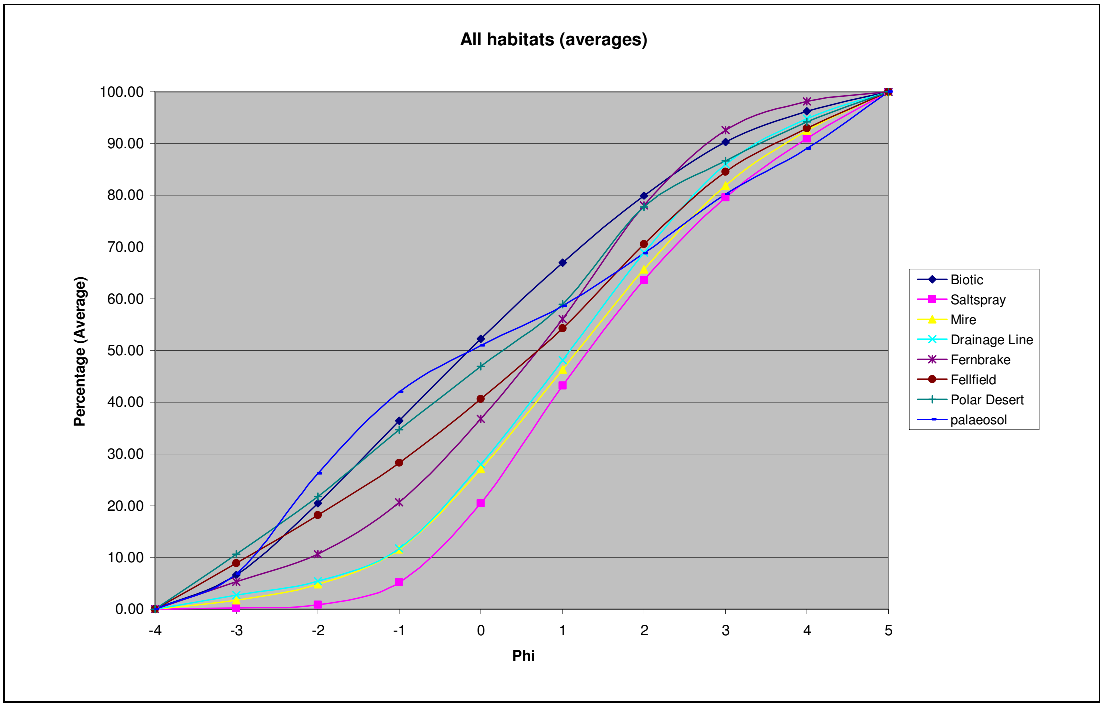
Graph C-49: Fellfield habitat average.



Graph C-50: Polar desert habitat average.

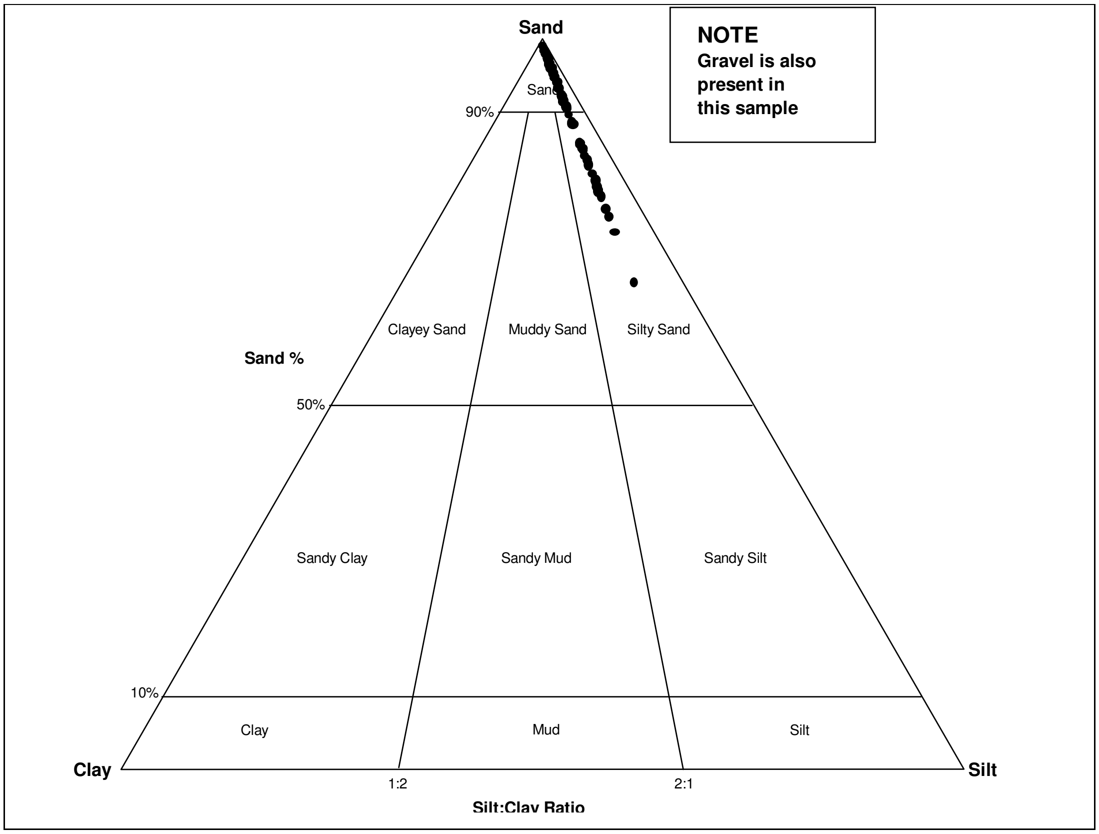


Graph C-51: Palaeosol average.



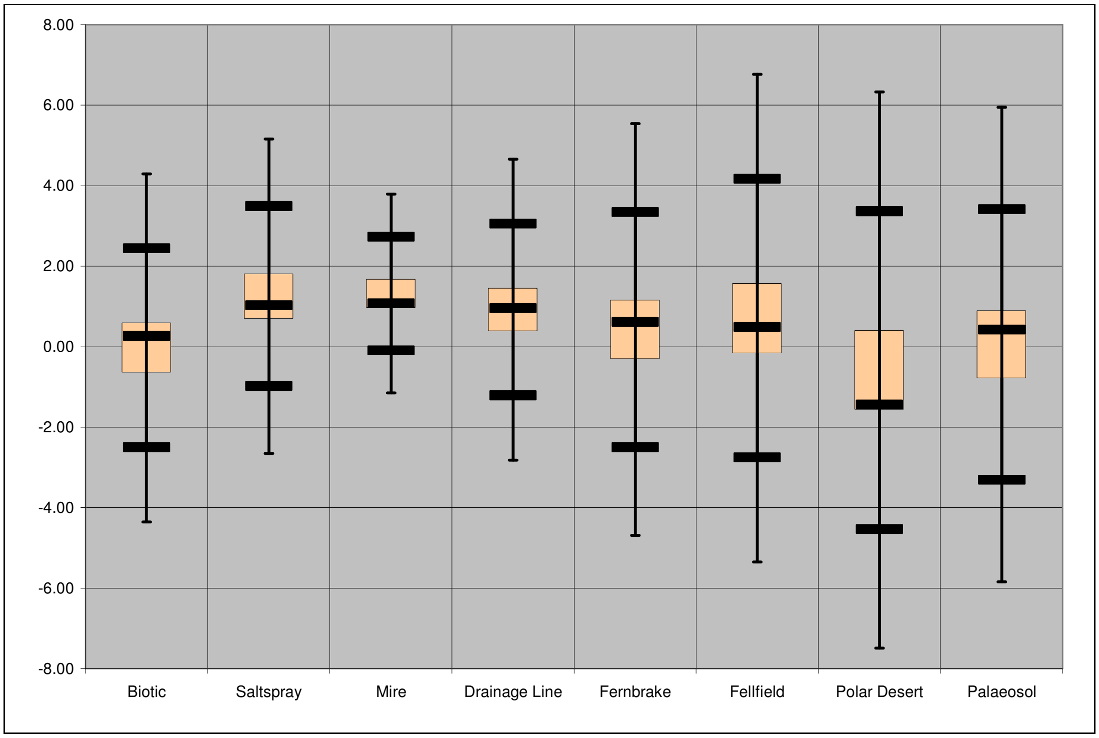
Graph C-52: All habitat averages.

Sand:silt:clay ternary diagram showing all results:

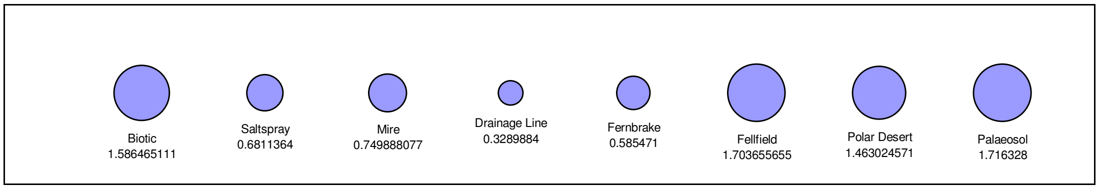


Graph C-53: Sand:silt:clay.

Statistical analysis of results:



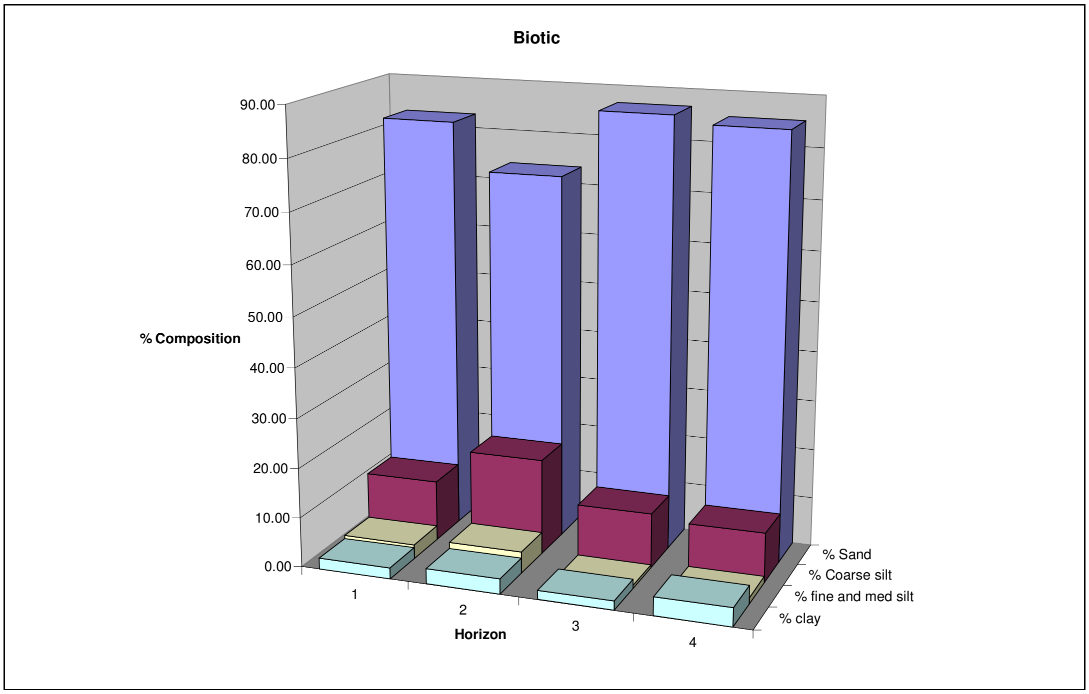
Graph C-54: Boxplot of sample means.



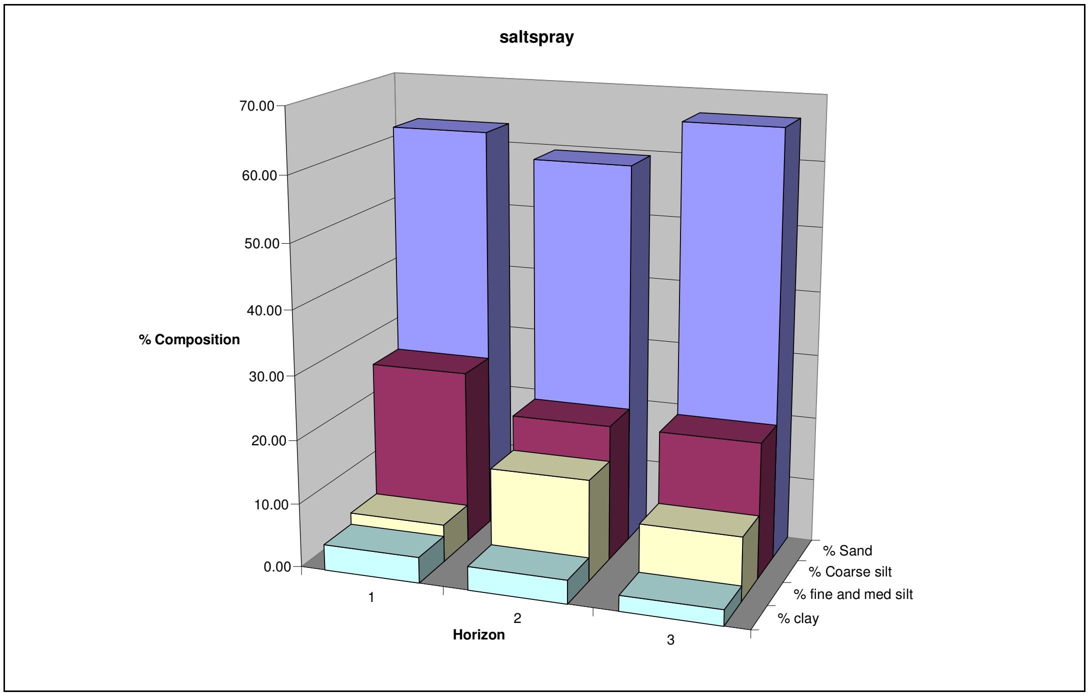
Graph C-55: Variance of means (the larger the dot, the greater the variance).

APPENDIX D:

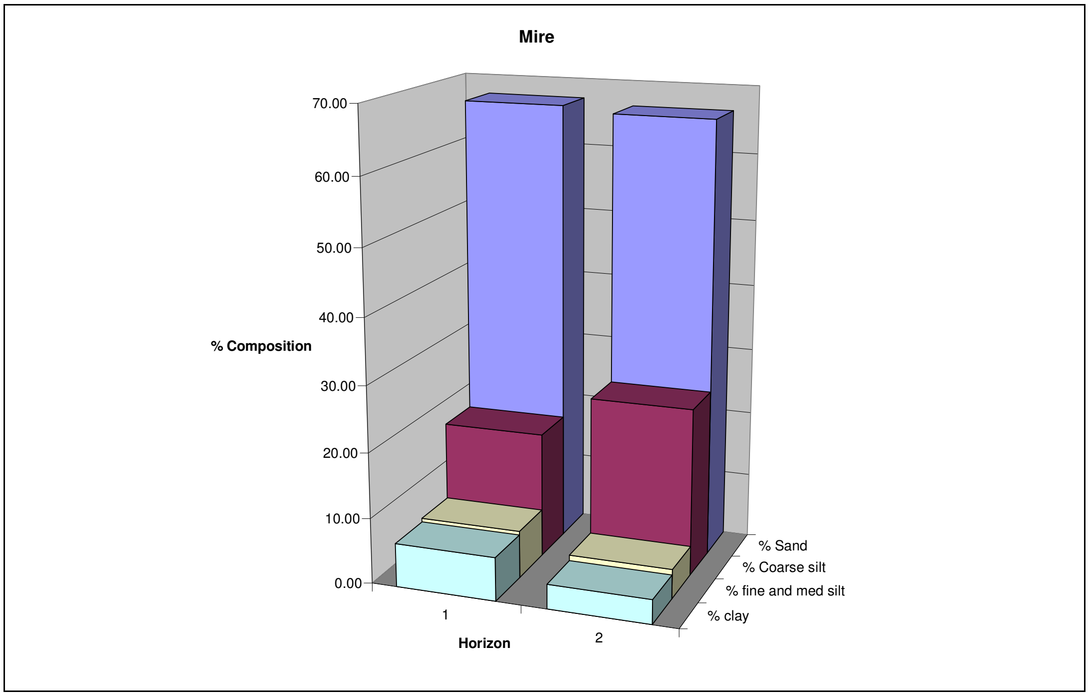
Fine Texture results



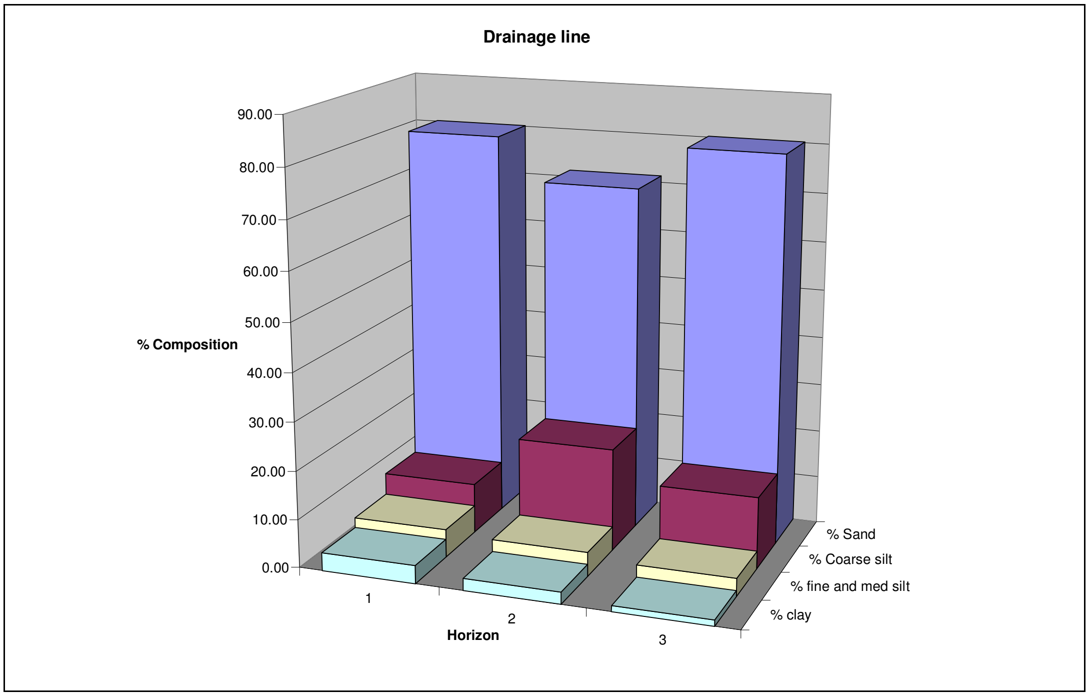
Graph D-1: Biotic habitat.



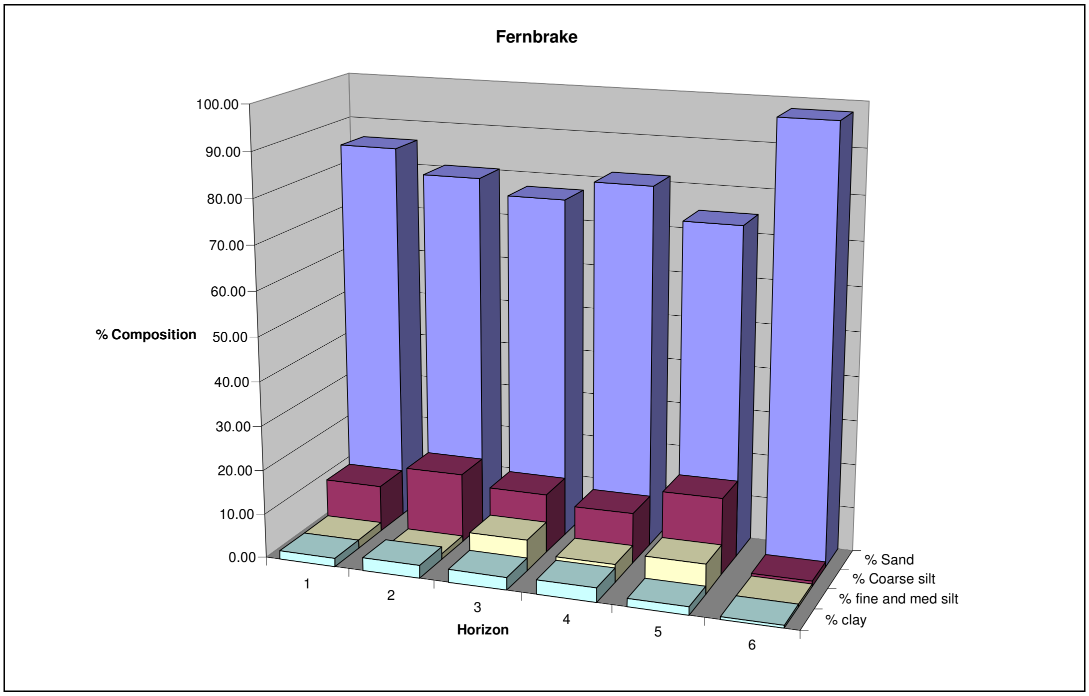
Graph D-2: Saltspray habitat.



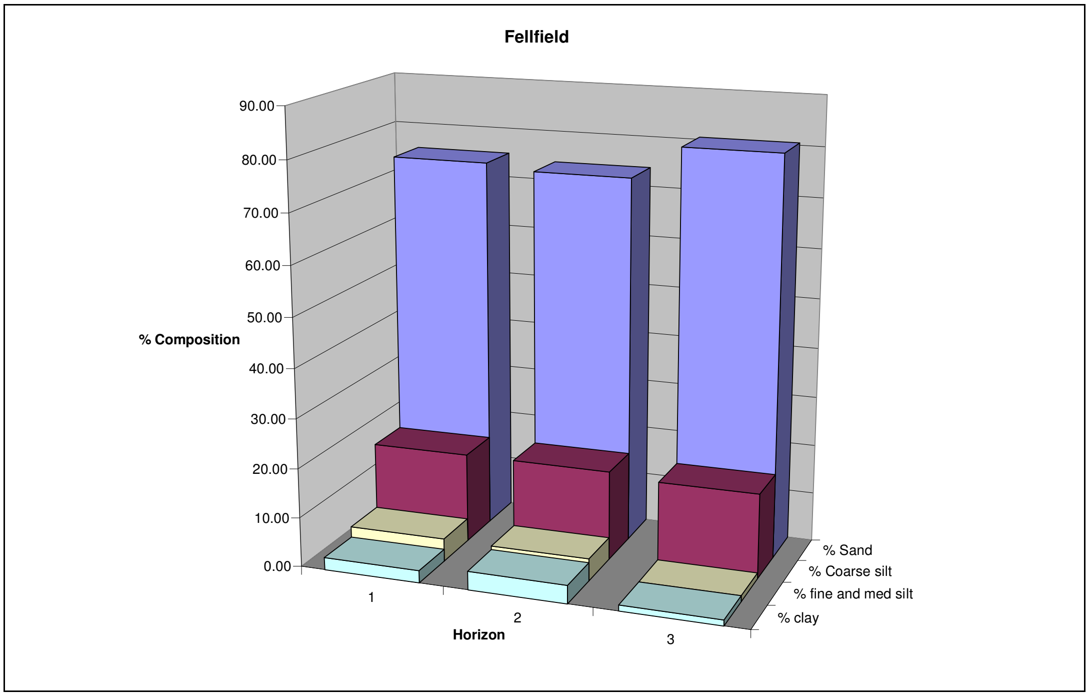
Graph D-3: Mire habitat.



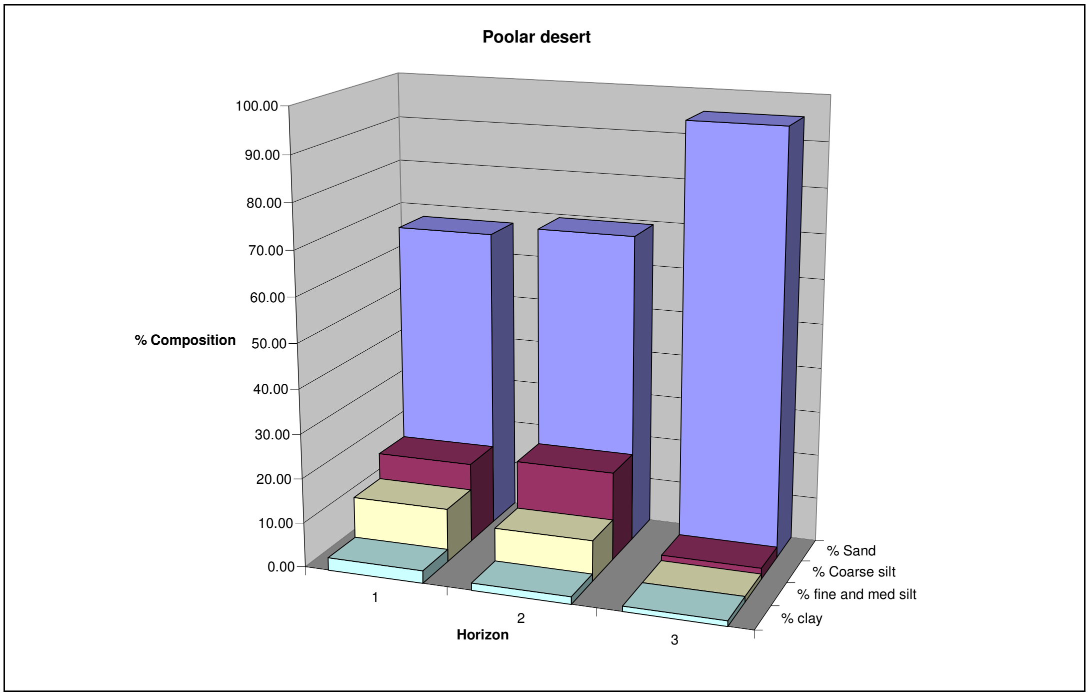
Graph D-4: Drainage line habitat.



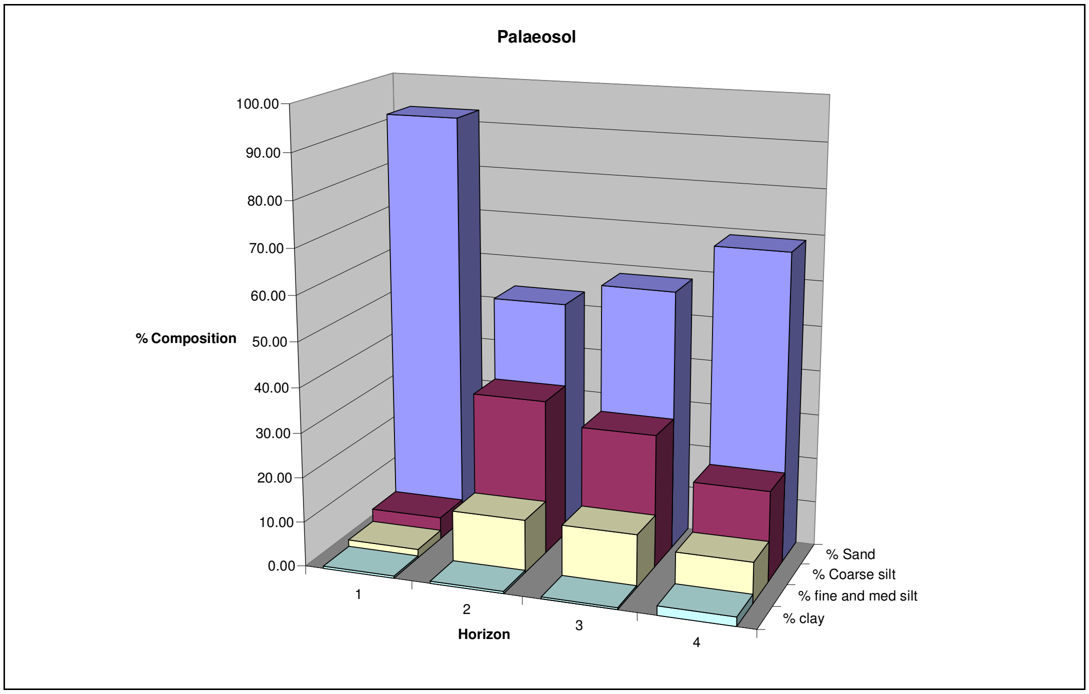
Graph D-5: Fernbrake habitat.



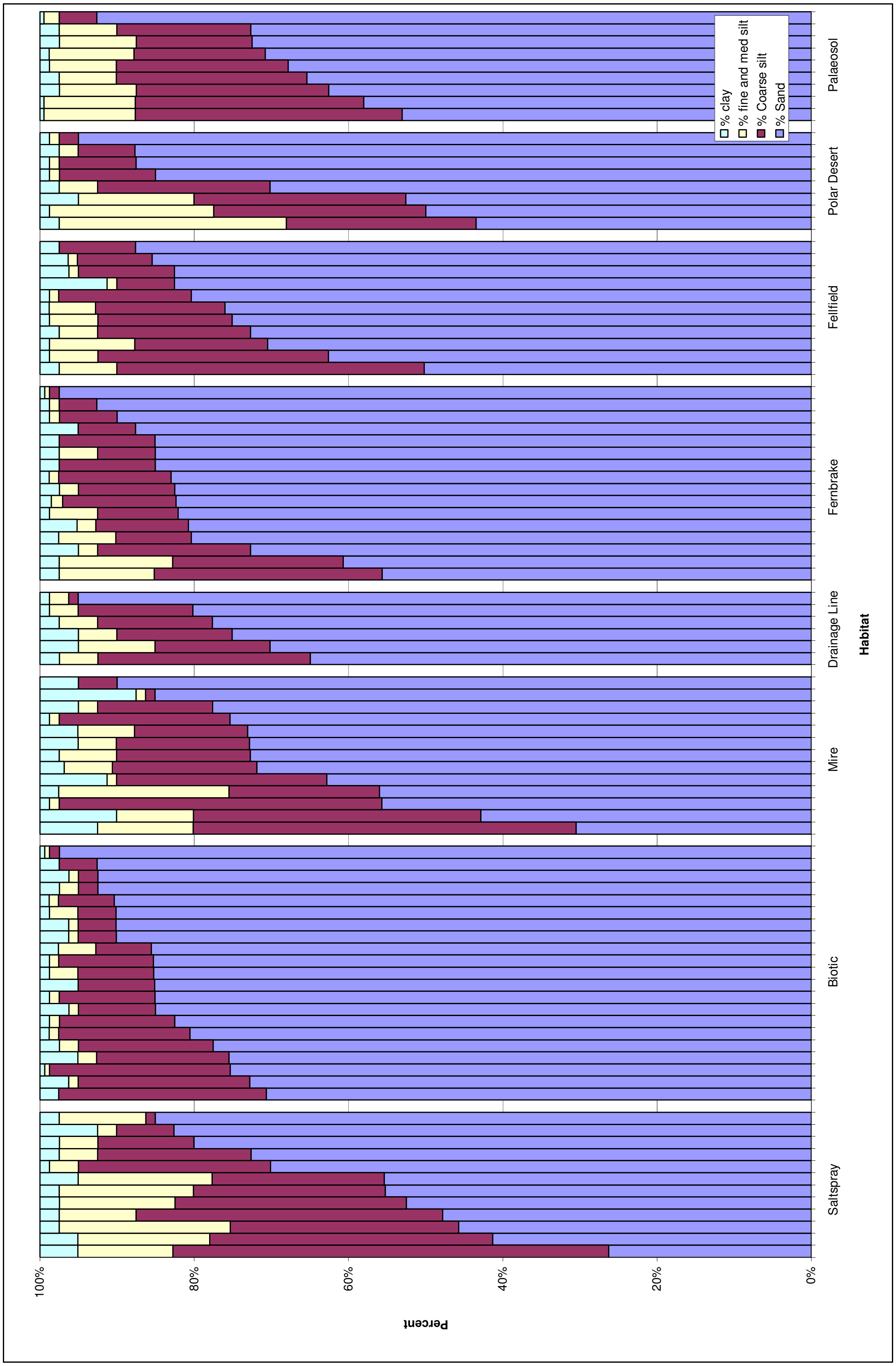
Graph D-6: Fellfield habitat.



Graph D-7: Polar desert habitat.



Graph D-8: Palaeosol.



Graph D-9: fine texture results of each sample, showing variance between samples.

APPENDIX E:

X-ray Fluorescence data

Table E-1: Site 01 (fernbrake) major elements.

%	01(1)	01(2)	01(3)	01(4)	01(Fe1)	01(Fe2)	01(Fe3)
SiO_2	Not determined (fused bead broke)	36.40	21.38	27.33	37.41	28.57	31.48
TiO_2		4.35	4.30	5.21	3.58	4.06	4.03
Al_2O_3		17.07	15.89	16.70	16.84	15.27	15.79
Fe_2O_3		14.26	21.39	9.04	14.31	24.35	16.27
MnO		0.18	0.37	0.08	0.19	0.16	0.24
MgO		6.17	2.05	2.17	6.24	3.56	4.27
CaO		7.29	3.46	5.07	7.67	4.97	6.32
Na_2O		1.73	0.83	1.32	2.11	1.16	1.51
K_2O		0.68	0.28	0.44	0.78	0.46	0.53
P_2O_5		0.59	0.80	1.11	0.58	0.66	0.58
Cr_2O_3		0.04	0.03	0.03	0.04	0.03	0.04
NiO		0.01	0.00	0.00	0.01	0.00	0.01
V_2O_5		0.05	0.06	0.05	0.05	0.05	0.05
ZrO_2		0.04	0.03	0.05	0.04	0.03	0.03
LOI		10.35	27.72	29.90	9.52	16.48	18.42
TOTAL		99.23	98.60	98.51	99.37	99.80	99.56

Table E-2: Site 01 (fernbrake) trace elements.

Ppm	01(A)	01(2)	01(3)	01(4)	01(Fe1)	01(Fe2)	01(Fe3)
As	3	3	4	8	8	5	3
Cu	46	66	78	73	67	61	63
Ga	10	24	23	27	24	23	25
Mo	1	3	4	1	4	6	4
Nb	12	42	43	43	43	41	42
Ni	43	120	67	50	101	63	98
Pb	3	3	3	5	3	5	7
Rb	4	17	9	8	19	14	16
Sr	239	449	241	341	464	322	426
Th	3	3	3	3	6	6	5
U	3	3	3	3	3	3	3
W	380	232	109	92	158	117	298
Y	8	33	35	33	34	35	35
Zn	71	114	106	130	105	91	102
Zr	103	292	291	301	292	272	280
Cl	684	667	651	343	585	287	582
Co	466	17	2	2	7	2	122
Cr	135	209	141	163	178	154	171
F	791	206	100	557	370	100	100
S	3,561	246	574	779	243	419	319
Sc	15	21	22	24	20	18	20
V	84	162	233	128	158	164	162
Cs	9	9	9	9	9	9	9
Ba	348	95	48	113	87	42	101
La	4	10	13	10	12	14	5
Ce	95	83	127	155	83	95	94

Table E-3: Site 02 (polar desert) major elements.

%	02(1)	02(2)	02(3)
SiO_2	43.25	42.22	43.33
TiO_2	4.81	5.13	5.22
Al_2O_3	16.22	17.34	16.80
Fe_2O_3	14.93	15.69	15.53
MnO	0.17	0.20	0.20
MgO	5.72	5.09	4.70
CaO	8.65	8.08	8.04
Na_2O	2.79	2.75	2.96
K_2O	1.10	1.08	1.18
P_2O_5	0.58	0.63	0.63
Cr_2O_3	0.02	0.01	0.01
NiO	0.00	0.00	0.00
V_2O_5	0.06	0.06	0.07
ZrO_2	0.04	0.04	0.04
LOI	0.89	1.69	0.75
TOTAL	99.21	100.03	99.47

Table E-4: Site 02 (polar desert) trace elements.

ppm	02(1)	02(2)	02(3)
As	6	3	3
Cu	48	55	50
Ga	26	28	27
Mo	6	7	6
Nb	45	48	50
Ni	65	52	38
Pb	6	14	4
Rb	28	27	29
Sr	595	573	599
Th	10	10	11
U	9	8	11
W	318	266	423
Y	35	40	43
Zn	115	123	135
Zr	297	320	324
Cl	259	270	241
Co	28	22	37
Cr	59	44	18
F	154	100	116
S	281	189	121
Sc	15	16	17
V	188	192	190
Cs	9	9	9
Ba	136	121	140
La	4	4	5
Ce	60	86	93

Table E-5: Site 03 (biotic) major elements.

%	03(1)	03(1)	03(3)
SiO_2	45.92	44.97	46.55
TiO_2	3.42	3.38	3.41
Al_2O_3	15.55	15.23	15.80
Fe_2O_3	13.34	13.02	13.25
MnO	0.17	0.16	0.17
MgO	4.88	4.47	5.00
CaO	9.73	9.74	9.87
Na_2O	2.94	2.92	2.93
K_2O	1.13	1.16	1.11
P_2O_5	0.82	1.37	0.64
Cr_2O_3	0.01	0.01	0.01
NiO	0.00	0.00	0.00
V_2O_5	0.06	0.05	0.06
ZrO_2	0.03	0.03	0.03
LOI	0.19	1.52	-0.13
TOTAL	98.17	98.04	98.69

Table E-6: Site 03 (biotic) trace elements.

ppm	03(1)	03(1)	03(3)
As	6	4	3
Cu	55	57	52
Ga	24	24	23
Mo	6	6	7
Nb	41	39	40
Ni	49	38	70
Pb	8	6	11
Rb	29	29	29
Sr	607	610	612
Th	9	8	10
U	8	9	10
W	633	1,038	474
Y	33	32	35
Zn	113	118	115
Zr	259	250	256
Cl	398	477	444
Co	202	252	136
Cr	22	23	21
F	527	1,026	435
S	251	432	188
Sc	15	14	15
V	172	168	175
Cs	9	9	9
Ba	154	153	138
La	8	12	10
Ce	67	65	62

Table E-7: Site 28 (fellfield) major elements.

%	28(1)	28(2)
SiO_2	37.12	37.07
TiO_2	4.63	3.68
Al_2O_3	17.21	17.30
Fe_2O_3	15.48	15.49
MnO	0.19	0.18
MgO	6.41	8.21
CaO	7.50	8.03
Na_2O	2.14	1.75
K_2O	0.77	0.55
P_2O_5	0.56	0.51
Cr_2O_3	0.03	0.04
NiO	0.01	0.01
V_2O_5	0.06	0.06
ZrO_2	0.04	0.03
LOI	6.32	5.46
TOTAL	98.45	98.38

Table E-8: Site 28 (fellfield) trace elements.

ppm	28(1)	28(2)
As	3	3
Cu	54	63
Ga	25	24
Mo	5	5
Nb	45	42
Ni	92	146
Pb	16	8
Rb	20	15
Sr	490	457
Th	9	8
U	4	6
W	133	106
Y	33	32
Zn	112	112
Zr	296	283
Cl	163	189
Co	4	9
Cr	109	192
F	153	281
S	269	226
Sc	17	19
V	163	175
Cs	9	9
Ba	104	88
La	4	4
Ce	86	83

Table E-9: List of major elements found in the samples analysed.

%	
SiO_2	Silicon dioxide
TiO_2	Titanium dioxide
Al_2O_3	Aluminium oxide
Fe_2O_3	Iron oxide
MnO	Manganese oxide
MgO	Magnesium oxide
CaO	Calcium oxide
Na_2O	Sodium oxide
K_2O	Potassium oxide
P_2O_5	Phosphorous pentoxide
Cr_2O_3	Chromium(III) Oxide
NiO	Nickel(II) oxide
V_2O_5	Vanadium pentoxide
ZrO_2	Zirconium dioxide
LOI	Loss on Ignition

Table E10: List of trace elements determined.

ppm	
As	Arsenic
Cu	Copper
Ga	Gallium
Mo	Molybdenum
Nb	Niobium
Ni	Nickel
Pb	Lead
Rb	Rubidium
Sr	Strontium
Th	Thorium
U	Uranium
W	Tungsten
Y	Yttrium
Zn	Zinc
Zr	Zirconium
Cl	Chlorine
Co	Cobalt
Cr	Chromium
F	Fluorine
S	Sulphur
Sc	Scandium
V	Vanadium
Cs	Caesium
Ba	Barium
La	Lanthanum
Ce	Cerium

APPENDIX F:

X-ray diffraction data

Table F-1: X-ray diffraction results of Site 01.

	01(A)	01(2)	01(3)	01(4)	01(Fe1)	01(Fe2)	01(Fe3)
Plagioclase	60.7	48.83	47.37	48.91	52.59	57.35	49.26
Diopside	26.4	31.39	32.39	35.09	29.6	31.33	29.04
Forsterite	1.94	13.45	11.54	9.56	10.07	2.49	14.41
Magnetite	2.77	1.91	3.39	3.78	3.34	1.69	2.13
Hematite	8.19	4.42	5.3	2.65	4.4	7.13	5.15

Table F-2: X-ray diffraction results of Site 02.

	02(1)	02(2)	02(3)
Plagioclase	58.9	64.82	72.29
Diopside	22.51	15.91	9.62
Forsterite	11.84	13.05	12.87
Magnetite	5.57	4.72	4.56
Hematite	1.19	1.5	0.67

Table F-3: X-ray diffraction results of Site 03.

	03(1)	03(2)	03(3)
Plagioclase	69.64	68.6	65.32
Diopside	16.28	19.15	19.26
Forsterite	9.28	7.12	9.53
Magnetite	3.88	4.37	5.21
Hematite	0.93	0.76	0.69

Table F-4: X-ray diffraction results of Site 28.

	28(1)	28(2)
Plagioclase	51.11	46.4
Diopside	26.94	30.39
Forsterite	14.84	17.02
Magnetite	5.02	4.64
Hematite	2.09	1.55

Table F-5: Comparison of XRD results from this study and other research.

	Biotic	**Fernbrake**	**Fellfield**	**Polar Desert**	**Mid-ocean ridge basalt [*1]**	**Indian Ocean ridge basalt [*1]**	**Marion Island Grey lava [*2]**	**Marion Island Black lava [*2]**
Feldspar group [*3]	67.85	52.14	48.76	65.34	51.61	50.17	66.09	57.73
Diopside	18.23	30.75	28.67	16.01	21.62	22.38	7.85	11.74
Olivine group [*4]	8.64	9.07	15.93	12.59			12.14	19.94
Hematite group*5	0.79	5.32	1.82	1.12	2.96	2.26	3.42	3.24
Magnetite	4.49	2.72	4.83	4.95	4.44	3.9	7.66	1.86
Hypersthene					17.19	18.62		
Nepheline							2.16	4.06
Apatite							0.91	1.01

*1: Winter (2000).
*2: Abbot (1963).
*3: Feldspar group minerals (orthoclase, anorthite and albite).
*4: Olivine group minerals (forsterite and fayalite).
*5: Hematite group minerals (hematite and ilmenite).

APPENDIX G:

Clay mineralogy (XRD)

Table G-1: Clay mineralogy results (as determined by the ISCW).

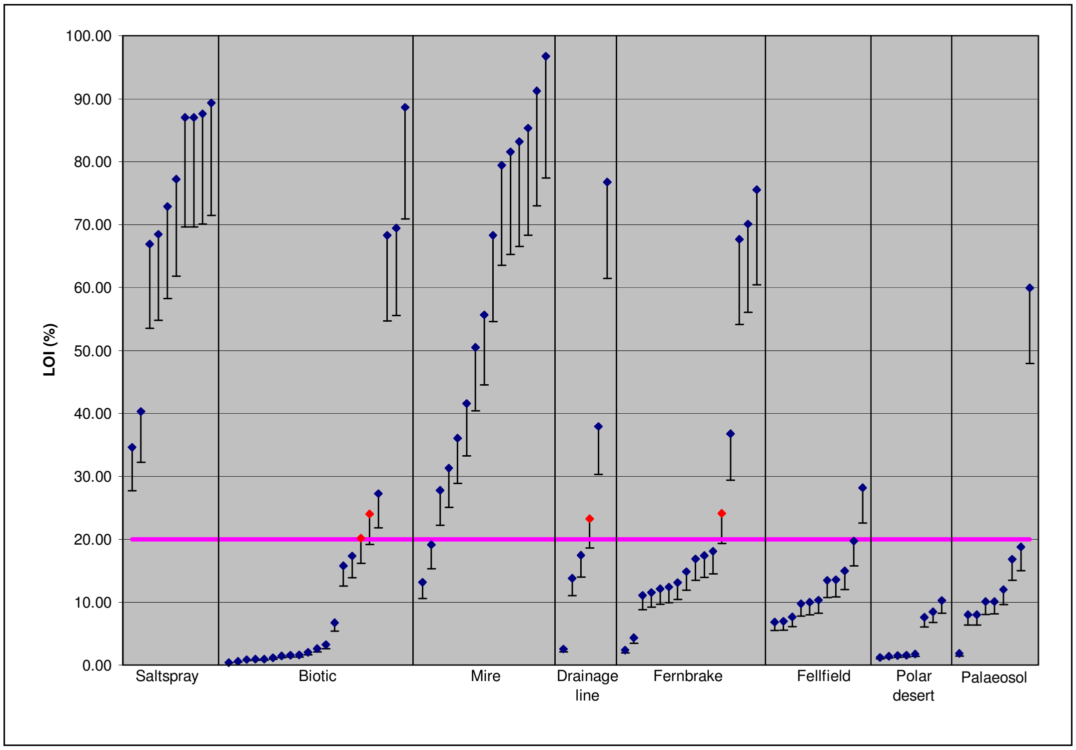
Sample	Habitat	Quartz (%)	Feldspar (%)	Smectite (%)	Gibbsite (%)
38	Mire	80	20	0	0
19	Fernbrake	63	11	26	0
37	Fernbrake	44	28	28	0
32	Fellfield	37	12	51	0
34	Polar desert	59	12	22	7

APPENDIX H:

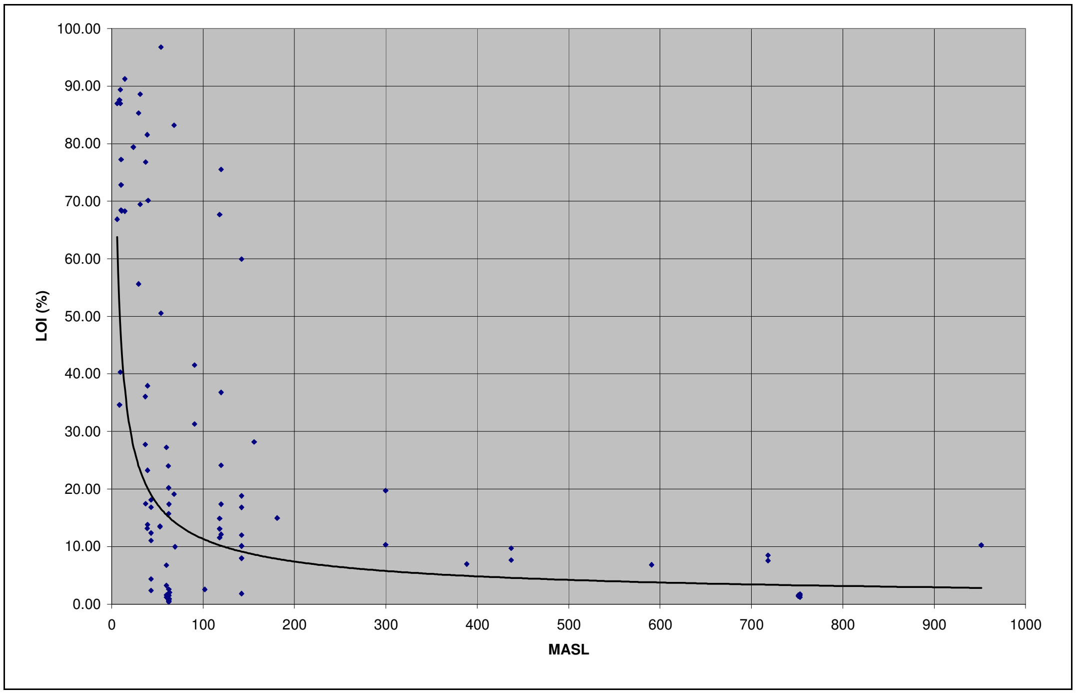
Loss on Ignition results

Table H-1: Loss on ignition results.

Site & Sample no	Habitat	LOI (measured)	LOI (Less 20%)
1(A)	Fernbrake	67.66	54.13
1(2)	Fernbrake	13.08	10.46
1(3)	Fernbrake	11.55	9.24
1(4)	Fernbrake	14.87	11.89
2(1)	Polar desert	1.52	1.22
2(2)	Polar desert	1.75	1.40
2(3)	Polar desert	1.22	0.97
3(1)	Biotic	0.61	0.49
3(2)	Biotic	2.61	2.09
3(3)	Biotic	0.4	0.32
4(A)	Biotic	6.74	5.39
4(B)	Biotic	3.24	2.59
4(C)	Biotic	1.62	1.30
4(4)	Biotic	27.26	21.81
5(O)	Saltspray	87.34	70.07
5(A)	Saltspray	34.63	27.71
6(O)	Mire	85.33	68.26
6(A)	Mire	55.63	44.51
7(1)	Biotic	1.19	0.95
8(1)	Biotic	0.95	0.76
9(1)	Biotic	1.47	1.17
10(1)	Biotic	1.59	1.27
11(1)	Biotic	0.91	0.73
12(1)	Biotic	2.03	1.62
13(1)	Biotic	0.87	0.70
14(1)	Biotic	20.19	16.15
15(1)	Biotic	15.75	12.60
16(1)	Biotic	17.35	13.88
17(1)	Biotic	24.02	19.21
18(O)	Mire	81.57	65.26
18(A)	Mire	13.17	10.54
19(O)	Fernbrake	75.53	60.42
19(A)	Fernbrake	36.77	29.42
19(B1)	Fernbrake	24.13	19.31
19(B2)	Fernbrake	12.12	9.69
19(B3)	Fernbrake	17.39	13.91
20(O)	Mire	36.07	28.85
20(A)	Mire	27.75	22.20
21(O)	Saltspray	87.00	69.60
21(A)	Saltspray	66.88	53.50
22(O)	Mire	91.23	72.98
22(A)	Mire	68.28	54.63
23(1)	Palaeosol	1.83	1.46
23(2)	Palaeosol	18.79	15.03
23(3)	Palaeosol	16.81	13.45
23(4)	Palaeosol	12.00	9.60
23(5)	Palaeosol	10.09	8.07
23(6)	Palaeosol	8.00	6.40
23(7)	Palaeosol	7.98	6.39
23(8)	Palaeosol	59.94	47.95
23(9)	Palaeosol	10.12	8.09
24(1)	Fellfield	28.17	22.54
25(A)	Drainage line	37.92	30.34
25(B)	Drainage line	23.24	18.59
25(C)	Drainage line	13.79	11.03
26(1)	Mire	79.40	63.52
27(O)	Mire	41.54	33.23
27(A)	Mire	31.28	25.02
28(1)	Fellfield	7.63	6.11
28(2)	Fellfield	9.73	7.78
29(1)	Fellfield	6.97	5.58
30(1)	Polar desert	8.47	6.77
30(2)	Polar desert	7.57	6.05
31(1)	Fellfield	6.86	5.49
32(1)	Fellfield	10.31	8.25
32(2)	Fellfield	19.73	15.78
33(1)	Fellfield	14.98	11.98
34(1)	Polar desert	10.26	8.21
35(O)	Mire	96.77	77.41
35(A)	Mire	50.52	40.42
36(1)	Fernbrake	70.09	56.07
37(O)	Fernbrake	18.11	14.49
37(A)	Fernbrake	16.84	13.47
37(Fe1)	Fernbrake	11.04	8.84
37(Fe2)	Fernbrake	12.38	9.90
37(Sc)	Fernbrake	2.37	1.90
37(Sed)	Fernbrake	4.34	3.48
38(O)	Mire	83.20	66.56
38(A)	Mire	19.14	15.31
39(O)	Biotic	88.61	70.89
39(A)	Biotic	69.45	55.56
40(A)	Fellfield	13.43	10.75
40(B)	Fellfield	13.54	10.83
41(O)	Drainage line	76.78	61.42
41(A)	Drainage line	17.43	13.95
42(1)	Fellfield	9.97	7.97
43(1)	Drainage line	2.58	2.06
44(1)	Biotic	68.30	54.64
45(1)	Polar desert	1.37	1.10
45(2)	Polar desert	1.57	1.26
46(O)	Saltspray	89.35	71.48
46(A)	Saltspray	87.00	69.60
46(B)	Saltspray	40.31	32.25
47(O)	Saltspray	77.24	61.79
47(A)	Saltspray	72.84	58.27
47(B)	Saltspray	68.45	54.76



Graph H-1: Loss on ignition results, indicating 20% error bars, by habitat.



Graph H-2: LOI vs. altitude (mamsl).

APPENDIX I:

Infrared Graphs

Method of interpretation of infrared spectra

Infra-red spectra were compared visually against one another to determine whether any noticeable pattern existed. Infra-red spectra were analysed and interpreted as described by Smith (1999):

1. Use quality data.
2. Avoid mixtures if possible.
3. Use other knowledge of the sample.
4. Before looking at a spectrum, note its resolution, the sampling method used and whether any spectral manipulations (subtraction, smoothing, baseline correction, *etc.*) were performed on the spectrum.
5. Read the spectrum from left to right noting the presence or absence of the intense group wave numbers (as shown in Table I-1).

Table I-1: Intense wave group numbers (Smith, 1999).

Band position in cm^{-1}	Functional group
3500 – 3200	O-H or N-H
3200 – 2800	C-H
2250 – 2000	C≡N, C≡C
1800 – 1600	C=O
<1000	C=C, Benzene rings

6. Assign the intense bands first.
7. Track down the secondary bands of the functional groups whose presence you suspect based on evidence gathered in steps 5 and 6.
8. Assign other bands as needed.
9. Write down the functional groups you think exist in the sample.
10. Get help from spectral atlases, library searching or interpretation software.

It is noted that not all the steps as described above (Smith, 1999) are fully appropriate for mixtures, and, therefore, the applicability of each step is described along with the interpretation of results below:

1. **Use quality data:** Some of the spectra obtained were very noisy, with many sharp peaks throughout the spectrum. Such data may be caused by interference and were discarded from the analysis. Seven of the 74 spectra were discarded (9% of the sample) and not further considered in the interpretation process.

2. **Avoid mixtures if possible:** Mixtures result in highly complex spectra which may be very difficult to interpret. Any molecule within the mixture that can absorb in the infra-red spectrum will be picked up, adding to the number of peaks present as well as the intensity of the bands observed. Since a soil sample is being analysed, a

number of different components will be included in the sample, and these components cannot feasibly be separated. It should also be noted that due to the small size of the sub-sample used for infra-red analysis, not all components of any soil sample will necessarily be included in the sample analysed.

3. **Use other knowledge of the sample:** As shown in the other sections of this chapter other knowledge pertaining to the samples has been gained. It has been determined that the soils have low bulk density and pH. Soils are coarse and have high organic matter content. Soils are of typical basaltic origin, and clay minerals are present in the sample.

4. **Before looking at a spectrum, note its resolution, the sampling method used and whether any spectral manipulations were performed on the spectrum:** the infra-red spectra obtained for the samples analysed were manipulated using OPUS software. The samples were smoothed (13 smoothing points) and baseline corrected (Rubberband baseline correction with 128 baseline points). The smoothing function cleaned the data to some degree and smoothed out some of the noise. The baseline correction function normalises the data by flattening the baseline in order to make it more easily comparable with other data. Peaks were also picked by the software to allow for easier interpretation.

5. **Read the spectrum from left to right noting the presence or absence of the following intense group wave numbers:** The presence of intense wave group numbers as (described by Smith, 1999) are indicated in Table I-2.

Table I-2: Intense wave group numbers (Smith, 1999) found in samples analysed.

Band position in cm^{-1}	**Functional group**	**Presence *[1]**	**Habitats *[2]**	**E.g. *[3]**
3500 – 3200	O-H or N-H	100%	All	5 19(A)
3200 – 2800	C-H	34%	Saltspray, Biotic, Mire, Drainage line, Fernbrake.	4 18(O)
2250 – 2000	C≡N, C≡C	None	N/A	N/A
1800 – 1600	C=O	100%	All	6 20(O)
<1000	C=C, Benzene rings	100%	All	7 25(A)

Note
*[1] *Presence: refers to the % of the samples collected in which the particular functional group was present.*
*[2] *Habitats: refers to which habitats showed presence of the functional group described.*
*[3] *E.g.: refers to the figure number (above) and the sample number (below) clearly showing the particular IR-band. Refer to Graphs I-4 to I-7 for figures.*

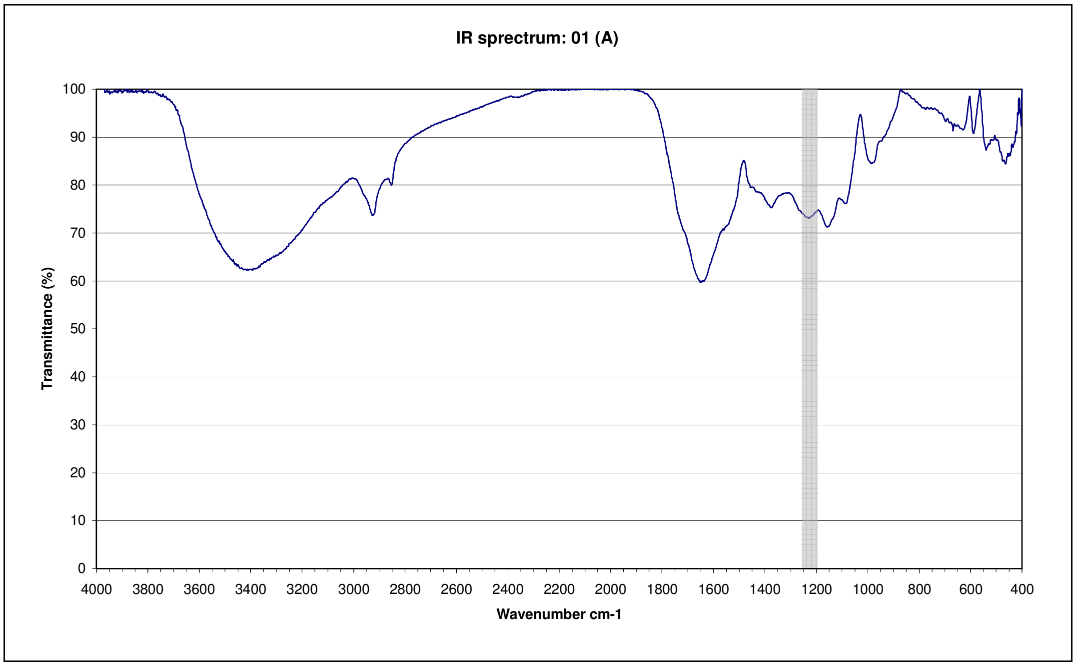
6. **Assign the intense bands first:** In most of the samples analysed, three intense bands stood out in particular. These were :
    - Water: Water is clearly identified by two bands, a broad intense O-H stretch band found between 3500 and 3000, as well as an O-H scissor band at approximately 1638.
    - Wavenumber ±3420: O-H stretch.
    - Wavenumber ±1640: O-H bend.
    - Wavenumber ±1390: C-CH3 symmetric bend.
    - Wavenumber ±1080: C-C-O asymmetric stretch.
    - Wavenumber ±975: C-H bend (out of plane).
    - Wavenumber ±660: O-H bend (out of plane).

7. **Track down the secondary bands of the functional groups whose presence you suspect based on evidence gathered in steps 5 and 6:** Since the samples analysed will all be mixtures, the chemical formulas of components cannot be precisely determined, and this step is thus not relevant to this study.

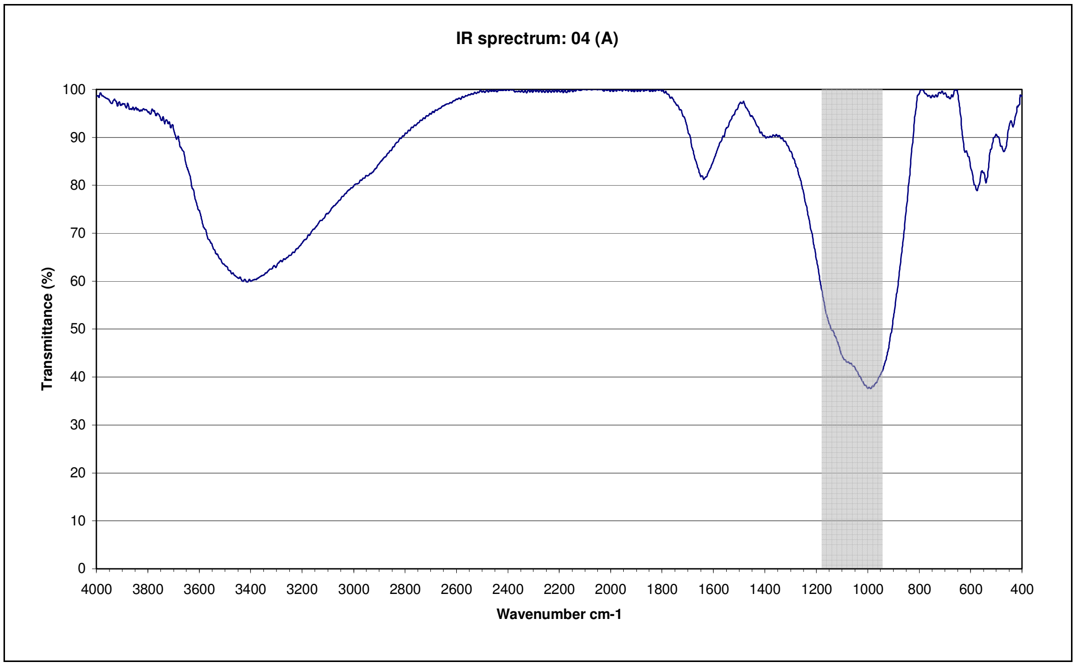
8. **Assign other bands as needed:** other bands are assigned in the samples analysed in the section below.

9. **Write down the functional groups you think exist in the sample:** Since the soil samples analysed are mixtures, it would not be appropriate to attempt to determine the chemistry of individual components since a number of components are interfering with each other (refer to step 2). As mentioned above, uric acid ($C_5H_4N_4O_3$) constituted 80% of the nitrogen in the faeces of both king and macaroni penguins on Marion Island (Smith & Froneman, 2008). It is likely that uric acid may be found in some of the samples analysed.

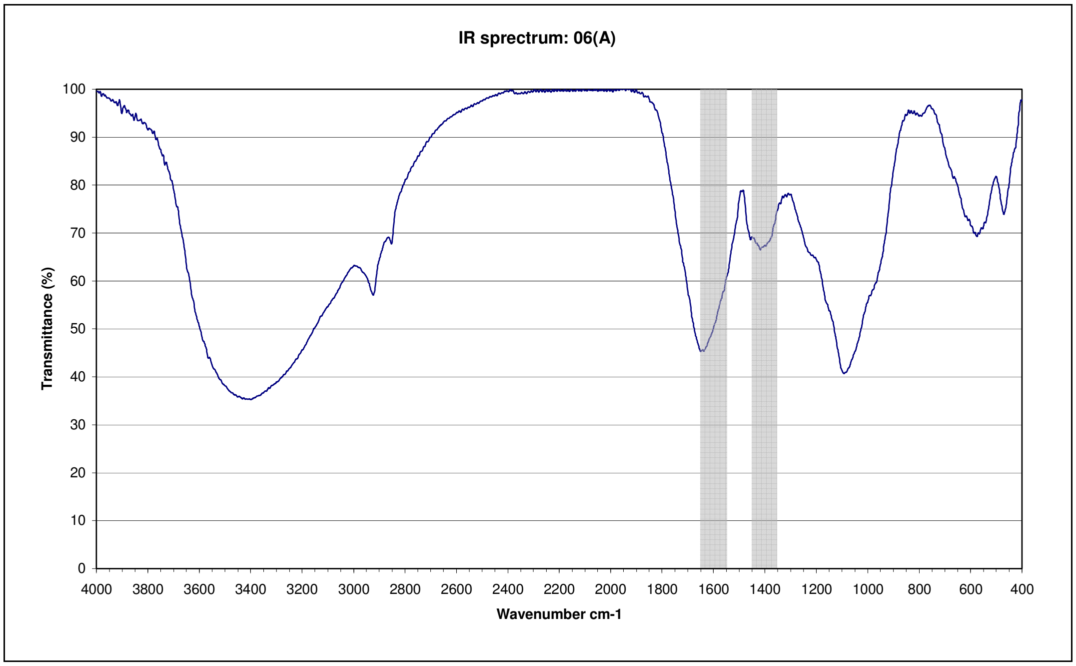
10. **Get help from spectral atlases, library searching or interpretation software**: Infra-red spectra from Smith (1999) as well as Pouchert (1981) were used to aid in the identification of components present in the samples analysed.



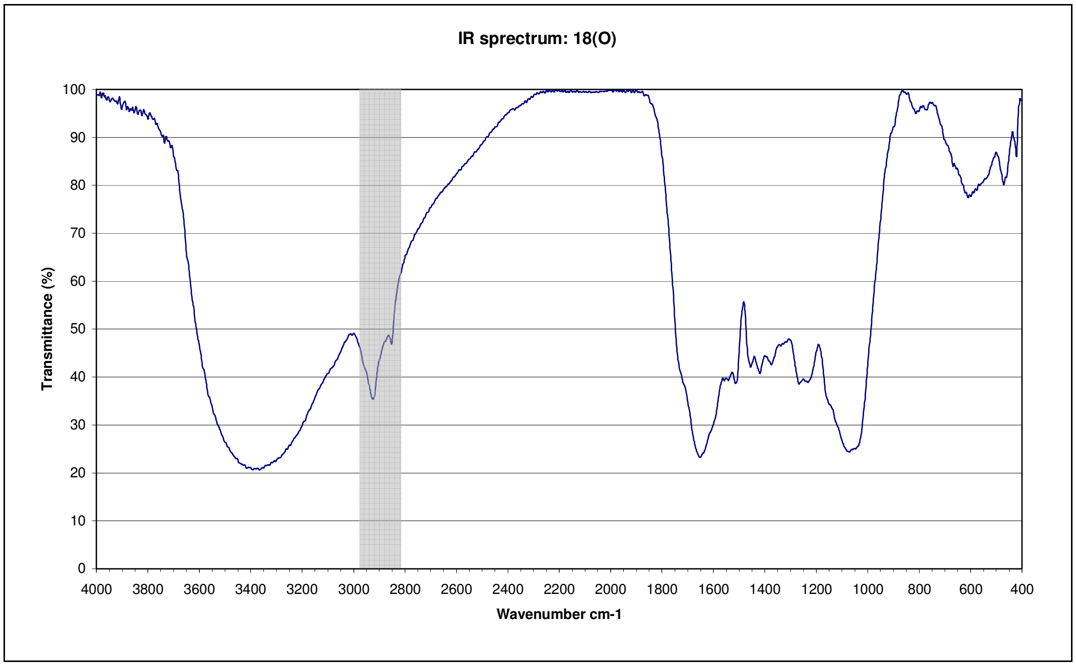
Graph I-1: Occurrence of C-O stretching and O-H bending of –COOH.



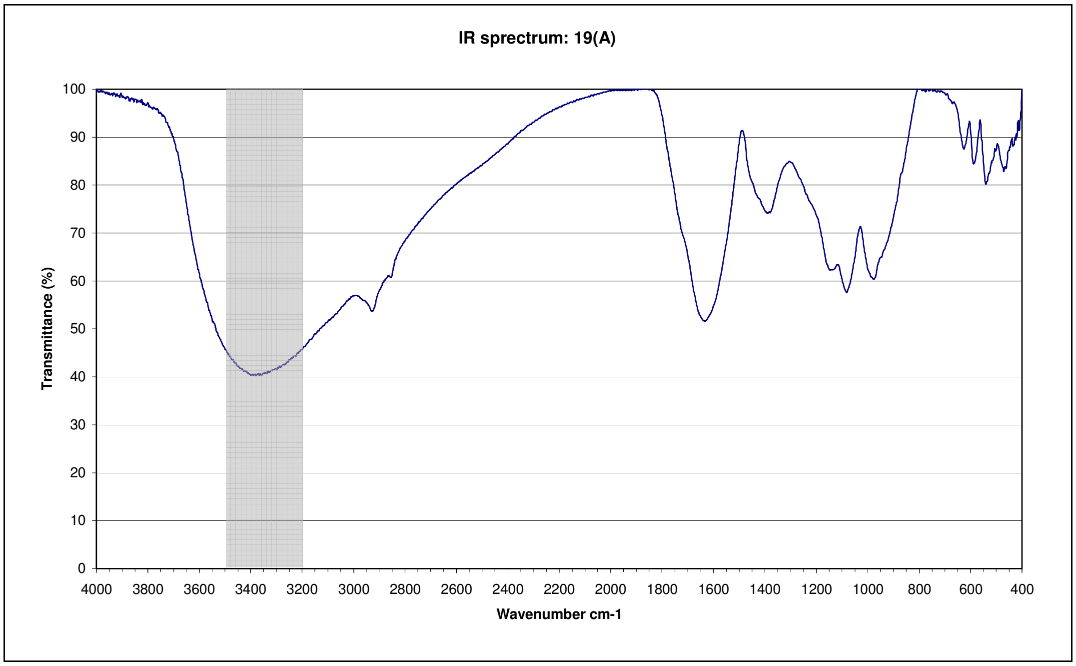
Graph I-2: Occurrence of C-O stretching of polysaccharides.



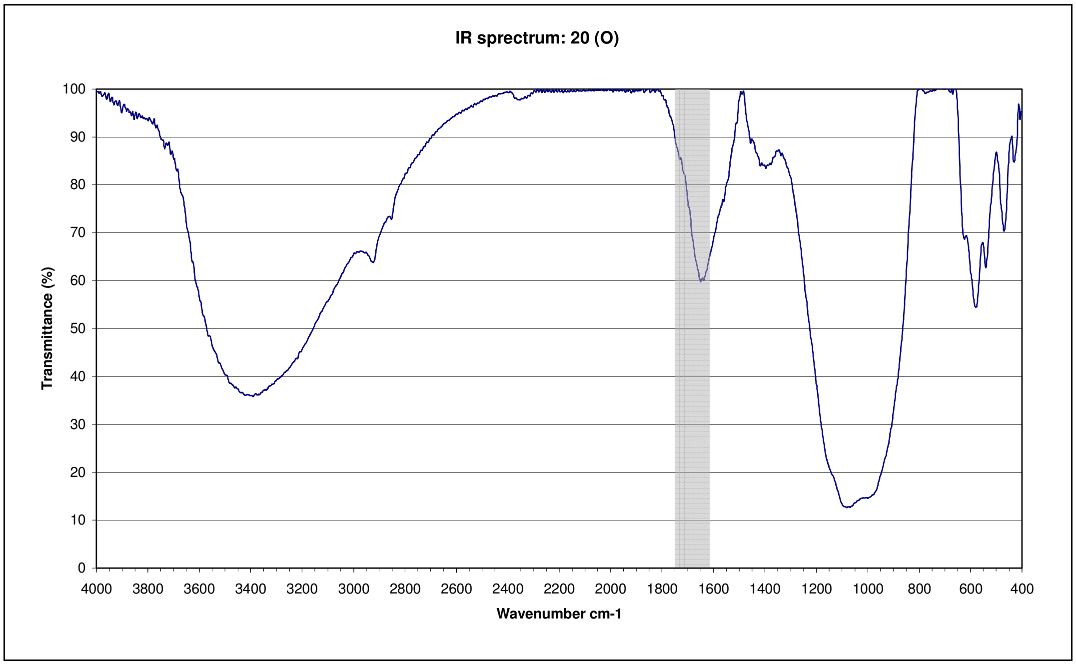
Graph I-3: Occurrence of asymmetric and symmetric COO- stretching of carboxylic acid salts.



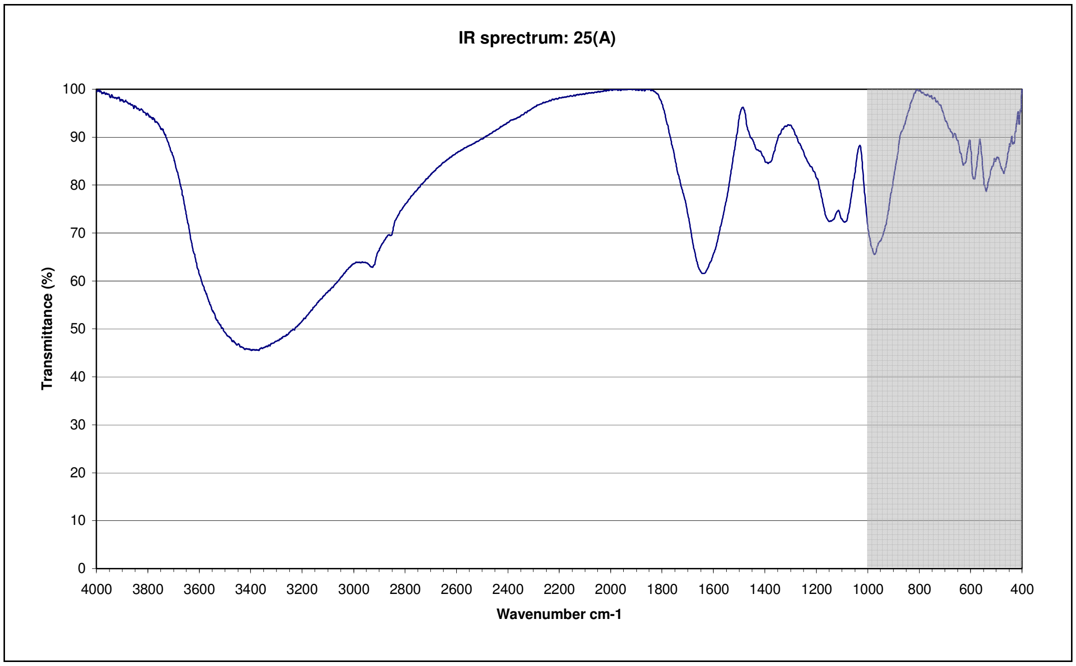
Graph I-4: Occurrence of aliphatic C-H stretching.



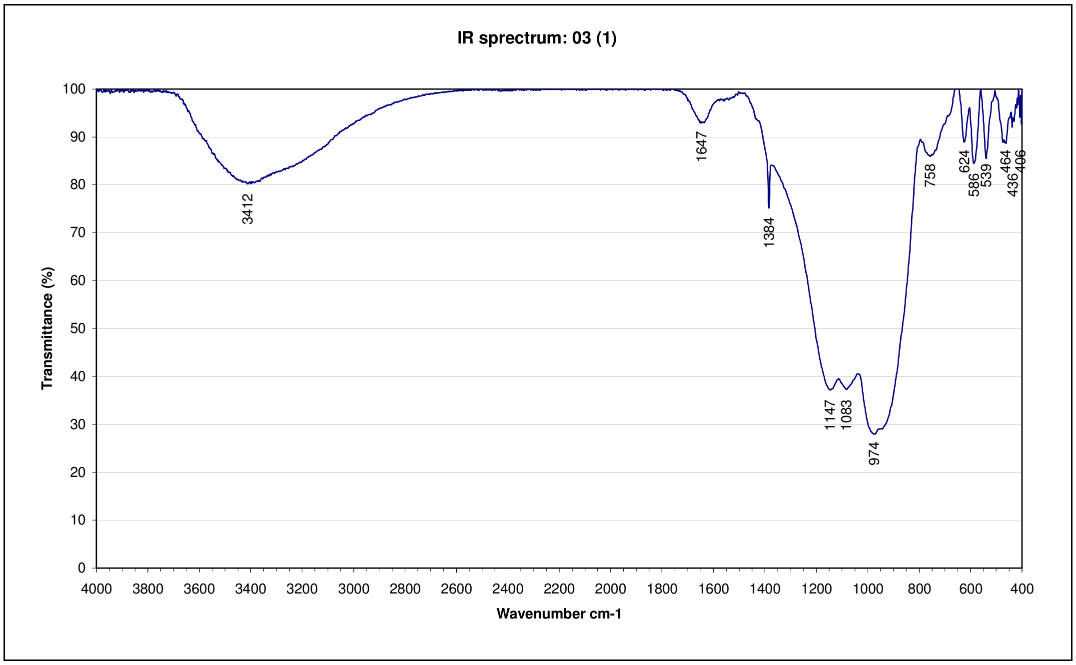
Graph I-5: Occurrence of O-H stretching of carboxylic acids, phenols, alcohols, and / or the presence of N-H.



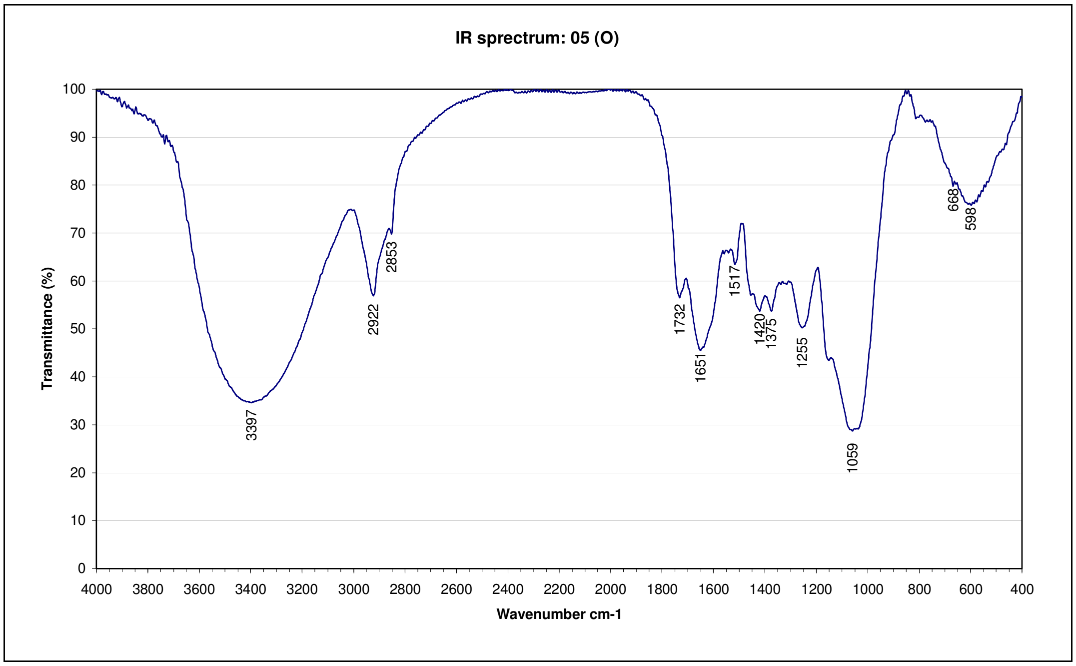
Graph I-6: Occurrence of C=O stretching of carboxylic acids, amides, ketones.



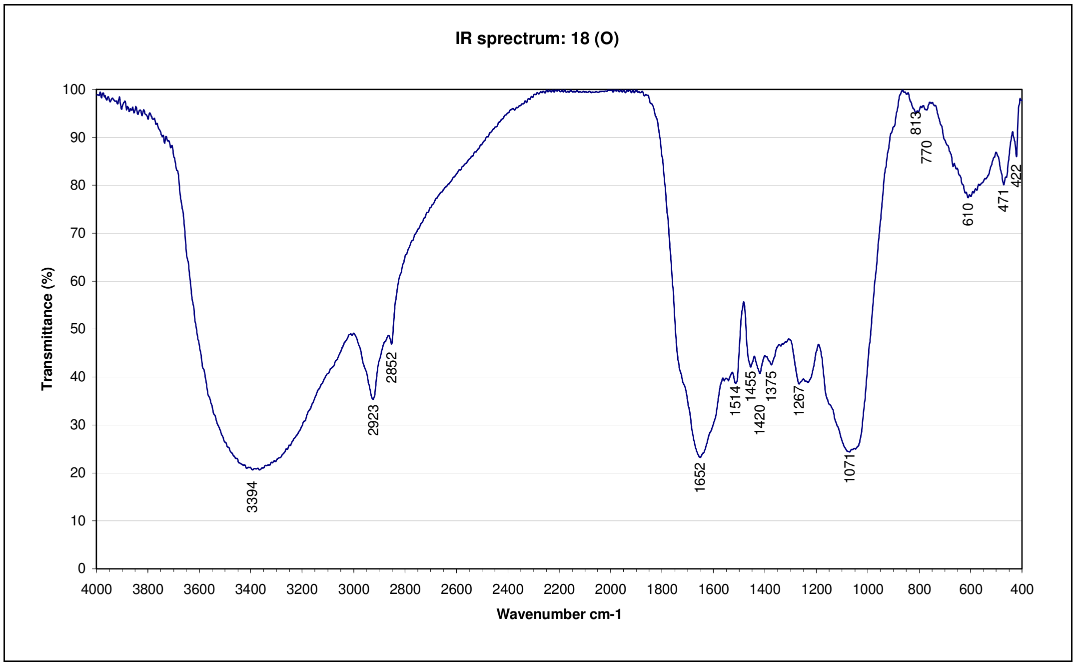
Graph I-7: Occurrence of Graph J-6: Occurrence of C=O stretching of carboxylic acids, amides, ketones.



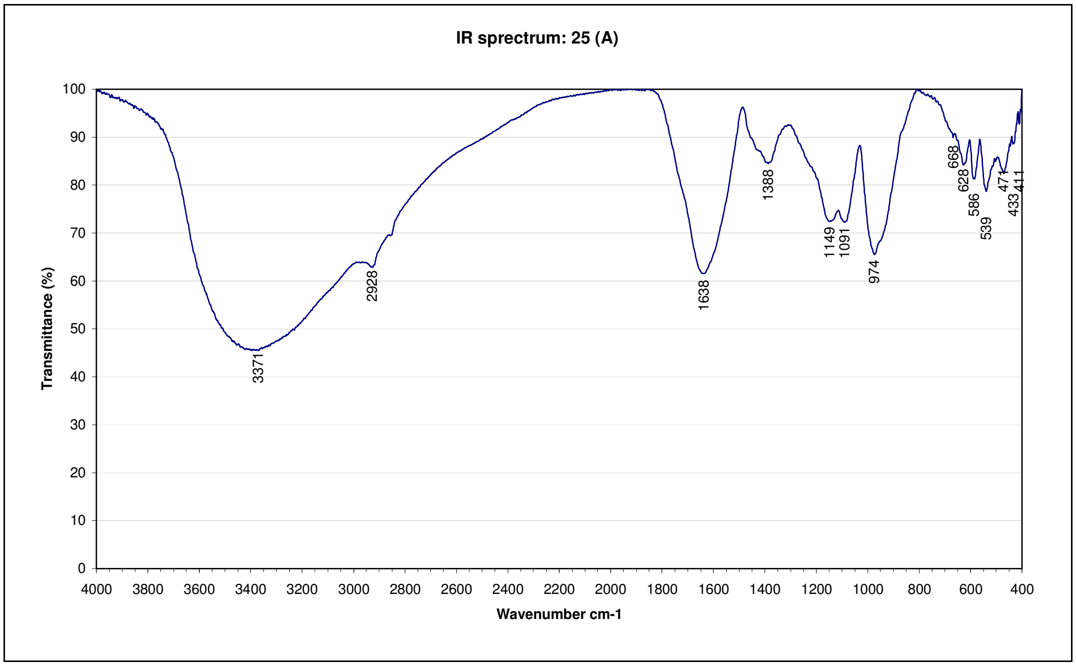
Graph I-8: Typical infrared spectrum from a biotic habitat.



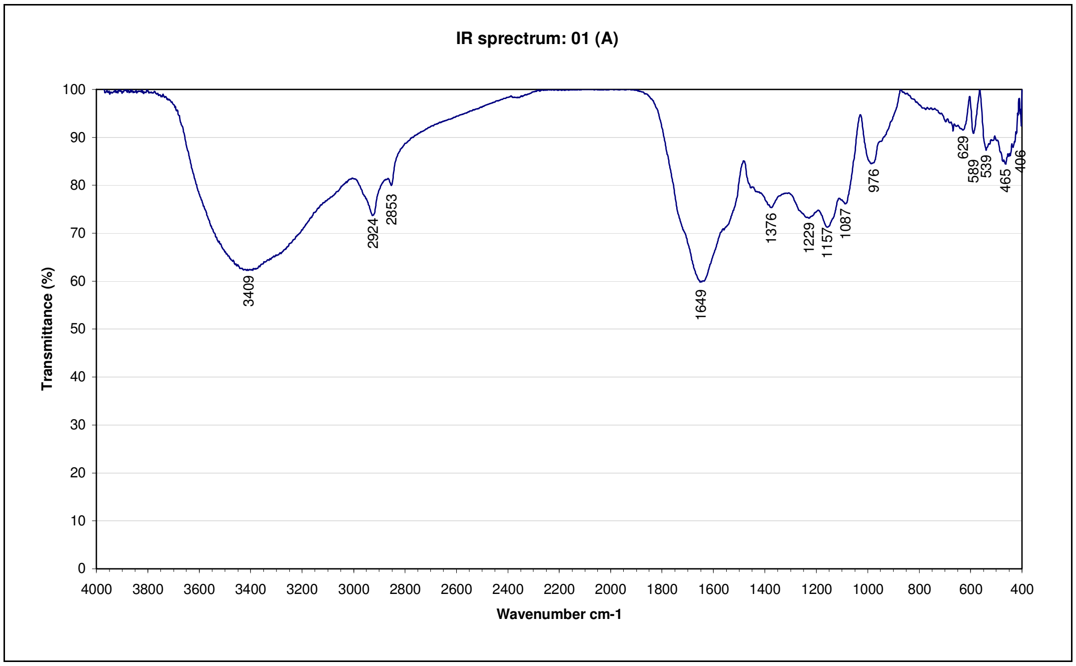
Graph I-9: Typical infrared spectrum from a saltspray habitat.



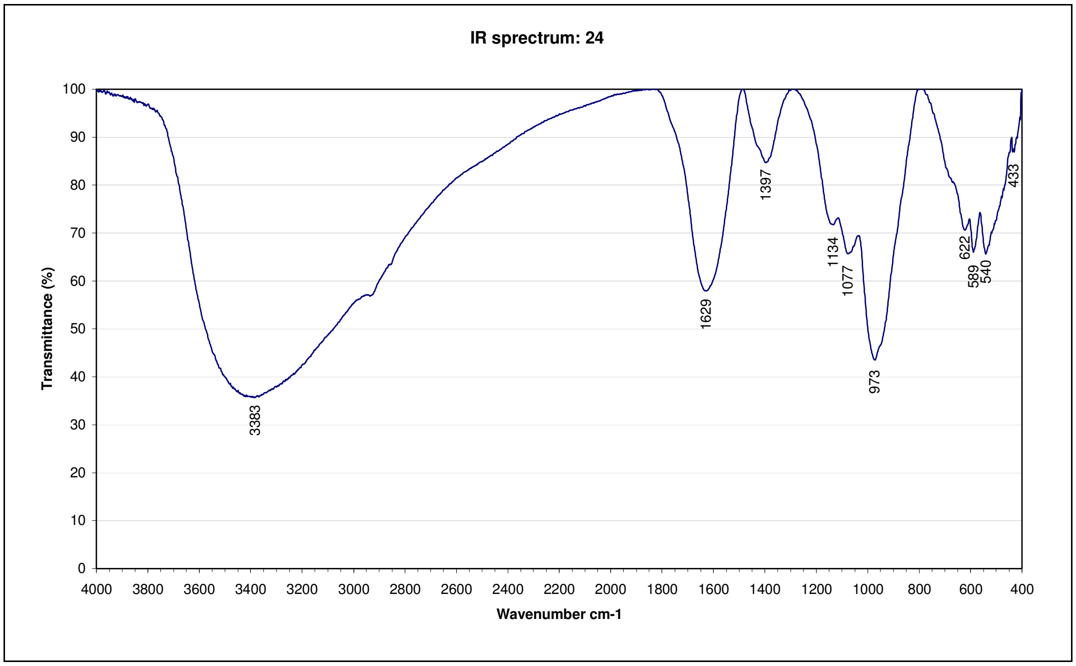
Graph I-10: Typical infrared spectrum from a mire habitat.



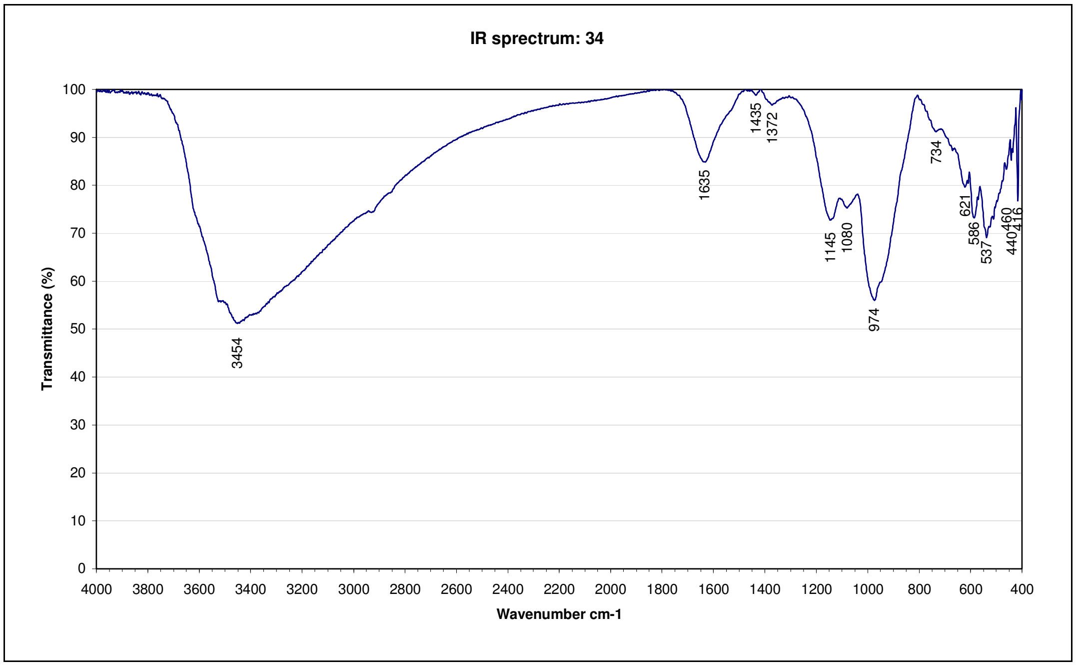
Graph I-11: Typical infrared spectrum from a drainage line habitat.



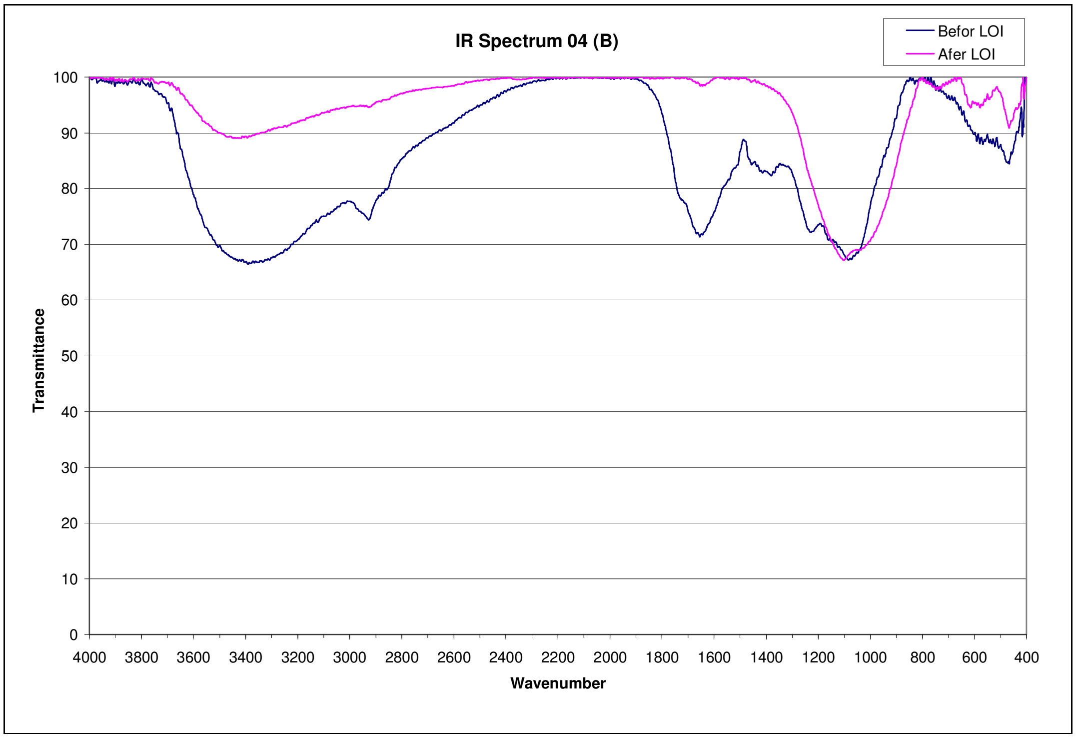
Graph I-12: Typical infrared spectrum from a fernbrake habitat.



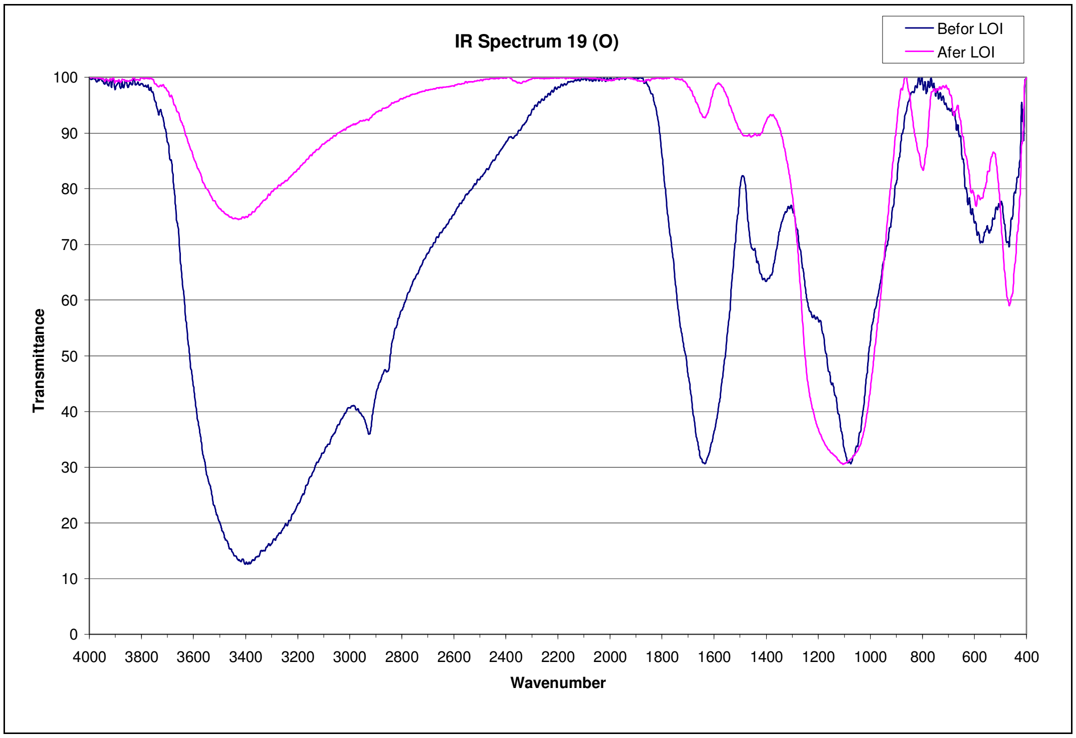
Graph I-13: Typical infrared spectrum from a fellfield habitat.



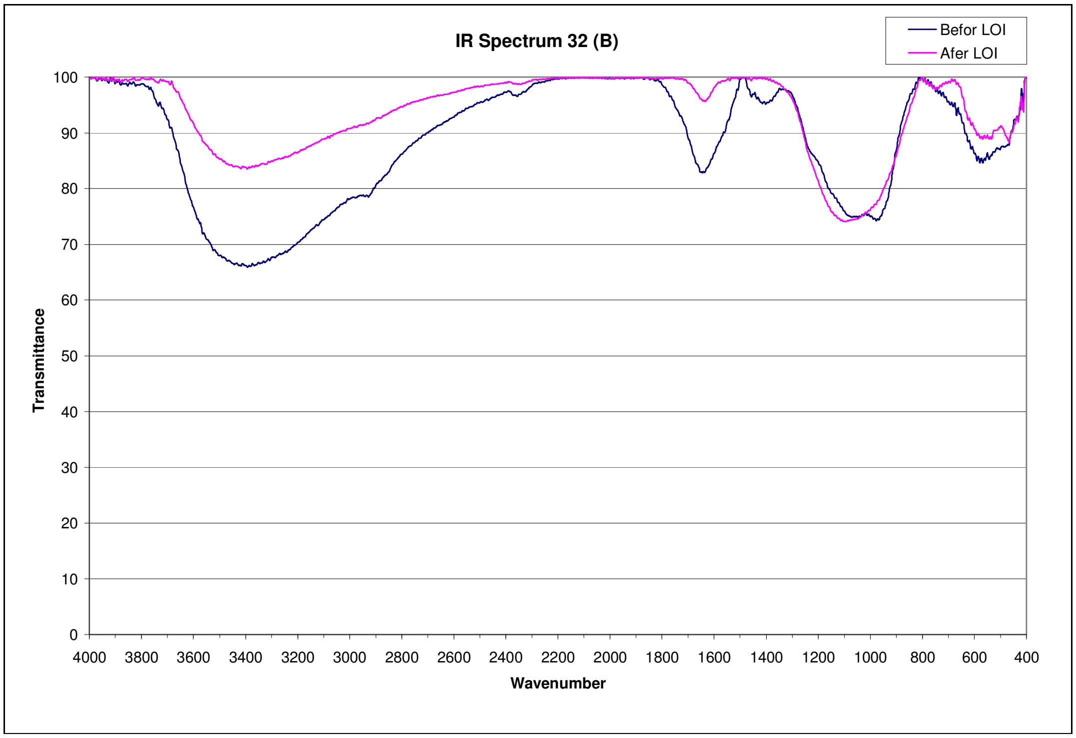
Graph I-14: Typical infrared spectrum from a polar desert habitat.



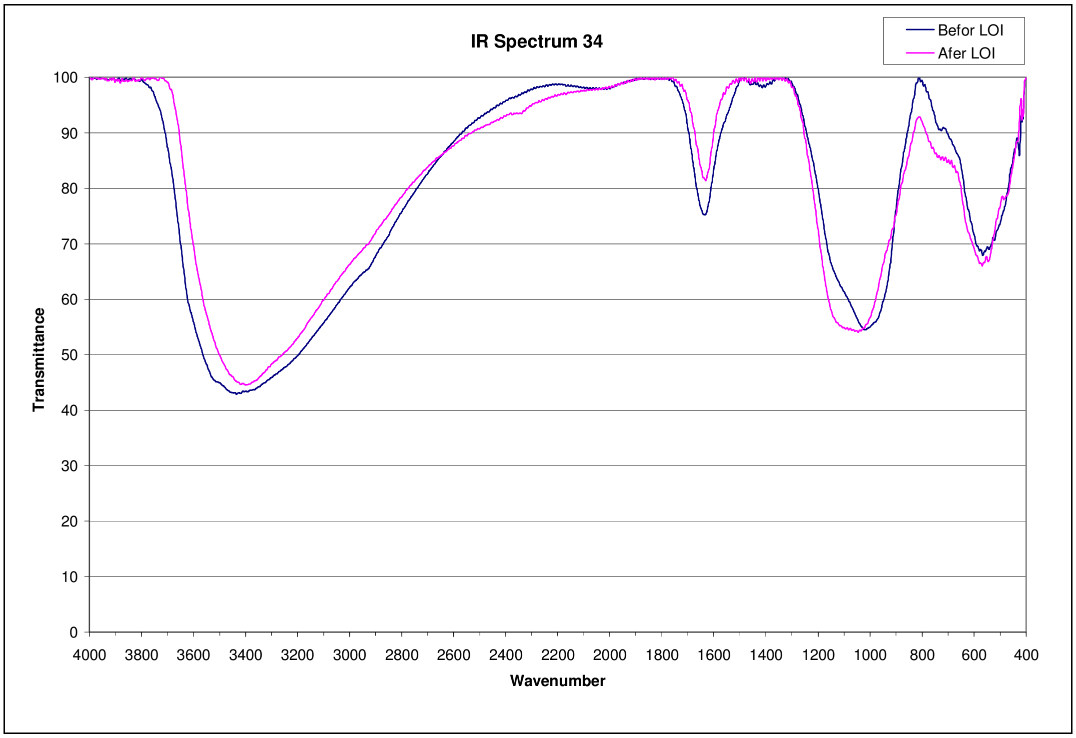
Graph I-15: Infrared spectra of a biotic sample before and after loss on ignition.



Graph I-16: Infrared spectra of a fernbrake sample before and after loss on ignition.



Graph I-17: Infrared spectra of a fellfield sample before and after loss on ignition.



Graph I-18: Infrared spectra of a polar desert sample before and after loss on ignition.

APPENDIX J:

ARCGIS model for creation of soil map

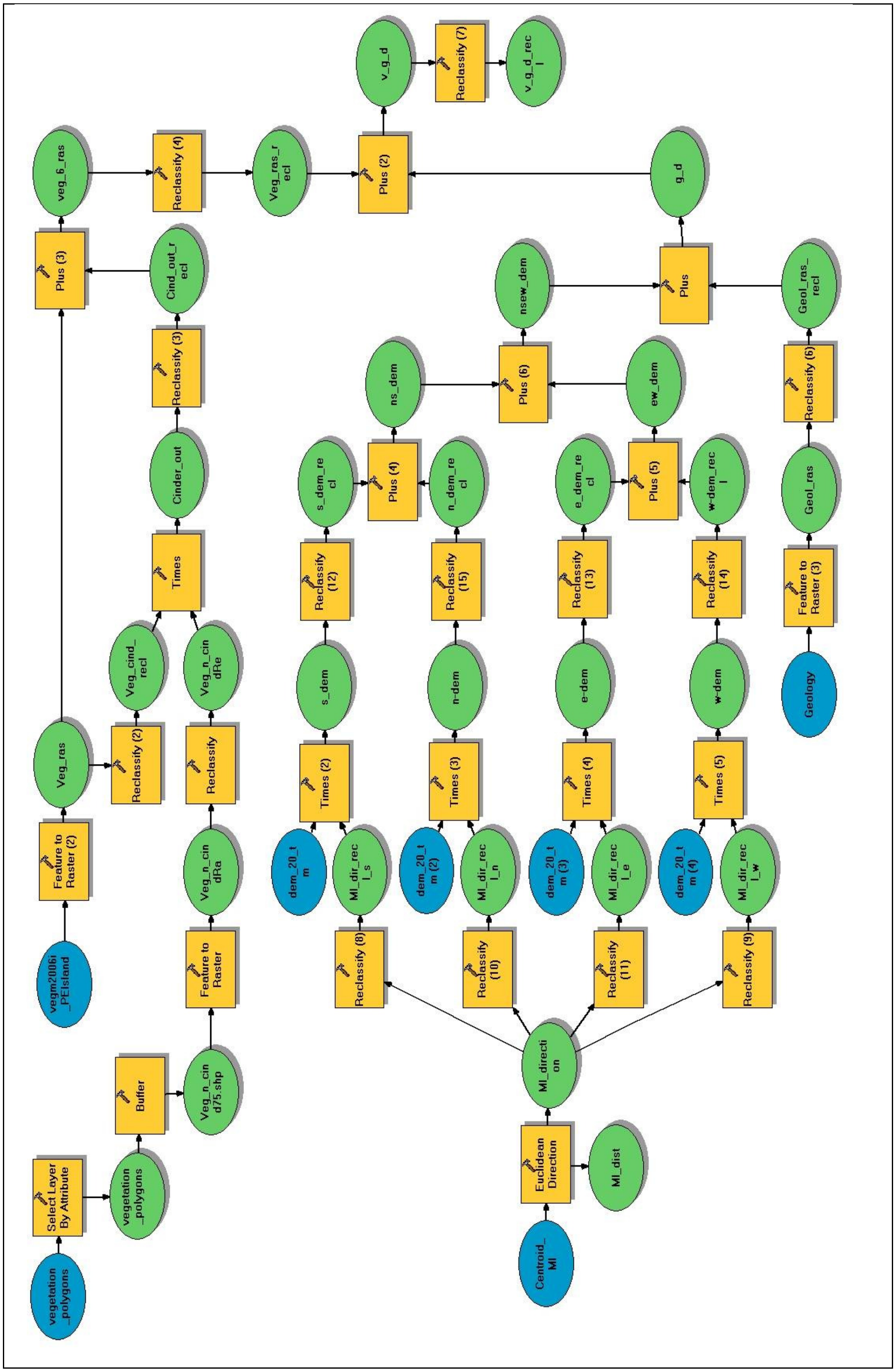


Figure J-1: ARCGIS model used to create the soils map.

APPENDIX K:

Reclassification of composite GIS data for final soils map

Table K-1: Reclassification criteria.

Class	DEM value	Vegetation type	Geology type	Soil class	New class
111	(1) 0-50	Coastal	Black	Histosol	1
112	(1) 0-50	Coastal	Grey	Histosol	1
113	(1) 0-50	Coastal	Scoria	Histosol	1
115	(1) 0-50	Coastal	Rock	Unclassified sediment	5
141	(1) 0-50	Mire/Slope	Black	Histosol	1
142	(1) 0-50	Mire/Slope	Grey	Histic Andosol	2
143	(1) 0-50	Mire/Slope	Scoria	Histosol	2
151	(1) 0-50	Fellfield	Black	Histic Andosol	2
152	(1) 0-50	Fellfield	Grey	Histic Andosol	2
161	(1) 0-50	Polar Desert	Black	Andosol	3
162	(1) 0-50	Polar Desert	Grey	Andosol	3
211	(2) 50-100	Coastal	Black	Histosol	1
212	(2) 50-100	Coastal	Grey	Histosol	1
213	(2) 50-100	Coastal	Scoria	Histosol	1
215	(2) 50-100	Coastal	Rock	Unclassified sediment	5
221	(2) 50-100	Cinder I	Black	Andosol	3
223	(2) 50-100	Cinder I	Scoria	Andosol	3
231	(2) 50-100	Cinder O	Black	Histic Andosol	2
232	(2) 50-100	Cinder O	Grey	Histic Andosol	2
233	(2) 50-100	Cinder O	Scoria	Histic Andosol	2
241	(2) 50-100	Mire/Slope	Black	Histosol	1
242	(2) 50-100	Mire/Slope	Grey	Andosol	2
243	(2) 50-100	Mire/Slope	Scoria	Histic Andosol	2
245	(2) 50-100	Mire/Slope	Rock	Unclassified sediment	5
251	(2) 50-100	Fellfield	Black	Histic Andosol	2
252	(2) 50-100	Fellfield	Grey	Andosol	3
253	(2) 50-100	Fellfield	Scoria	Histic Andosol	2
261	(2) 50-100	Polar Desert	Black	Andosol	3
262	(2) 50-100	Polar Desert	Grey	Andosol	3
311	(3) 100-200	Coastal	Black	Histic Andosol	2
312	(3) 100-200	Coastal	Grey	Histosol	1
321	(3) 100-200	Cinder I	Black	Regosol	3
322	(3) 100-200	Cinder I	Grey	Andosol	3
323	(3) 100-200	Cinder I	Scoria	Andosol	3
331	(3) 100-200	Cinder O	Black	Andosol	2
332	(3) 100-200	Cinder O	Grey	Histic Andosol	2
333	(3) 100-200	Cinder O	Scoria	Histic Andosol	2
341	(3) 100-200	Mire/Slope	Black	Histic Andosol	2
342	(3) 100-200	Mire/Slope	Grey	Andosol	3
343	(3) 100-200	Mire/Slope	Scoria	Andosol	2
345	(3) 100-200	Mire/Slope	Rock	Unclassified sediment	5
351	(3) 100-200	Fellfield	Black	Histic Andosol	2
352	(3) 100-200	Fellfield	Grey	Andosol	3
353	(3) 100-200	Fellfield	Scoria	Andosol	3
355	(3) 100-200	Fellfield	Rock	Unclassified sediment	5
361	(3) 100-200	Polar Desert	Black	Regosol	3
362	(3) 100-200	Polar Desert	Grey	Andosol	3
363	(3) 100-200	Polar Desert	Scoria	Andosol	3
421	(4) 200-500	Cinder I	Black	Andosol	3
423	(4) 200-500	Cinder I	Scoria	Regosol	4

Class	DEM value	Vegetation type	Geology type	Soil class	New class
431	(4) 200-500	Cinder O	Black	Histic Andosol	2
432	(4) 200-500	Cinder O	Grey	Andosol	3
433	(4) 200-500	Cinder O	Scoria	Andosol	3
451	(4) 200-500	Fellfield	Black	Andosol	3
452	(4) 200-500	Fellfield	Grey	Andosol	3
453	(4) 200-500	Fellfield	Scoria	Andosol	3
455	(4) 200-500	Fellfield	Rock	Unclassified sediment	5
461	(4) 200-500	Polar Desert	Black	Andosol	3
462	(4) 200-500	Polar Desert	Grey	Regosol	4
463	(4) 200-500	Polar Desert	Scoria	Andosol	3
465	(4) 200-500	Polar Desert	Rock	Unclassified sediment	5
523	(5) 500-700	Cinder I	Scoria	Unclassified sediment	4
533	(5) 500-700	Cinder O	Scoria	Regosol	4
561	(5) 500-700	Polar Desert	Black	Andosol	3
562	(5) 500-700	Polar Desert	Grey	Unclassified sediment	4
563	(5) 500-700	Polar Desert	Scoria	Regosol	4
565	(5) 500-700	Polar Desert	Rock	Unclassified sediment	5
621	(6) 700+	Cinder I	Black	Unclassified sediment	4
623	(6) 700+	Cinder I	Scoria	Unclassified sediment	4
624	(6) 700+	Cinder I	Polar Desert	Unclassified sediment	4
631	(6) 700+	Cinder O	Black	Unclassified sediment	4
632	(6) 700+	Cinder O	Grey	Unclassified sediment	4
633	(6) 700+	Cinder O	Scoria	Unclassified sediment	4
634	(6) 700+	Cinder O	Polar Desert	Unclassified sediment	4
661	(6) 700+	Polar Desert	Black	Unclassified sediment	4
662	(6) 700+	Polar Desert	Grey	Unclassified sediment	4
663	(6) 700+	Polar Desert	Scoria	Unclassified sediment	4
664	(6) 700+	Polar Desert	Polar Desert	Unclassified sediment	4
665	(6) 700+	Polar Desert	Rock	Unclassified sediment	5