A polar paradise: the glaciation of South Victoria Land, Antarctica
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CHAPTER 4: SELECTED CASE STUDIES OF COLD-BASED GLACIERS, SOUTH VICTORIA LAND, ANTARCTICA

Abstract

Recent developments in glaciology and three case studies of cold-based glacial activity in South Victoria Land, Antarctica are reviewed. This is intended to challenge the conventional view that cold-based glaciers are basally inactive because basal sliding does not occur. The three case studies differ in several respects, such as the scale of cold-based activity, the environmental context and type of overridden substrate.

1. INTRODUCTION

Conventional thinking among glaciologists and geomorphologists is that cold-based glaciers are basally inactive because basal sliding does not occur (Boutlon, 1972; Drewry, 1986; Paterson, 1994). However, as research into modern cold-based glaciers gathers momentum, there is a developing tension between glaciologists, modellers and geomorphologists. On the one hand glaciologists and modellers maintain that cold-based glaciers are incapable of basal activity and preserve the landscape (Paterson, 1994; Dowdeswell and Siegert, 1999; Näslund et al., 2003) whereas a recent number of geologists and geomorphologists have begun to report cases of cold-based glacial erosion, deposition and tectonism (Atkins et al., 2002; Bennett et al., 2003; Waller, 2003).

Cold-based glaciers are defined as a glacier in which basal temperatures are permanently below the pressure melting point (Paterson, 1994; van der Veen, 1999). The lack of net basal melting justifies the assumption that no basal sliding, erosion, bed deformation and debris entrainment takes place. Instead the glacier is frozen to its substrate (Boulton, 1972) and moves only by slow internal deformation (Paterson, 1994), having minimal or no influence on the landscape.

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Chapter 4

The premise of landscape preservation by cold-based glaciers has resulted in the concept of ‘relic landscapes’. These are landscapes that have been geomorphologically unaffected despite glacial overriding, with examples reported from Scandinavia (Clarhäll and Kleman, 1999; Kleman et al., 1999) and North America (Clarhäll and Jansson 2002). This bought about the term ‘palimpsest landforms’ (Kleman, 1992; Stea, 1994), which are landforms that are identifiable despite later overprinting by younger glacial landforms. This school of thought plays a foundational role when considering the interpretation of lithostratigraphy and glacial geomorphology in formerly glaciated terrain. For example, a binary approach is commonly adopted where a recognisable preglacial landscape means it has been covered by cold-based ice, but a modified landscape equates to temperate-based glacial activity.

This chapter aims to contest the above assumptions associated with a binary approach, by briefly reviewing glaciological developments that relate to cold-based glacial activity. This is followed by three cases studies reporting cold-based glacial activity in South Victoria Land, Antarctica.

2. DEVELOPMENTS IN GLACIOLOGY

Speculation as to whether rock fragments or sediment could be entrained into cold ice began in the 1970s. In 1971 Mercer reported that the cold-based McCarthry Glacier in the central Transantarctic Mountains (TAMS) contained “granitic fragments from gravel through to boulders 3m in diameter...(that) must have been quarried beneath the glacier”. He also observed striated clasts in ice-cored moraines on the east side of Buckley Island nunatak in upper Beardmore Glacier (Mercer, 1971). Holdsworth’s (1974) landmark paper regarding observations of the basal zone of the cold-based (-17°C) Meserve Glacier, Antarctica triggered interest when he described a basal ‘pavement’ of large boulders cemented together by ice, clay and silt. These field observations were later accompanied by theoretical proposals that liquid water might exist between ice and foreign bodies at sub-freezing temperatures (Gilpin, 1979).

Since the mid 1980’s research into processes operating within the subglacial and marginal environments of cold-based glaciers has been on the increase. Shreve (1984) followed by Fowler (1986) postulated that
basal sliding was theoretically possible at sub-freezing temperatures. This was accompanied by actual field observations of basal sliding and subglacial deformation at sub-freezing temperatures in the cold-based Urumqi Glacier No.1 in China (Echelmeyer and Zhongxiang Wang, 1987). Despite Echelmeyer and Zhongxiang Wang's (1987), significant findings of direct basal sliding and deformation at sub-freezing temperatures, it is important to appreciate that their measured temperatures of -4°C to -5°C are far higher than Holdsworth's (1974) measured temperature of -17°C for the Meserve Glacier debris-rich basal ice.

In the last eight years, three different glaciers and/or their forefields have been investigated in South Victoria Land, Antarctica. Even though, South Victoria Land has remained cold, dry and stable throughout the Quaternary (Denton et al., 1993; Barrett, 1999) each glacier demonstrates direct or indirect evidence for cold-based glacial activity. The first case study is a revisit of the cold-based Meserve Glacier, Wright Valley where Cuffey et al., (1999, 2000) published evidence for cold-based glacial sliding and entrainment at the nanometre scale, which is manifested at the metre scale in terms of entrained debris. The second case study is from the Suess Glacier, Taylor Valley, where Fitzsimons (1996a) and Fitzsimons et al., (1999; 2001) report subglacial deformation at the cm-scale as well as thrust-block moraines dm long. The third case study (Atkins et al., 2002) documents erosional striae on bedrock and relatively large-scale depositional features (>10m²) in the forefield of the cold-based Manhaul Bay Glacier (informal name), Allan Hills.

3. **THE MESERVE GLACIER, WRIGHT VALLEY, ANTARCTICA**

The Meserve Glacier (Fig. 1) is an alpine glacier, flowing northward from an elongated cirque in the Asgard range. The glacier is about 8km in length and terminates at an elevation of ~400 metres above sea level (masl).

Cuffey et al., (1999) built upon the field work and observations of Holdsworth (1974), theoretical work of Shreve (1984) and Fowler (1986) and laboratory work of Dash et al., (1995) by observing glacier sliding and ice segregation beneath Meserve Glacier and attributing this to the role of thin brine films. The brine films (Fig. 2) are thought to occur at the ice-
rock interface, and vary between 20-40\(\mu\)m in thickness depending on pressure, rock type, surface morphology and ice solute content (Hooker et al., 1999). They argue that these brine films play an important role in ice deformation processes at the base of the Meserve Glacier and facilitate sliding and entrainment of basal fine-grained sediments. Their proposed mechanism is that interfacial films affect the bulk mechanical properties of ice (Cuffey et al., 1999) thereby inducing particle entrainment (Cuffey et
al., 2000). This is achieved by supercooled liquid occurring between ice and immersed particles, which is ‘allowed’ to exist because of the interfacial free energy afforded by separating of the two solid interfaces (Wettlaufer et al., 1996). The supercooled liquid or brine films then permit slip at the ice-rock interface and subsequent entrainment (Cuffey et al., 2000) of silt and sand explaining their occurrence in the basal layers of the Merseve Glacier (Holdsworth, 1974).

It is appreciated that this case study is not a perfect analogue for large ice sheets, but it does provide an excellent first hand account of cold-based glacial erosion and particle entrainment, which over the time scale of millennia has the potential to considerably alter the landscape. For example, ice thickness measurements by radar along the middle portion of the Meserve Glacier revealed a U-shaped trough (Cuffey et al., 2000), suggesting significant landscape modification.

4. SUESS GLACIER, TAYLOR VALLEY, ANTARCTICA

Suess Glacier descends from 1750m on the Asgard Range, terminating within Taylor Valley, which is part of the McMurdo Dry Valleys, a relatively ice free, polar desert in South Victoria Land, Antarctica (Fig. 3). The climatic conditions of the Dry Valleys are unique with summer temperatures rarely above 0°C and the mean annual air temperature (MAAT) ~ -17°C (Keys, 1980). Snowfall is between 5-10 mm yr⁻¹ on the valley floors (Lewis et al., 1998), rainfall unknown and most of the area

![Fig. 3 Location map of Suess Glacier in Taylor Valley. 'L' as in 'L Chad' stands for lake.](image-url)
experiences a moisture deficit (Hooker et al., 1999). Suess Glacier itself is an alpine glacier with a basal temperature of -17°C, hence its classification as cold-based (Fitzsimons et al., 1999, 2001).

During the Antarctic summer season in 1996 a tunnel (2m x 1.50m x 25m) was excavated through part of the Suess glacier basal zone using chainsaws and a demolition hammer. The tunnel was extended in 1997 and a vertical shaft 4.5m high was cut at the end of the tunnel to expose the entire debris zone underneath the glacier (Fig. 4).

![Figure 4: Position of the subglacial tunnel within Suess Glacier, Taylor Valley.](image)

For further information on the methodology see Fitzsimons et al., (1999, 2001). Key observations of the basal ice debris zone in the tunnel made by Fitzsimons et al., (1999) were that parts of the basal substrate had been entrained into the ice and that in many cases this occurred without disaggregation. This observation supports Cuffey et al.,'s (2000) concept of cold-based sediment entrainment, but is further elaborated because deformation of the entrained sediment was also noted. Fitzsimons et al., (1999) observed two styles: (1) the more common ductile structures associated with basal ice having low debris concentrations, such as folds and boudinage (Fig. 5A-B) and (2) brittle deformation within areas of high debris concentration owed to broken blocks of frozen sediment (Fig. 5C).

Direct shear tests also conducted within the basal ice revealed that the amber ice (salt-rich basal ice; Holdsworth, 1974) was significantly weaker than the englacial ice, basal stratified ice and the substrate. This
observation is consistent with the behaviour of amber ice in other Dry Valley glaciers (Fitzsimons et al., 2001). However, at this stage the direct shear tests were unable to provide a clear explanation as to the subglacial process of erosion and entrainment by Suess Glacier as the results showed that the substrate had almost double the average peak shear strength (2.53 Mpa) of the basal ice (1.28 Mpa) and glacial ice (1.39 Mpa) samples (Fitzsimons et al., 2001). Despite this, spatial and temporal variation in the structural strength of the basal ice and its substrate cannot be discounted; for at times peak shear strength readings for basal ice and the substrate were closely matched (Fitzsimons et al., 2001).

Fitzsimons (1996a) also observed well developed (thrust-block) moraines (Fig. 6) at the margins of Suess Glacier, which have important implications when considering the ability of cold-based ice in modifying ice-marginal landscapes (Ehlers, 1996). Moreover, the processes responsible for such features should be considered, as conventional explanations such as an elevated pore-water pressure or Weertman’s (1961) ice-debris accretion hypothesis require abundant subglacial meltwater. Three proposals made by Fitzsimons (1996a) for the formation of these thrust-block moraines
Fig. 6  Part of the north-east snout of the cold-based Suess Glacier. The smaller moraines in front of far larger ones are low sandy ridges (highest is approx. 20 m high) consisting of blocks of planar-bedded sand inferred to be thrust-blocks of fine-grained deltaic sediment (Fitzsimons, 1996a).

include: (1) sediment block entrainment linked to frozen-bed deformation, (2) entrainment by over-riding and accretion of debris aprons and marginal ice and, (3) temporary wet-based conditions as Suess Glacier flowed into one of its ice-marginal lakes. Certainly, the two former conclusions are significant when considering the fact that cold-based ice masses may in themselves (without an external input such as water from a lake) entrain, deform and deposit their substrate, which in turn alters their ice-marginal geomorphology.

5. THE ALLAN HILLS, ANTARCTICA

The Allan Hills are a low lying nunatak located high in the TAMS of South Victoria Land (1600-2100 masl; Fig. 7A-C). The centre of the nunatak is occupied by the cold-based Manhaul Bay Glacier (informal name), which is approximately 6km long and 200m thick. It flows into the centre of the Allan Hills from the north and exposed areas of its snout are bubble rich and fractured. This points towards former glacial advance by ice block apron overriding (Shaw, 1977a); a common observation for some cold-based glaciers in South Victoria Land (Chinn, 1985, 1989, 1991).
Atkins et al., (2002) reported four types of erosional and depositional features, which they attributed to an advance of the Manhaul Bay Glacier at the Last Glacial Maximum (LGM). ‘Type I broad scrapes’ occurring on sedimentary bedrock, are up to 500mm wide, 40mm deep and 1200mm long (Fig. 8). They are unweathered and consist of many smaller striae cms and mms in width. On several occasions the abrading tool is also observed at the striae terminal wall, and cm-scale levees occur along the sides of the abrasion marks. ‘Type II individual striae and grooves’ are linear, often isolated and typically cms in width and dm long. Some have a ‘nailhead’ morphology or maintain a more tapered form with veneers of crushed sandstone on local bedrock surfaces. ‘Type III are unweathered scrapes’ found on the stoss side of lodged, weathered dolerite boulders within or
upon the Sirius Group tillite. The scrapes are thin, but a striking contrast to the ventifacted varnish of the weathered boulder. 'Type IV ridge and groove lineations' are fine parallel lineations displaying a sheen similar to slickensides and are found in carbonaceous layers of sedimentary bedrock. Type I and II erosional features are only found close to the snout of the Manhaul Bay Glacier, whereas types III and IV are more widespread throughout the Allan Hills.

The depositional landforms are more varied in form and distribution than the erosional structures. 'Type I' are 'sandstone and siltstone breccia' that are un lithified, friable deposits <30cm thick and <3m across and are recognisably composed of the immediate sedimentary bedrock (sandstone and siltstone). The deposits are usually found on up-glacier escarpments or vertical walls, and occasionally have a linear form tapering away from the glacier snout. 'Type II isolated boulders' are up to 3m in diameter and dispersed throughout the Allan Hills, up to >2km away from the Manhaul Bay Glacier. On the lee side of several promontories the boulders form a train. 'Type III ice-cored debris cones' have been observed as far as 1km inland from the Manhaul Bay Glacier and range in size from 3m high to 7m in diameter. In each instance, the ice-cored cone is covered in loose bedrock debris (ranging in size from sand to boulders). The 'type IV sandstone debris on lee slopes' (Fig. 9) is crushed and toppling bedrock on the lee side of bedrock promontories or northern face of depressions. The
scale of the features range from <1m through to 10m²+, and are characterised by extensional fractures sub-parallel to the margin of the Manhaul Bay Glacier.

Atkins et al., (2002) followed the principal of Drewry (1986) and inferred that the type I and II striae are the result of glacial ice dragging debris over or upon the bedrock as a result of basal slip or forward movement. The abrading particles were observed to be the same lithology as the bedrock, with little contrast in hardness explaining the broad shallow form of the striae and presence of broken, crushed fines that are likely to be sheared remnants of the former striating tool. These have survived because no meltwater has washed them away. A similar process was inferred for the type III forms where basal debris came into contact with wind-polished boulders lodged in tillite and projecting upglacier. The fastened status of the boulders meant they were not entrained, but nonetheless abraded and occasionally overturned. Fourthly, the type IV were interpreted by Atkins et al., (2002) to be a glaichtectonic structure formed by differential slip on the thin and weaker carbonaceous siltstone layers within the bedrock in response to increased shear stresses on the lee side of bedrock promontories. The type I depositional debris, is local failure and crushing of up-ice bedrock promontories, which is proposed to constitute a form of glaichtectonite (Pedersen, 1988; Benn and Evans, 1998). The type II scattered boulders are the result of glacial plucking and passive englacial
transport, because no abrasive marks are associated with the boulders, as might be expected if they were basally transported. The type III ice-cored cones are interpreted to be passive deposition features formed by retreating glacial ice being covered in loose debris that have subsequently been preserved in the cold and hyper-arid climate in the Allan Hills. The final type IV depositional structure is interpreted to be glaciitectonic in origin, where cavities on the lee side of bedrock promontories facilitated tensional fracturing and toppling of bedrock knobs or promontories downslope and down-glacier.

6. SUMMARY

This chapter has reviewed three Antarctic case studies which illustrate cold-based glacial sliding, entrainment, erosion and deformation at increasing scales of impact. The smallest scale is demonstrated by Cuffey et al.,’s study (1999, 2000) where brine films 20 and up to 40m thick are responsible for particle by particle entrainment of silt and sand fines into basal ice. On a marginally larger scale, Fitzsimons et al., (1999) provide a first hand account for ductile and brittle deformation of such entrained basal debris, even though the mechanism for this remains elusive, because of the substrate’s higher shear strength when compared to basal or clean glacial ice (Fitzsimons et al., 2001). At a larger scale, mechanisms for thrust-block moraine formation by the Suess Glacier were proposed by Fitzsimons (1996a) and the geomorphological potential for cold-based glaciers realised. The largest scale, and one that involves lithified bedrock as opposed to soft sediment substrate, is illustrated by Atkins et al., 2002. Here mm and cm scale striae are found in conjunction with depositional landforms >10m² in size.

In an oral presentation to the Antarctic Earth Science community, Lloyd Davies et al., (2003) stated that the preservation potential of the above cold-based glacial features is very low beyond polar climates, such as Antarctica, because of the rapid weathering in sub-polar and temperate regimes. They argued that this explains the perceived absence of cold-based glacial activity in the Pleistocene record of today’s temperate regions which most likely experienced cold-based glaciation during past glacial maxima. Examples include the apparently palimpsest landscapes of Scandinavia and North America.
Case studies: Antarctic cold-based glaciers

The vast majority of research and theories to date concerning the subglacial environment are derived from observations and measurements made from temperate-based glaciers (Hart and Rose, 2001). However, it is hoped that this paper will prompt other earth scientists to shift attention towards the cold-based subglacial environment, especially as its character appears to differ significantly from temperate-based glaciers.

7. CONCLUSION

In conclusion:

- There is a developing tension between glaciologists, modellers and geomorphologists regarding the ability of cold-based glaciers to interact with their substrate and ice-marginal environment, so to result in landscape modification.
- There is a momentum of evidence pointing towards cold-based glacial erosion, entrainment, deformation and deposition on both soft substrate and lithified bedrock. Therefore, any glacial geological record, however inconspicuous, might be attributed to cold-based glacial ice (keeping in mind all other variables such as the sedimentology and environmental context).
- We accept that many landscapes may experience significant periods of cold-based coverage with no or minor modification. However, the assumption that cold-based glaciers are utterly inert and their landscapes completely unscathed should be abandoned. This, in particular, has implications for modelling ice sheet dynamics (cf Näslund et al., 2000, 2003) or automatically equating glacially modified landscapes to temperate-based glaciers only.

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“Research is what I'm doing when I don't know what I'm doing.”

Wernher von Braun, 1912-1977