A polar paradise: the glaciation of South Victoria Land, Antarctica

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CHAPTER 5: COLD-BASED GLACIER ADVANCE IN THE ALLAN HILLS, SOUTH VICTORIA LAND, ANTARCTICA: EVIDENCE AND PRESERVATION POTENTIAL

Abstract

New evidence is presented from the Allan Hills, South Victoria Land, Antarctica that confirms cold-based glaciers are capable of erosion, substrate deformation and deposition. Four types of erosion, three types of deposition and three scales of glacitectonism resulting from cold-based glacial advance are described, and a model derived from these observations and those of advancing cold-based glaciers elsewhere. The model entails: (i) ice block apron overriding and entrainment and (ii) ice-bed separation leading to the formation of a cavity on the down-glacier side of escarpments. The model is most effective for a horizontally stratified, lithified sedimentary bedrock substrate. The preservation potential for cold-based glacial features is high in polar climates (e.g. Antarctica) but is very low beyond on account of the more rapid weathering in sub-polar or temperate climates. This explains the perceived absence of cold-based glacial features in the Pleistocene record of today’s temperate regions that most likely experienced cold-based glaciation during past glacial maxima.

1. INTRODUCTION

The interface between glacier ice and the underlying substrate has attracted considerable interest over recent years, following general acceptance that processes operating at the base of glaciers and ice sheets affect their behaviour (Boulton and Jones, 1979; Engelhardt and Kamb, 1998; Hooke et al., 1992). However, the vast majority of these studies have focused on warm, wet-based ice masses, in particular the ‘deformable bed’ (e.g. Hart and Rose, 2001). Very few studies have addressed the behaviour of cold-based glaciers and ice sheets. This is because of the universally held assumption that basal sliding, abrasion and bed deformation do not take place beneath cold-based ice (Boulton, 1972; Hubbard and Sharp, 1989; Holmlund and Näslund, 1994; Näslund, 1997) and that consequently,
relict features (and therefore 'older' landscapes) are actually protected beneath cold ice. (Falconer, 1966; Bergsma et al., 1984; Sugden et al., 1991; Kleman, 1994; Stroeven and Kleman, 1999; Kleman and Hättestrand, 1999; Clárhall, 2002; Näslund et al., 2003).

As Waller (2001) states, “a growing body of field evidence suggests that basal processes may remain active beneath cold-based, ice masses”. Such evidence is cold-based glacier basal sliding at $\approx -5^\circ C$ (Echelmeyer and Zhongxiang Wang, 1987) and $-17^\circ C$ (Cuffey et al., 1999), as well as entrainment (Cuffey et al., 2000) and cold-based glacier ductile and brittle deformation of entrained debris (Fitzsimons, 1996a; Fitzsimons et al., 1999; Bennett et al., 2003). Additionally, evidence from Quaternary, glacial environments (Broster and Claue, 1987) such as ductile deformation in permafrost of Pleistocene age (Astakhov et al., 1996) have been reported.

The purpose of this chapter is to develop further the model outlined in Atkins et al., (2002) and provide more comprehensive documentation of cold-based features found in central Allan Hills, Antarctica (Fig. 1A-C). We also discuss the preservation potential of these features, so as to provide criteria for the recognition of cold-based glaciation elsewhere.

2. **THE ALLAN HILLS**

The Allan Hills (76°43' S, 159°40' E) are a low lying nunatak located high in the Transantarctic Mountains (TAMS) of South Victoria Land (1600-2100 metres above sea level or masl; Fig. 1A-C). The annual ablation rate for ice in the Allan Hills is 4-5 cm$\text{w}^{-1}$ and much of the surrounding ice is stagnant (Annexstad and Schultz, 1982). Mean annual air temperature (MAAT) of the region is $-30^\circ C$ (Robin, 1983).

The centre of the nunatak is occupied by the Manhaul Bay Glacier (informal name), which is approximately 6km long and 200m thick, with basal temperatures of $\approx -24^\circ C$ (Atkins et al., 2002), and which flows into the centre of the Allan Hills from the north. Currently, the Manhaul Bay Glacier is retreating by sublimation (Atkins et al., 2002) and exposed areas of its snout are bubble rich and fractured (Fig. 2; Lloyd Davies and van der Meer, 2001) suggesting former glacier advance by ice block apron
Cold-based glacier advance in Antarctica

Fig. 1 The Allan Hills.
A. Location of the Allan Hills, within South Victoria Land, Antarctica.
B. The shape of the Allan Hills, showing the respective positions of Mount Watters (highest point in the Allan Hills, 2123 masl), the Manhaul Bay and Odell Glaciers as well as contemporary ice flow direction (black arrowheads).
C. View of Allan Hills from the south-east. Ice from the South Polar Plateau (left) is here deflected north before flowing east toward the Ross Sea (right). Thick arrows indicate contemporary ice flow direction for the Manhaul Bay and Odell Glaciers.

overriding (Shaw, 1977a). Bordering the eastern Allan Hills is the Odell Glacier, which flows from south-west to north-east, between the Allan and Coombs Hills. It is about 20km long and also estimated at around 200m thick, from which we conclude that it too is cold-based.

The geology of the Allan Hills largely comprises sub-horizontal Permian and Triassic sandstones, carbonaceous siltstones and coal measures of the Beacon Supergroup. These are intruded by sills and thin dykes of Jurassic Ferrar Dolerite (Ballance and Watters, 1971), as well as bodies of a co-eval Mawson Formation, a volcanic explosion breccia, in the west and southern parts of the nunatak. Central Allan Hills also includes several thin (>10m thick) patches of Sirius Group tillite totalling around 2km² in area (Atkins and Barrett, 2001; Holme, 2001). These deposits record extensive wet-
based glaciation at least 2 million years ago, based on cosmogenic dating of boulder surfaces in the Sirius (Tschudi, 2000), but more likely at least 15 million years ago, based on the studies of landscape evolution of the Dry Valleys region (Summerfield et al., 1999). Strike and dip measurements of glacitectonised bedrock (thick arrows in Fig. 3) demonstrate that flow directions of the older glacial event which deposited the Sirius tillite were quite different from the flow directions of the Manhaul Bay and Odell Glaciers today.

The shape of the Allan Hills and details of many recent glacial features are shown in a geomorphological map (Fig. 3) based on spot observations from four field seasons (1997-2001). They were described and photographed in the field, the locations being recorded by GPS or compass triangulation. Aerial photographs and a Topcon© stereoscope were also used to confirm sight lines to certain features such as isolated boulders or boulder trains. The dominating feature is the stepped relief decreasing in elevation towards the lobes of the Manhaul Bay and Odell Glaciers. Other significant features include Trudge Valley in central eastern Allan Hills, which is over 1km long and nearly 1km wide, its eastern end terminating at the Odell Glacier. Minor but locally significant features are two dolerite dykes, one aligned north-west to south-east across central Allan Hills, and the other, north-south (Fig. 3). Two canyons, containing ‘dry’ fluvial channels, mark the ends of Trudge Valley on the south side (Lloyd Davies and van der Meer, 2002). Parallel crested ridges of possible aeolian origin cover large areas of floors and sides of valleys within Allan Hills and are found in clusters oriented east-west. They range from a few metres long and centimetres high, to over 200 metres long and nearly 4 metres in height.
Fig. 3  Geomorphological map documenting the full range of cold-based erosional, depositional and glaciectonic features observed in the Allan Hills to date. (See enlarged colour version of map on pages 280-281 for a clearer viewing.)
3. COLD-BASED FEATURES AT ALLAN HILLS

Erosional, depositional and especially deformational features attributed to the presence of cold-based glacier flow are found most commonly on exposed platforms of Beacon bedrock, but are also found superimposed upon Sirius tillites or Beacon bedrock thought to be initially tectonised by Sirius glacial event(s). The main erosional and depositional features have been described by Atkins et al., (2002), and are summarised in Tables 1 and 2. These are briefly reviewed and additional observations are presented, with an emphasis on the glacitectonic evidence, as these structures are particularly common and well-preserved.

3.1 Erosion

The four types of cold-based glacial erosional features (Table 1) are primarily the result of abrasion of the Beacon bedrock surface and the upper surface of Sirius tillite. All have a ‘fresh’ appearance, whether exposed, protected beneath debris or superimposed upon older material. Those directly exposed on bedrock (see Fig. 4A-B for types I and II respectively) are only found close to the current snouts of the Manhaul Bay and Odell Glaciers, whereas types III and IV (Fig. 4C-D respectively) are found more widely throughout the Allan Hills. For example, type III has been observed as thin fresh scratches oriented north-south on weathered dolerite boulders embedded within Sirius tillite (Fig. 4C). Furthermore, several dolerite boulders have been overturned to expose unweathered facets (Fig. 4E). One example is a considerable distance from the present margins of either the Manhaul Bay or the Odell Glacier (1.6km and 2.2km respectively) and over 100m higher in elevation (1725 masl), and records the minimum extent of the most recent advance of the local ice margin. The age of the advance is uncertain, but the fresh and unweathered appearance of all these features led Atkins et al., (2002) to conclude that they were acquired during an advance corresponding to the Last Glacial Maximum (LGM).

3.2 Deposition

Four types of cold-based depositional features have been described by Atkins et al., (2002), three of which are outlined in Table 2. As with the erosional features, these occur on Beacon bedrock surfaces and the upper surface of Sirius tillite (Fig. 3). The fourth type ('Sandstone Debris on Lee
Cold-based glacier advance in Antarctica

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Distribution in Allan Hills</th>
<th>Dimensions</th>
<th>Principal Characteristics</th>
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</table>
| I    | Broad scrapes | <50m to Manhaul Bay and Odell Glacier snouts | Width: ≤500mm  
Depth: ≤40mm  
Length: ≤1200mm | • Unweathered scrapes  
• Consist of many smaller striae or grooves on mm-cm scale  
• Abrading tool often present  
• cm scale levees along flanks of the abrasion marks |
| II   | Individual strie and grooves | <50m to Manhaul Bay and Odell Glacier snouts. Occasionally inland beneath protected brecciated sandstone | Width: ≤100mm  
Depth: ≤15mm  
Length: Decimetres | • Unweathered individual linear abrasions, may also occur in sub parallel clusters  
• Nail head or symmetrical morphology  
• Linear groups of striae up to 2m in length also occur  
• Abrading tool often present  
• cm scale levees along flanks of the abrasion marks |
| III  | Scraped boulders | Wide distribution throughout Allan Hills, up to 1.8km inland of present Manhaul Bay Glacier snout | Width: ~50mm  
Depth: mm scale  
Length: cm-dm scale | • Unweathered scrapes  
• Occur on stoss side of weathered and lodged dolerite boulders, being clearly identifiable  
• Boulders occasionally overturned exposing the fresh side and not the characteristic dark brown desert varnish |
| IV   | Ridge-and-groove lineations | Wide distribution in central Allan Hills within the Manhaul Bay Glacier advance limit | Width: mm scale  
Depth: mm scale  
Length: ≤500mm | • Parallel fine lineations  
• Platy and dark surface  
• Sheen appearance similar to slickensides  
• Occur within carbonaceous slickensides beneath brecciated sandstone debris |

Slopes') will be discussed here under cold-based glaciectonic observations, because we consider it more closely related to these features. All three depositional types are related to the removal, entrainment and deposition of Beacon bedrock, and their distribution may be seen in Fig. 3.

The Atkins et al., (2002) type I sandstone and siltstone breccias or Manhaul Glacial Diamict (Lloyd Davies and van der Meer, 2002) is proposed in this paper to be named the Manhaul till (not a formal stratigraphic name), because it was deposited subglacially (Atkins et al., 2002) as a diamicton by glacial ice (Dreimanis, 1988). The Manhaul till (Fig. 5A) has been described by Atkins et al., (2002) as a “sandstone and siltstone breccia...unlithified, poorly compacted and typically less than 30cm thick and less than 3m across, consisting of crushed or brecciated Beacon sandstone and siltstone.” The deposit is part of a continuum that extends from intact Beacon bedrock to crushed and brecciated Beacon
Erosional Type I: broad scrapes consisting of multiple grooves on Beacon sandstone.

Erosional Type II: individual striae and grooves (black arrow) upon Beacon sandstone. The white arrow indicates former glacier flow direction away from the current Manhaul Bay Glacier, and the abrading tool (black circle) is still visible at the distal (terminal) end of the feature. Ice axe is 80cm long.

Erosional Type III: scraped dolerite boulder, the scrapes being highlighted by the white arrows. The black arrow indicates former glacier flow direction. Visible head of rock hammer is 12cm wide.

Erosional Type IV: ridge and groove lineations. Overlying breccia was removed to reveal the platy sheen of the type IV abrasions on this layer of carbonaceous siltstone (black arrow). The white arrow indicates former glacier flow direction away from the current Manhaul Bay Glacier. Note ice axe for scale.

Over turned and striated dolerite boulder also revealing a lump of Manhaul till (above 33cm long rock hammer). The overturned facet is distinct because it is not as ventifacted as the other dolerite boulders in the Allan Hills.
which grades into the Manhaul till per se, this being a matrix supported
deposit containing clasts. In central Allan Hills it is composed of
fragmented carbonaceous siltstone and sandstone bedrock with fragments
of coal; in north-west Allan Hills where the bedrock is Mawson Formation,
this is reflected both in the matrix and clasts in the till. Depending on the
local lithology the till is grey-yellow in colour, with a 1.5-2cm weathering
rind resulting in a more yellow-green appearance. The Manhaul till is
poorly sorted, its matrix is friable and structureless, and contains
subangular clasts up to 40cm, but commonly 1-6cm, in diameter. Any
'structures' are inherited from the underlying bedrock (e.g. laminations).
The interface between the underlying substrate and Manhaul till,
especially on the vertical faces of escarpments, commonly displays thin
(<2cm) veneers of a silty-clay matrix (with underlying ridge and groove
lineations) that appear 'plastered' onto the bedrock (Atkins et al., 2002;
Fig. 5B). In carbonaceous layers with a dark, platy sheen these lineations
are similar to slickensides and indicate north-south movement (Atkins et
al., 2002). The Manhaul till is in places relatively cohesive and has been
observed on the vertical faces of boulders and escarpments.

The Manhaul till is commonly patchy in distribution; its average thickness
is 5-8cm. Its occurrence is associated with broken-up bedrock or boulders,
ice-cored debris cones and boulder trains. The best preserved deposits are
associated with bedrock escarpments, especially vertical faces close to the
Manhaul Bay and Odell Glaciers (Atkins et al., 2002). Hitherto, the
thickest deposit is found within ~100m of the Manhaul Bay Glacier snout,
against a steeply descending slope, where the deposit is up to 5-6m thick
although the majority of this is thought to be buried ice.

As Fig. 3 demonstrates the Manhaul till is widely distributed and not just
found around the snout of the Manhaul Bay Glacier (cf. Lloyd Davies and
van der Meer, 2001). The highest occurrence is on the top of the northern
wall of Trudge Valley (1894masl; Fig. 5C).

Large, isolated boulders (up to 3m) are considered a depositional feature
and occur on exposed platforms of Beacon. These have not ploughed into
softer sediment or tectonised underlying bedrock. Isolated boulders are
not associated with Manhaul till or erosional features but are widespread
in north-central Allan Hills, resting on the Beacon bedrock (Fig. 5D).
Fig. 5  Examples of cold-based glacial depositional features in the Allan Hills.
A. Typical light-coloured patch of Manhaul till (black arrow) on darker Beacon sandstone in the Allan Hills. Note ice axe for scale.
B. Thin (<2cm) veneers of Manhaul till ‘plastered’ onto bedrock (as shown by white and black arrows). This occurs on an ice proximal escarpment facing the Manhaul Bay Glacier. Ruler is 30cm long.
C. A thick deposit of Manhaul till, outlined by white dashed border. The till is located on the steep stoss side of an escarpment and this is the highest occurrence of Manhaul till to date at 1894 masl. Note ice axe (black arrow) for scale.
D. A ‘typical’ isolated boulder upon a platform of Beacon bedrock.
E. An ice-cored cone close to the Manhaul Bay Glacier snout in the background, note person to the left for scale.

Seven ice-cored cones covered by loose Beacon debris (ranging from sand to boulders in size; Table 2; Fig. 5E) have been identified in the Allan Hills. Four cones are found adjacent to and below escarpments, suggesting a relation. North-south trains of broken and crushed sandstone or carbonaceous siltstone blocks, and veneers of Manhaul till, are occasionally associated with the ice-cored cones. Two ice-cored cones are part of such a train that is close to
Cold-based glacier advance in Antarctica

Table 2
Cold-based depositional features at Allan Hills (modified from Atkins et al., 2002).

<table>
<thead>
<tr>
<th>Type</th>
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<th>Distribution in Allan Hills</th>
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</tr>
</thead>
</table>
| I    | Sandstone and siltstone Breccia (Manhaul till) | Central, Allan Hills. Up to 2.5km inland of Manhaul Bay Glacier snout and 1894masl | ~30cm thick 300cm across Linear trails of till up to 10m long | • Poorly compacted, un lithified, crushed bedrock (majority being local Beacon)  
• Commonly found as sporadic thin (~30cm thick) patches or thin veneers plastered on vertical walls of Beacon escarpments facing present day Manhaul Bay and Odell Glaciers  
• Occasionally tapers inland from glacier margin  
• Associated with some boulder and cobble trains aligned north-south |
| II   | Isolated boulders | Central Allan Hills and 2.25km inland into Trudge Valley | ≤3m diameter | • Subangular to subrounded  
• Usually Beacon sandstone or siltstone in lithology  
• Occasionally found in areas of relatively flat relief  
• When associated with glacitectonised bedrock, size decreases distally from ice |
| III  | Ice-cored debris cones | Central Allan Hills, up to 1km inland of present day Manhaul Bay Glacier snout | On average <5m high, highest recorded ~8m. On average 7-9m in diameter (at base), widest recorded ~12m | • Ice-cored  
• Covered by loose Beacon debris, ranging from sand to boulders ~1.2m thick  
• Occasionally a small boulder (cobble) train, aligned north-south, <100m long, trends up to and beyond the feature |

the Manhaul Bay Glacier snout. The train extends for 17m, is 2m wide, and is composed of Manhaul till as well as brecciated and broken cobbles of local lithology. An ice-cored cone, followed by a large sandstone boulder terminates the train’s distal side. In line with this configuration and 25 metres farther south is another ice-cored cone 8m high and 12m in diameter at the base (largest observed). Both the debris train and ice-cored cones are positioned below an escarpment that is one of the highest (1675masl) points in central Allan Hills. The farthest inland ice-cored cone is 1km from the edge of the ice (Atkins et al., 2002), and the distribution of the remaining cones may be seen in Fig. 3. One ice-cored cone has been observed approximately 100 metres above the Odell Glacier margin (Lloyd Davies and van der Meer, 2002), and is labelled with a question mark in Fig. 3, as it was not possible to fully access the deposit.

3.3 Glacitectonics

Three scales of glacitectonic deformation, boulder trains, stone lines and ploughed boulders thought to be related to an advance of the Manhaul Bay and Odell Glaciers are evident in central Allan Hills. The three scales are
small (~30m², type I), medium (~30-100m², type II) and large (>100m², type III) as summarised in Table 3. Thirty three examples of deformed bedrock were identified as shown in Fig. 3; twenty of these are the smaller scale (type I), nine of the type II scale, and four of the largest type III scale. Fig. 3 outlines the distribution of the glacitectonic features which are discussed below.

A common observation for all three scales of glacitectonised bedrock, but more so in types II and III, is that the stoss parts of the feature are relatively intact with more deposits of Manhaul till. In contrast the distal regions are far more deformed as shown by fracturing, quarrying, brecciation, some Manhaul till and ‘sandstone debris on lee slope’ deposits (Atkin et al’s., 2002, type IV depositional feature). In places the fractures are filled with Manhaul till, wind blown fines or both. The fractures have sharp edges and vary in form: linear or concave and convex, in isolation or merging and branching. The fracture density commonly increases until complete brecciation dominates. Larger fractures in types II and III delineate regions which are more brecciated and in places fracture density increases within sandstone and siltstone with a higher carbonate or organic matter content. Furthermore, the clearest examples of deformed bedrock are in areas of highly irregular topography such as the raised ridge and its adjacent depression or ‘valley’, facing the easternmost lobe of the Manhaul Bay Glacier (Fig. 3).

3.3.1 Type I (~30m²). Type I cold-based glacitectonic features are commonly observed on flatter regions of bedrock, and is less obvious in the field than types II and III. Examples are extensional fractures within bedrock and small bedrock promontories being sheared off on their lee sides, producing brecciated clasts (Fig. 6A). The fractures are oriented parallel to the glacier margin, usually a few cm’s wide, and up to 2 metres in depth and length. Manhaul till is associated with type I features, but not as commonly as in types II and III.

3.3.2 Type II (~30m²-100m²). Type II examples include large, split boulders or other isolated boulders that have deformed and brecciated their underlying bedrock as well as regions of irregular bedrock platforms expressing subparallel extensional fracturing, quarrying and brecciation. Two isolated boulders were observed that acted as the tools to deform their underlying bedrock (Figs. 3 and 6B-C). The more northerly example (Fig.
Cold-based glacier advance in Antarctica

<table>
<thead>
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</table>
| I    | Small scale | Majority within 0.6km of Manhaul Bay Glacier snout, found upon a ridge at the cleft of the glacier and surrounding bedrock escarpments | ~30m² | • 20 cases recorded  
• More frequently observed upon flatter regions of bedrock  
• Tensional fractures within bedrock  
• Small bedrock promontories sheared off on lee side with brecciated clasts  
• Occasional Manhaul till |
| II   | Medium scale | Found from within 0.5km of Manhaul Bay Glacier snout and farther inland up to 1.8km. Commonly associated with steep valley edges | ~30-100m² | • 9 cases recorded  
• Isolated (intact and split), displaced boulders  
• Isolated, displaced boulders which have been the glacial tool in deforming their underlying bedrock  
• Irregular bedrock with subparallel tensional fracturing and brecciation  
• Ice distal ends of bedrock ridges display tensional fracturing, quarrying, brecciation and blocks sliding downslope  
• Manhaul till commonly on stoss side |
| III  | Large scale | Found in association with steep edges of a valley or variation in relief; within 0.4km of the Manhaul Bay Glacier snout and up to 1.6km inland | >100m² | • 4 cases recorded  
• Deformed bedrock ridges  
• Includes top of largest boulder train  
• Stoss side has Manhaul till, abrasion marks, cobbles and large boulders  
• Lee side characterised by dense extensional fracturing, quarrying, brecciation and rafting of bedrock downslope |

6B) is approximately 450m from the Manhaul Bay Glacier, consists of Beacon sandstone and sits upon a carbonaceous siltstone platform that is fractured and brecciated below the point of contact. Scattered sandstone clasts lie within 4m around the sandstone boulder, as does Manhaul till directly overlying fractured coal and brecciated carbonaceous siltstone. The other isolated boulder (Fig. 6C), with underlying glacitectonised bedrock, is over 2km from the Manhaul Bay Glacier snout and ~1.6km from the Odell Glacier snout (Fig. 3).

Other type II glaictectonic features include the stoss side of bedrock promontories composed of a relatively thick cap of Manhaul till that grades from brecciated and distorted siltstone. In contrast the lee side Beacon bedrock of these features are broken, brecciated and inclined down slope becoming increasingly distorted and brecciated, but grading into Manhaul till is less common (Fig. 6D). The extensional fractures (oriented parallel to the nearest glacier snout), increase in density, but decrease in width away from the glacier. In places certain fractures delineate areas of bedrock with varying levels of glaictectonic deformation. The widest

63
Cold-based glacier advance in Antarctica

Fig. 6 Examples of cold-based glacial glaciitectonic features in the Allan Hills.

A. Type I cold-based deformation of a small ridge about 60cm high and a few metres long. The background is the stoss side.
B. Detail of an isolated boulder being the tool that deformed (fractured) its underlying carbonaceous siltstone bedrock (white arrows highlight main fractures). The lee side is to the right. Note ice axe below tilted white arrow for scale.
C. Heavily brecciated bedrock directly beneath an isolated boulder (as shown by white arrow). The lee side is to the left. Boulder is approx. 2m high.
D. Type II cold-based deformation of bedrock. Note the increase in fracture density, brecciation intensity and deformation towards the lee end of the bedrock platform (towards the left). The thick white arrow indicates former glacier flow direction away from the current Manhaul Bay Glacier; note also ice axe (black arrow) and measuring tape (white arrow) for scale.
E. Type III cold-based deformation of bedrock. The stoss maintains intact bedrock (foreground), but there is complete fracturing, quarrying, brecciation and toppling of the ice distal ledge (background). The deformation observed here is on a scale of decimetres. The black arrow indicates former glacier flow direction away from the current Manhaul Bay Glacier.
F. Top of the largest boulder train in Trudge Valley. Note the quarried appearance of the bedrock; among the large boulders are smaller bedrock blocks and fines as well as Manhaul till. The large white arrow indicates former glacier flow direction away from the current Manhaul Bay Glacier, which is <2km to the right (Fig. 3). Large boulder in the immediate foreground (small white arrow) is 2m across.
G. The largest boulder train in the Allan Hills. The boulder train widens laterally in the valley bottom with distance from the Manhaul Bay Glacier. The large boulders in the foreground (bottom) of photograph are ~3-4m in diameter.
H. A ploughed boulder in the lowest point of Trudge Valley. Note the dilated Sirius tillite on the lee side of the ploughed boulder, indicating the direction of pressure was from left to right in the photograph, as indicated by the white arrow. Ice axe for scale.
I. A creamy white quartz stone line (~2m wide) at the lowest point in Trudge Valley, oriented east-west. The steep, retreating snout of the Odell Glacier is in the background. View to the east.

fractures are up to 15cm, but most are 7cm and the smaller more fissure like fractures are less than 1cm wide. The fractures (~1 to 2+m long) commonly penetrate downwards (sub-vertically) into different strata of Beacon bedrock.

3.3.3 Type III (>100m²). Only four clear examples of this scale of glaciitectonic deformation have been recognised, and all occur on bedrock platforms at relatively higher elevations than type I or type II deformation (1675-1725 masl; Fig. 6E). Type III is characterised by the ice proximal
(stoss) part of the platform expressing relatively subtle extensional fracturing (oriented parallel to the nearest glacier snout), a lag of boulders (≥1.5m in diameter) and cobbles with some Manhaul till. The ice-distal side of the platform, by comparison, is characterised by complete fracturing, brecciation and rafting of bedrock steps, which results in a ‘concertina toppling’ effect down to a lower elevation. Pulverised bedrock that occasionally grades into Manhaul till is associated with this intense deformation and the fractures decrease in length and width away from the ice with Manhaul till bridging some of these fractures. Towards the apex of the rafted and brecciated bedrock are fractures over 2m wide, and within them are nearly 1m sized boulders. Other boulders decrease in size toward the distal margin of the feature, in concert with increasing levels of brecciation. In summary, type III glacitectonics are consistently associated with deposits of Manhaul till and a surface lag of boulders and cobbles on their stoss sides, with the lee side characterised by abundant extensional fracturing, quarrying, brecciation and block displacement further downslope.

3.3.4 Boulder trains. Fig. 3 shows a number of boulder trains, the most prominent of which descend from bedrock promontories into Trudge Valley. Of the four adjacent boulder trains in this area, the second largest one has been described by Atkins et al., (2002) and the two smaller ones were mapped using aerial photographs. The most conspicuous boulder train (≥1km long) was investigated in the field. The gradient on the northern flank of Trudge Valley, close to where the longest boulder train begins, is 026°. The top of this boulder train reveals quarried, rafted and brecciated bedrock with large (>4m) displaced boulders and cobbles’ long axes orientated 045° in the direction of the boulder train (Fig. 6F). From the northern slope of the valley the boulder train thins out towards the valley bottom where it expands laterally (Fig. 6G). It ends one third the way up the southern slope of the valley upon an ice and snow field (Fig. 3). The boulder train itself is chaotically arranged with many of the large (3-4m) sandstone boulders precariously balanced upon the northern valley side. Characteristically, sporadic deposits of Manhaul till are also apparent at the top of, and within, the train on the stoss sides of boulders.

Farther north and close to the Manhaul Bay Glacier is a second conspicuous boulder train of coal. The train extends north-south (166°) for 105m, and increases in clast size and density towards the south (its end), before it terminates at a downstepping escarpment (Fig. 3).
Cold-based glacier advance in Antarctica

3.3.5 Ploughed boulders. Most ploughed boulders are found on the bottom of Trudge Valley close to the snout of the Odell Glacier, as indicated in Fig. 3. The clasts vary in size from large cobbles (c. 20cm) to large boulders (1-2 m; Fig. 6H). The boulders and cobbles are desert varnished dolerite, oblong and ploughed into the underlying Sirius tillite. Ridges of dilated, friable Sirius ~50cm high are found on the lee side of the boulders.

3.3.6 Stone lines. Other, substantially smaller ‘boulder trains’, which we describe here as stone lines are found at the lowest point of Trudge Valley. They stand out because of their contrasting colour of creamy white overlying the red-grey Sirius tillite (Fig. 6I). There are three stone lines, all oriented perpendicular to the Odell Glacier snout and each composed of white quartz. The longest one begins with a crushed boulder (≥1m in diameter) from which the lineation is derived. It is made up of small to medium sized cobbles and boulders (~60cm maximum in diameter) and extends 110° east for 30m. All the clasts are partially embedded (on average 5-10cm deep) in the Sirius tillite surface, while some neighbouring dolerite clasts and boulders are similarly aligned and ploughed (see above). The two smaller, parallel stone lines of quartz are to the south-east of this feature and measure just over 10m long. One quartz clast is superimposed upon brecciated and fissured carbonaceous siltstone infilled with Sirius tillite, indicating post Sirius Group deposition. The clasts’ underside display faint slickensides oriented parallel to the stone line indicating ice movement into Trudge Valley from the east. The slickensides are similar to the Atkins et al., (2002) ridge and groove lineations (erosional type IV). Fig. 3 demonstrates the distribution of the stone lines, which occur within 200m of the Odell Glacier snout.

4. DISCUSSION

Long established principles hold that cold-based glaciers do not affect their substrate as these glaciers are supposed to be frozen solidly to their bed. However, from the description above it is clear that an advance of the Manhaul Bay and Odell Glaciers, which were certainly cold-based (Atkins et al., 2002), left a very distinct imprint on the landscape. This raises the question regarding which processes are responsible for the geomorphic work.
As a starting point, we maintain that a cold-based glacier is frozen to its bed and that large parts of the bed are, and remain, inactive, although some authors suggest cold-based glaciers may slide albeit very slowly (Echelmeyer and Zhongxiang Wang, 1987; Cuffey et al., 1999). The obvious place where a cold-based glacier is in active contact with its bed is at the margin, especially when the glacier is advancing. When the glacier starts to grow, after a quiescent phase, the forward momentum will not be enough to break the bond between glacier and bed. Consequently the glacier will steepen its margin and will continue to do so until oversteepening leads to failure and a frontal apron of ice blocks and rubble. This is due to the intermittent process of ice blockfall, as seen in advancing cold-based glaciers elsewhere (Chinn, 1985, 1989, 1991; Evans, 1989). Freezing of blocks and rubble will reconnect this material to the glacier, which can now move forward over the apron. Effectively the ice block toppling and refreezing, acts as a ‘rolling carpet’ or ramp for the glacier to move forward over the apron (Chinn, 1985, 1991; Bennett et al., 2003). It is now appropriate to reconstruct how such an advancing ice front affects the landscape.

The first area of influence will be when the advancing cold-based glacier and associated ‘rolling carpet’ of ice blocks encounter surface boulders and cobbles as depicted in Fig. 7A-F. The frontal ice block apron begins to surround, wedge under and envelope the surface of encountered boulders and debris leading to their gradual incorporation within the carpet of ice blocks (Fig. 7D; Evans, 1989). Boulders are incorporated into the glacier’s basal zone (Fig. 7E), with the potential for lifting off the bed due to variation in the ice flow velocity profile (Fitzsimons et al., 1999) and compressive flow (Fig. 7F).

When variations in relief are encountered the ice block apron begins to build up between the glacier and higher escarpment, incorporating boulders and debris (Fig. 8A-D). The apron of ice blocks acts as a ramp to induce upward transport of the incorporated boulders and debris (Fig. 8A; Chinn, 1985, 1991). As the glacier advances upon its ice block apron, first around and then upon, the higher escarpment (Fig. 8B), higher pressure points between the glacier and the stoss side of the ridge will induce glaciectonic brecciation of the apron ice (Chinn, 1991), substrate as well as deposition of Manhauil till (Fig. 8B-C; Atkins et al., 2002). Some boulders will contact the bedrock, rotate, and then be dragged along the stoss surface of the bedrock ridge, forming abrasion marks (Figs. 4A-B and 8C;
Cold-based glacier advance in Antarctica

Fig. 7  A proposed sequence for cold-based glacier incorporation of boulders and other debris via ice block entrainment in the Allan Hills. Glacial ice is light grey, Beacon substrate and boulders are dark grey.

A. A cold-based glacier which is not advancing and frozen to its bed. The convex or steep margin reflects the passive state, much like the Manhaul Bay and Odell glaciers of today.

B. Upon forward movement of the ice with the glacier still being frozen to its bed (i), the margin becomes steeper, leading to marginal overhanging and fracturing (ii).

C. Over steepening of the glacier snout leads to ice block calving and toppling (i), resulting in the formation of an ice block apron (ii). (iii) The ice block apron is frozen onto the base of the glacier and acts as both a ramp and a ‘rolling carpet’ for the forward motion of the glacier.

D. The frontal ice block apron begins to surround, wedge under and envelope boulders and debris.

E. Incorporation of the ‘rolling carpet’ now includes boulders and debris as well as the ice block apron (Evans, 1989; Bennett et al., 2003).

F. Boulders are incorporated higher in the basal zone because of the subglacial ‘ramp’ on the ‘rolling carpet’ (Chinn, 1985, 1991).

Atkins et al., 2002). Forward motion of the glacier, its compressive flow against the substrate, and the occurrence of connected fractures will induce sub-vertical extensional fracturing whose spacing will decrease with continued glacier advance, and aid quarrying of the lee side of the ridge (Addison, 1981; Rastas and Seppälä, 1981; Iverson, 2002). As the glacier covers the bedrock ridge, the lee end is covered by a downward sloping thick apron of ice blocks. The thick ice block apron acts as a ramp for the ‘descending’ glacier (Fig. 8C), resulting in ice-bed separation and
the potential for further deformation as well as boulder and debris entrainment. This is due to two processes: the separation of ice from the bedrock and the utilisation of the space now created adjacent to the raised escarpment. The ice-bed separation means that ‘point’ stress differences are maximised due to some of the glacier weight being ‘shifted’ to the zone of ice-bed contact. Therefore, there is more compressive stress on a relatively small portion of the substrate, increasing the overall effective

![Diagram A](image1)

**Fig. 8** Proposed model for cold-based glaciological deformation types I, II and III of bedrock. Glacial ice is light grey, Beacon substrate and boulders are dark grey and the thick arrows indicate glacier flow direction.

A. The advancing glacier approaches a change in relief (i.e. bedrock ridge) and the ice block apron begins to build up between the glacier and higher escarpment, incorporating and lifting boulders and debris as described in the text.

B. 
1) High pressure points between the glacier and bedrock (on the stoss side of the ridge) induce glaciological brecciation, Manhaul till deposition, and rotation and dragging of boulders along the bedrock stoss side, forming striae.
2) Incipient sub-vertical extensional fractures occur in the bedrock.

C. 
1) Processes on bedrock stoss surface continue as described in Fig. 8Bi).
2) Extensional slip and fractures open up in the substrate, the glacier now capping the bedrock ridge.
3) At the lee end of the ridge an ice block apron forms, acting both as a ramp for the ‘descending’ glacier and forming a cavity. This encourages glaciologicalism as shown by extensional slip, widened fractures, quarrying and brecciated bedrock.

D. 
1) With retreat of the glacier, larger boulders, Manhaul till (black triangles) and abrasion marks are predominantly found on the stoss side.
2) Extensional slip, fracturing, quarried and brecciated bedrock with smaller boulders and some Manhaul till are found on the lee side.
pressure upon an already well jointed substrate. This, in combination with a developing cavity, induces tensile fracturing, extensional slip, widened fractures, brecciated bedrock and quarrying as the adjacent ‘gap’ permits the broken bedrock to go somewhere. With retreat of the glacier, larger boulders, Manhaul till and abrasion marks are predominantly found on the stoss side of the ridge, and extensional slip, fracturing, quarrying and brecciated bedrock dominate the lee side (Fig. 8D). Such a model is in accordance with both our field observations as well as those from elsewhere (Puranen, 1990; Benn and Evans, 1998; Iverson 2002).

Fig. 9A-E is a proposed model for the formation of subglacial boulder trains, and may be seen as a continuation of the model just described in Fig. 8; the difference being a greater contrast (downwards) in relief. As Fig. 3 demonstrates, the boulder trains are all associated with a major step down in relief, the tops of which have been quarried (Fig. 6F). As the glacier and its ice block apron approach a relatively steep distal escarpment (Fig. 9A), fracture development and boulder contact with the stoss sides would take place as described above (Fig. 9B). However, with the steep descent of the glacier upon its ice block apron, extensive ice-bed separation would occur (Fig. 9C), orders of magnitude greater than that described in Fig. 8. This would place very high pressure on the stoss side of the bedrock step, immediately up ice from the point of ice-bed separation (Fig. 9C-D), for the same reasons as outlined above. The greater the descent, the larger the separation would be between the ice and the bed, and therefore the higher the deforming and quarrying potential. This effect would be limited only by the strength of the ice (Iverson, 2002).

Furthermore, as described above, the lee side breach and resultant relative lack of confining pressure, allow extensive quarrying to loosen boulders and rock fragments which may then spall off into the cavity (Röthlisberger and Iken, 1981) initiating the subglacial boulder train (Fig. 9C-D; Puranen, 1990). For this reason the majority of boulder trains terminate at the descending slope’s lowest point (e.g. valley bottom) where the cavity would be smallest (Fig. 9D). With retreat of the glacier a non-sorted linear boulder train as well as some Manhaul till remain (Fig. 9E).

No model has been proposed for the formation of the stone lines and ploughed boulders, as currently we are unable to find an explanation as to how they were formed by cold-based ice. Their context and orientation suggest they were both formed by a westward expansion of the Odell
Fig. 9 A proposed model for the formation of cold-based subglacial boulder trains. Glacial ice is light grey, Beacon substrate and boulders are dark grey and the thick arrows indicate glacier flow direction.

A. The glacier advances upon its 'rolling carpet' of ice blocks towards a bedrock step with a sudden drop in elevation on its distal side. (Sub)-vertical extensional fractures develop in the underlying sedimentary bedrock.

B.

i) Up glacier high pressure points induce brecciation, Manhaul till deposition and abrasion on the stoss side of the step.

ii) The number of (sub)-vertical extensional fractures increases and their spacing decreases.

iii) The advancing glacier covers the step and an ice apron as a 'descending ramp' develops on the lee side of the step.

iv) Over steepening and topple of ice blocks at the glacier margin continues to form an ice block apron. On this occasion the ice block apron thins and spreads out toward the valley bottom due to the steep descent of the escarpment.

C.

i) Brecciation, Manhaul till deposition and abrasion would continue on the stoss side.

ii) The separation of ice and bedrock and the formation of a lee-side cavity facilitates extensional fracturing, quarrying, brecciation and the removal of bedrock blocks. The blocks can then move downslope into the overridden ice block apron.

D. The glacier continues to advance over its 'extended' ice block apron.

i) Brecciation, Manhaul till deposition and abrasion would continue on the stoss side.

ii) As long as ice-bed separation and a cavity exist, extensional fracturing, quarrying, brecciation and the removal of bedrock blocks occur.

iii) The lee-side cavity filled with ice blocks, but not solid ice, is exceptionally large due to the steep slope and terminates as the relief levels out. This provides the space for quarried boulders and debris to accumulate as gravity
Cold-based glacier advance in Antarctica

pulls boulders into line. As the glacier approaches flatter relief, and the subglacial 'rolling carpet' thins, the boulders spread out laterally into remaining open areas of the lee-side cavity (Fig. 6G).

E. Upon glacier retreat a subglacial boulder train remains.
   i) Manhaul till (black triangles) and abrasion features characterise the stoss side of the bedrock step.
   ii) Sub-vertical tensional fractures occur in the bedrock.
   iii) The top of the boulder train is intensively fractured and quarried, reflecting the displacement of large boulders and brecciation of clasts (Fig. 6F).
   iv) A linear boulder train is left which spreads out laterally towards its end. The train's boulders are not sorted, and some Manhaul till is apparent.

Glacier into Trudge Valley. Moreover, their fresh appearance, especially that of the dilated, friable Sirius ridges found on the lee side of ploughed boulders is too recent to be of Sirius tillite age, that being between ~15 million years (Summerfield et al., 1999) and 2 million years (Tschudi, 2000). This suggests the 'Sirius ridges' were probably formed during the LGM. The question remains how a cold-based glacier could have crushed and aligned clasts and small boulders along flat terrain, as well as induced subglacial ductile deformation brought about by boulder ploughing in the same area.

Finally, compelling evidence for the use of an ice apron as a 'rolling carpet' to entrain boulders and debris, as well as facilitate glaciopectonism, is bubble rich and fractured ice at the basal snout of the Manhaul Bay Glacier (Figs. 2 and 3). Ice block apron materials contain a high number of air voids, especially between fallen blocks, explaining the presence of trapped air (bubbles). In this context bubbly ice is indicative of having formed by ice block apron entrainment (Shaw, 1977a). An alternative explanation is that the boulders are formed by summer melt, but during the four field seasons no basal or frontal melting from the Manhaul Bay or Odell Glaciers was observed. However, it cannot be discounted that melting may have occurred in the past, even though this fails to explain the high fracture density associated with the bubble rich basal ice. Fine-grained material is also known to be entrained by frontal aprons (Shaw, 1977a; Chinn, 1985; Bennett et al., 2003) and subglacial regelation (Cuffey et al., 1999, 2000) as well as the over-riding and subsequent freezing on of ice-cored or covered debris (Chinn, 1991).
5. **PRESERVATION POTENTIAL**

As there is no published suite of landforms and sediments related to cold-based glacial conditions Kleman (1994) and Kleman & Borgström (1994) used preserved, unscathed landforms once covered by ice as positive evidence of former cold-based conditions. Shaw (1977a and b), on the other hand, has described sedimentological characteristics of 'cold-based tills' in Taylor Valley, Antarctica derived from fine-grained and or lacustrine proglacial sediments. This was done with the assumption that such tills, within the correct context, have the potential to establish former cold-based conditions elsewhere. However, the effects on these sediments of changing climatic conditions have not been considered. We consider below the preservation potential for all the described ‘cold-based subglacial’ features when they are subjected to environmental change driven by climatic amelioration. Four different scenarios: 1) deglaciation under polar, arid conditions, 2) deglaciation as characterized by temperate ice, 3) paraglacial processes within a periglacial environment and 4) temperate (interglacial) conditions are discussed as these reflect the changes experienced by present day temperate areas that were once covered by cold-based glaciers.

### 5.1 Deglaciation under polar, arid conditions

The contemporary cold and arid environment of the Allan Hills, and other ice free areas of South Victoria Land, is geomorphologically stable (Denton et al., 1993) in comparison to other formerly glaciated regions worldwide. The local ice masses are cold-based (Atkins et al., 2002), precipitation levels are low, and there is minimal liquid water in the form of melting snow patches (Lloyd Davies and van der Meer, 2001). A significant geomorphological process is wind (Miotke, 1982; Campbell and Claridge, 1987; Hall, 1989), with estimated speeds up to 250 km/hr in nearby ice free areas (Malin, 1985). Ever since interstadial conditions began as early as 13,000 years ago (Lorius et al., 1985), gradual retreat of the local polar outlet glaciers has taken place. As the climate has since remained cold and dry (Barrett, 1999), the most active geomorphological process acting upon the cold-based features described is therefore wind. Deflation surfaces of ventifacted dolerite blocks, parallel crested ridges and wind sculptured isolated boulders are testament to the abrasive effect wind has in the Allan Hills. Despite this, the glacitectonic features, boulder trains and ploughed
boulders are intact across central Allan Hills, although certain boulders show evidence of wind abrasion. The ice-cored cones in the contemporary cold and arid environment are most susceptible to sublimation, even though their preservation potential is improved by a debris mantle (Carrarra, 1975; Driscoll, 1980; Hindmarsh et al., 1998). The faster the wind the more rapid the rate of sublimation (Law and van Dijk, 1994), especially when the ice formation is not shielded from the wind (Seligman, 1963; van Dijk and Law, 1995).

The field experiments of de Jong and Kachanoski (1988), illustrate this further as increased wind speeds from 0 to 1.5 m$^{-1}$ resulted in a higher sublimation rate (upon ice) from 7 to 400 gm$^{-2}$h$^{-1}$. The current distribution of ice-cored cones in Fig. 3 further supports this idea, as five of the seven cases are found in the lower, wind protected area. The two other ice-cored cones are found at the very snout of the Manhaul Bay Glacier, where they have been recently released. Given that 80cm of debris cover preserves Antarctic ice for at least 18,000 years (Chinn, 1991), we estimate that the ice-cored cones, with an average cover of 120cm (Table 2), would last ~24,000 years under constant polar, arid conditions. Therefore, protection from the wind and age, appear to be significant variables regarding the preservation potential of ice-cored cones. After final sublimation of the ice core all that will be left is a loose, inconspicuous rubble mound that is subject to removal by wind. Isolated boulders deposited by the ablating ice will also be preserved, with some being more exposed to ventification or 'wind sculpturing'. Thirdly, the Manhaul till is very friable and loose (Lloyd Davies and van der Meer, 2001, 2002; Atkins et al., 2002) and will be eroded by the wind. No examples were found on exposed bedrock; the best preserved outcrops are behind steep (wind protecting) escarpments (Fig. 3). Other patches of Manhaul till are associated with glacial-tectonised bedrock, where the till is protected from the wind. Northerly platforms of undulating Beacon bedrock, which are more exposed to the southerly, katabatic wind, contain sporadic patches of Manhaul till or small Manhaul till lineations (Fig. 3). Consequently they are more vulnerable to wind erosion, which explains their inconspicuous distribution.

Features that are only present on bedrock or boulder surfaces have been protected from the wind, while the relative lack of liquid water in the Allan Hills prevents the degree of frost wedging found in wetter environments, and thus such features will change little over time. As such we include
ridge and groove lineations beneath brecciated bedrock, scraped boulders (usually marked on the stoss side), broad shallow scrapes, and singular or grouped striae (Atkins et al., 2002). The latter two will be eroded by the wind first, with the crushed and smeared centimetre scale levees being the most vulnerable, as demonstrated by the comparable example from the Canadian High Arctic, where $4.8 \text{ kg m}^{-2}$ of surface soil was eroded (in one hour) by wind speeds between 80 and 150 km hr$^{-1}$ (Lewkowicz, 1998). This explains the distribution being confined to areas close to the margins of the glaciers or in wind protected situations.

5.2 Deglaciation under temperate conditions

A different type of deglaciation would occur if the climate were to change from polar arid to temperate, as may have happened in the northern hemisphere during the Pleistocene. Subglacial, supraglacial and marginal meltwater features are characteristic of temperate deglaciation (Evans and Twigg, 2002) and this in itself would have significant implications for the preservation potential of features produced under cold-based conditions. Meltwater would quickly remove the friable Manhaul till, and the smaller clasts from glacitectonised bedrock or boulder trains. An example in support of meltwater's capability to remove and transport sediment is shown by Hicks et al., (1990) in their field experiment which measured $300 \text{ kg m}^{-2} \text{ yr}^{-1}$ of sediment discharge from the snout of the temperate Ivory Glacier, New Zealand. Moreover, depending on the meltwater pressure, extensional fractures could be widened further, and bedrock subsequently weakened and disrupted. As the majority of cold-based deformational structures are found on the down ice part of escarpments, the widened fractures would increase the probability of subglacial block removal and the creation of roches moutonnées. Some larger cold-based glacitectonic features might remain intact, but with a temperate overprint such as a subdued morphology (Kleman, 1994) brought about by subglacial meltwater erosion. Depending on the level of hydrostatic pressure, a number of boulders would remain preserved, although possibly more rounded by subglacial abrasion. Where hydrostatic pressures are high enough, boulders up to 2m could be transported, contributing to depositional landforms such as eskers, as seen elsewhere (e.g. Ireland, Warren and Ashley, 1994).

One of the probable changes would be the production of wet-based till, in which ploughed boulders would remain, but no longer distinguishable as a
product of cold-based conditions, as boulder ploughing occurs under temperate glaciers. The number of ice-cored cones might increase upon deglaciation due to stagnating and isolated areas of ice being covered in supraglacial or paraglacial debris. This may develop into extensive marginal zones of very irregular, debris covered ablating ice. However, to differentiate between ice-cored cones deposited by ablating cold-based ice or retreating and stagnating temperate ice would be difficult. The broad, shallow singular or grouped striae would be eroded by the intensive subglacial processes associated with till production and meltwater increase, as would any exposed ridge and groove lineations, even though the scratched boulders might remain. Overall however, it will simply be a replacement of ‘cold ice striae’ by ‘temperate ice striae’, save the rare one that may be preserved and unique in appearance, but no longer clear as having a cold-based origin.

Therefore, as described, deglaciation would cause former, continuously cold-based areas underneath ice masses to shrink in form with many of the related cold-based features being destroyed by the inward migration of thermal conditions and thawed zones during deglaciation (Kleman, 1992). However, some cold-based patches may escape meltwater conditions (Kleman, 1994) and be preserved, but have yet to survive postglacial processes.

5.3 Paraglacial processes within a periglacial environment

In this section we describe paraglacial processes within a periglacial environment undergoing climatic amelioration in more detail than those in the polar and permafrost setting. This is because we primarily consider the preservation potential of cold-based features when subjected to a ‘warming’ climate with its relatively higher rates of geomorphic activity when compared to paraglacial processes in the polar context. Depending upon whether the withdrawal of glacier ice happened under polar arid or under temperate conditions, completely different suites of landforms will remain. The departure of ice means that the exposed landscape is unstable and therefore apt to change, as erosion and sediment release occur at rates generally exceeding ‘usual’ denudation levels (Ballantyne, 2002). Such an example of paraglacial processes in a temperate setting has been documented by Ballantyne and Benn (1994) where an undulating sediment covered slope exposed by the temperate Fäbergstølsbreen Glacier, Norway became a badland of deep gullies, with
destroyed lateral moraines and commonly exposed bedrock within 48 years of glacier retreat (Ballantyne, 2002). However, relief modification also occurs in the polar, arid environment (see dense distribution of rock and debris fall in Fig. 3; Fitzsimons, 1996b), but at far lower orders of magnitude.

Paraglacial modification upon glacier forelands has two prominent impacts: firstly relief modification and secondly changes in sedimentological characteristics of surface and near surface sediments (Ballantyne, 2002). Both directly affect the preservation potential of remaining subglacial cold-based glacier formations. In our model of climatic amelioration (temperate conditions), mass movement would reduce steep slopes to gentle gradients and therefore diminish overall relief by redistributing sediments into depressions and low lying areas. Processes such as solifluction, fluvial activity, slopewash, frost sorting, downwash of fines and wind erosion would contribute to both the relief modification and changes in sedimentological characteristics (Ballantyne, 2002). Two of these processes; fluvial and aeolian activity, would ubiquitously affect cold-based subglacial features, the latter (as described) being a dominant process for the deglaciation of the polar, arid environment in the Allan Hills today. However, when considering paraglacial activity under increasingly temperate conditions fluvial processes would be most active immediately following deglaciation, when meltwater discharge is highest (Fitzsimons, 1990, 1996b), and channels would erode, redeposit or alter any of the described cold-based features. Wind’s eroding efficacy is also highest during the early stages of the paraglacial cycle (Riezebos et al., 1986; Benn and Evans, 1998) following temperate deglaciation, especially once the glacier foreland is drier, but before vegetation colonises. For example, Boulton and Dent (1974) describe wind’s erosive effects on recently deglaciated (temperate) tills in south-east Iceland, where after only one year’s exposure, 30-40% of the till surface was covered in clasts, due to the removal of surficial fines. Thus one would expect wind erosion to cause deflation and redistribution of sediments (including any remaining Manhaul till), in addition to winnowing of fines from glaicectonic structures and further ventifactation and sculpturing of isolated (ploughed) boulders, boulder trains and stone lines. Furthermore, increased sublimation rates, due to high aeolian activity, would lead to the deterioration of any ice-cored terrain, which alongside the features described above, is already occurring in the polar setting of the Allan Hills today.
When considering other processes, glacitectonic (large scale) structures on the lee sides of steep escarpments would be highly susceptible to downslope rafting by toppling and mass movement, and those on shallow gradients would experience solifluction. Solifluction is important when modifying moderate slopes of recently (temperate) deglaciated terrain (Ballantyne, 2002). This is because the faster solifluction rates (within 50 years) at the ice margin would reflect the higher moisture content (from a study in Jotunheimen, Norway cf. 70% moisture content at the ice margin with <10% moisture content 45 metres from the ice margin; Ballantyne and Matthews, 1982). The boulder trains found on such slopes would thus lose stability and distinction because of these processes, and accumulate in valley bottoms where they would not necessarily stand out from other slope deposits. Frost action processes (e.g. frost heave, frost creep) and freeze thaw activity would produce a wide variety of frost sorted patterned ground, and affect the preservation potential of the ploughed boulders and Manhaul till. The former would have its surrounding sediment redistributed on a small but significant scale, causing separation of fine and coarse debris, even the small boulders (~0.5m) are subject to this phenomenon (Ballantyne and Matthews, 1982). Sorting of particles and downward translocation of silt and clay by water derived from the retreating ‘temperate’ ice, would irreversibly affect the original sedimentological characteristics of any remaining Manhaul till, as would frost induced fissuring change its structure. Furthermore, Manhaul till associated with glacitectonic structures or steep slopes would be subject to mass movement, solifluction or slopewash following precipitation. Isolated boulders on undulating bedrock would remain preserved, but an undulating sediment substrate would give rise to frost action sorting processes that may group the ‘isolated’ boulders, within a matter of decades (Ballantyne, 2002). Furthermore, the boulders on a slope would be subjected to mass movement and solifluction and would be redistributed downslope. Ice-cored cones which do not encounter glaciifluval activity immediately after deglaciation, might be preserved somewhat longer, depending on sublimation rates. As stated, a small number of (protected) ridge and groove lineations and scraped boulders would escape temperate ice abrasion, but may still be subjected to slopewash activity.

Paraglacial processes within a periglacial environment play a crucial role in the preservation of these cold-based landforms and deposits, as
significant modification or removal of these features takes place, especially under temperate conditions, as this occurs rapidly on a decadal time scale (Ballantyne, 2002). In contrast, under polar conditions, permafrost will have developed and the paraglacial conditions may therefore persist for longer timescales (1000 to 2000 years; Fitzsimons, 1996b) but at a lower intensity. However, in such polar environments, wind and other periglacial processes such as gelification, thermo-erosion induced by seasonal meltwater streams, active layer detachment sliding, permafrost creep and thermo-karst lake development (Ballantyne, 2002) would continue to shape the landscape, each impacting the remaining cold-based configurations in a similar fashion to that observed today in the Allan Hills.

5.4 Temperate (interglacial) conditions

Further climatic amelioration introduces rain and the rapid spread of a stabilising and protective vegetation cover (Matthews, 1992, 1999). Rain would remove any surviving Manhaul till, and until plant succession takes place, slopewash would continue to affect glaciitectonic structures or boulder trains. All striae would be absent or impossible to distinguish from striae formed by temperate ice. As pedogenesis and vegetation develop, many remaining glaciitectonic structures already affected by temperate ice as well as paraglacial and periglacial processes, would be covered in soil and foliage, rendering them inconspicuous. This would also apply to isolated boulders; the combined effect of paraglacial and periglacial slope processes upon boulder trains would make them indistinct. Potentially the least affected would be isolated boulders, but their random distribution, weathered aeolian appearance and (partial) incorporation into soil means they are unreliable as evidence for former cold-based glaciation.

6. SUMMARY

Despite the widely-held assumption that cold glaciers are inactive at their base, we have presented evidence for cold-based glacier erosion, deposition and deformation from the Allan Hills. Fig. 3 summarises the distribution of these observations as well as the direction of movement for the Manhaul Bay and Odell Glaciers when they last expanded. The directions of the two glaciers has been determined from abrasion marks, strike/dip measurements of cold-based glaciitectonised bedrock, boulder
Cold-based glacier advance in Antarctica

train and stone line orientations (thick and thin blue arrows in Fig. 3 on pages 280-281). This is contrary to the direction of movement (south-west to north-east) of the East Antarctic Ice Sheet (EAIS) that deposited the Sirius tillite (thick pink arrows in Fig. 3 on pages 280-281).

A model explaining the stone lines and ploughed boulders formed under cold-based glaciers has yet to be proposed. However, a model has been outlined regarding boulder and debris entrainment, subglacial glacitectonism and boulder train formation by cold-based glaciers. This model involves two important processes: (i) ice block apron overriding and entrainment, (ii) ice-bed separation leading to the formation of a cavity on the lee side of escarpments. Furthermore, the model requires a specific physical setting to facilitate these two processes, as topography and lithology are significant variables in relation to cold-based debris entrainment (Zdanowicz et al., 1996) and glacitectonism (van der Wateren, 2002). For the Allan Hills the prerequisite is a jagged, horizontally stratified, lithified sedimentary bedrock substrate.

The preservation potential of cold-based subglacial features observed in the cold, arid and geomorphologically stable environment of the Allan Hills has been discussed. This involved deglaciation ranging from cold-based to temperate interglacial conditions, as must have been experienced by present day temperate areas, once dominated by cold-based conditions during the Pleistocene. If the Allan Hills is subjected to climatic amelioration very few of the features depicted in Fig. 3 would survive, and those that do survive would not indicate an exclusively cold-based origin.

7. CONCLUSION

The following conclusions are to be drawn from this chapter:

- The Manhaul Bay Glacier moved at least 2.6km farther south than its present margin and the Odell Glacier expanded westwards at least 0.4km into its neighbouring valley during the LGM. At this time the Manhaul Bay (most likely) or Odell Glacier covered bedrock as high as 1894 masl.
- Cold-based glaciers are capable of subglacial erosion, deposition and glacitectonism, with the latter being the most conspicuous.
• Erosional, depositional and glacitectonic features provide the means for reconstructing cold-based glacier advance (and retreat) in other regions that have experienced continuous polar, arid conditions since the LGM.

• Fig. 3 shows a dense array of cold-based features, which suggests they have a high preservation potential in polar climates. However, when subjected to climatic amelioration and increased geomorphic activity their preservation potential is extremely low. Therefore, the Allan Hills are different from the areas recognized in Scandinavia that have a cover of regolith, subsequent till deposition by temperate ice (Kleman and Stroeven, 1997), soils and periglacial structures unlike anything in the Allan Hills.

• The combination of a specific physical setting in our model and very low preservation potential when subjected to a warming climate, explains the ‘perceived absence’ of cold-based glacier activity in the Pleistocene record.

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“Let us not take it for granted that life exists more fully in what is commonly thought big than in what is commonly thought small.”

*Virginia Woolf, 1882-1941*