

## **The shape of glacial valleys and implications for southern African glaciation**

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### **Abstract**

The classic U-shaped valley is a typical expression of glacial erosion, but situations can occur where the glacier effects little to no change in the landscape. Such an occurrence would be where the glacier is cold-based and remains so during its demise – never entering into a warm-based (erosional) phase. Here two present-day examples are provided where glaciers exist but valley form has remained unaltered despite multiple glacial events. The key to such a situation is suggested to be the altitudinal/latitudinal spatial location such that the ice has completely disappeared before, during the move towards an interglacial, there is the time for it to transform into warm-based ice. The argument is then made that perhaps the same is the situation for the reconstructed, small glaciers in the Lesotho-Drakensberg area. The ice was cold-based due to a combination of its thinness and the cooling effect of shading. Cold-based ice would explain the lack of striated clasts found in the moraines, the absence of any change to valley form, and the preservation of breaks in slope observed in the area of the former glacier.



## **1. Introduction**

Simplistically, consideration of a glacial geomorphology (e.g. Benn and Evans, 1998, Fig.9.42) or general geomorphology (e.g. Trenhaile, 2004, p.164) text will indicate that non-glaciated valleys have a typical fluvial V-shaped form while glacial modification evolves this V-shape into a U-shape. Ultimately, a strong indicator of glaciation is this “typical” U-shaped form (Fig. 1). While this is clearly so, and not in contention, the question arises as to the possibility, under certain conditions, of a fluvial valley containing a glacier that fails to modify the V-shape. Benn and Evans (1998, p. 351) provide an excellent review of literature and thought regarding the development of the U-shaped glacial trough. Notably they (Benn and Evans, 1998, p. 353) identify the work of Sugden (1974) who suggested that some hanging valleys “may exhibit little or no evidence of glacial erosion and may retain pre-glacial profiles, particularly in areas where the ground adjacent to troughs was occupied by thin, cold ice” – the essence of what is to be presented here. Although Atkins et al. (2002) have shown that it is possible for cold-based glaciers to abrade, nevertheless cold-based ice is less dynamic in regard to erosion than the warm-based ice associated with large glacial troughs.

In essence, for the preservation of the original V-shape, it must be such that the ice does not erode, so preserving the original valley form. To achieve this, it is argued, not only does there need to be cold-based ice within the valley but that during the warming associated with deglaciation the ice does not transform into warm-based ice – and hence become a more effective eroding agent. Sugden (1974) provides a number of arguments regarding the absence of a glacial impact on ice-covered terrain. An obvious key attribute is that the ice is cold, and that this may be due to it being thin, and thus does

not achieve its pressure melt point and thereby facilitate basal slip and hence erosion. It is argued (Sugden, 1974, p. 191) that topography “is a local variable which is likely to have some effect on the distribution of landscapes with little or no glacial erosion. The position and altitude of a massif may be such that it is covered only thinly by ice, and basal temperatures may never rise to pressure melting point”; essentially the argument that will be made here with respect to certain valley glaciers. Sugden (1974, p. 191) also observes that the presence of porous rocks reduces glacial erosion by decreasing the ability of the ice to maintain basal water.

Given the presence of cold-based ice, so it is necessary to formulate why, during deglaciation, it may not change its thermal state, become warm-based, and so begin erosion. Two main (possibly complementary) reasons to explain this possibility occur: (1) that the ice is very thin such that it disappears before it can change its thermal state (essentially the argument of Sugden, 1974), and/or (2) that, despite its thickness, it is in a topographic location such that throughout its demise it remains in a cold state (a variation of the first argument). Possible examples of both situations are provided together with evidence of a distinct V-shape being retained, even with a glacier present within the valley.

In respect to southern Africa, there has been much discussion regarding possible glaciation (e.g. Nel, 2001; Boelhouwers, et al., 2002; Boelhouwers and Meiklejohn, 2002; Sumner, 2004; Mills and Grab, 2005; Mills, et al., 2009a & b; Carr et al., 2009) that has recently taken on some degree of rigour through the work of Mills (2006). Part of the problem with the identification of glaciation in this region has been the absence of an (uncontestable) glacial footprint, such as moraines or U-shaped valleys. The work of

Mills (2006) has identified a number of depositional landforms, the evidence for which appears to support a glacial (moraine) origin. To date, glacial erosional landforms have not been found, and the former glaciers reconstructed by Mills (2006) fail to show any glacial erosional imprint. Although an explanation for this absence of erosional form has not been previously discussed, it is here suggested the absence of (resulting glacial) form may, if indeed the landforms are of a glacial origin, be due to the presence of cold-based ice that effected no impact on the underlying relief.

## **2. Glacial valleys *not* exhibiting a typical U-shape cross-section**

### *2.1 Example 1: Tibet*

In the Kunlun Mountains of Tibet (35° 50'N, 94° 05'E; 4,800-5,000 m a.s.l.) are to be seen a number of small, cold-based glaciers (Ding, et al., 2006) within distinctly V-shaped valleys (Fig. 2). These glaciers exist within a valley form strongly indicative of a fluvial, V-shape (Fig. 3) and, despite the longevity of glacial presence (Liu, et al., 2006), appear to have effected no change whatsoever on that original fluvial form. It is here suggested that because these glaciers are cold-based and so they are unable to significantly change their valley form and, due to their small size, will disappear before they can transform to a warm-based glacier. Thus, upon their demise there will have been no impact on the valley form that would indicate the former presence of a glacier. Thus, as can be seen in Figure 3, there is a sharply V-shaped valley within which there is presently a glacier and that, available evidence indicates, this valley may have experienced glacial episodes for perhaps as long as 1.5-2.4 Ma (Kidd and Molnar, 1988) and certainly since 700-500 ka BP (Liu, et al., 2006).

## *2.2 Example 2: Antarctica*

In the Terra Nova Bay region of Antarctica (74° 41'S, 164° 07'E), the Priestley Glacier (Fig. 4) is one of five glaciers that drain Eastern Dome C, southern Talos Dome and northern Taylor Dome of East Antarctica (Frezzotti, et al., 2000). Until the Late Miocene, glaciers in this area were temperate but since then have been polar such that “present-day glacial erosion is negligible and denudation has been exceedingly slow since 7.5Ma” (Baroni, et al., 2005, p. 212). As discussed at length by Baroni, et al. (2005) there has been much argument regarding the possible fluvial origin of the initial valley network within this region, a fluvial network that was then modified by glacial erosion. It has been suggested that the fluvial landscape predates the Miocene and that it was eroded by warm-based ice (e.g. Prentice, et al., 1998). Within the context of the present argument, the key attributes are the possible fluvial origin of the valleys coupled with the lack of glacial impact for the past 7.5 Ma. During fieldwork within this area the British Antarctic Survey undertook flights utilizing a new radar system to map sub-glacial conditions in this region. In one flight over the Priestley Glacier, the (rough output field) data analysis (Frearson, Pers. Comm., 2005) indicated a sharply V-shaped valley, below the present ice, high up on the side of the large (>3 km deep) U-shaped Priestley Glacier trough. It was but one cross-section and there is no knowledge regarding the linkage of this valley to the proposed drainage network (Baroni, et al., 2005). However, what was extremely clear was that this valley, which was quite deep (c.300 m or more), had maintained (as exemplified by radar imagery) an extremely sharp V-shape with no indication of any glacial modification of cross-sectional form. It is suggested that this is a

palaeo-fluvial valley that has not, in terms of cross-sectional form, been modified by glacial ice. The location, high up on the side of the larger Priestley trough, suggests that as present (cold) ice is lost so this valley becomes ice-free without experiencing any warm-based ice due to its altitude (somewhat akin to example 1 above) while the Priestley Glacier, that goes down to sea level, does, at a later stage in deglaciation or at the start of glaciation, experience warm-based ice as exemplified by the large U-shaped trough in which it resides. Due to the altitude and polar position, during the on-set of glaciation the higher level valley is filled with cold-based ice and so the valley form is maintained.

### *2.3 Summary*

Thus, the argument is made that, under certain conditions whereby the ice within a valley remains cold throughout its presence there, a glacial valley may not evolve into the classic U-shape generally associated with glaciation. Clearly the spatial/temporal conditions are highly limiting and appear to be related largely to altitude; aside from the substrate arguments made by Sugden (1974). Whatever the case, that valleys can maintain their fluvial V-shape despite their temporal occupation by glaciers, appears possible (e.g. Fig. 3). Clearly more work is required, but such work needs to be founded upon the conceptual possibility of glacial valleys *not* necessarily experiencing modification of form.

### **3. The South African context**

There has been much discussion regarding possible glaciation in southern Africa (see Hall, 2004, In Press; Osmaston and Harrison, 2005; Mark and Osmaston, 2008 for reviews) but recent work by Mills (2006) has provided the first scientific evidence

pointing to a possible limited glaciation in parts of the Lesotho-Drakensberg area. Mills (2006) and other workers (e.g. Grab, 1996; Mills and Grab, 2005; Mills et al., 2009) have used the term ‘niche glacier’ but seemingly without adequate recourse to the discussion on this form of glacier by Groom (1959). Accepting the possibility of glaciation, so the terminology may be important and may be significant within this present discussion. In the original use of the term by Drygalski, (1911), *Nischengletscher* included all forms of ice located in hollows of valley sides, peaks and ridges, but with the caveat that they all “enlarge to a funnel shape” (Groom, 1956, p. 370). Further, Salisbury (1895) had described glaciers of similar form (the ‘funnel shape’) on the cliffs of Greenland as “cliff glaciers”. Although the type-case glaciers in Bünsow Land, central Vestspitsbergen, were first defined as “slab glaciers” (Sweeting and Groom, 1956, p. 640), these were subsequently reclassified as “niche glaciers” (Groom, 1959). As discussed by Groom (1959, p. 371), such a glacier is defined in the following manner: “The triangle of ice normally has a slightly convex surface profile and lies in a shallow funnel-shaped hollow developed on steep slopes with gradients up to 42°.” Further, Groom (1959, p. 371) notes five forms of niche glacier, all of which are (in some manner) characterized by a “funnel-shaped” form. Of the three “niche” glaciers identified by Mills (2006, Figs 10.6, 10.8 & 10.9), only that for the Leqooa Valley (Fig 10.9) has what might be deemed a niche glacier form according to Drygalski (1911) or Groom (1959). However, from the three-dimensional reconstructions (Mills, 2006) all have a slightly convex profile and, more importantly for the arguments here (see below), all are very thin.

Significantly, Groom (1959, p. 374) notes “While variation in lithology is necessary for the development of the breaks of slope on which niche glaciers originate,



lithology also controls the shape of the hollow which subsequently develops.” Further, it is suggested that the niche glacier form becomes “rounded”, but is later incised by running water (during ice loss) that can create a gully. The (lithology-induced) step form within the hollow is seemingly maintained and not destroyed by glacial action. At the southern African site there are clearly the required breaks in slope, the rounded form and the incised gully, *but* the (required) classic (p. 374) “rounded half-funnel-shaped hollow” appears not to be present – at least as modeled by Mills (2006). However, in fairness, Mills (2006) does not refer to the works of Salisbury (1895), Drygalski (1911), Sweeting and Groom (1956) or Groom (1959), so the knowledge regarding niche glacier form was not there and thus the term was used somewhat ‘loosely’ as a positional descriptor. Recognizing this, it is only fair to ask whether, given the knowledge of work associated with the term, the form of the reconstructed glaciers (for which only parts of the boundaries, as shown by moraine remnants, are available) may not have been more ‘funnel shaped’ – as Fig 5 indicates is not, necessarily, unreasonable. Based on the detailed study of Mills (2006) the previous recourse to niche glaciers by Grab (1996, p. 400) is discounted as this applies Groom’s (1959, p. 372) model of “plateau ice overflow” as the originator of the niche glacier and evidence (e.g. Mills, 2006) is clearly (presently) lacking for this.

The questions, not covered by Groom (1959), or other researchers, outside of the suggested application of nivation, are the maintenance of form (the rounded form rather than a “glacial” imprint) and that the breaks in slope are not also destroyed by glacial action (in the Groom study there was not sufficient time or change in conditions for the breaks in slope to develop *subsequent* to ice loss). Neither Grab (1996) or Mills (2006)

identified these issues or saw them as a glacial question, possibly assuming that the development of breaks in slope were post-glacial in origin. However, it is not unreasonable to suggest that, if the moraine form is able to be maintained since the Last Glacial Maximum, the breaks of slope may not be (at least entirely) post-glacial in creation. Thus, as has been shown (Mills, 2006), the ice was very thin, therefore there is the possibility that it may have been cold (rather than temperate in nature). If analogous to the situation presented here for Tibet, then the presence of the ice, while not maintaining a V-shape (there not being one to start with) rather kept (i.e. did not destroy/modify) the somewhat rounded outline and the breaks in slope – it simply did not leave an *erosional* glacial imprint; the question will, though, arise as to how the moraine was formed. This notion of cold ice is not necessarily an obtuse idea as Mills (Pers. Comm., 2009) noted that she had not found any glacially striated clasts (although this may relate to weathering of the basalts post glaciation). Last, although more recent research (Nel and Sumner, 2008) has suggested temperatures may not be as low as previously thought (Grab, 1994), nevertheless the MAAT may have been in the order of -1°C to -3°C (Grab, 1996) and that, coupled with the shadow effects (Mills, 2006) at these sites may have produced temperatures conducive to the very thin ice being cold. Thus, given the present suggestions of:

- 1) small, very thin glaciers,
- 2) an absence of a glacial erosional imprint on the valley,
- 3) lithological breaks in slope within the valleys being maintained,
- 4) an absence of striated clasts, and
- 5) a low MAAT coupled with localized shading effects on temperature

so it is *possible* that the ice (if present) may have been cold-based.

Two main (critical) questions arise from the above hypothesis. The first, more broad-based, relates to the assumption of a U-shape as a glacial valley form. The second question, is the reality of cold ice to the southern African situation and the problems that arise from that: (a) could there be such localized cold ice, (b) if there were, how were the moraines formed, and that leads to (c) are they indeed moraines? In respect of the issues in Question Two, these are (at this point) somewhat rhetorical and are avenues for new research, not the least being confirmation that the ridges are of a moraine origin as so much hinges on this assumption; the questions raised below having not been tackled (recognized?) by either Grab (1996) or Mills (2006). While Mills (2006) certainly provides valuable new information, the question must still arise as to the (unequivocal) origin of the ridges. If indeed moraines, then quite how were they formed? If warm ice, why so little impact on the landscape, if cold ice then what was the transport mechanism? Can it be over (glacier) ice transport to produce a ridge (akin to proglacial rampart formation but here over ice rather than snow) that is not truly (*sensu stricto*) a 'moraine'; thus explaining the absence of striated clasts and negating the necessity to explain glacial transport? If not moraines at all – then what is the origin? Might they be related to simply nivation and be akin to proglacial ramparts (*sensu strictissimo*) or might they be pseudo-ridges due to incision of old fluvial sediments? Given the, at this time, good evidence for glaciation, then perhaps the argument that the ice was cold is the best solution *if* an origin for the moraines can be found? That (normally) cold ice requires environmental conditions associated with permafrost – and hence permafrost-related landforms – may

not be too big a stumbling block once the highly localized nature of the “cold” is recognized. Perhaps, through such as the boulder streams (Boelhouwers, et al., 2002), or “rock glaciers” as suggested by Grab (1999), there is wider evidence for cold, possibly permafrost, conditions. This, though, is equally as contentious as is the presence of glaciers and unresolved at this time.

In respect to Question One above, there are really two issues – that of the form of glacial valleys and, flowing from this, the ‘rounded’ nature of the hollows in respect of both niche glacier hollows and the hollows here in the Drakensberg. As Graf (1970) argued sometime ago, the cross-section of a glacial valley is that of a parabola and it is only where (p. 310) “the intensity of glaciation increases, the form of the valley changes to become relatively more narrow and deep”. Thus, there is no reason why low intensity, highly limited erosion would not produce a shallow parabola rather than the “classic” deep U-shaped valley. The questions with respect to the present study would be (a) was there adequate activity to produce the moraine, and if so (b) why did it not remove the step forms found within the feature? That Groom (1959) refers to a “rounded” attribute to the hollow would seem at odds with the presence of cold ice and its lack of impact on the landscape. However, that the snow/ice (Mills, 2006) occurs in rounded hollows may but reflect the original hollow form (rounded and not subsequently impacted by cold ice). The role of rock control may also be significant, the more so as Whalley (pers. Comm. 2010) notes that the valleys in this region that flow to the South are V-shaped.

Ultimately, the notion of thin, cold-based ice is as equally contentious and problematic as are the other reconstructions and suffers, as they do, from a lack of reliable evidence. The extrapolation from other (currently more severe) cold environments to this part of Africa is not as problematic as has been suggested (Boelhouwers, Pers. Comm. 2010) as reconstructions of the Drakensberg/Lesotho palaeo-climate are still in a state of flux and, as with permafrost, small, highly location-specific sites may have been cold enough to sustain small, thin cold-based glaciers. It is the absence of ancillary information that is the problem – the (unequivocal) identification of the presence of permafrost would solve many problems as, for example, Benn and Clapperton (2000) suggest the presence of thin, cold ice at the margins of Patagonian glaciers based on evidence for permafrost. Rather, it is the corollaries that become just as important – if not cold, but rather warm-based, then where is the suite of evidence for that? If not ice, then what is the origin of the ‘ridges’. Thus, Mills (2006), in providing much new evidence, has begged many new questions. Certainly, it is clear, the argument for cold-based ice has many problems as well, and yet it offers some answers to questions raised (indirectly) by Mills (2006) – whilst begging others. That presented here but offers another ‘thought’ to add to the already extensive controversy and significant question regarding the question of glaciation in the Lesotho/Drakensberg region of southern Africa.

#### **4. Conclusions**

Although glaciated valleys will normally exhibit evidence of glacial modification, there can be situations where there is no glacial imprint. Within the present context, the most common situation wherein a glacier effects no modification of its valley is that where the

glacier is cold-based and, during retreat, disappears before it transforms into a (more effective modifying) warm-based glacier. Thus, there can be situations where a glacier has been present but there is little to no erosional evidence of its former presence left in the landscape. Utilizing this notion, so it may be that the very thin and small glaciers reconstructed for the Lesotho-Drakensberg region may (if they existed), due to that very thinness coupled with shadowing, have been cold-based. If this were so then they would have effected little to no erosional change in the landscape – an attribute clearly evident today. Although it can be argued that post-glacial weathering has destroyed any evidence of erosion, this is countered by the longevity and clarity of the observed moraine forms. The possibility of cold-based ice would not only explain the absence of glacial form, but also (to date) the lack of glacial imprint (e.g. striations) on clasts and the maintenance of lithological breaks in the slopes where the glaciers once were. Such an hypothesis is not at odds with the present glacial reconstructions and helps explain some of the perceived anomalies but, in so doing, begs many other questions and the need for much new research, clear thought, and open minds.

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proactive discussion and help – her doctoral dissertation being the first rigorous work on this highly contentious topic. One can but hope that the future may bring more collaborative, open, rigorous work on this fascinating issue. I would like to thank Profs Brian Whalley and Jan Boelhouwers for many thoughtful and valuable suggestions on this paper; where I fail to answer the questions/problems raised, I leave it to them, and others, to show the way.

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## **Figure Captions**

Fig. 1: A typical U-shaped valley (from Île Kerguelen) exhibiting the classic steep valley walls and narrow form.

Fig. 2: A view of the Kunlun Mountains (Tibet) showing both V-shaped valleys and what might be inferred as typical niche glacier forms.

Fig. 3: Close-up of a glacier (snout) in a sharp V-shaped valley in the Kunlun Mountains near Xidatan, Tibet.

Fig. 4: A view inland of the Priestley Glacier near Terra Nova Bay, Antarctica.

Fig. 5: View of the former glacier site showing a lateral moraine together with a possible reconstruction of the glacier form (photo I. Meiklejohn).