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# Development of tongue-shaped and multilobate rock glaciers in alpine environments – Interpretations from ground penetrating radar surveys

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ABSTRACT

Rock glaciers occur as lobate or tongue-shaped landforms composed of mixtures of poorly sorted, angular to blocky rock debris and ice. These landforms serve as primary sinks for ice and water storage in mountainous areas and represent transitional forms in the debris transport system, accounting for ~60% of all mass transport in some alpine regions. Observations of active (flowing) alpine rock glaciers indicate a common association between the debris that originates from cirque headwalls and the depositional lobes that comprise them. The delivery of this debris to the rock glacier is regulated primarily by the rate of headwall erosion and the point of origin of debris along the headwall. These factors control the relative movement of individual depositional lobes as well as the overall rate of propagation of a rock glacier. In recent geophysical studies, a number of alpine rock glaciers on Prins Karls Forland and Nordenskiöldland, Svalbard, Norway, and the San Juan Mountains of southwest Colorado, USA, have been imaged using ground penetrating radar (GPR) to determine if a relationship exists between the internal structure and surface morphology. Results indicate that the overall morphologic expression of alpine rock glaciers is related to lobate deposition during catastrophic episodes of rockfall that originated from associated cirque headwalls. Longitudinal GPR profiles from alpine rock glaciers examined in this study suggests that the difference in gross morphology between the lobate and tongue-shaped rock glaciers can be attributed primarily (but not exclusively) to cirque geometry, frequency and locations of debris discharge within the cirque, and the trend and magnitude of valley gradient in relation to cirque orientation. Collectively, these factors determine the manner in which high magnitude debris discharges, which seem to be the primary mechanism of formation, accumulate to form these rock glaciers.

## 1. Introduction

Rock glaciers are lobate or tongue-shaped landforms composed of mixtures of poorly sorted angular to blocky rock debris and ice. Within alpine environments, these landforms are the visible expression of mountain permafrost, and thus, serve as principal climatological indicators within alpine geosystems. Rock glaciers are relevant in paleoclimatic and landscape evolution studies in cold regions because the formation and development occur over several thousand years (Haeberli et al., 1998). Rock glaciers generally occur in dry, continental areas where latitude, elevation, sun direction, and limited snow cover favor persistence. Site conditions that favor the presence (or formation) of rock glaciers includes the presence of permafrost and/or glaciers, the past presence of glaciers, relatively low levels of snowfall, and a supply of rockfall debris. Ground temperature, air temperature and the formation of ice may also be seen as dominant factors (Harrison et al., 2008). Although rock glaciers are located in cirques and valleys of many mountain ranges throughout the world, they remain poorly understood constituents of alpine debris systems.

Active (advancing) alpine rock glaciers are in motion because of the inner deformation of ice (Barsch, 1992, 1996), which probably has a polygenetic source (Haeberli and Vonder Mühll, 1996; Haeberli et al., 1998). The spatial distribution of structures and layers within rock glaciers, however, remains relatively unknown. This lack of understanding has fundamental implications for explaining the process of debris and ice accumulation on rock glaciers and the proposed continuity of talus cone-rock glacier systems (Giardino and Vitek, 1988; Haeberli et al., 1998; Humlum, 2000; Janke, 2005). In terms of two-dimensional dynamics, improved knowledge regarding internal structure is useful for identifying shear zones and patterns of displacement (and ultimately the evolution of rock glaciers), which would enable assessments of the age of a rock glacier and time-dependant rates of rock wall retreat (Humlum, 2000) to be made. Such knowledge can also help to differentiate relic rock glaciers from rock avalanche deposits. To obtain comprehensive information about the internal structure of rock glaciers, however, a technique more efficient than drill coring or excavating is needed. Over the last decade or so, ground penetrating radar (GPR) has provided this capability.

Here, a conceptual model is presented for the development of active alpine rock glaciers based on findings from GPR surveys in various locations in Svalbard, Norway, and Colorado, USA. These

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surveys include longitudinal and transverse GPR profiles from tongue-shaped and lobate rock glaciers on Prins Karls Forland and Nordenskiöldland, Svalbard, and from the San Juan Mountains in Colorado.

### 1.1. The formation of a rock glacier

Rock glaciers are a physical response to glacial, periglacial, and talus processes (Johnson, 1984; Shakesby et al., 1987; Humlum, 2000; Janke, 2005; Johnson et al., 2007; Frauenfelder et al., 2008). The pioneering work of Wahrhaftig and Cox (1959) and Liestøl (1962) led to the idea that rock glaciers form by permafrost processes to create a frozen mixture of rock debris and ice within talus or morainal debris. This hypothesis was expanded by subsequent studies (see Haeberli, 1985; Barsch, 1996; Barsch and Jakob, 1998) and by the advent of new technologies as global interest in the recognition and study of rock glaciers increases. A number of studies (e.g., Potter, 1972; Whalley, 1974; Clark et al., 1994; Shroder et al., 2000; Dobhal, 2008) also provide evidence of thick massive ice in the interior of rock glaciers and suggest that some rock glacier forms are actually debris-covered glaciers. The geomorphic setting and nature of ice within a rock glacier are, therefore, important elements to consider when developing models for flow dynamics and understanding the processes of formation involved.

In general, formation of rock glaciers that lack solid (e.g., glacial) ice cores begins with accumulation of ice and debris in the upper reaches of the rock glacier. The ice–debris mixture flows downslope, where the ice ablates slowly at the base of the active layer or melts within the debris of the rock glacier. Requirements that favor the formation of alpine rock glaciers are (i) joint spacing and weathering characteristics conducive to the formation of blocky debris; (ii) low to moderate snowfall sufficient for production of debris avalanches and low insulating cover; (iii) microclimate conducive to daily freeze–thaw cycles; (iv) the proper geographic location and position to allow for periglacial processes and sub-zero ground temperatures; and (v) talus supply that is promoted by steep, rough terrain and comprised of materials that are glacially derived and/or produced by frequent freeze–thaw cycles. In the alpine, rock glaciers are generally situated at the base of massive, homogeneous and fractured cliffs and are seldom located where debris is finely crushed or where headwall fractures are excessively large (Wahrhaftig and Cox, 1959; Evin, 1987; Ikeda and Matsuoka, 2006).

From a continuum perspective, rock glaciers are appropriately considered to be transitional forms generated during glacial or periglacial processes (Giardino and Vitek, 1988). Thus, a variety of process-pathways can lead to the formation of a rock glacier. For example, the process of collection and deposition of glacial debris is distinct from the formation of frost-shattered slope debris, but both processes can generate rock glaciers as they progress to two distinct landform end-members (i.e., till or colluvium). Landform identification can be difficult in such cases because site moisture balance and climatic conditions may support the formation of ice in the interstices of a talus body, or conversely, ice within a rock glacier may melt during warming climatic conditions, leaving a deposit that may easily be mistaken for a clast-rich till. Recent work has been directed at identifying processes that can provide for such occurrences. For example, the process of winter ascending air circulation has been attributed to the development of coarse sediment accumulations such as talus slopes and rock glaciers situated in discontinuous permafrost zones of the Swiss Alps (Delaloye and Lambiel, 2005).

### 1.2. Movement and persistence of rock glaciers

The volume of literature that addresses the mode of formation of rock glaciers has grown considerably in the last decade. In spite of this, the movement and persistence of rock glaciers remain poorly understood. It is therefore necessary to preface the discussions made in this paper with a brief review of the contemporary debates on active rock glacier development. An active rock glacier is defined here as one that is presently undergoing flow deformation, which is detectable by physical measurement and/or identification of morphologic features that are diagnostic of a present movement. A more thorough treatment of rock glacier development and morphological classification, including issues of contention, can be found in Whalley and Azizi (1994), Barsch (1996), Burger et al. (1999), and Harrison et al. (2008).

Active rock glaciers may comprise buried remnant glacial ice, or, the void spaces between the debris and blocks making up the lithic portion of the rock glacier may be filled (or cemented) with ice. Both forms have been observed in the same locale in some cases (Kellerer-Pirklbauer et al., 2008), and it is possible that a combination of these are present in some rock glaciers (Harrison et al., 2008). Haeberli (1985) relegates use of the term “rock glacier” to permafrost bodies, rather than glacially derived forms, and therefore considers rock glaciers to be indicative of permafrost. Despite this contention, there are sufficient examples in the literature of rock glaciers that clearly contain cores of glacial ice, and for which there is no evidence of permafrost development (Whalley and Azizi, 2003). On this basis, the presence of a rock glacier cannot be considered as conclusive evidence for the presence of permafrost. Alternatively some rock glaciers may simply be the result of rapid burial and compaction of large volumes of snowpack by numerous catastrophic releases of rockfall debris emanating from the cirque headwall. This model of formation is gaining increased acceptance as more GPR results become available (e.g., Berthling et al., 2000; Degenhardt et al., 2002; Otto and Sass, 2006; Monnier et al., 2008).

Regardless of the mode of origin of a rock glacier, it is apparent that debris supply is an important variable in the development and behavior of permafrost ice–debris systems. Most models for rock glacier permafrost are based on the premise that meltwater is able to accumulate in significant quantities within the pore spaces of the debris and freeze interstitially. However, it is noted by Harrison et al. (2008) that the debris may retard the creep of interstitial ice, meaning the rock glacier mass would have a lower overall shear strength relative to the shear strength of the same mass if devoid of interstitial ice (Whalley and Azizi, 1994). Therefore, it may be that creep only takes place in those portions of a rock glacier where large lenses of ice are present (Azizi and Whalley, 1995; Whalley and Azizi, 2003).

The movement and persistence of rock glaciers also require a continuous (though not necessarily steady) supply of talus, which is derived from discontinuities in the bedrock. These discontinuities are defined by fracture patterns and linear fracture density (Humlum, 2000; Johnson et al., 2007), where the influence of weathering by ice and water generates a rate-dependent supply of debris to the landform. Thus, for a rock glacier to remain in contact with its source area, a talus slope must exist below the rockwall to serve as temporary debris storage. As such, the rate of advance of the rock glacier must be slow enough to compensate for periods of low talus production. An increase in flow velocity, however, can serve to detach a rock glacier from its source cliff as it moves over terrain of increasing slope angle (i.e., downvalley). The movement of rock glaciers and talus production are normally very stable; therefore rockwall height, talus production rate, rock glacier size, and flow velocity may represent a slow-moving dynamic system that maintains equilibrium over a period of thousands of years.

Our current understanding of the movement of rock glaciers is based on models of creep flow or solifluction adopted from studies of glaciers and limited physical data from rock glaciers around the world (e.g., Barsch et al., 1979; Giardino, 1983; Haeberli, 1985; Barsch, 1996; Burger et al., 1999; Konrad and Humphrey, 2000; Haeberli et al., 2006). Observations and creep theory suggest that the velocity distribution varies with depth according to a parabolic function, with the surface of the rock glacier moving faster than the base (Wahrhaftig and Cox, 1959). In support of this model, research on the