

Beyond confusion: Rock glaciers as cryo-conditioned landforms

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ABSTRACT

Whether rock glaciers are permafrost creep features or may also be related to glaciers in non-permafrost environments, and whether they should be defined by genesis or appearance, have caused heated debate for several decades. This paper analyses the rock glacier debate from a theoretical viewpoint, in order to highlight and discuss underlying problems and with the aim of providing a common conceptual framework from which to proceed. It is suggested that the morphological rock glacier definition should be abandoned. A new genetic definition is proposed where permafrost is the primary condition, but where the deforming ice/debris may be of both glacial and periglacial origin.

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1. Introduction

The term 'rock glacier' has been used to describe or categorize a group of landforms with origins ranging from creep of mountain permafrost (e.g. [Haeberli, 1985](#); [Barsch, 1996](#)), glaciers (e.g. [Humlum, 1988, 1996](#)) and rock avalanches (e.g. [Johnson, 1984](#)). Landforms regarded as active rock glaciers consist of a coarse debris layer, covering ice supersaturated debris or pure ice. Despite the large number of papers written to discuss what exactly a rock glacier is (e.g. [Hamilton and Whalley, 1995](#); [Haeberli, 2000](#)), the rock glacier term remains contested. One position is what I will refer to as the permafrost creep school (e.g. [Haeberli, 1985](#); [Barsch, 1996](#)), which is more or less equivalent to that arising from the single most influential paper on rock glaciers ([Wahrhaftig and Cox, 1959](#)). The competing stance is that rock glaciers also can develop from true glaciers, and that the rock glacier term represents a continuum with respect to mixing of ice and debris from variable sources. This view will be termed the continuum school in the following. Some authors ([Whalley and Martin, 1992](#); [Whalley and Azizi, 2003](#)) continue to incorporate catastrophic rockfalls/rock avalanches in the 'rock glacier' term, but I will pay little attention to this view in the following.

Between these schools there is not only a disagreement on the content of the rock glacier term, but also about the foundation on which to define a landform. The permafrost creep school emphasizes processes and genesis, and following [Haeberli \(1985\)](#) 'Active rock

glaciers are the visible expression of steady-state creep of supersaturated mountain permafrost bodies in unconsolidated material'. The continuum school claims rock glaciers should be defined by morphology, e.g. like [Potter \(1972, p. 3027\)](#): 'A rock glacier is [...] a tongue-like or lobate body usually of angular boulders that resembles a small glacier, generally occurs in high mountainous terrain, and usually has ridges, furrows, and sometimes lobes on its surface, and has a steep front at the angle of repose.' Following morphological definitions, a rock glacier could then be the product not only of permafrost or glacial processes, but also of rock avalanches (e.g. [Whalley and Azizi, 2003](#)).

This paper analyses the rock glacier controversy itself from a more theoretical viewpoint, in order to highlight and discuss underlying problems and with the aim of providing a common conceptual framework from which to proceed. Throughout this paper, I shall refer to 'rock glacier' without any pretension of preciseness, but when necessary I shall follow [Humlum \(1988\)](#) and use 'talus-derived rock glaciers' and 'glacier-derived rock glacier' to differentiate between opinions. Further, I will only consider active landforms. As the debate partly is on the foundation of landform classification, the paper starts with a brief discussion on the theory of ordering systems within science and the question on 'natural kinds', which will be further linked to discussions on reductionism and emergence in geomorphology (e.g. [Harrison, 2001](#)). Then, the contentious issues in rock glacier science are evaluated and discussed, before the present rock glacier definitions are examined. Finally a new definition is proposed, and linked to the concept of cryo-conditioning as a basic control on landform and landscape development in cold regions ([Berthling and Etzelmüller, 2011](#)).

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2. The limits of classification schemes, 'natural kinds' and the role of landforms

Ordering systems have always been a controversial issue within the sciences, but aid communication and are basic to all forms of science. Mayr and Bock (2002) argue that some kind of ordering system is necessary even a priori to scientific explanations, and that *scientific* ordering systems (including classification) never are theory-free. Artificial classifications are constructed for a specific purpose and based on a limited number of criteria, whereas natural classification schemes have been defined as "those that correspond to the fundamental theory of the particular science" (Mayr and Bock, 2002, p. 172).

Classification in geomorphology involves the problem of separating different topographic elements from each other – across a continuous topographic space and according to the appropriate spatial scale – from either human observation (traditional geomorphological mapping) or supervised computer-aided classification, or automatically through unsupervised classification procedures (specific geomorphometry). Due to the rapid current developments in GIS and remote sensing, most present discussions on landform classification are related to computer-aided techniques. Recently, Minar and Evans (2008) discuss how topography can be classified through considering a set of basic 'elementary forms' that are indivisible at a specific scale. Landforms may then be classified based on a composition of elementary forms. Minar and Evans (2008, p. 237) seem to consider the 'elementary forms' as 'natural kinds': "... the most specific geometrical (and simultaneously genetic) geomorphic individuals [...] might be described as 'natural'."

'Natural kinds' is a concept that is meant to represent groups or entities that are 'natural' in the sense that they are objective, mind-independent and bound by natural laws at the appropriate scale. Landforms are one main candidate for 'natural kinds' in geomorphology. However, the real existence of natural kinds remains controversial, also in the geomorphological context (Rhoads and Thorn, 1996; Inkpen, 2005; Slaymaker, 2009). Landforms are evolutionary features and it could be argued that only the processes (or the natural laws) are the 'real' components of the landscape, while the landforms are artifacts of the human mind due to the characteristic time scale of human observation. One possible extension of such a reductionist view is that the focus of research should be on processes only, and that classification of the land surface into landforms is an artificial human construction and thus either a matter of present theory (genetic classifications) or convenience (morphological classifications). On the other hand, some landforms probably are emergent properties of complex interactions between processes and the environment. Such landforms would be candidates for 'natural kinds' in geomorphology. Another main reason for giving landforms a scientific status is that they probably represent for geomorphology the ordering system considered by Mayr and Bock (2002) necessary a priori to scientific investigations.

3. Rock glaciers – the contentious issues

This section first provides a brief overview of the rock glacier controversy, followed by a discussion of the issues that are, in my opinion, at the center of the debate. For a fuller treatment of different aspects of rock glaciers, see Martin and Whalley (1987), Whalley and Martin (1992), Hamilton and Whalley (1995), Clark et al. (1998) and Haeblerli et al. (2006).

The continuum school has presented discussion papers where classification schemes and models for development and displacement of rock glaciers have been reviewed and developed (e.g. Martin and Whalley, 1987; Whalley and Martin, 1992; Clark et al., 1994a, 1998; Hamilton and Whalley, 1995); however, they have seldom presented ample measured evidence. A main argument has been that one should

adopt the original morphological description of Capps (1910) as a basis for rock glacier classification, rather than one founded on genesis. This view is discussed further below. Although the continuum school recognizes a periglacial origin for some rock glaciers, it is claimed that 'the mechanisms by which such [permafrost] ice accumulates, particularly in pre-existing, steeply dipping rubble, are poorly understood and largely untested' (Clark et al., 1998, p. 179). Some earlier works also dismissed a periglacial origin entirely, on the grounds that talus slopes would not develop ice contents high enough to overcome the yield stress (Whalley, 1983).

The permafrost creep school emphasizes that in a permafrost environment, subsurface ice may develop from a range of processes – including burial of surface snow and ice (Haeblerli, 2000). In discussions on whether specific features are creeping permafrost or debris-covered glaciers (Haeblerli, 1989; Jakob, 1994) they tend to claim that there is often little evidence to support the glacier-derived interpretation of a certain 'rock glacier' landform. They certainly acknowledge, however, the possibility of incorporation of sedimentary ice in the permafrost (e.g. Haeblerli, 1989; Haeblerli and Vonder Mühll, 1996; Käb et al., 1997; Haeblerli et al., 2006). This school has undisputedly provided the best available field data on rock glacier internal structure, thermal characteristics and surface and subsurface deformation available (see references in Haeblerli et al., 2006).

The rock glacier controversy is often conceived as a discussion about whether a debris-covered glacier with some visual resemblance of a rock glacier (often termed 'glacier-derived' or 'ice-cored' rock glaciers in the literature) should be classified as a rock glacier. If classification only was the issue, and thus the confusion was *only* about names, it should be possible to agree upon a reclassification of these features simply into (a) debris-covered glaciers and (b) rock glaciers (or another more appropriate term). To some degree, this is a valid argument, as proponents of the continuum school partly use 'debris-covered glacier' and 'rock glacier' without any clear distinction (e.g. Clark et al., 1994b; Konrad and Clark, 1998). Three problems demonstrate however that the confusion is not only about classification. First, the terms 'glacier-derived' and 'ice-cored' are poorly defined terms. Second, the proposed continuum between a glacial and a periglacial origin of rock glaciers suggests that it would be difficult to draw the line between debris-covered glaciers and rock glaciers. Third, and probably most important, 'permafrost' is a well-defined term with respect to temperature conditions, but *not* with respect to materials.

3.1. The case of a glacial ice core

As used in the literature, the term 'glacier-derived' describes both (1) the main origin of the ice in the rock glacier and (2) a situation where a glacier in some way has developed into a rock glacier. It should be stressed that although these are not identical cases, they are mostly treated without distinction. The term 'ice-cored' was coined by Potter (1972, p. 3027): 'rock glaciers that are composed of relatively clean glacier ice that is mantled by debris will be called ice-cored rock glaciers.' As stressed by Haeblerli (2000) and Haeblerli et al. (2006), however, the meaning of 'glacier ice' is not clear, both because glaciers receive their ice from a variety of different sources and processes, and also because this ice changes through time due to glacial deformation in a similar way as in rock glaciers (flow metamorphism). What Potter (1972) goes on to describe for this 'ice-core', is how ice is formed from windblown and avalanching snow, and later covered by debris further downglacier. This description is compatible both with accumulation on a normal glacier and the situation in the perennial snow banks so typical for alpine permafrost environments. A positive mass balance over years (depending on temperature and accumulation rate) is necessary for this snow to be transformed into sedimentary ice at depth, and decades to centuries would be required for such sedimentary ice (material) to develop into a glacier (a topographic

entity). No long term mass balance data are available from the Galena Creek rock glacier (Potter, 1972), but ice core data presented by Steig et al. (1998) underscore that the mechanism may apply. This mechanism, however, relates equally well to permafrost as to glacial environments. Further, this mechanism requires that a positive ice mass balance is maintained only in a very narrow ribbon along the foot of slope, so that rock material mainly will be added beneath the equilibrium line and therefore not buried by snow/ice. As such, this model fits well for an alpine permafrost environment where snow accumulates in excess in narrow zones due to wind-drift and avalanches. It cannot be called upon as a general model for how a glacier continuously develops into a rock glacier.

Haeberli et al. (2006) state that even with sophisticated investigations it is difficult to distinguish 'glacier ice' from 'permafrost ice'. Thus, the many visual observations of 'glacier ice' presented in favor of 'glacier-derived' rock glaciers (e.g. Whalley et al., 1994) seem to be of little value. Haeberli and Vonder Mühll (1996) and Haeberli (2000) also reject the term 'glacier-derived' because ice bodies at the head of 'glacier-derived' rock glaciers are smaller than true glaciers. Although this argument seems formally valid in spite of a question from Clark et al. (1998), it could be criticized as giving more weight to an artificial classification than to the actual processes involved, and – more importantly – to ignore that these glacierets may have been larger during, for example, the Little Ice Age (LIA). This leads to part (2) of the term 'glacier-derived': the suggestion that during glacier retreat, a glacier is transformed through a debris-covered glacier and into a rock glacier. This idea has been put forward e.g. for the LIA to present transition on Northern Iceland (Hamilton and Whalley, 1995; Whalley et al., 1995) and in the European Alps (Whalley and Palmer, 1998; Berger et al., 2004). However, where relationships between rock glaciers and LIA glaciers have been investigated with appropriate methods, results point to glaciers overriding older permafrost bodies and significant glacier/permafrost interactions (e.g. Lugon et al., 2004; Ribolini and Fabre, 2006; Ribolini et al., 2010).

Debris-covered glaciers have been much studied, especially in high-mountain tropical regions. Common features of such glaciers are an extended ablation area in relation to the accumulation area, down valley increasing sediment thickness (e.g. Hambrey et al., 2008; Kellerer-Pirklbauer et al., 2008a), down valley sharp decrease in surface flow velocity and loss of directional homogeneity (e.g. Bolch et al., 2008; Hubbard and Clemmens, 2008), local maxima of ice mass loss and subsidence due to supraglacial lakes (e.g. Rohl, 2008) and very irregular surface topography. Thus, although some of these descriptions fit, the surface displacement field and morphology of debris-covered glaciers in general lack obvious similarity to rock glaciers.

For a general glacier to rock glacier transformation model to work, as an alternative to the permafrost model, there are some criteria that must be met. First, the presence of permafrost must be ruled out. Second, measurements or modeling must show that the melting of the ice core would not proceed at a rate higher than what would allow for a coherent surface morphology to be maintained and developed. Third, the age of the feature must be compatible with known periods of glacial advance and subsequent retreat. Fourth, the sediment store in the glacial-derived rock glacier should match the relevant processes and available time.

Whalley and Martin (1994) claim that 'glacier-derived' rock glaciers in the Tröllaskagi area of Northern Iceland are decoupled from the domain of mountain permafrost. Lack of permafrost at this site is maintained by Whalley and Azizi (2003). Their considerations, based on extrapolation of air temperature measurements, fail to recognize the processes involved in energy transfer between atmosphere and subsurface which cause distinct thermal offsets. Later work, combining ground temperature measurements and numerical modeling, has shown a more widespread permafrost distribution in this area (Etzelmüller et al., 2007; Farbrót et al., 2007a,b). Thus, although Farbrót et al. (2007a) agree on a glacier origin for some of these Icelandic rock

glaciers, they nevertheless regard them as true permafrost features. Such a view also seems to be in line with Humlum (1988, 1996) for rock glaciers on Greenland. For the Galena Creek rock glacier, available temperature measurements from ice coring (Clark et al., 1998) point to possible permafrost conditions and so do the ice-cored lateral moraines described by Ackert (1998) along the upper part of this rock glacier. Likewise, for the rock glaciers in Sierra Nevada investigated by Clark et al. (1994b), the geomorphic setting with 'talus-derived' rock glaciers at lower altitudes than the 'glacier-derived' rock glaciers clearly indicates a permafrost environment (Jakob, 1994). Also 'glacier-derived' rock glaciers in Austria are considered in a permafrost context (Krainer and Mostler, 2000; Hausmann et al., 2007).

The melting of buried glacier ice has been studied both in permafrost and non-permafrost settings. Such studies show that lateral melting due to exposure of ground ice in near-vertical walls locally is a dominant process. In non-permafrost environments, however, melting from below may be the dominant process (Krüger and Kjær, 2000; Kjær and Krüger, 2001). An average downwasting rate of 0.9 m yr^{-1} was measured for a 20 year period in permafrost conditions on Svalbard (Schomacker and Kjær, 2008). Everest and Bradwell (2003), however, report on slow melt rates and old ice (decades to >200 years) in areas of Iceland that, according to Etzelmüller et al. (2007), should be permafrost free. In general, these studies imply that in non-permafrost environments, long-term surface coherence cannot be expected where subsurface ice is present.

Age estimates for rock glaciers on Northern Iceland (Wangensteen et al., 2006; Kellerer-Pirklbauer et al., 2008b) have provided much older values than the LIA origin proposed for the Nautárdalur rock glacier by Hamilton and Whalley (1995). Indeed, Whalley et al. (1995) provide surface velocities that indicate a ka age for this rock glacier, and have to make the (not unreasonable) assumption of a thicker LIA glacier in order to fit an LIA age to the rock glacier. Few datings with absolute methods are published from rock glaciers; where available (Haeberli et al., 1999; Konrad et al., 1999) they point to ages of several ka. These values are compatible with assuming present flow conditions to be representative for long term conditions (Haeberli et al., 1999).

An independent estimate of age can be obtained by considering the sediment budget of the rock glacier. Barsch (1996) and Humlum (2000) provide data on rock wall retreat rates from rock glacier sediment deposits which show that old ages are more compatible with likely rock wall retreat rates. From Northern Iceland, Farbrót et al. (2007a) provide similar estimates of headwall retreat rates; forcing these values based on an LIA age yields unreasonable high weathering rates. Berthling and Etzelmüller (2007) utilize the rock glacier sediment store and the assumption of stable long term flow conditions to propose a model for estimating rock glacier age. Applied on Prins Karls Forland, marginal to the Weichselian ice cover on Svalbard, this model suggests rock glaciers older than 10 ka.

Although it would be possible to increase the age of the 'glacier-derived' rock glaciers to overcome the problems with age estimates and sediment budgets (where absolute dating has not defined age precisely), this would most certainly put the existence of these rock glaciers at stake in a non-permafrost environment. Although heat exchange between buried ice and atmosphere is slowed down considerably by the presence of a debris cover, thousands of years would be sufficient to melt this ice in the absence of permafrost conditions. Thus, the probability of debris-covered glaciers turning into rock glaciers in a non-permafrost environment seems to be small.

3.2. The concept of a glacier-rock glacier continuum

Potter (1972, p. 3027) states that 'it does not seem unreasonable to expect that there should be a continuum from clean glaciers at one extreme to rock glaciers composed of considerable debris cemented by interstitial ice at the other extreme.' This view is shared by many

other writers, and the continuum concept for the ‘glacier’–‘rock glacier’ transition has been developed in some detail by Ackert (1998). Such a continuum is discussed for relict rock glaciers by Harrison et al. (2008), and for talus-derived landforms in general by Shakesby et al. (1987). A continuum concept is also embraced by Haeberli et al. (2006, p. 190): “Two extremes represent the ends of a geomorphic continuum: (a) steadily creeping perennially frozen and ice-rich debris on non-glacierised mountain slopes; and (b) debris-covered glaciers in permafrost-free areas.”

The basis for the continuum concept is that rock glaciers consist of two main components: ice and debris. In principle, the components can be mixed in any proportion. This can be approached from either side of the continuum. For a glacier, the ice component comes from snow precipitation, wind drift, avalanches and superimposed ice in excess of annual melting. For most glaciers, the mass surplus of the accumulation area is substantial and the addition of debris is insignificant in proportion. However, in polar or continental areas the mass balance gradient may be much lower. Further, in situations of warming atmosphere, the surplus may be replaced by a temporary negative mass balance which causes the equilibrium line to rise. Thus, the added (and previously accumulated) debris component becomes relatively larger (all other factors being equal). Low flow velocities and large debris input are required for the debris component to become a substantial proportion of the total volume, conditions that are more likely to be found in small and cold or polythermal glaciers. Alternatively, large valley glaciers that collect accumulation from many smaller corrie glaciers in high alpine areas would develop a high debris component beneath the equilibrium line, where englacially and subglacially transported debris appears at the surface. After glacial retreat in these situations, substantial ice-cored moraines would be the result if permafrost is present; if not, melt out of the buried ice proceeds through time regardless of a protective debris cover. In a slope setting, the ice-cored moraines could themselves start creeping (Østrem, 1971; Barsch, 1996), but again permafrost is a requirement for the ice-core to be preserved through time.

From the other side of the continuum, a talus-derived rock glacier builds up from the debris and ice added on a talus slope. Talus-derived rock glaciers are generally regarded as supersaturated in ice, with an ice content estimated to be 40–70% based on data from coring and direct observations (Haeberli et al., 2006). Talus slopes can be found in many areas, but are typical for alpine periglacial regions. A rapid and effective process of subsurface ice development in talus is the burial of surface snow and ice (typically perennial snow banks and avalanche snow) by debris (Isaksen et al., 2000; Humlum et al., 2007). Further, ground ice can build up in the talus slope by segregation ice developing as water is transported along temperature gradients into the permafrost, and by freezing onto the permafrost table at a long term rate limited by the rate of debris accumulation and/or a compressive flow regime (given a stable climate). The latter processes have been questioned by Whalley and Martin (1992), Clark et al. (1998) and Whalley and Azizi (2003). Although high ice contents are common below the permafrost table in many permafrost regions (cf. French, 2007), and there is little reason to assume that slopes should be significantly different in this respect, the processes causing thick supersaturated ice bodies in talus slopes have been little studied. Apart from the numerous literature on debris accumulation and talus modification from snow avalanches and debris flows (e.g. Blikra and Nemec, 1998), process studies have so far focused on thermal conditions within talus slopes (e.g. Hanson and Hoelzle, 2004). There are few investigations to document processes and rates of ice development in talus from either surface accumulation of snow or ice (e.g. Humlum et al., 2007) or from the coupled ground hydrological and thermal conditions (Sawada et al., 2003; Rist and Phillips, 2005; Sawada, 2008; Phillips et al., 2009). Further, the majority of talus slopes in permafrost areas do not develop into rock glaciers, and it is not unusual with rock glaciers developed from talus slopes looking

similar to neighboring talus slopes that lack creep features altogether (e.g. Berthling and Juliussen, 2008). Therefore, the interplay of thermal and hydrological conditions and slope processes relating to rockfalls, debris flows and snow avalanches most likely form a complex system where minor differences in inputs or controls lead to divergent geomorphic development.

The central part of the continuum should have ice contents in excess of 70%. Humlum et al. (2007) suggest that the Larsbreen rock glacier on Svalbard, is avalanche-derived. Ice and debris accumulates in layers up to 100 cm yr⁻¹ as summer melt-out of debris inhibits complete melting of avalanche snow. Such a situation may very well define a central part of the continuum.

3.3. The ambiguity of the permafrost term

The permafrost creep school maintains that permafrost conditions constitute the control enabling a ground ice content to build up and survive over time scales required to develop the coherent creep features typical of rock glaciers. Permafrost is often stated as being defined purely in terms of thermal conditions, namely at least one or two years of ground (soil and rock) temperatures at or below 0 °C. The commentary to this definition (Van Everdingen 1989) excludes glaciers from the permafrost realm. The terms ‘permafrost’ and ‘periglacial’ are for this reason conceived as distinctly non-glacial. Nevertheless, old, buried (glacial) ice has later often been included into the permafrost definition (e.g. Harris, 2004). Strictly, following present definitions, a debris covered glacier or ice-cored moraine may have a permafrost layer on top of the ice as well as in the ground beneath the glacier. Regelation ice and subglacial till frozen onto the glacier from below can also be considered ‘permafrost’. However, even at temperatures beneath the pressure melting point, the glacier itself would not be ‘permafrost’. By the same token, glacier-derived rock glaciers would be outside the permafrost realm, regardless of the fact that permafrost seems to be a factor that is required, although not necessarily sufficient, to maintain their surface integrity.

However, many permafrost scientists allow for sedimentary ice to be incorporated into the permafrost (Haeberli, 1989; Haeberli and Vonder Mühl, 1996; Käb et al., 1997; Farbot et al., 2007a). Dobinski (2006) even suggests including glacier ice at temperatures below the pressure melting point in the permafrost domain. Haeberli et al. (2006, p. 191) can also be interpreted as going far with respect to treating buried ice as permafrost: ‘Permafrost is used here to describe a specific ground thermal condition (temperature at or below 0 °C for a minimum of one – or even better – two years), irrespective of ice content or lithology’. Whatever individual researchers may feel about nudging artificial classifications, it is clear that the question whether the glacier-derived rock glaciers are regarded as permafrost per se or only dependent on permafrost conditions for their development, emphasizes the importance of considering interactions between permafrost and glaciers. Haeberli (2005 p. 30) remarks that rock glaciers ‘may be the most striking case of interpreting cryogenic phenomena as being exclusively glacial or permafrost in origin, as if there were no possibility for the two to coexist or interact.’ One reason why there is disagreement about the term rock glacier may therefore be a lack of appreciation as to the widespread distribution of mountain permafrost and its importance, not for strictly periglacial processes only, but also for other surface processes operating in these environments.

4. Defining and classifying rock glaciers

This section is devoted to a discussion on fundamental aspects of defining and classifying rock glaciers. The classification systems proposed earlier, e.g. by Martin and Whalley (1987) and Whalley and Martin (1992), will not be central to this discussion, for the simple reason that no such system has gained general recognition, apart from

the distinction between active, stagnant and fossil rock glaciers. The section will also show how definitions are (mis)used in the literature, as regards geomorphological explanations.

It should be stressed that there is no common agreement regarding what should be the basis for classifying and naming landforms in geomorphology. Most textbooks treat landforms in a genetic context. Nevertheless, landforms have often been named when identified as something peculiar; sometimes based on traditional words, or from a simplified description of the process involved in the formation of the landform, for example solifluction. Quite often, names of landforms are based on morphological descriptions, such as 'terrace', 'crag and tail' and 'stone polygons'. Also very general and everyday words, like 'valley' or 'plain', are used even though they lack specific genetic content. Occasionally, such words and names are relatively unambiguous. Quite often, however, a given name causes discussions regarding its content. The rock glacier controversy is not unique in this respect; a similar discussion exists for example with respect to 'palsas', and the definition of solifluction has changed since it was first introduced. The main part of this discussion will consider the rationale behind choosing a morphological definition for rock glaciers.

4.1. The morphological rock glacier definition

The general idea of a morphological definition seems to be practical: if two or more genetic models may apply to rock glaciers, morphological criteria provide some common ground that allows the features to be recognized and for example to be mapped without additional investigations.

Hamilton and Whalley (1995) are the only authors who consider the rationale for a morphological definition in some detail, but their discussion is superficial. Their 'main requirement is for an *inclusive* morphological definition which permits the inclusion of all viable rock glacier "models"' (Hamilton and Whalley, 1995, p. 74). They found their opinion on Putnam's (1975) concept of a 'stereotype', but there is no explanation of the problem how the 'stereotype' relates to the term in question through a causal reference chain. In Putnam (1975), the 'stereotype' of a term *refers* to a natural kind term, and this reference is fixed by an expert test. The 'stereotype' changes as opinions about the kind are modified. However, Hamilton and Whalley (1995) define the rock glacier *in terms of* the 'stereotype', in other words there is no reference to an expert test: 'This usage of "rock glacier" allows recognition of the feature [...]. However, it says nothing about the meaning of the stereotype.' (Hamilton and Whalley 1995, p. 74).

Geomorphologists want to provide explanations rather than descriptions of landforms. Explanations are necessary to infer information from landforms for other purposes (for example palaeoclimate). Any scheme to identify rock glaciers based on morphological criteria would very likely separate a talus-derived rock glacier and the talus from which it may originate. However, as stressed by a number of investigations of rock glacier flow fields and internal structures (e.g. Käab et al., 1998; Berthling et al., 1998, 2000, 2003; see also Haeblerli 2000), the talus is an integral part of the rock glacier system. This implies that to provide explanations about rock glaciers, it is not sufficient to study the 'rock glacier'. As theory determines the kinds of questions asked, a focus on morphology may cause us to view nature as elements rather than connections, and therefore to ask questions that are not to the point. There is also a certain power to a scientific term (such as 'rock glacier') leading to assumptions or presuppositions as regards the quality of knowledge and clearness of meaning. Names, definitions and classification suggest that there is an independent *basis* for these names or schemes. A student confronted with the term 'rock glacier' will presume that this is indeed something whose sense we know. This constitutes a risk of 'name magic' (Schumm, 1991; Cox, 2007) to slip into the literature. It might work to state that a feature is a rock glacier because it looks like a rock glacier, if we at the same time state that we

do not know how the landform in question has developed. However, such restrictions are seldom made.

Consider the following student field trip thought experiment. The first day we visit a site and inform that "this is a typical rock glacier, developed from a glacier maybe since the Little Ice Age". Next day, at a new site, we tell them "here is another rock glacier deposited as a rock avalanche about 8000 years ago". The third day at still another site the students are told that "this is also a typical rock glacier, developed by creep of mountain permafrost over millennia". This is what proponents of a morphological rock glacier definition ask us to do; however it can hardly be illuminating for students, or when communicating with the general public or the rest of the scientific community. There is an even worse possibility: simply stating that this feature we are looking at 'is' a rock glacier. The feature has a name; so we 'know' what it is, and we can even represent it with a distinct symbol on a map. This is communicating words instead of concepts or everyday concepts instead of scientific ones. Consider the alternative: "This feature we are looking at is very interesting. It has these fascinating coherent surface structures we interpret as signs of movement. It could definitely be a rock glacier, developed by permafrost creep. However, we do not know what it is, there are other possibilities. It will be your challenge to investigate this properly in the future; to determine its origin and what it can tell us about environmental conditions and geomorphological development".

The road from name magic to circular arguments is also short (Cox, 2007), although this has nothing to do with the morphological definition per se. There are unfortunately examples in the literature where the authors first state that they regard rock glaciers to be (also) of glacial origin, then find glacial ice in their 'rock glacier' study object and finally state that they have proved the rock glacier to be of glacial origin. This is circular, except if the permafrost creep definition of rock glaciers denies the possibility of other processes to create the same morphology – which is not the case. What these studies may prove is that there *are* landforms with a glacial ice core, *not* that these landforms are rock glaciers. Ironically, Whalley and Azizi (1994, p. 49) state that "Supporters of the permafrost model of rock glaciers have been entirely dismissive of the glacial model, even though there is plentiful evidence to show that at least some rock glaciers may be derived from glacier ice. [...] It is semantically obtuse to say that the buried glacier cannot be a rock glacier if rock glaciers are defined to exclude this possibility." A similar argument is put forward by Clark et al. (1994a) in response to critique by Jakob (1994). They first state that 'we dispute Jakob's insistence that all rock glaciers are wholly periglacial; in our view, rock glaciers are a morphological form, not a singular genetic form' (Clark et al., 1994a, p. 359). Later they declare that 'His contention that debris-covered glaciers do not display transverse ridges and other "typical rock-glacier" morphologies is similarly invalid because he denies the possibility that at least some rock glaciers are debris-covered glaciers' (Clark et al., 1994a, p. 360). Both these responses are logically flawed. If I define rock glaciers as creeping permafrost, I *do not* make the claim that any feature looking like a (periglacial) rock glacier is one. These other features are rather regarded as *something else* than a rock glacier. One cannot use reference to a definition to substantiate the same definition. This becomes clear by considering the following example: Hydrogen is defined as any atom with atomic number 1, thus both Deuterium and Tritium is Hydrogen. However let's suppose there are opposing definitions: another school considers nuclear mass, rather than nuclear charge, as the basis for classifying elements. According to this school, Deuterium and Tritium are separate elements. It is impossible to 'prove' any of these definitions; they follow from choices in the scientific community.

4.2. Are rock glaciers 'natural kinds'?

The continuum school suggests a morphological definition of 'rock glaciers' to incorporate all viable genetic models. However, if several genetic models apply, then 'rock glaciers' is a group of landforms

(despite the continuum), and the terminology should acknowledge this. Harrison et al. (2008) use the term 'discrete debris accumulations' when discussing relict varieties of rock glaciers and rock avalanches. For active landforms, one could suggest *ice–debris landforms* as a suitable umbrella term, fitting rock glaciers, debris-covered glaciers and ice-cored moraines.

Abandoning a morphological definition of rock glaciers do not, however, provide any solution to the rock glacier controversy. There are no grounds on which to claim that debris-covered glaciers in permafrost areas could not be called 'rock glaciers', if scientists want to do this. One may draw a parallel to other landforms, such as tors (Slaymaker, 2004), and maintain that equifinality is at play and that rock glaciers should be given a genetic definition implying development either from glacial or periglacial conditions, or in some other manner based on the continuum hypothesis. This view would be logical if rock glaciers – along with other landforms – could be considered a 'natural kind'.

Comparing landforms to chemical elements, it is obvious that there is a much more rigid basis for considering the elements 'natural kinds'. All 'oxygen' will have atomic number 8, although the element can be in the form of O₂ or O₃, have isotopes, be gas or liquid, and a constituent of other materials etc. However, no other element has atomic number 8. Such a unique property cannot be ascribed to landforms. A rock glacier can be depicted by morphology, but will share morphology with other types of geophysical flows. It can further be described by a certain mixture of debris and ice, but will share this property with at least some parts on a glacier and ice-cored moraines, and ground ice in other types of terrain. Further attempts at identifying 'core properties' of the rock glacier could consider surface material, displacement etc., but again these could easily be met by other features also in similar settings, for instance by deformation of permafrost in front of an advancing glacier (e.g. Haeberli, 1979). Consequently, stacking a set of criteria would be necessary to describe a rock glacier properly, fuzzy boundaries are inevitable and the basis for considering rock glaciers natural kinds questionable.

Above, however, I have argued that landforms emerging from complex process systems could possibly be defined as natural kinds. Brazier et al. (1998) suggest independent developmental paths depending on the local ice–debris flux for rock-glacier landforms in the Ben Ohau Range, New Zealand, but the landforms are still classified as rock glaciers. Harrison et al. (2008) discuss relict rock glaciers and although they do not use the term, it is clear from their discussion that they consider rock glaciers to emerge from a continuum of processes (glacial/periglacial) and materials (ice–debris). The argument is that rock glaciers develop either from glaciers or from talus, because this ice–debris system is insensitive to initial conditions and ice–debris flux. However, I have earlier in this paper argued that the same system is highly sensitive to thermal conditions. With temporally continuous permafrost, such systems could develop into a rock glacier. When there is no permafrost, or it is temporally discontinuous, the system will either not start developing at all (because of a lacking ice component) or develop into a debris-covered glacier left to disintegrate over relatively short time scales (decades to centuries). Therefore, rock glaciers may well be emergent phenomena, but with the limiting threshold of permafrost conditions.

The continuum school has only considered the relative ice and debris contents of the landform in question. However, the relative mixture of ice and debris does not define a landform; geomorphic development through time must also be discussed. As underscored earlier, not all debris covered glaciers appear like rock glaciers. It would, probably, be better to start with the question why a debris covered glacier may resemble a talus-derived rock glacier. What are the determining processes or controls in this case? If this question is been resolved, can we go on to discuss whether such debris-covered glaciers should also be classified as rock glaciers. So far, the continuum hypothesis cannot be regarded as rigorously tested.

Dynamical modeling of the systems would be one way to determine whether a 'continuum' of ice and debris mixing really suggests convergence in landform development, and if cryo-conditioning controls development as hypothesized here. Modeling efforts in rock glacier research so far can be divided into attempts to reproduce observed rock glacier displacement (surface and vertical velocity profile – e.g. Wagner, 1992; Käab et al., 2007), constitutive relationships (e.g. Whalley and Azizi, 1994), rock glacier landform development and controls (Olyphant, 1983) and their distributional pattern and areal development through time (Frauenfelder et al., 2008). Interestingly, they all use a Glen's flow law type of representation of the creep component. Of course, this could open for a discussion whether the process of permafrost creep is essentially different from glacial flow. Although glacial flow often consists of more components than just creep, this is a relevant question. Modeling landforms through time is much more than explaining a static flow condition, but the essential process in the downslope displacement of both talus-derived rock glaciers and cold or polythermal glaciers is the creep component of the internal ice. The common development of the characteristic lobate surface ridges (e.g. Rignot et al., 2002; Käab and Weber, 2004) and a steep frontal slope on both periglacial and glacier-derived rock glaciers, may illustrate that despite a diverse origin of the ice and debris components, the creep process and landform development is common for these systems. This supports a view of rock glaciers as an emergent property of ice–debris systems on slopes in permafrost areas.

4.3. A genetic definition of rock glaciers

The discussion so far has provided some support for a still untested view of rock glaciers as landforms emerging from an ice/debris continuum, under the requirement of permafrost conditions. What then would be the status of the permafrost creep definition of rock glaciers? It is worth emphasizing that the rock glacier definition of Haeberli (1985) is genetic in the sense that it states the deformation process and the material that is deformed; however the origin of this material is not defined more specifically than 'supersaturated mountain permafrost bodies'. The definition of permafrost is the critical point; the question again being if ice bodies of surface origin should be incorporated. Allowing for this provides a more or less unified rock glacier concept. In these environments an advancing glacier could transmit stress that leads to deformation of permafrost beneath and in front of the glacier (e.g. Haeberli, 1979; Etzelmüller and Hagen, 2005). These cases would normally be considered 'glacial' processes, and the result 'moraines' but the morphology of the resulting landform may in some cases be similar to rock glaciers (e.g. Østrem, 1971). However, for a rock glacier where a glacieret is present at the rock glacier head, stress levels transmitted from the glacieret to the rock-glacier would probably be of little significance.

Even if we do not allow for inclusion of buried sedimentary ice in the permafrost domain, it may still be possible to provide a common concept for rock glacier development from glaciers and permafrost by referring to the requirements of permafrost conditions. I propose to define active rock glaciers as *the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions*. This definition is genetic in the sense that it puts weight on the process responsible for deformation (and thus morphology), but it is not genetic in terms of origin of the ice and debris. In essence, the definition is identical to the definition of Haeberli (1985) but with subtle alterations based on Haeberli (2000). The proposed definition allows for incorporation of surface ice into permafrost, which the Haeberli (1985) definition of rock glaciers does not allow, if one follows the permafrost definition of Van Everdingen (1989) closely. The definition deliberately excludes rock avalanche deposits (except where these have been deposited on a glacier or later have developed ice content).

The distinction between a rock glacier and a debris-covered glacier will be discussed further, based on an ice-debris landform in Sunndalsfjella, Southern Norway (Fig. 1). The surface ice part of this feature is listed as a cirque glacier in the inventory of Østrem *et al.* (1988). This glacier has a size of $\sim 0.15 \text{ km}^2$ with some crevasses that show deformation. The debris part ($\sim 0.25 \text{ km}^2$) shows all typical morphological characteristics of a rock glacier. Since the aerial photographs were taken in 2006 much of the thin, steep part of the glacier has melted – while no changes can be seen on the debris part. The front of the landform is at about 1480 m a.s.l., while the permafrost limit according to modeling by Etzelmüller *et al.* (2003) is around 1450 m a.s.l.; thus the landform is very probably developed in permafrost. No field data are so far available from the site. The debris part can be divided in two longitudinal sections. The western section has a steep frontal slope and a morphology that more closely resembles a rock glacier (Fig. 1, Profile A–B). The eastern part lacks the steep frontal slope (Fig. 1, Profile A–C), but the characteristic transverse ridges are continuous between the two parts. The frontal lake is colored by suspended sediments, which in such settings are indicative of subglacial sediment production and evacuation.

It is comprehensible that the development of such landforms in the past has been conceptualized as for instance a Little Ice Age glacier developing through a debris-covered glacier into a rock glacier, after glacier retreat. Such conceptualization fails, however, to properly consider the contrasting temporal scales involved in the dynamics and cumulative effects of (i) surface ice accumulation and ablation, (ii) debris production from periglacial and glacial sources, debris entrainment, transport and accumulation through glacial processes, and (iii) permafrost aggradation or degradation. Although it seems quite likely that glacier ice is an important or dominant component with respect to ice present within the debris part of the landform in Fig. 1, this is not the same statement as claiming that the glacier has developed into a rock glacier. Most or all cirque glaciers in Norway are relatively clean. There is no reason to believe that a single glacier advance period such as the Little Ice Age could explain the landform of Fig. 1, whether in terms of total debris volumes or with respect to processes necessary to cover main

parts of the ablation area. A more likely scenario is that the glacier repeatedly has formed frontal ice-cored moraines which have started creeping, and thus that the landform is a debris rock glacier in the sense of Barsch (1996). The visual impression of a landform can provide the only available basis for classification for mapping purposes, but for scientific objectives, visual information should merely provide a basis for developing testable hypotheses. Field investigations would be necessary to examine the system of process interactions at the site to discuss the glacier–permafrost dynamics further.

5. Rock glaciers as cryo-conditioned landforms

Following the definition above, rock glaciers would neither belong entirely to the ‘periglacial’ or the ‘glacial’ realm, nor can they be conceptualized as an interaction between periglacial and glacial processes, since end members are found. However, as permafrost conditions determine their long-term development, and since their creep rate is further fundamentally dependant on temperature conditions (Kääb *et al.*, 2007), thermal conditions are an overarching spatiotemporal control. Berthling and Etzelmüller (2011) developed the idea of ‘cryo-conditioning’ in a geomorphic context, defined as the interactions between ground and surface thermal regimes with a sub-zero diurnal, seasonal or long-term pattern, and earth surface processes. The importance of this idea is the emphasis on a common control on processes in cold areas, which provides a way of conceptualizing process studies that cuts across traditional research boundaries. Thus it is well suited as a flexible concept for explaining rock glaciers, because it mutually considers the glacial and periglacial domain and since it can be applied at all relevant spatial and temporal scales.

It is well established that glaciers in even marginal permafrost areas have a thermal regime that is influenced by the cold climate, and which itself influences permafrost conditions beneath the glacier due to the high thermal conductivity of ice. A cold glacier front leads to decreasing flow velocities and the development of shear horizons that increase the supraglacial sediment load (cf. Etzelmüller and Hagen, 2005), causing a positive feedback with respect to cooling because of

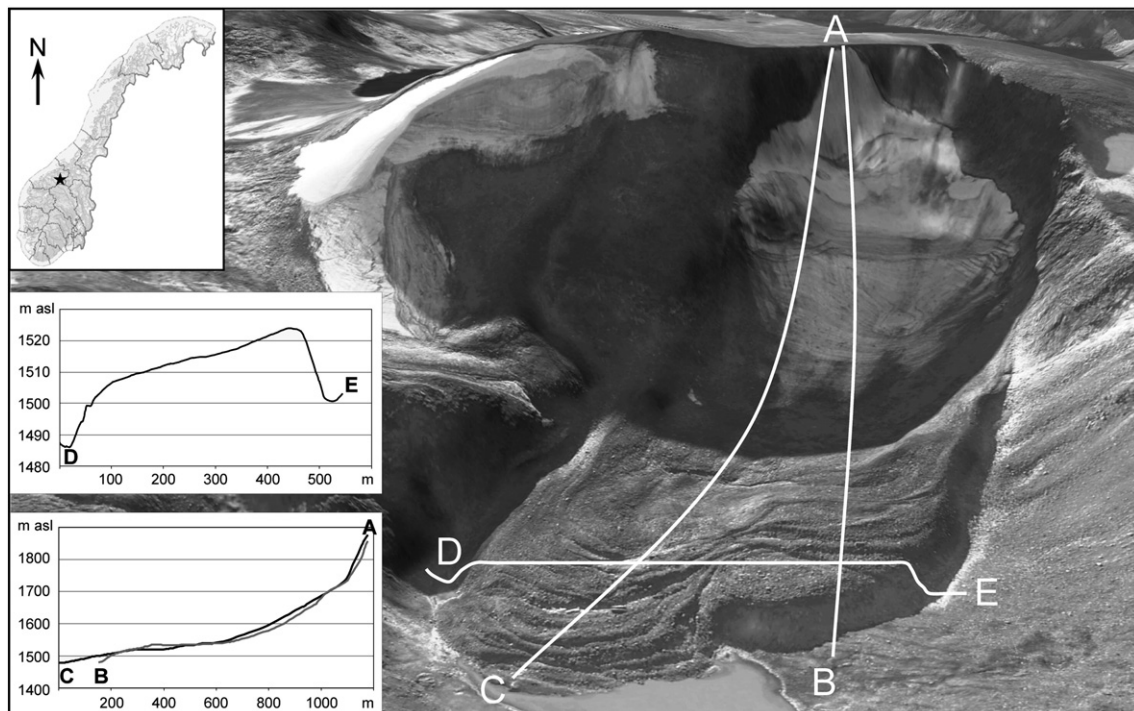


Fig. 1. An ice-debris landform in Sunndalsfjella, West-Central Norway (UTM32 691900, 500500), developed in a permafrost area and displaying both debris-covered glacier and rock glacier characteristics. Picture adapted from Norkart Geoservice Virtual Globe. View is towards Southwest. Frontal height along the northwestern (right) margin is about 25 m.

thermal offset effects (e.g. Farbrøt et al., 2007a) and further decrease of flow velocity. Nevertheless, even completely buried glacier ice will continue to creep if the shear stress is high enough to overcome the yield stress of the ice body. Whether this should be called 'permafrost creep' or 'glacial flow' would not be very relevant if the creep component can be modeled by a similar constitutive relationship.

Following retreat of polythermal glaciers, permafrost may be present as former subglacial or newly aggraded permafrost (Kneisel, 2003; Kneisel and Kääh, 2007). During periods of glacier expansion, newly developed ground ice, old buried surface ice and old permafrost could be incorporated into the basal ice. Thus, there may be exchange of ice between the glacial and permafrost domain during periods of advancing or retreating glaciers. Such exchange is relevant for rock glacier development in areas where permafrost and glaciers interact in time and space, and underscores both the importance of cryotic conditions as a basic control, and the need for crossing boundaries of scientific domains when studying these systems.

6. Conclusions

The study has critically examined the rock glacier controversy, and suggests and discusses some underlying problems that may have contributed to the heated debate. Rock glacier definitions are evaluated, and it is suggested that the morphological definition should be abandoned. A new genetic definition is proposed, where active rock glaciers are considered *the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions*. Following this definition, rock glaciers do not belong entirely to either of the 'periglacial' or 'glacial' realms. The definition is genetic with respect to the creep process but not to the origin of the creeping material. Rock glaciers are considered landforms emerging from ice–debris accumulation systems, given the overarching control on the system provided by permafrost conditions, and is therefore regarded as cryo-conditioned landforms.

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