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PERMAFROST PROPERTIES IN THE McMURDO SOUND–DRY VALLEY REGION OF ANTARCTICA

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Abstract

The properties of permafrost at 230 sites in the coastal McMurdo Sound and Dry Valley regions of Antarctica were investigated. The permafrost properties are related to the climate, with the thickness of the active layer and the water content of the permafrost varying according to regional climatic differences. Inland, at colder, drier, locations, ground ice is sporadic and the permafrost at many sites is dry frozen. Study of surfaces disturbed by earth moving construction, and other geomorphic evidence, indicates that ground ice formation in Antarctica is extremely slow. On young surfaces, the salinity of the ground ice is frequently greater than in the active layer and extensive precipitation of salts on the surface may result from soil disturbances. Measurements of climatic parameters and soil thermal properties showed that ground surface albedo and soil salinity strongly influence the soil thermal regime, which in turn determines active layer depth and permafrost properties.

Introduction

Permafrost (i.e. earth material which remains below 0°C continuously for more than two years) is an important feature of ice-free Antarctica and is found in almost all exposed bare ground areas. Bockheim (1995) summarised existing knowledge about Antarctic permafrost and showed that information about its properties and environmental relationships is scarce. In particular, the ice-free Dry Valleys (Figure 1) comprise one of the largest areas of bare ground in East Antarctica, and data about the permafrost here is mainly from a few observations in the 1960's and 1970's (Black, 1973; Cameron and Conrow, 1969).

With growing concern about the effects of increasing human activity in the Antarctic Dry Valleys (Vincent, 1996), along with the possible impacts of global climate change, there is a need for more information about Antarctic permafrost and its relationship to environmental factors. In this paper, results of permafrost investigations in the Dry Valley region of Antarctica since 1990 are summarised.

Landscapes, materials and environments

The ice-free areas of the McMurdo region (Figure 1) comprise a highly complex landscape system influenced by repeated glaciations since Miocene or earlier times. Glacial erosion from either ice sheet invasions or mountain glaciers is negligible, because of extreme cold, and most landscape modification has resulted from subaerial processes. The predominant surface deposits are tills ranging in age from Recent to Miocene. The younger tills usually occur at lower altitudes (Campbell and Claridge, 1978, 1987; Marchant et al., 1993) and near the glacier margins while older deposits are found, mainly, at higher altitudes. On the dominantly moraine covered landscapes, the tills are unconsolidated and bouldery, with a sandy matrix. The <2 mm fraction typically comprises 25–80% of the < 50 mm material. Soil weathering consists essentially of superficial particle oxidation and salinization (Campbell and Claridge, 1987). Weathering is negligible on younger surfaces (<50,000 yrs) but prominent on old surfaces.

The weathering environment is characterised by low temperatures and arid conditions. Mean annual temperatures in the coastal McMurdo Sound region are around –18°C (Bromley, 1994). Summer soil surface temperatures may rise above 0°C , sometimes exceeding 15°C, but there are very few freeze thaw cycles. Inland in the Dry Valleys and the higher mountains, mean annual temperatures are lower (circa –25°C). Maximum summer soil surface temperatures are similar to those in coastal areas but diurnal cooling is greater (Campbell et al., in press).

Precipitation is derived solely from snowfall with heaviest falls near the coast and lowest falls in the Dry Valleys. At Vanda (Figure 1) for example, precipitation (water equivalent) over 20 years averaged 13 mm yr^{-1} but around 100 mm yr^{-1} in nearby upland mountains

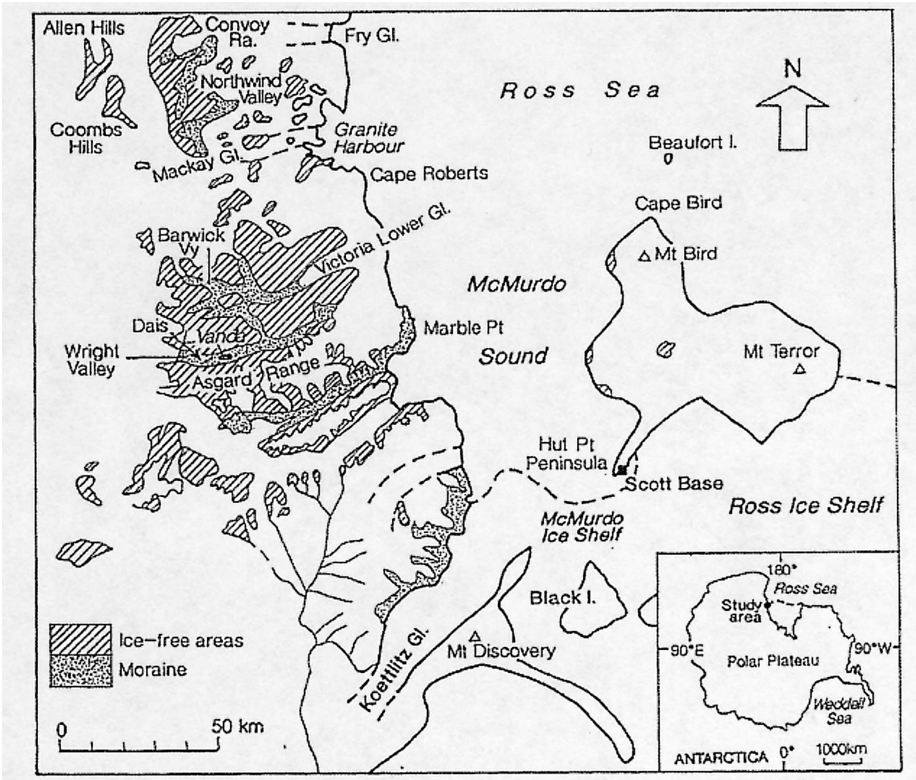

Figure 1. The McMurdo Sound–Dry Valleys region of Antarctica, showing locations noted in the text.

(Chinn, personal communication). Most snowfall is lost, however, either through removal by wind or ablation and little liquid water is therefore available in the soils.

Investigation sites and methods

REGIONAL INVESTIGATION

We investigated the relationship between the permafrost properties and regional climatic differences at various sites in the McMurdo Dry Valley region. The sites investigated included coastal areas bordering McMurdo Sound, mainly at Marble Point and Ross Island; surfaces on the floors and sides of some of the Dry Valleys; and upland surfaces of the higher mountains and the valley systems bordering the Polar Plateau. The areas studied are known to have differing climates in response to altitude and distances from the coast and the interior Polar Plateau (Weyant, 1966; Campbell and Claridge, 1987). Permafrost was investigated on a wide range of surfaces, including typical moraine-covered landscapes, surfaces wetted by summer thaw waters, and raised coastal beaches. Land surfaces with ages ranging from Recent to Miocene (Campbell and Claridge, 1978; Marchant et al., 1993) were studied.

At each of the 230 sites, pits were excavated to the surface of the ice-cemented material, temperatures were measured in the walls of the pit and samples collected. The ice-cemented permafrost was sampled by core drilling. Thaw layer depths were assessed at the time of sampling from temperature measurements. Active layer and permafrost water contents were determined gravimetrically from 1 430 samples that were oven dried shortly after collection. The <2 mm size fraction was determined for all field samples.

PERMAFROST IN DISTURBED TERRAIN

To assess the rate of formation of ground ice, we examined terrain which had been disturbed for aircraft runway construction in the late 1950's at Marble Point (Figure 1). Permafrost in undisturbed ground was compared with permafrost in disturbed ground where fill materials had been placed during the runway construction (Campbell et al., 1994). In addition, at Scott Base on Ross Island (Figure 1), an experiment was established to measure the rate at which water was lost from the permafrost following the removal of the active layer as outlined in an interim report by Balks et al. (1995). The water contents of the active layer and permafrost were compared with those in an adjacent undisturbed area using the neutron probe technique, and soil temperatures to 0.6 m depth were measured with thermocouples. Evaporation rates for disturbed and undisturbed surfaces were measured by weighing small lysimeters.

SOIL MICROCLIMATE AND PERMAFROST

The thermal regimes of one coastal (Scott Base) and two inland mountain (Coombs Hills, Northwind Valley) sites (Figure 1) were each investigated for periods of several days during the 1994/5 summer (Campbell et al., 1998). Measurements included radiation flux densities and albedo, air and soil tempera-

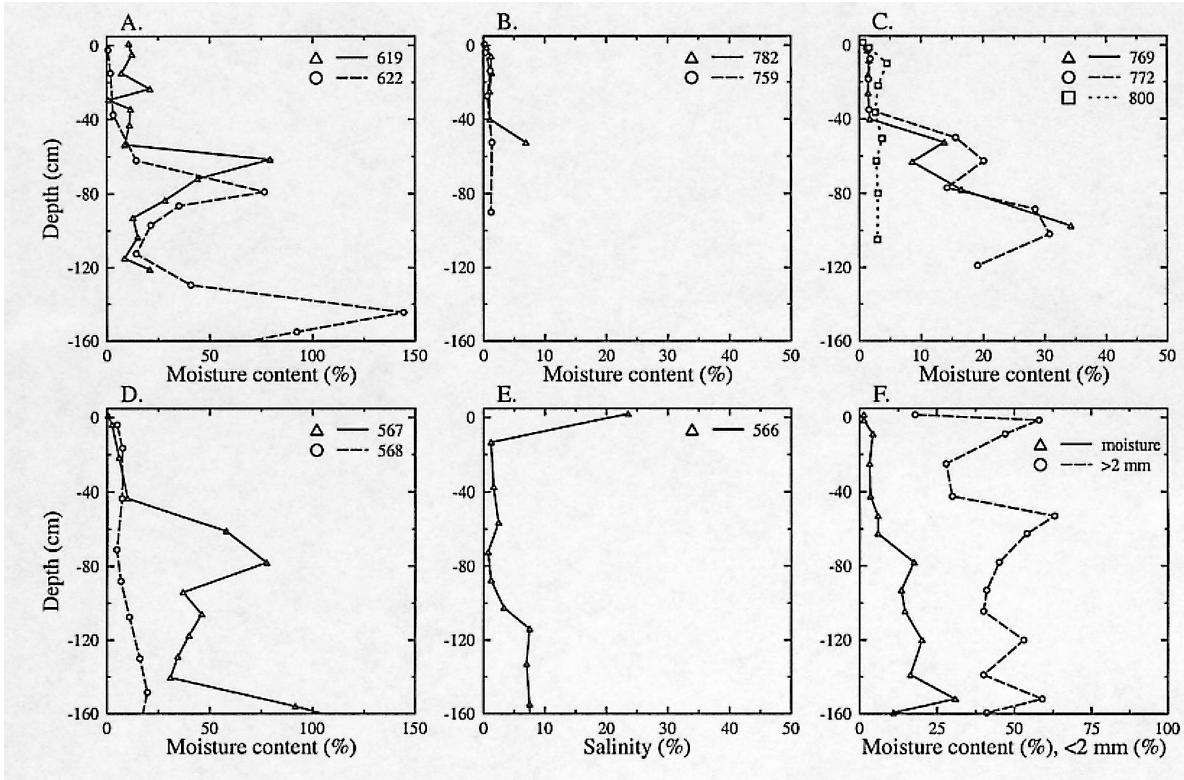

Figure 2. Active-layer and permafrost properties at selected sites in the McMurdo Sound region (see Figure 1 for locations). Note differing moisture content scales. All moisture contents are gravimetric. A. Active layer and permafrost water contents for typical coastal sites: 619 well drained; 622 moist site; B. Active layer and permafrost water contents for Dry Valley sites: 759 dry frozen soil, Wright Valley; 782 ice-cemented permafrost, Barwick Valley; C. Active layer and permafrost water contents for upland sites: 769 dry frozen soil, Beacon Heights; 772 ice cement at depth in permafrost, Beacon Heights; 800 Coombs Hills, maximum moisture content is in salty horizon; D. Active layer and permafrost water contents in disturbed and undisturbed soils at Marble Point: 567 undisturbed soil; 568 fill placed 35 years prior to sampling, over an undisturbed soil; E. Water soluble salts in the active layer and ice-cemented permafrost of a soil at Marble Point; F. Moisture content and percentage of material finer than 2 mm of a soil at Marble Point.

tures, as well as soil physical and thermal properties following the methods described in Campbell et al. (in press).

Results

On moraine-covered landscapes in the coastal McMurdo Sound region, ice-cemented permafrost typically occurs at around 60 cm depth. The active layer water content increases downwards with average values of around 0.5% at the soil surface to 10% at the base of the active layer. In the upper, ice-cemented, permafrost zone, the moisture content is usually much higher, with lesser values at greater depth, although zones with more ice are also present (Figure 2A, soil 622). The average permafrost water content for all coastal sites was 40%. At sites moistened by some summer water flow, the active layer is around 25 cm thick and water contents are higher than at dry sites but permafrost water contents are lower (Figure 2A, soil 619). The shallower depth to permafrost results from the higher amounts of energy required for conversion of ice into water with insufficient energy being available to heat the soil to greater depths.

At sites on the Dry Valley floors, but well away from streams and lake edges, the active layer is around 40 cm thick and the permafrost is typically dry frozen (i.e. has insufficient water for ice cementation of soil particles to occur). The active layer water content is very low, averaging <1%, with similar or slightly higher values in the dry frozen permafrost (Figure 2B).

In the higher upland valleys and mountains, the active layer thickness averages about 10 cm. At many sites, and more especially on older surfaces, the soil is dry frozen and ice cement (i.e. sufficient frozen water to strongly cement soil particles) is generally not encountered within 1–2 m depth (Figure 2C, soil 800). The moisture content of the active layer averages between about 1.5% and 3% with the higher values found in areas where precipitation is greater. Moisture contents in the dry frozen permafrost are similar to those of the active layer. At some sites where ice cement is present, the active layer water contents are similar to those found where ice cement is absent. Moisture contents within the ice-cemented permafrost, however, are generally lower than those found in the permafrost of the coastal regions and the occurrence of the ice cement does not coincide with the upper surface of the permafrost, but commences some distance below it.

At Marble Point where terrain was disturbed by construction activity 35 years previously, the active layer and the permafrost water contents in fill material were the same (Figure 2D, soil 568). The moisture contents of the active layer were similar to those of undisturbed sites (Figure 2D, soil 567) but there was no corresponding water increase in the permafrost in the fill material. On a series of coastal beach ridges at Marble Point dated at up to 6000 yrs old (Nichols, 1968), the moisture contents of the permafrost increased progressively from the lowest to the highest and oldest surface. This, along with the negligible increase in permafrost moisture in the disturbed soils, suggests that the rate of formation of permafrost ice is very slow.

Results of a typical water-soluble salt analyses (Figure 2E) of the active layer and permafrost from a younger land surface showed that salt content is high near the soil surface, and in the ice-cemented permafrost it is higher than in the sub-surface part of the active layer. Similar values were found in permafrost on older land surfaces under a cooler inland climate (Claridge and Campbell, 1985). The results of particle size analyses (Figure 2F) suggest that there is little relationship between the moisture contents of either the active layer or the permafrost and the proportion of <2 mm fraction that is present in the soil.

Following the removal of the active layer at the Scott Base experimental site in December 1993, the newly exposed ice-cemented permafrost warmed rapidly, causing melt-out and surface subsidence. Active layer depth was re-established within a period of days, however volumetric moisture contents were much higher (30–50%) than in the active layer of the undisturbed site (10–25%). Evaporation rates up to 3 mm d^{-1} were measured for the disturbed surface, while the dry undisturbed surface had negligible evaporation (Balks et al., 1995). After one year, volumetric soil moisture contents of the new active layer in the disturbed site had decreased by 5–10%, compared to negligible changes in the undisturbed site. After two years the disturbed surface had subsided by an average of 8.6 cm due to melting and loss of ground ice.

The active layer depth and soil thermal behaviour are determined by soil physical properties and the radiation and climatic environment. Soil albedo is the most important surface factor affecting the availability of energy for soil warming in summer. The greatest heating was found on dark-coloured basalt and dolerite surfaces (Scott Base and Coombs Hills respectively), where albedos were approximately 6%, and the least heating was found on a light coloured sandstone soil (Northwind Valley) with an albedo of 26% (Figure 3A). The presence of even a thin snowpack in summer markedly reduces soil heating because of the increased albedo.

Maximum soil surface temperatures are primarily radiation-controlled, so that summer temperatures above 0°C can occur in all climate zones where there are bare surfaces. Minimum temperatures are, in contrast, strongly linked to air temperature, hence the greatest ranges of soil surface temperature are found in the highest and coldest environments.

Soil salinity appears to play an important role in determining both the type of permafrost (ice-cemented or non ice-cemented) and the thickness of the active layer. At the coastal Scott Base site where the soil soluble salt content was 0.52% and volumetric soil moisture content was 6%, the soil became ice-cemented just below 0°C. Phase changes of soil water are accompanied by the release and uptake of latent heat energy, which has a very conservative influence on soil tempe-

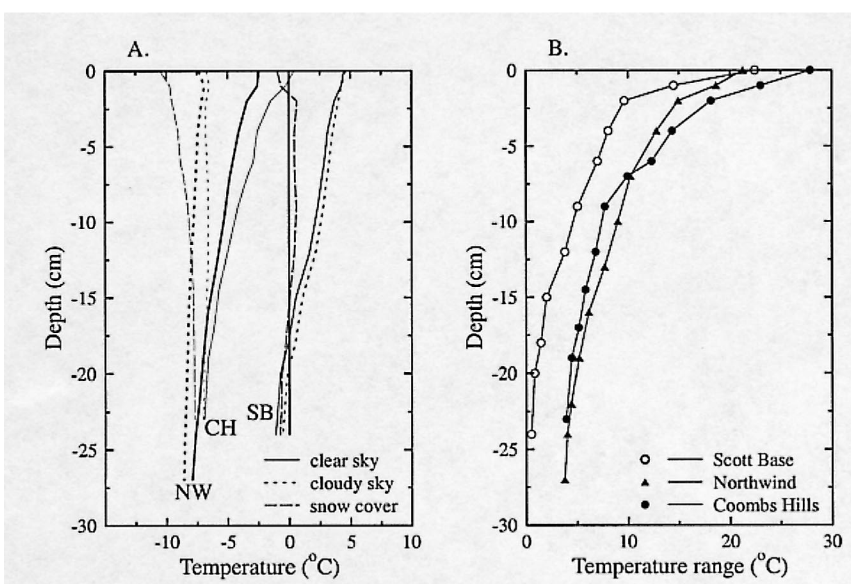

Figure 3. Thermal regimes of soils at three sites during January 1995. A. Mean daily temperatures for a range of conditions at Coombs Hills (CH), Northwind Valley (NW) and Scott Base (SB); B. Diurnal ranges (max–min) temperatures versus depth for clear-sky days.

rature variations. Hence the summer soil thermal regime was shallow and diurnal temperature variations damped out at the base of the active layer, coinciding with the top of the ice-cemented zone, at about 24 cm depth (Figure 3B). In contrast, the two upland sites, with saline soils (soluble salt contents of 8% and 10.5% and volumetric soil moisture contents of 3% and 4% respectively) had no shallow ice-cement in the permafrost zone, and diurnal temperature variations continued to a much greater depth than at the non-saline site (Figure 3B). The higher salt content causes the freezing point of the soil solution to be depressed, and to occur across a wide range of temperatures, an observation which is supported by laboratory measurements by Anderson and Tice (1989).

Discussion and conclusions

The results clearly show that the thickness of the active layer and the moisture content of the permafrost are related to regional climate. The active layer is deepest in the coastal areas where climate is warmest and very thin in the colder inland and upland regions. Moisture contents in both the active layer and the permafrost are greatest in the coastal region where there is more precipitation and lower inland where precipitation is less. However, there is considerable variation from site to site due to differences in energy receipt, air temperature and salinity. The amount of energy available for soil heating is closely linked to albedo which is, in turn, influenced by surface factors including aspect, ground texture, surface colour, rock polish and snow cover.

The absence of ice-cement in permafrost in many Dry Valley sites is probably a reflection of the climatic conditions which include extremely low precipitation and persistent katabatic winds. On the other hand, the absence of ice-cement in many of the other inland sites is less readily explained but may sometimes be related to site age or windiness. Analyses of field data from sites from the Dry Valley region and along the Trans-Antarctic Mountains showed that ice-cemented permafrost is nearly always present at shallow depths on young surfaces, but it is frequently not found at depths of up to 2 m on very old surfaces that lack patterned ground features. The proximity of surfaces of different ages with differing permafrost properties suggests that slow desiccation, perhaps combined with increasing salinity may account for these differences.

The experimental work showed that there is a quick response to soil disturbance with a rapid loss of permafrost water and precipitation of salts at the soil surface. However, judged from human disturbances and geomorphic evidence, the rate of accumulation of water in permafrost appears to be very slow. It is likely that the greatest impacts of global climate change in the McMurdo oasis will be experienced on the younger soils of the coastal regions which have the highest permafrost moisture contents.

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