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Thermokarst landforms in the Transantarctic Mountains region of Antarctica

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ABSTRACT: Thermokarst terrain occurs in numerous places in the Transantarctic Mountains region and some examples are described. Thermokarst terrain is typically associated with the tills of young moraines near stagnant or retreating glacial ice. The largest known area is an occurrence in McMurdo Sound of around 1000 km^2, known as the "dirty ice". The landforms in this locality have resulted from ablation of anchor ice containing shallow sea floor sediments. Thermokarst terrain is also found in some glacial valleys where distinctive knob and kettle topography has formed due to recent ablation of stagnant glacial ice. Adjacent to US and NZ bases on Ross Island thermokarst landscapes have formed because of human disturbance in areas where massive ice and ground ice are present. Removal of the active layer in an experimental area near Scott Base showed that water loss from the permafrost soon occurred with ground shrinkage and subsidence continuing for 7 years.

1 INTRODUCTION

Landscapes of the Transantarctic Mountains region are of considerable interest since they span timescales extending to before the Miocene (Campbell & Claridge 1978, Marchant et al. 1993) and provide important evidence of the glacial history since that time. Some very old glacial tills are underlain at depths of <1 m by massive ice (Claridge & Claridge 1968, Sugden et al. 1995) that is assumed to be stagnant glacial ice. These occurrences raise interesting questions regarding the capacity for ancient massive ice to survive for long periods and the possibilities that old land surfaces may have been modified by thermokarst processes.

In the Transantarctic Mountains and Ross Sea region, late Last Glaciation and younger landscapes are predominantly found in coastal locations following retreat of ice from the Ross Glaciation, a former massive ice expansion of the present Ross Ice Shelf. Thermokarst features occur widely in the McMurdo Sound region but have not specifically been identified as thermokarst by some workers. Healy (1975) pointed out their thermokarst origin and described their role in landform development.

Most of the established bases in the Ross Sea region are located in these younger landscapes where there is a greater likelihood for the occurrence of massive ice and thermokarst formation. Since the Antarctic Treaty forbids significant human disturbance to the ntarctica environment, an understanding of thermokarst formation in younger landscapes is important.

In this paper, we discuss examples of thermokarst landforms and consider their significance.

2 THERMOKARST LANDFORMS

2.1 *The dirty ice*

The largest area of thermokarst terrain in the Transantarctic Mountains region occurs at the southern end of McMurdo Sound between the Ross Ice Shelf and the Koetlitz Glacier where several ice masses form a complex floating glacier system. As described by Keys (1990), surface ablation of the floating ice is compensated for by growth of sea ice on the underside. The central portion of this zone is marked by an extensive area of till with a strong linear pattern of sediments and melt pools. Here, ice is apparently formed on the sea floor as anchor ice. As surface ablation continues, the anchor ice rises, carrying sediment frozen into the ice from the sea floor. The sediments, which include large amounts of rock debris and much marine organic material, accumulate at the surface and are redistributed, forming a myriad of hillocks and ponds as surface ablation continues.

Due to the complicated interactions between the marine and non-marine ice forming the "dirty ice" there is a very large diversity in the local environmental conditions. Some of the ponds, for example, are fresh water from local thaw waters; others vary from slightly saline to highly saline while some are tidal. The ponds of this area have an extremely large concentration of organisms supporting a variety of cyanobacterial and diatom dominated communities (Howard-Williams et al. 1990).

As "the dirty ice" landscape is intimately related to the marine environment, the continuation of this thermokarst landscape is likely to be closely related to future sea level rise and sea temperature warming and the likelihood of ice shelf break up.

2.2 *Glacial valley thermokarst*

The glacial valleys of the Transantarctic Mountains are part of a landscape system that has evolved through glaciations since the Late Oligocene or Miocene (Armstrong 1978, Campbell & Claridge 1978, 1987, Denton et al. 1993, Marchant et al. 1993). The major glaciers flowing into the Ross Ice Shelf are outlet glaciers from the Polar Plateau, commonly flowing at 1000 to 1500 metres below adjacent ice-free plateau type landscapes (Fig. 1).

These high level surfaces have very old weathered soils that are believed to date from least from the Early Miocene (Claridge & Campbell 1967, Campbell & Claridge 1978) and represent an early phase of Antarctic glacial history. Evidence for later glacial episodes is found on lower lying valley surfaces. On some of these surfaces, there is unequivocal evidence of ice having advanced up the valleys from the direction of the Ross Ice Shelf (Nichols 1961, Calkin & Bull 1972, Campbell and Claridge 1987). These up-valley ice advances are attributed to periodic ice shelf grounding resulting from fluctuating sea level. The ice drainage reversals from lowered sea level have caused ice to flow back into valleys that in many cases were previously dry. With later sea level rise and thinning of the West Antarctic Ice Sheet, ice levels in the valleys lowered and in some side valleys ice became stranded. Thermokarst topography has developed on some of these stranded ice masses as ablation has proceeded (Fig. 1).

Figure 1. Thermokarst in Thousand Lakes Valley, a stagnant lobe of the Hatherton Glacier. Fluted lower slopes are around the landward edge of the knob and kettle terrain. The plateau surface above has Miocene aged soils.

2.2.1 *Example 1, La Gorce Mountains*

In the La Gorce Mountains near the head of the Scott Glacier, (Latitude 86°32′S, altitude 1650 m) a thermokarst landscape was observed forming during the initial stages of till accumulation from ablating stagnant ice. This area has a very cold inland climate. At the glacier margin, the clean ice surface passes into scattered rocks, then with increasing distance from the glacier and with an increasing till cover (around 5 cm) hummocky patterned ground was formed. The patterned ground cracks were formed entirely within the stagnant glacial ice. A few scattered frozen melt pools were also present.

2.2.2 *Example 2, Cox Peak*

In this area at a lower elevation in a side valley of the Scott Glacier (Latitude 86°02′S, altitude 1150 m), stagnant up-valley ice is ablating at a point where it was earlier joined with the local valley-head alpine glacier (Fig. 2). The thermokarst terrain here comprises a strongly undulating and hummocky terrain in fresh

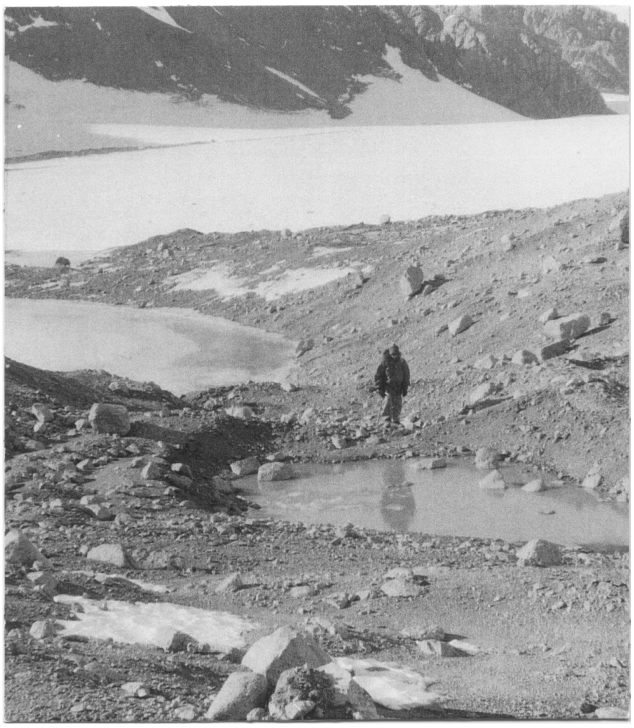

Figure 2. Part of an extensive area of thermokarst in the Cox Peaks area of the Scott Glacier. Slump scarps are on the left side of the pond.

unweathered till with numerous melt pools and kettle holes. Larger pools may remain frozen except for a moat, but smaller pools become ice-free. The dynamic nature of the thermokarst landscape here was indicated by the variety of pool sizes, slump features, dirt cones present and active thawing that was observed. The dirt cones (Campbell & Claridge 1975) are formed from weakly stratified accumulated pond sediments that have persisted as sediment mounds while landscape lowering by ablation and ice thaw was continuing.

2.2.3 *Example 3, Hatherton Glacier*

The Hatherton Glacier (Fig. 1) is a branch of the Darwin Glacier and is a good example of the re-occupation of former ice-free valleys due to ice shelf thickening and up-valley back flow of ice during periods of lower sea level. With the subsequent lowering of the Ross Ice Shelf and the Darwin and Hatherton Glaciers at the end of the Ross Glaciation, ice in some of the side valleys stagnated and ablation at the ice margins resulted in the formation of areas of thermokarst terrain (Fig. 1). In The Thousand Lakes Valley (Latitude 79°58′S, altitude 1000 m), the landscape comprises a myriad of frozen pools, up to 100 m across and separated by ridges and hillocks up to about 15 m high. The soils on this terrain are unweathered and appear to be of recent age. Many of the lakes thaw for a short period in summer. At the landward margin of this intensively pock marked terrain, the lower steep slopes of the adjacent land surface are in some places strongly fluted and underlain by massive ice, which is assumed to be residual stagnant glacier ice. This fluted topography is thought to represent land surface adjustment, primarily by retrogressive sliding, as the thermokarst landscape in the adjacent embayment lowered through ablation of the stagnant ice body.

2.2.4 *Example 4, Koetlitz Glacier*

During the Last Glaciation, the West Antarctic Ice Sheet expanded into the Ross Sea and ice from the Ross Glaciation reached about 1000 m altitude in the McMurdo Sound region. Ice also entered the adjacent Taylor and Wright dry valleys. When sea level rose, the West Antarctic Ice Sheet shrank and the Ross Ice Shelf was formed. In some areas adjacent to the Ross Sea and the Ross Ice Shelf, remnants of the former expanded West Antarctic Ice Sheet remain. One such area lies to the northwest of the Koetlitz Glacier at Walcott Bay (Fig. 3). Here, a number of small ponds are formed on a till covered bench like surface in massive ice, about 100 m above the Koetlitz glacier. The massive ice was observed in the bottom of some of the ponds and also along the upper slopes of a steep escarpment (Fig. 3) where retrogressive thaw slumping was taking place.

Figure 3. Thermokarst at Walcott Bay. The Koetlitz Glacier is to the right. Retrogressive slumping and exposures of massive ice are visible on the slopes in the distance. Material in the foreground is slump debris.

3 HUMAN ACTIVITY INDUCED THERMOKARST

The most extensive area of land occupied by human activity occurs at the southern end of Ross Island in McMurdo Sound where the U.S. McMurdo Station and N.Z Scott Base are located. In the late 1950s and 1960s, extensive active layer scraping of hilly land immediately north of McMurdo Station took place to provide earth material for roads and building site constructions. Some of this hilly land (Fig. 4) was underlain by massive ice, probably residual ice from the earlier Ross Glaciation ice that occupied the Ross Sea. A thermokarst landscape comprising hillocks, slump features and stream channels soon developed on this terrain (Fig. 4) and have been observed by us since 1964. Although removal of the active layer for soil material ceased in this area in the 1980s, land surface instability has continued and has been accompanied by appreciable summer thaw water run off. In some places, extensive surface precipitation of soluble salts ensued. Fuel pipelines and some other structures on this terrain have been re-sited because of the land instability.

In 1990, holes drilled to 1.2 m at a number of sites were found to have massive ice underlying the active layer that ranged from 10–30 cm in thickness. At one location, we also observed massive stratified ice in an erosional cirque that had formed by retrogressive thaw slumping.

Figure 4. Thermokarst terrain at McMurdo Station, southern Ross Island in 1983. Renewed ground scraping triggered extensive land surface instability with ongoing earth movement thaw runoff and salinization. Permafrost scraping is visible on hill slopes beyond.

Other areas of land in the vicinity of McMurdo and Scott Base Stations were also extensively scraped for earth material. However, as most of this land is underlain by ground ice that is typically in lenses or wedges in the permafrost cracks, the soils are not subject to large scale mass movements. Subsequent to the removal of surface soil materials however, there has been extensive ground shrinkage, and because of a greater water loss from the ice wedges, hummocky patterned ground or thermokarst mounds have developed.

4 EXPERIMENTAL DISTURBANCE

In January 1994 (the middle of the Antarctic summer), a field experiment to assess the rate at which water was lost from the permafrost following removal of the active layer was commenced near Scott Base (Balks et al. 1995). A bulldozer was used to remove the 30 cm thick active layer over a 30 m^2 area at the site. Seven neutron probe access tubes were then installed to approximately 1 m depth in permafrost. Neutron probe access tubes were also installed to a similar depth in the permafrost at the adjacent undisturbed area. Observations showed that permafrost thaw and water loss in the disturbed area began immediately and that some loss continued over the succeeding winter months and continued during the following summer. Subsequent indications of the effects of the initial ground disturbance have been derived from periodic ground shrinkage measurements made alongside the neutron probe access tubes. In December 1995, almost two years after the active layer removal, the average ground shrinkage measured at the 7 tube sites was 8.8 cm. The average ground shrinkage value increased to 10.6 cm by January 1998, 11.5 cm in January 1999 and 11.6 cm by December 1999. In December 1999, ground shrinkage variation at the tube sites ranged from 5.2 cm to 19.5 cm.

5 DISCUSSION

The examples outlined here illustrate that thermokarst terrain can form under a variety of environmental conditions in the Transantarctic Mountains region of Antarctica. In the most southerly area observed, approximately 350 km from the South Pole, thermokarst was limited to low hummocky terrain with a few small pools. The very cold climate here restricts the amount of thermal energy available for soil warming, ice thaw and sediment resorting. At lower altitude in the Robert Scott Glacier where temperatures are much warmer, soil heating results in greater thawing of underlying stagnant ice and landscape reworking is active. In the Thousand Lakes Valley, an area with a climate warmer than the Cox Peaks region, the multitude of thaw pools probably indicates even warmer soil temperatures. The adjacent fluted surfaces give an indication of the extent to which the stagnant ice may have thinned by ongoing ablation of the former stagnant ice body. At Walcott Bay, the exposure of ice and retrogressive thaw slumping may partly be related to recent lowering of ice levels in the adjacent Koetlitz glacier.

It is possible that the thermokarst in the glacial valleys may have formed in response to gradual or recent climatic change in the Transantarctic Mountains. However, in the absence of long-term climate data or materials for dating, no firm inferences can be drawn.

The thermokarst landforms induced by human activity adjacent to McMurdo Station clearly indicate the sensitivity of Antarctic terrain to human disturbance especially where massive ice is present. The initial disturbance by ground scraping soon resulted in the formation of hummocky ground. After renewed ground scraping in the early 1980s, accelerated thaw and retrogressive slumping resulted in very active land instability and stream flow with extensive salt precipitation on some surfaces. With the absence of significant soil disturbance since, a very hummocky thermokarst landscape has formed. Areas of scraped ground underlain by ground ice had developed hummocky patterned ground 5 years after the active layer removal.

6 CONCLUSIONS

Thermokarst landforms occur in numerous places in the Transantarctic Mountains region and the degree of development appears to be related to the local climatic and soil thermal conditions. These occurrences are an indication of disequilibrium in soil thermal conditions and may be an indication of late glacial climate change. Increased temperatures in the region are likely to result in further thermokarst development.

Human disturbance on land surfaces underlain by massive ice and ground ice soon results in the formation of thermokarst landforms, with the ground instability continuing until thermal equilibrium has been reached.

REFERENCES

Armstrong, R.L. 1978. K-Ar dating: Late Cenozoic McMurdo Volcanic Group and dry valley glacial history, Victoria Land, Antarctica. N.Z. Journal Geology & Geophysics 21 (6): 685–698.

Balks, M.R., Campbell, D.I., Campbell, I.B. & Claridge, G.G.C. 1995. Interim results of 1993/94 soil climate, active layer and permafrost investigations at Scott Base, Vanda Station and Beacon Heights, Antarctica. University of Wai kato Antarctic Research Unit Special report No. 1 Hamilton, New Zealand.

Calkin, P.E. & Bull, C.1972. Interaction of the East Antarctic Ice Sheet, alpine glaciation and sea level in the Wright Valley area, southern Victoria Land. In R.J. Adie (ed.), Antarctic Geology and Geophysics. Universitetsforlaget, Oslo. 625–673.

Campbell, I.B. & Claridge, G.G.C. 1975. Occurrence of dirt cones in Antarctica (Note). N.Z Journal of Geology & Geophysics. 18 (2): 349–355.

Campbell, I.B. & Claridge, G.G.C. 1978. Soils and Late cenozoic history of the Upper Wright valley area, Antarctica. NZ Journal of Geology and Geophysics 21 (5): 635–643.

Campbell, I.B. & Claridge, G.G.C. 1987. Soils, weathering processes and environment. Elsevier Science Publishers, Amsterdam.

Claridge, G.G.C. & Campbell, I.B. 1968. Soils of the Shackleton Glacier region, Queen Maud Range, Antarctica. New Zealand Journal of Science 11 (2): 117–218.

Denton, G.H., Sugden, D.E., Marchant, D.R., Hall, B.L. & Wilch, T.I. 1973. East Antarctic Ice Sheet sensitivity to Pliocene climatic change from a Dry Valleys perspective. Geografiska Annaler 75A (4): 155–204.

Healy, T.R. 1975. Thermokarst – a mechanism of de-icing ice- cored moraines. Boreas 4: 19–23.

Howard-Williams, C., Pridmore, R., Broady, P. & Vincent, W.F. 1990. Environmental and biological variability in the McMurdo Ice Shelf ecosystem. In K. Kerry & G. Hempel (eds.), Ecological change and conservation of Antarctic ecosystems. Springer Verlag. Berlin. 23–31.

Keys, J.R. 1990. The ice forms. In T. Hatherton (ed.), Antazrctica the Ross Sea Region. DSIR Publising, Department of Scientific & Industrial Research, Wellington, New Zealand. 118–136.

Marchant, D.R., Denton, G.H., Sugden, D.E. & Swisher, C.C. 1973. Miocene glacial stratigraphy and landscape evolution of the western Asgard Range, Antarctica. Geografiska Annaler 75A (4): 303–330.

Nichols, R.L. 1961. Multiple glaciation in the Wright Valley, McMurdo Sound, Antarctica. Abstracts of Symposium Papers, Tenth Pacific Science Congress, Honolulu. 317.

Sugden, D.E., Marchant, D.R. & Potter, N. 1995. Preservation of Miocene glacier ice in East Antarctica. Nature 376: 412–414.