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Schutt-Textur in Tuckerman Ravine, New Hampshire: Belege für einen zungenförmigen Schuttgletscher

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Article abstract

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TALUS FABRIC IN TUCKERMAN RAVINE, NEW HAMPSHIRE: EVIDENCE FOR A TONGUE-SHAPED ROCK GLACIER

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ABSTRACT Tuckerman Ravine is a glacial cirque located in the White Mountains of New Hampshire. The Ravine contains four talus accumulations formed through rockfall and toppling and characterized by large joint blocks with long axes of at least one meter. Previous research has classified one of the deposits (identified as Site 1 in the current study) variously as a moraine, a lobate rock glacier, and a protalus rampart. To resolve this controversy and provide a more reliable interpretation, block fabric analysis was performed at this and the other three talus sites. A bimodal fabric distribution was encountered at Site 1 and implies that the blocks at the base of the deposit collectively met some obstruction to movement. Such arrangement is not accounted for in simple talus accumulation models or in previous interpretations. The fabric data and its other characteristics support the classification of Site 1 as a relict tongue-shaped rock glacier. Fabric analysis indicates that the majority of blocks at Sites 2, 3, and 4 have a preferred orientation in the downslope direction and that these deposits represent rockfall talus which has not experienced post-depositional movement or activity. The mere presence of the talus deposits and their locations (which include the cirque headwall) do not support the reactivation of cirque glaciers in the White Mountains during the Holocene.

RÉSUMÉ *L'organisation des blocs dans les talus d'éboulis du Tuckerman Ravine (New Hampshire) : les indices d'un glacier rocheux en forme de langue.* Le Tuckerman Ravine est un cirque glaciaire situé dans les White Mountains. Le ravin comprend quatre talus d'éboulis résultant de glissements et de basculements et caractérisés par de gros blocs jointifs avec de longs axes d'au moins un mètre. Les recherches antérieures avaient défini le dépôt du site n° 1 comme étant soit une moraine, soit un glacier rocheux lobé, soit un éboulis de blocs glissés. Pour mettre un terme à la controverse et fournir une explication plus juste, on a mesuré l'orientation des blocs au site n° 1 et de ceux des autres sites. Au site n° 1, on a constaté le caractère bimodal de l'orientation des blocs, ce qui implique que les blocs situés à la base du dépôt ont dans leur ensemble rencontré des obstacles en cours de transport. Les modèles simples de talus d'éboulis et les interprétations antérieures ne tiennent pas compte de tels agencements. À partir de ces données et d'autres caractéristiques, on peut considérer le site n° 1 comme étant un glacier rocheux relique en forme de langue. L'analyse indique que la majorité des blocs des sites nos 2, 3 et 4 sont en grande partie orientés vers le bas de la pente et qu'il s'agit de talus d'éboulis rocheux qui n'ont pas connu de déplacement après leur mise en place. La seule présence de ces talus d'éboulis et leur localisation implique qu'il n'y a pas eu réactivation des glaciers de cirque à l'Holocène dans les White Mountains.

ZUSAMMENFASSUNG *Schutt-Textur in Tuckerman Ravine, New Hampshire : Belege für einen zungenförmigen Schuttgletscher.* Tukkerman Ravine ist ein Kar, das sich in den White Mountains von New Hampshire befindet. Der Graben enthält vier durch Steinschlag und Kippung gebildete Schuttanhäufungen, die durch breite aneinanderstoβende Blöcke mit langen Achsen von mindestens einem Meter Länge charakterisiert sind. Frühere Forschungen haben eine der Ablagerungen (in der vorliegenden Studie mit Platz 1 bezeichnet) verschiedentlich als eine Moräne, einen Loben-Schuttgletscher und eine Schutthalde aus gerutschten Blöcken klassifiziert. Um die Kontroverse zu beenden und eine verlässliche Interpretation zu geben, wurde an diesem und zwei anderen Schuttplätzen die Block-Textur analysiert. Am Platz 1 hat man eine bimodale Textur-Verteilung festgestellt, was bedeutet, dass die Blöcke an der Basis der Ablagerung alle auf ein Hindernis beim Transport gestoβen sind. In den einfachen Schuttakkumulationsmodellen oder in früheren Interpretationen wird einer solchen Anordnung nicht Rechnung getragen. Die Textur-Daten und andere Charakteristika stützen die Klassifizierung von Platz 1 als einen zungenförmigen Relikt-Schuttgletscher. Die Textur-Analyse zeigt, dass die Mehrheit der Blöcke an Platz 2, 3 und 4 eine bevorzugte Orientierung hangabwärts haben und dass es sich bei diesen Ablagerungen um Steinschlag-Schutt handelt, der keinen Transport oder keine Aktivität nach der Ablagerung erfahren hat. Das einfache Vorkommen von Schutthang-Ablagerungen und ihre Lage (welche die Kar-Steilwand einschlieβen) belegen nicht die Reaktivierung von Kar-Gletschern in den White Mountains während des Holozän.

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INTRODUCTION

The majority of previous geomorphic studies in the Presidential Range of the White Mountains of New Hampshire have primarily focused upon establishing either the presence or absence of cirque glaciers following the retreat of the Laurentide (continental) Ice Sheet (Waitt and Davis, 1988). Controversy surrounding the larger question of glaciations has hindered the study of small-scale geomorphic features that have been used to construct glacial sequences. Therefore, the majority of the pertinent body of literature is marked by a lack of basic agreement concerning the origin and classification of the few such features that have been examined at more than a cursory level. These include deposits in the northern Presidential Range (Eskenasy, 1978; Bradley, 1981; Gerath and Fowler, 1982; Fowler, 1984; and Gerath, Fowler, and Hazelton, 1985) and those in Tuckerman Ravine, a glacial cirque in the central portion of the Range.

Tuckerman Ravine is located in the White Mountain National Forest, approximately 1.5 km southeast of the summit of Mount Washington. It is actually a composite cirque whose upper portion is separated from its lower portion by the Little Headwall (Fig. 1). Geomorphic features indicative of either pre- or post-Laurentide cirque glaciation are absent, as they are in the remainder of the Range. However, four large relict talus deposits are present in Tuckerman Ravine (Fig. 2). The deposits have resulted from previous episodes of mass wasting and are characterized by large boulders and blocks with A-axes (long axes) of at least one meter.

Talus Site 1 is a relatively linear feature that heads in the downvalley end of the upper cirque and spills over the scarp of the Little Headwall into the lower cirque. Most of this deposit lies at the foot of a buttress known as Lion Head. In the course of earlier, primarily reconnaissance-level research, Site 1 was thought to have derived from no less than three different geomorphic processes. This deposit has been classified variously as a moraine (Antevs, 1932), a lobate rock glacier containing felsenmeer boulders (W.F. Thompson, 1961), and a protalus rampart (Goldthwait, 1965; Waitt and Davis, 1988). Talus Sites 2 and 3 are located on the north wall of the upper cirque and Site 4 is situated at the downvalley edge of the south wall of the upper cirque. Site 2 has a conical shape that is typical of talus deposits and Sites 3 and 4 are irregularly shaped due to the morphology of the cirque walls.

FIGURE 1. Tuckerman Ravine from the Hermit Lake Shelters. The main headwall is at the center and a portion of the Little Headwall crops out on the left. The numbers 1, 2, and 4 indicate the locations of three of the four talus deposits that were studied.

Le Tuckerman Ravine à partir des Hermit Lake Shelters. Le mur de rimaye principal est au centre et une partie du petit mur (Little Headwall) se présente à gauche. Les chiffres 1, 2 et 4 donnent l'emplacement de trois des quatres talus d'éboulis à l'étude.

The purpose of this investigation is to resolve the controversy concerning the origin of Site 1 and to comprehensively study the remaining talus deposits with the goal of identifying and classifying any post-depositional movement or activity. It therefore also involves an examination of talus source areas (in order to determine the corresponding methods of slope failure), individual talus components, and talus morphology.

FIELD AREA

The Presidential Range is located in northern New Hampshire and consists of eleven peaks that exceed 1,750 m. The highest summit is Mount Washington at 1,917 m. Several Quaternary continental glaciations and at least two episodes of cirque glaciations (Illinoian and Wisconsinan) have produced the peaks and the twelve cirques (locally referred to as “ravines” or “gulfs”) of the range (Goldthwait *et al*., 1987). The cirques have cut into all but the western side of the range. Most cirque walls or floors are covered by varying amounts of talus composed of relatively large boulders and blocks.

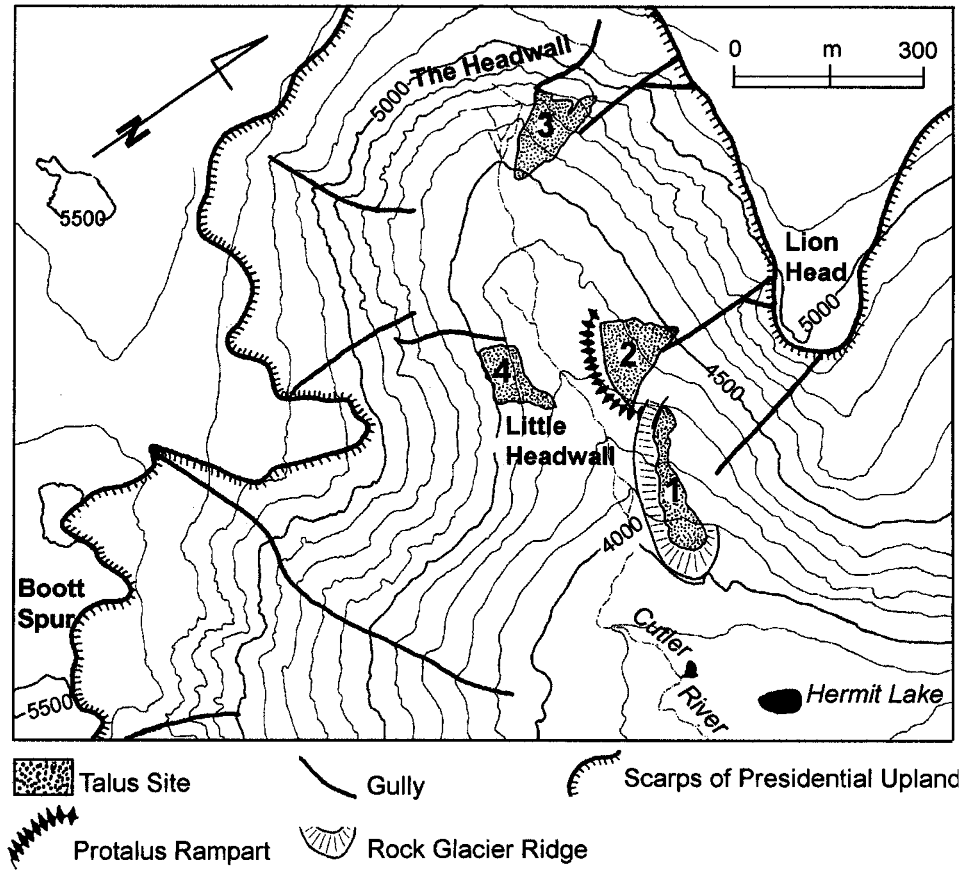
The bedrock comprising the field area, as well as the majority of Tuckerman Ravine, is the upper unit of the Littleton Formation (Billings *et al*., 1979). This unit consists of coarse-grained mica schist and interbedded micaceous quartzite. It has recently been subdivided into several different members (Eusden *et al*., 1996). Surficial deposits in the Ravine have been classified as ablation till and are generally referred to as ground moraine (Goldthwait *et al*., 1951). These deposits are sandy and are well-exposed on the floor of Tuckerman Ravine. Slopes in the cirque are primarily covered by unsorted colluvium or consist of bare rock cliffs. Several avalanche scars are present, indicating episodes of mass wasting (Kull and Magilligan, 1994; Davis *et al*., 1996).

METHODOLOGY

Fabric analysis was utilized in examining the large surficial talus blocks that make up the deposits. This involves two values (trend and plunge) that respectively refer to the orientation and inclination of the long axes of talus components in space. Fabric analysis is commonly employed to study the small constituent particles (with A-axes of less than one meter) which form colluvium, fluvial deposits, glacial till, debris flows, and, infrequently, talus. This study therefore broadens the method to large talus components (A-axes greater than one meter). The trend and plunge and respective dimensions (A-, B-, and C-axes) of each accessible talus

FIGURE 2. Location of the talus deposits in Tuckerman Ravine, New Hampshire (contour interval = 100 feet [30.48 m]).

Localisation des talus d'éboulis dans le Tucklerman Ravine, dans le New Hampshire (courbes de niveaux aux 100 pieds [30,48 m]).



block at the four sites were recorded. Emphasis was placed on the horizontal orientations of the A-axes and these were plotted as rose diagrams smoothed with a 30° moving average to eliminate "noise" in the data. Fabric orientations within and between each site were then compared under the common assumption that preferentially orientated fabric is likely to develop in response to movement and can therefore be used to infer geomorphological processes.

In determining the methods of slope failure in Tuckerman Ravine, a joint survey was undertaken along the cirque walls above each talus site. The data were displayed on smoothed rose diagrams. In addition, the spacing between joints at the source areas was recorded wherever possible. The orientation and spacing of joints and the size and shape of individual talus blocks were then compared to determine how fracturing controls block development.

A geomorphological map of Tuckerman Ravine was constructed on the basis of field observations, aerial photograph interpretation, and the 1:5,000 scale map of Tuckerman Ravine, Boott Spur, and Lion Head compiled by Washburn (1993). Finally, lichenometry was employed in an effort to provide age control on the talus deposits. However, this method proved to be of little use as it met with shortcomings similar to those encountered by Mayewski and Jeschke (1978), Eskenasey (1978), and Larson (1983) in other studies in the region.

PREVIOUS STUDIES IN TUCKERMAN RAVINE

Previous studies of the talus deposits in Tuckerman Ravine have almost exclusively taken place in order to determine glacial sequences in the region. As a result, the deposits have mainly been cited as evidence of one or the other glacial sequence model. The initial investigations of the talus deposits were made by J.W. Goldthwait (1913a, b) who concluded that the "block heaps" represent avalanche and rockfall debris which was most likely to have been deposited during and immediately after the wasting of the Laurentide ice sheet. Later, Antevs (1932) examined the "train of boulders" (Site 1) and the prominent ridge that borders its southern and western sides (Figs. 1 and 2). He argued that a portion of the boulders was talus and also noted that the ridge has a steep eastward-facing slope, is concave in plan, and eventually merges with the cirque wall. Upon viewing these features from the opposite side of the Ravine (on Boott Spur), Antevs concluded that the boulders and ridge represent a moraine which has been truncated by a valley glacier in the lower cirque.

The talus features were later studied by W.F. Thompson (1961) who concluded that protalus ramparts formed at Site 1 and adjacent to the south side of Site 2 in a manner which was very different to that later outlined by Washburn (1979). Thompson stated that talus on the slopes had become differentiated into a congeliturbate layer mantled by "felsenmeer" boulders (literally a "sea of rock" or a blockfield according to

Washburn, 1973, 1979). Thompson (1961) postulated that the downslope creep of the felsenmeer upon the margin of the existing valley fill thrust up the fill and formed the protalus ramparts. Thompson also surmised that a large bulge of boulder-laden material at Site 1 subsequently moved out from the protalus rampart toward the cirque floor. He therefore classified the deposit as a lobate rock glacier using the system proposed by Wahrhaftig and Cox (1959).

W.F. Thompson (1961) stated that the ridge that parallels the southern side of his lobate rock glacier is similar to those which border rock glaciers in Alaska as described by Wahrhaftig and Cox (1959). These authors concluded that such “moraine-like” ridges result from the development of longitudinal shear planes near the edges of rock glaciers. The shear planes form as a result of slower flow rates and increased viscosity at the margins. Material at these locations therefore stands as a ridge separated from the main body by a furrow. Nicholas (1994) has recently proposed an alternative mechanism for the formation of such ridges. In studying rock glaciers in Utah, he concluded that ridges form when debris slides off the edges of a rock glacier as it flows. Due to lack of ice, the zone between the rock glacier and the ridge becomes a well-defined longitudinal shear plane that forms a furrow.

The talus deposits on the north side of Tuckerman Ravine were later examined by R.P. Goldthwait (1965). He initially interpreted the deposits of large blocks (Site 1 and Site 2) as protalus ramparts and made no mention of the ridge that borders these deposits. In a later work (Goldthwait, 1970a), he altered his conclusions and stated the prominent medial ridge in Tuckerman Ravine (which borders the southern sides of Site 1 and Site 2) “fits the form” of a protalus rampart which is nearly concealed by an abutting and overriding talus apron. Goldthwait also stated that the blocky composition of Site 1 “suggests rock glacier accumulations”. Soon thereafter he concluded (Goldthwait, 1970b) that Site 1 represents a lobate rock glacier bounded by a “moraine-like” marginal ridge, which was much the same as W.F. Thompson's (1961) conclusion.

Research conducted during the 1980s has generally supported the earlier work of the Goldthwaits. In concordance with J.W. Goldthwait (1913a, b), Larson (1983) concluded that Sites 2, 3, and 4 represent rockfall talus. (Site 1 was not included in Larson's field area). Using trailside studies and aerial photograph interpretation, Waitt and Davis (1988) reiterated R.P. Goldthwait's (1965) observation that the blocks comprising Site 1 represent a protalus rampart. However, review of the above literature demonstrates little consensus about the development of talus along the north wall of Tuckerman Ravine.

SLOPE FAILURE IN TUCKERMAN RAVINE

The cirque walls above the four sites are deemed to have served as the respective talus source areas based upon their similar lithologies, the angularity of the talus, and the presence of couloirs above Sites 1, 2, and 3. The joint survey data indicate that two primary sets of joints are present above each talus site. One of these is oriented generally parallel to the cirque walls and the other is perpendicular to them. The number of joints recorded at the source areas ranged from 36 above Site 1 to 17 above Site 4. These exceed the amount (12 to 15) proposed by Kohlbeck and Scheidegger (1977) as necessary to define at least two joint sets (should they exist). In addition, the majority of discontinuities dip very steeply (between 70° and 90°) and those parallel to the cliffs were determined to be dipping into the cliff faces.

It is widely recognized that fracture patterns govern not only slope stability but also the scale and style of mass movements (Terghazi, 1962; Goudie, 1981; Hoek and Bray, 1981; and Selby, 1982). It has been shown that steep, bare rock slopes which are inclined at angles greater than 40° experience failure mainly by rockfall and toppling, and that these processes are greatly influenced by the frequency and orientation of fractures (Small and Clark, 1982; Alexander and Rendell, 1986). In addition, Kull and Magilligan (1994) concluded that rockfall is the most prevalent means of slope failure in the White Mountains. The cliffs in Tuckerman Ravine possess slope angles of at least 53° and appear as aggregates of joint-defined blocks and columns (Fig. 3). Large landslide or avalanche scars, which commonly have joints that dip out of the free face and are indicative of plane or wedge failure, are not evident. Rockfall and toppling are therefore regarded as the primary types of slope failure in Tuckerman Ravine.

Mass wasting by rockfall occurs as blocks separate from free faces due to water pressure and ice wedging in joints (Statham and Francis, 1986). The characteristics of the talus deposits (large, well-sorted, subrounded to angular debris with an openwork texture) also support the view that the slopes have been subject to rockfall (Mudge, 1965; White, 1981). Similar to most talus slopes, the longitudinal profiles for Sites 2, 3, and 4 are classified as rectilinear in their upper portions and concave in their lower portions. The longitudinal profile for

FIGURE 3. The irregular, joint-controlled surface of Lion Head. This cliff face is indicative of rockfall and toppling, the primary methods of slope failure in Tuckerman Ravine.

La surface irrégulière à Lion Head déterminée par les fractures. Ce front atteste bien des glissements et des basculements survenus sur le versant, les principaux processus à l'œuvre au Tuckerman Ravine.

Site 1, however, does not fit these patterns as the deposit is primarily situated parallel to and at the foot of the slope.

Based upon source-area fracture characteristics (Goodman and Bray, 1977), block toppling is concluded to have been responsible for many of the slope failures in Tuckerman Ravine. This involves vertical or nearly vertical joint sets that strike within 30° of the slope crest and dip into the slope face. These sets are intersected by orthogonal joint sets and thus define a series of tall narrow rock columns and blocks. Such configurations characterize the joints above each talus site. If the center of gravity of a column acts outside its base, the potential exists for it to rotate and move toward the free face of the cliff. A toppling column can therefore thrust against the ones directly beneath it, inducing what Wyllie (1980) called a “domino effect” (Fig. 4). Block toppling is concluded to have occurred along joints parallel to the cliff faces where the intersecting subvertical joints guided the direction of movement. Further evidence of toppling in the Ravine includes obsequent scarps (a back-facing scarp on the downthrown side of a rock column) and tension cracks (an opening on the slope crest where a rock column has rotated forward).

The talus deposits are thought to have formed through the relatively slow or infrequent input of debris, not from a rapid slope failure. This is supported by the steep angles characterizing the deposits at Sites 2, 3, and 4. However, Site 1 differs from the other deposits in that it primarily lies at the foot of the slope and not upon the slope itself. Given that the Presidential Range was covered by the Laurentide ice sheet, the deposits are concluded to have formed during the early Holocene when climatic conditions created an environment which was conducive to slope failure of the magnitude observed (Goldthwait, 1940).

TALUS IN TUCKERMAN RAVINE

GENERAL DESCRIPTION OF THE TALUS DEPOSITS

The distinguishing characteristic of the talus deposits is the large size of their constituent blocks that create a microrelief of at least one to two meters. Considering the spacing of the fractures (up to three meters) corresponds very closely to the block dimensions, it is clear that the blocks were defined by source-area joints. The sites contain sporadic vegetation (lichens, grasses, shrubs, and trees) and are devoid of fines as the large block sizes have obviously facilitated eluviation of smaller debris. Based upon these characteristics and the lack of fresh constituents and recent avalanche scars above them, the talus deposits are thought to be relict features.

To characterize the talus deposits further, their angles of repose, individual particle morphology (shape, roundness, and sphericity), and degree of sorting were determined. With the exception of the lower portion of Site 1, the deposits have angles of repose that lie between 35° and 40°, which are very similar to the currently accepted values of 38° and 40° for talus (Statham and Francis, 1986). In order to determine their morphology, fifty blocks were selected from each site by systemic random sampling. The majority of blocks at Sites 1, 3, and 4 are bladed to elongate, which generally reflects the joint sets that were responsible for their formation. Block shapes at Site 2 are distributed among platy, bladed, and elongate, probably as a result of the relatively greater azimuthal range in joint orientations at the source area. Furthermore, most blocks are subrounded to angular and have low-to-moderate sphericity as a result of being defined by joints. Finally, downslope increase in block size was only observed at Site 2. Blocky talus is generally incapable of sorting due to its angularity, mass, friction, and large surface area.

FIGURE 4. An example of block toppling that exhibits a “domino effect” on the west side of Connection Gully, the couloir above Site 2.

Exemple de blocs basculés par « effet domino » sur le côté ouest du Connection Gully, gorge située au-dessus du site n^o 2.

TALUS FABRIC IN TUCKERMAN RAVINE

The number of talus blocks measured at each site ranged from 209 at Site 1 to 62 at Site 4. The block fabric data were plotted as smoothed rose diagrams (Fig. 5) which indicate that the most complex arrangement of talus occurs at Site 1 where field investigation initially discerned a bimodal fabric distribution. The blocks at the distal end of this deposit were observed to be oriented northeast-southwest, or perpendicular to the main body of the talus, while those in its central portion and close to its apex were oriented northwest-southeast or parallel to the main body.

The Site 1 data were subsequently divided into two groups, corresponding to the upper and lower portions, and were plotted as smoothed rose diagrams (Fig. 6). These disclose a striking bimodal fabric distribution in which block orientation on the lower portion of Site 1 (Site 1a) appears to have arisen as the talus came to a collective halt upon cessation of movement or upon meeting some obstruction. Such an arrangement of fabric is not explained by simple talus accumulation models and is therefore concluded to be indicative of post-depositional movement or activity. The fabric of the upper portion of Site 1 (Site 1b) is concluded to have developed from blocks that moved downslope, in this case to the southeast.

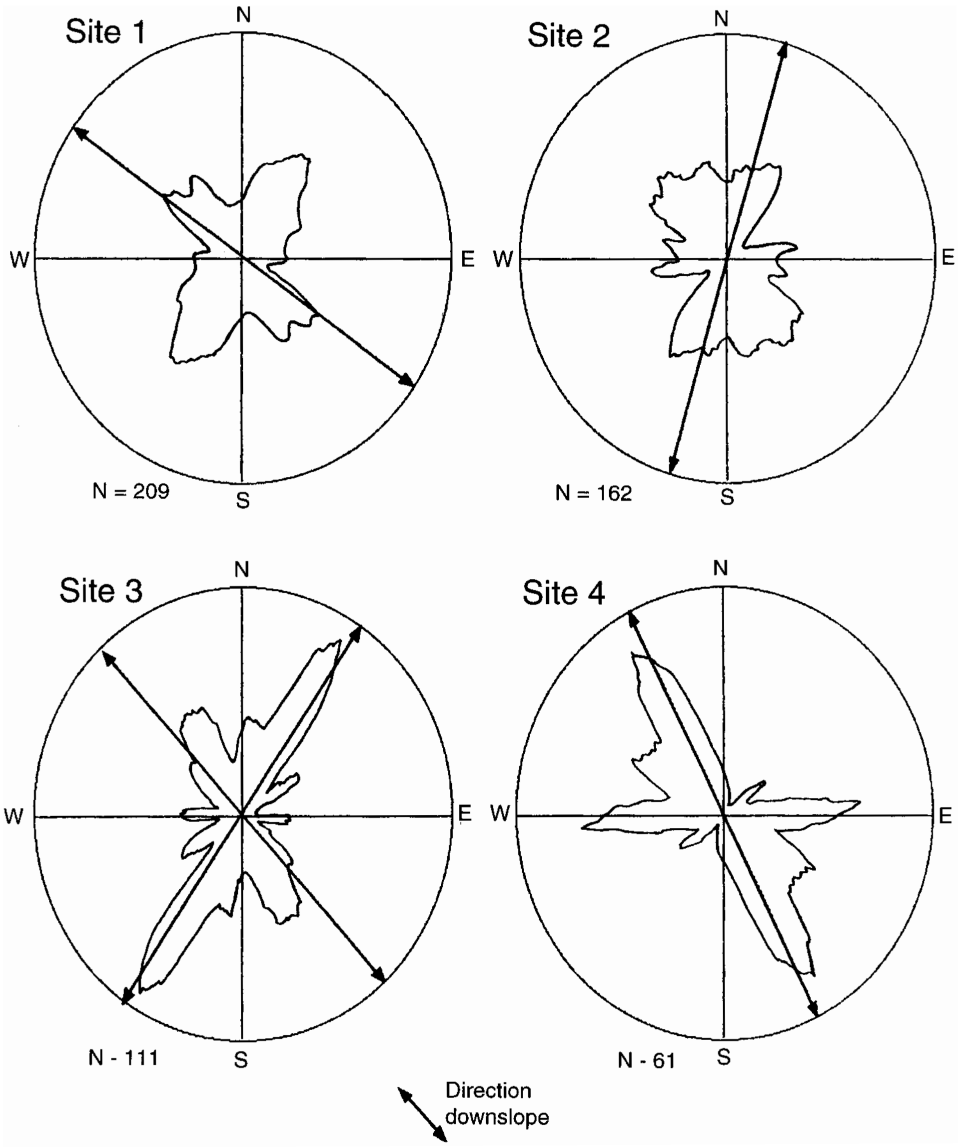


FIGURE 5. Fabric analysis for each talus site plotted as smoothed rose diagrams. The diagrams indicate a preferred downslope orientation of blocks at Sites 2, 3, and 4.

Diagrammes circulaires de l'orientation des blocs dans les cônes d'éboulis. Les diagrammes donnent l'orientation préférentielle des blocs vers le bas aux sites n^{os} 2, 3 et 4.

The majority of blocks at Sites 2, 3, and 4 are preferentially orientated in the downslope direction. According to Akerman (1984), a preferred orientation does not vary by more than 25°. Examination of the fabric data indicates that the downslope spread (approximately 45°) is by far the largest at Site 2. This spread represents a "fanning out" of the talus and is accounted for by the large lateral width (approximately 150 meters) of this deposit and by several variations in slope aspect. The two downslope modes in the data for Site 3 are a function of the location of this site at the corner of the cirque. One downslope mode corresponds to the north wall of the cirque and strikes at N030°E, while the other is related to the corner of the cirque at the edge of the headwall and strikes at N035°W. The spread in the downslope pattern at Site 4 also results from differences in slope aspect, in that this deposit is situated along the perimeter of the upper cirque.

The preferred downslope orientation of blocks at Sites 2, 3, and 4 is considered to be the result of rocks and toppling columns of blocks that fell and incrementally came to rest upon those which had previously been deposited. It also appears to be indicative of sliding, a conclusion reached in many previous talus investigations (McSaveney, 1972; Albjar *et al.*, 1979; Perez, 1989; Salt and Ballantyne, 1997). Evidence of sliding lies in the imbricate structure of the talus deposits. Such arrangement suggests that blocks have partially overridden those that brought their motion to a halt. Many of the blocks plunge less steeply than the talus surface and therefore have a strong upslope imbrication. Such arrangement has been observed in much smaller debris by Caine (1969), Perez (1986), and Salt and Ballantyne (1997). Some of the blocks may also have acquired their preferred orientations by gliding over snow or ice as Perez (1988, 1990) also encountered. The fabric data indicate that the blocks at Sites 2, 3, and 4 did not experience post-depositional movement or activity.

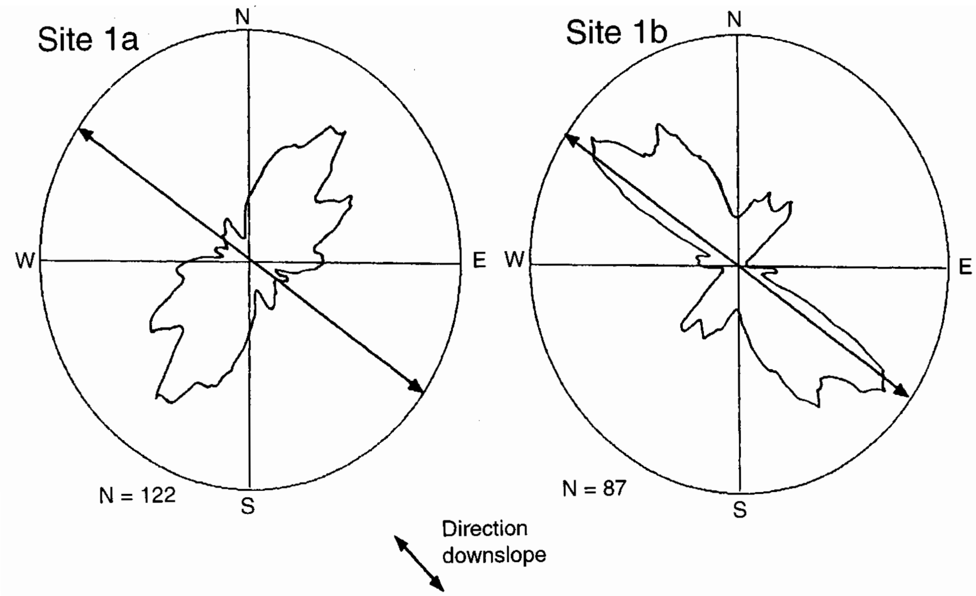


FIGURE 6. Rose diagrams illustrating block orientation data for Site 1. Site 1a pertains to blocks at the distal end of the deposit and Site 1b to those in the upper and middle portions.

Diagrammes circulaires de l'orientation des blocs au site n^o 1. Le site n^o 1a concerne les blocs situés à la partie distale du dépôt, tandis que le site n^o 1b se rapporte aux blocs des parties supérieure et mitoyenne.

The features at Site 2 have generated disagreement about both the classification of the talus and the origin of the adjacent protalus rampart. Thompson (1961) initially confused the situation by terming the talus blocks as felsenmeer, a periglacial landform which is clearly distinguishable from talus in both form and genesis (Washburn, 1973, 1979). Although the ridge is generally regarded as a protalus rampart (Thompson, 1961; Goldthwait, 1970a; and Waitt and Davis, 1988), Thompson envisioned that the rampart was formed by felsenmeer that crept downslope and pushed up the valley fill on the cirque floor. This process has not been confirmed or even mentioned elsewhere in the literature and is not deemed to be a means of protalus rampart formation. The rampart is concluded to have formed by the universally accepted process outlined by Washburn (1979). Snow probably remained at this location and not in the vicinity of Site 1 due to its higher elevation and location within the relatively more protected upper cirque. Slope failure apparently continued while the snowbank melted as the conical shape of Site 2 suggests that this feature consists of rockfall talus that has filled the depression above a protalus rampart.

INTERPRETATION OF SITE 1 TALUS FEATURES

DISCUSSION OF PREVIOUS WORK

The bimodal fabric distribution exhibited by Site 1 strongly argues against Antevs' (1932) interpretation that it is a moraine. In addition, the blocks that comprise this site are subrounded to angular and lack markings such as striations and grooves. Conversely, moraines commonly contain fines and are composed of more rounded and weathered materials with etched surfaces (Ritter, 1986). Given the absence of space between it and the cirque wall, where glacial ice would typically be present, Site 1 cannot be classified as a medial moraine. Finally, morainic materials are usually randomly oriented, while the blocks of Site 1 have a strongly preferred orientation.

The form, location, texture, and nature of source area associated with Site 1 seem to support its classification as a protalus rampart (Waitt and Davis, 1988). Despite these similarities, the deposit lacks the characteristic depression between it and the cirque wall and its components have a preferred orientation. Although Harris (1986) found weakly developed fabrics on the proximal and distal slopes of a protalus rampart (fabrics that trend perpendicular to the ridge crest), these are quite different from the bimodal fabric distribution encountered in the present study.

Finally, although similar fabrics, openwork textures, block angularities, imbrication, and arrangement parallel to slope are also found in blockfields (Rapp, 1960; Potter and Moss, 1968; Caine, 1968, 1972; and White, 1976), the morphology and location of Site 1 markedly differ from those of such deposits. Unlike a blockfield, Site 1 is a narrow feature situated in a cirque. It is located on an uneven and fairly steep slope and has an obvious rockwall source area. The deposit also possesses steep margins and several breaks in slope, which suggests that it is too thick to be a blockfield.

In order to evaluate whether Site 1 is a rock glacier, previous investigations of rock glacier fabric were reviewed. Such studies are rare and have provided mixed results. Randomly oriented surficial components were encountered by Richmond (1962), Eskenasy (1978), Yarnal (1982), Nicholas (1994), and Nicholas and Garcia (1997). However, alignment of surficial materials parallel to flow was observed by Patton (1910), Wahrhaftig and Cox (1959), and Giardino and Vitek (1985). The last of these authors encountered components that were aligned parallel to surficial features and to the overall surface trend of rock glaciers. Fabrics perpendicular to surface trends were thought to result from internal deformation. Preferred fabric appeared to be influenced more by local conditions at the surface than by internal movement. Such fabric was concluded to develop in response to rock glacier movement and can be used to interpret the origin of such features.

However, the block fabric data for Site 1 mitigate against its interpretation as a lobate rock glacier (Thompson, 1961). The long axes of the blocks in the upper and central portion of the deposit would generally be oriented north to south had the blocks moved away from the cirque wall and toward the cirque floor as a lobate rock glacier. The fabric data indicate that the blocks in the above area have experienced movement over the Little Headwall in a northwest to southeast direction.

TONGUE-SHAPED ROCK GLACIER CLASSIFICATION

The bimodal fabric data for Site 1 support its classification as a tongue-shaped rock glacier under the system established by Wahrhaftig and Cox (1959). The crucial evidence lies in the fact that the blocks in its lower portion (Site 1a) are oriented perpendicular to those in its middle and upper portions (Site 1b). This may represent distortion of the orientation shown by blocks in the main body of the talus. It likely arose from compression caused by the arresting of motion as the snout of the rock glacier moved into the lower cirque and flowed against a stationary margin. The margin may have been stationary because there was little ice at this relatively lower elevation.

The form of a rock glacier is controlled by the topography immediately beneath it (Luckman and Crockett, 1978). Field observations and aerial photographs indicate that the Little Headwall exerts the greatest topographic control over Site 1. Viewing the deposit from Boott Spur gives the strong impression that it has the shape of a tongue and that it has flowed to the southeast over the scarp of the Little Headwall and into the lower cirque (Fig. 7). The deposit does not appear to have moved to the south toward the cirque floor as would be expected of a lobate rock glacier. Site 1 therefore reaches further downvalley than across it, contrary to the observation of Thompson (1961) that it spreads equally in both directions. Considering that it is elongated and has moved downvalley, Site 1 also fits the description of a tongue-shaped rock glacier according to the criteria listed by White (1981).

Although Thompson (1961) actually stated that Site 1 has the form of a tongue, he termed the deposit a lobate rock glacier primarily based upon its location along a cirque wall, not on the cirque floor. Tongue-shaped rock glaciers are usually regarded as exclusive cirque floor phenomena. This idea probably led Outcalt and Benedict (1965) to propose their classification scheme that separates rock glaciers into cirque-floor and valley-wall types. Tuckerman Ravine Rock Glacier therefore highlights the difficulty in classifying rock glaciers according to their geographical position.

ROCK GLACIER DESCRIPTION

Like many rock glaciers, Tuckerman Ravine Rock Glacier has a talus cone collection area at its head and therefore a distinct source area as well. A relatively small amount of talus appears to have been added from Lion Head. Moreover, the rock glacier has a fairly steep middle section where it passes over the scarp of the Little Headwall, and a more gentle and spreading lower section. The feature consequently has an uneven, stepped surface which is approximately 300 meters long, 50 meters wide, and 10 meters thick. Although small compared to the majority of rock glaciers, a minimum size for such deposits has not been formally established in the literature.

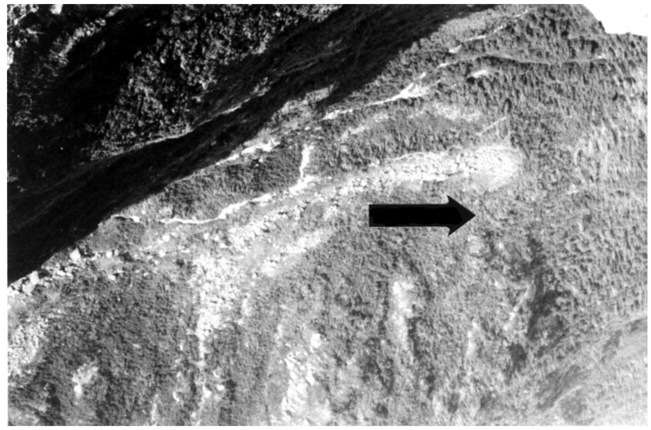


FIGURE 7. Tuckerman Ravine Rock Glacier looking to the north from Boott Spur. The arrow indicates the inferred direction of flow. This view supports that the deposit flowed to the southeast over the Little Headwall as a tongue-shaped rock glacier.

Vue vers le nord du glacier rocheux du Tuckerman Ravine, à partir de Boott Spur. La flèche donne la direction présumée de l'écoulement. Il semble bien que le dépôt se soit écoulé vers le sud-est au-dessus du Little Headwall en tant que glacier rocheux en forme de langue.

Many of the blocks that mantle the rock glacier are perched, which suggests that ice played a role in their movement and deposition. Several depressions are also present on the rock glacier. Their irregular distribution indicates that they may represent meltwater pits that formed due to ice melt. A more definitive interpretation cannot be made due to the inability to determine whether they are associated with ice melt or whether they simply reflect block coarseness. As the pits are not linear, fluvial action does not appear to have occurred beneath them.

Additional characteristics of Tuckerman Ravine Rock Glacier that are common to other rock glaciers are its sharply defined concentric frontal margin and marginal ridge. The presence of these features is regarded to be indicative of rock glacier flow. The bulging frontal margin slopes at approximately 33° and is quite conspicuous in the field and on aerial photographs. Perhaps the most prominent feature of the rock glacier is its marginal ridge. This is separated from the rock glacier by a furrow and it stands at least a meter above and away from the eastern (snout) and southern sides of the deposit. Where measurement was possible, the orientations of blocks comprising the ridge follow the trend of the ridge itself, thereby supporting that the deposit flowed to the southeast as a tongue-shaped rock glacier.

Had the deposit moved to the south as a lobate rock glacier, as advocated by Thompson (1961), longitudinal shear planes manifesting as furrows would occur north to south over its surface, rather than only along its margin and perpendicular to a supposed southerly flow direction. Furthermore, the marginal ridge is not considered a protalus rampart, in that it surrounds the rock glacier and appears to be part of the feature. Whether the ridge formed through the process described by Wahrhaftig and Cox (1959) or by Nicholas (1994) is uncertain. However, use of the term "moraine-like" ridge by the former authors to describe such marginal ridges should be avoided due to potential confusion with moraines deposited directly by a glacier.

ROCK GLACIER GENESIS AND STATE OF ACTIVITY

Rock glaciers are commonly classified according to their ice content (Potter, 1972; Barsch, 1988; and Clark *et al.*, 1994). Given that the slope beneath Lion Head is south-facing and therefore receives a significant amount of direct insolation, it is doubtful a block of continental ice or the remnant of a cirque glacier could have remained in this open, relatively low area after deglaciation without being closer to the headwall. Based upon these factors and its relatively small size and openwork texture, Tuckerman Ravine Rock Glacier is regarded to have been ice-cemented rather than ice-cored using the system proposed by Potter (1972). Interstitial ice in such rock glaciers is considered to develop in the numerous large interconnected voids between constituent talus blocks. Ice in ice-cemented rock glaciers has many possible origins. Among these are the freezing of direct precipitation or meltwater, drifting or avalanche snow, or the Balch ventilation effect (Corte, 1976; Haeberli and Vonder Muhll, 1996; and Harris, 1996). Limited penetration of heat may have also played a role in forming interstitial ice in that blocks on the surface would absorb most or all incoming solar radiation. Moisture produced by thaw at the surface could then have percolated down and become frozen incrementally (R.L. Anstey, personal communication, 1990).

Rock glaciers are also commonly categorized according to their state of activity. Tuckerman Ravine Rock Glacier is regarded as a relict feature because it lacks fines and has a blocky surface, possible meltwater pits, surficial vegetation, and a margin surrounded by a ridge (Corte, 1976; Barsch, 1988). Indications of water, ice, and surface or subsurface drainage were not observed. In addition, the junction between the main body of the rock glacier and its frontal margin is rounded and the angle of the frontal margin, 33°, lies within the range of 20°-35° established by Wahrhaftig and Cox (1959) for relict rock glaciers. The frontal margin is also covered with vegetation including trees in growth position. Finally, the deposit has the highest percentage of lichen cover (approximately 64 percent) of the talus deposits studied. Given that compelling indications of significant periglacial conditions during the Holocene have not been established (with the exception of those on the summit of Mount Washington), Tuckerman Ravine Rock Glacier was probably active for a relatively brief time during deglaciation.

CONCLUSIONS

This project constitutes the first comprehensive investigation of the talus deposits in Tuckerman Ravine as it includes an examination of talus constituents and source areas. Rockfall and block toppling were identified as the specific modes of slope failure. Block fabric analysis was employed to study the talus deposits and was crucial to the resolution of the controversy about the origin and classification of Site 1. A bimodal fabric distribution was encountered in the blocks of the upper and middle portions and at its base. Blocks in the former areas trend downslope (with the main body of the talus) and those in the latter area are transversely oriented and imply a collective cessation of movement. The fabric data and other characteristics indicate that Site 1 is a relict tongue-shaped rock glacier and do not support previous classifications as a moraine, lobate rock glacier, or protalus rampart. The blocks of the remaining deposits exhibit a preferred downslope orientation and have not undergone post-depositional movement. Thus, the results of this project demonstrate the utility of fabric analysis in studying comparatively large-sized talus.

The primary focus of geomorphological research in the Presidential Range has centered upon either proving or disproving the reactivation of cirque glaciers after the most recent continental deglaciation. The results of this project bear on this century-old dispute in that both the presence and locations of the talus deposits argue against significant post-Laurentide cirque glacier activity in Tuckerman Ravine. The deposits would probably have been obliterated had they been covered by a local cirque glacier. Given that Tuckerman Ravine represents perhaps the most suitable location in the region for snow and ice to persist and form a glacier, the refutation of cirque glacier activity during the Holocene is deemed applicable to the remainder of the White Mountains.

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