ICE SEGREGATION AS AN ORIGIN FOR LENSES OF NON-GLACIAL ICE IN "ICE-CEMENTED" ROCK GLACIERS

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ABSTRACT. In order to flow with the gradients observed (10° to 15°) rock glaciers cannot be simply ice-cemented rock debris, but probably contain masses or lenses of debris-free ice. The nature and origin of the ice in rock glaciers that are in no way connected to ice glaciers has not been adequately explained. Rock glaciers and talus above them are permeable. Water from snow-melt and rain flows through the lower part of the debris on top of the bedrock floor. In the headward part of a rock glacier, where the total thickness is not great, if this groundwater flow is able to maintain water pressure against the base of an aggrading permafrost, segregation of ice lenses should take place. Ice segregation on a large scale would produce lenses of clear ice of sufficient size to permit the streams or lobes of rock debris to flow with gradients comparable to those of glaciers. It would also account for the substantial loss in volume that takes place when a rock glacier stabilizes and collapses.

RÉSUMÉ. *La ségrégation de la glace à l'origine des lentilles de glace d'origine non glaciaire dans les glaciers rocheux soudés par la glace.* Pour qu'ils puissent s'écouler sur les pentes où on les observe (10° à 15°), les glaciers rocheux ne peuvent pas être simplement constitués de débris rocheux soudés par la glace, mais contient probablement des blocs ou des lentilles de glace dépourvus de sédiments. La nature et l'origine de la glace dans les glaciers rocheux, qui ne sont en aucune manière reliés à des glaciers de glace, n'a pas été correctement expliquée. Les glaciers rocheux et les talus qui les surplombent sont perméables. Les eaux de fusion et de pluie coulent à travers la partie inférieure des blocs sur le bedrock. Dans la partie haute d'un glacier rocheux, lorsque l'épaisseur totale n'est pas grande, si l'écoulement sur le bedrock est suffisant pour maintenir la pression hydrostatique contre la base d'un permafrost en contrepente, il peut y avoir ségrégation de lentilles de glace. La ségrégation de la glace sur une grande échelle produirait des lentilles de glace pure suffisamment importantes pour permettre aux courants et aux langues de débris rocheux de s'écouler sur des pentes comparables à celles des glaciers. Ceci expliquerait aussi la substantielle perte de volume qui intervient lorsqu'un glacier rocheux se stabilise et s'effondre.

ZUSAMMENFASSUNG. *Eisabsonderung als Ursprung für Linsen nicht-glazialen Eises in "eiszementierten" Blockgletschern.* Um auf den beobachteten flachen Hangneigungen von 10° bis 15° fliessen zu können, können Blockgletscher nicht einfach eiszementierter Schutt sein, sondern wahrscheinlich Massen oder Linsen schuttfreien Eises enthalten. Die Natur und die Herkunft des Eises in Blockgletschern, die nicht mit Eisgletschern verbunden sind, wurden bisher nicht ausreichend erklärt. Die Blockgletscher und der Schutt auf ihnen sind durchlässig. Wasser aus der Schneeschmelze und Regen fliesst durch den unteren Teil des Schuttes über den Felsuntergrund. Im vorderen Teil eines Blockgletschers, wo die Gesamtdicke nicht gross ist, kann die Absonderung von Eislinsen stattfinden, wenn dieser Grundwasserstrom einen ausreichenden Wasserdruck gegen die Basis eines aufsteigenden Permafrostes aufrecht erhalten kann. Eisabsonderung in grossem Umfang würde Linsen aus klarem Eis erzeugen, deren Grösse die Ströme oder Loben von Felsschutt bei Hangneigungen, die denen von Gletschern vergleichbar sind, zum Fliessen bringen könnten; sie könnte auch den hohen Volumenverlust erklären, der bei unbewegten und kollabierenden Blockgletschern eintritt.

ROCK GLACIERS are tongues or lobes of angular rock waste that generally head in steep cliffs, have ridges and troughs on their surfaces caused by flow, and have a steep unstable front at or near the angle of repose. All investigations of active rock glaciers have long recognized that ice of both glacial and non-glacial origin is present in these distinctive alpine landforms. The existence of glacial ice is easy to understand and explain, because in many areas, including the Rocky Mountains of Canada and the United States, and the central Andes of Argentina and Chile, glacial ice can be seen above debris-covered glacial ice, which changes down-slope into collapsing stagnant glacial ice (thermokarst) and/or ice-cored debris that displays the structural flow characteristics of a rock glacier (Corte, 1976[b]). Foster and Holmes (1965), Potter (1972), Luckman and Crockett (1978), Whalley (1976), White (1976), and many others have described active rock glaciers in which the frozen core is massive ice of glacial origin.

The presence of ice that is not of glacial origin in rock glaciers has been more difficult to explain. Wahrhaftig and Cox (1959) suggested that interstitial ice existed within the debris below the surface boulder layers or rock glaciers and that the rock glacier flowed down slopes because the frozen mass yielded to the stress caused by the unsupported weight of the debris–ice mixture. The origin of the interstitial ice has been attributed to snow melt and/or groundwater, which refreezes in pore spaces within the body of debris. The Balch ventilation process, in which cold air is trapped in the cavities

within talus, has been suggested as a means of refreezing percolating melt water (Thompson, 1962). Others have attributed much of the non-glacial ice to avalanching snow and ice masses that were buried by talus (Lliboutry, 1961). Most investigators of non-glacial rock glaciers have accepted the concept that interstitial ice is present, and that its deformation through creep results in the observed movement and surficial structures (White, 1976). Washburn ([c1979], p. 229), however, points out that although this view is widely held, it is more probable that rock glaciers contain ice in excess of that necessary to fill the pore spaces.

Active rock glaciers exist in regions of sporadic to continuous permafrost (Barsch, 1977[a]; Washburn, [c1979]; Corte, 1978), and if climatic conditions become sufficiently warm to destroy the frozen ground, the rock glaciers become inactive and ultimately collapse. Fossil rock glacier deposits studied in Nevada (U.S.A.) and in the central Andes (Argentina) generally have from 30 to 60% of the mass of associated active rock glaciers, so that the ice content of most active rock glaciers, regardless of its origin, evidently amounts to considerable volume.

The Río Blanco basin in the Cordón del Plata of the central Andes west of Mendoza, Argentina, contains examples of each type of active glacier described and defined by many authors (Wahrhaftig and Cox, 1959; Madole, 1972; White, 1976). Rock glaciers of several lithologies are present in the area; some are dominated by blocky quartzite and others are made up almost entirely of rhyolites that shatter into small fragments. Single rock-glacier tongues clearly connected to debris-covered glaciers have widths of 180–210 m. Compound rock glaciers formed from the coalescence of two or more single tongues range in width from 350–850 m and have surface gradients of 12° to 15° between steep (20° to 35°) falls over buried rock thresholds. Slender rock-glacier tongues 70–100 m across, with an upper surface slope of 11° to 12°, extend more than 1 000 m beyond the wide, thick parts of two of the rock glaciers that have their sources in glacier ice. They flow like a narrow stream through more stable inactive parts of the rock glacier. It seems unlikely that these long narrow tongues of debris could contain much ice of glacial origin, particularly after the rock glaciers have passed over one or more rock thresholds on the valley floor that cause them to thin greatly. Some active linguoid rock glaciers in the area head in talus sheets and have no connection to glacial ice. These are small, 100–150 m across by 200–600 m long; the ones examined have surface gradients that range from 8° to 21°. The area contains only a few lobate rock glaciers, all of which are small. Lengths and breadths of fossil rock glaciers in the area are similar to the active ones, and their surface features, somewhat muted, suggest similar characteristics in their origin and movement.

Altitudes of all the active lobate and tongue-shaped rock glaciers that are unrelated to glacial ice in the area are greater than 3 500 m, and heads of the lowest active rock glaciers of this type are approximately 3 700 m. The crest of the active edge of the rock glacier that extends to the lowest altitude is 3 300 m, although this rock glacier is a long tongue descending from an active glacier. Based on a lapse-rate for the area of 0.6 deg per 100 m and data from a meteorological station at 2 500 m in the basin, the 0°C isotherm is about 3 330 m, and the mean annual air temperature at 3 700 m would be approximately −2.2°C. Sunlight rarely reaches the south-facing cirques and steep valley walls where the rock glaciers begin, so the actual mean annual temperature there, based on summer temperature differences observed in the field, probably is 3 to 5 deg colder than the calculated mean for the altitude.

Excavations in the side of a rock glacier that is unrelated to glacial ice in the area studied, made 20 to 50 m down-slope from its upper end in March near the end of the melting season, revealed ice cementing the rock debris 1.0 m below the base of the boulder veneer, which at this place is 1 m thick. A lens of clear ice 10 cm thick about 1 m beneath the permafrost table had crystals 2.5 to 4.0 mm across with parallel alignment normal to the surface of the rock glacier. Rock debris with a sand–silt matrix below this lens is cemented with ice. Water could be heard trickling below the surface, and icings sloped into troughs within, along the side, and at the upper end of the rock glacier (Fig. 1A). Thickness of the boulder cover and instability of frontal slopes farther down the rock glacier made additional excavation deep enough to examine ice content impossible.

Several investigators have reported masses of clear ice within rock glaciers in regions that have not been glaciated. Johnson ([c1973]) attributed intermittent ice lenses overlying discontinuous dry permafrost in a rock glacier in Alaska to the burial of snow-banks by rock fall as did Lliboutry (1961) in the Childean Andes. Barsch (1977[b]) described continuous ice cement from the base of the active layer to a depth of more than 10 m in a bore hole, and he encountered several lenses of clear ice.

Rock glaciers, whether composed of large blocks of quartzites and granites or of the much smaller debris produced by frost shattering of fine-grained igneous rocks, consist of a surficial open mesh of rock
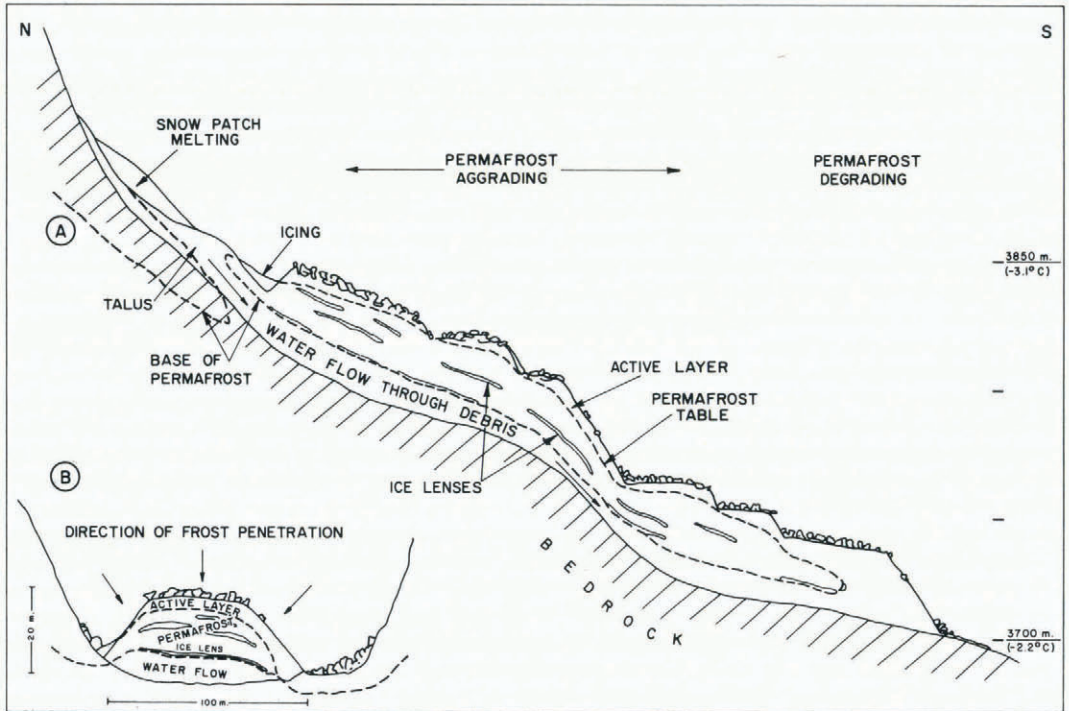
Fig. 1

A. *Diagram of rock glacier, showing permafrost body, ice lenses, and movement of water through base of debris. Sketch and
    altitudes based on those of rock glaciers not connected to glacial ice in the Andes west of Mendoza, Argentina; thickness and
    distribution of ice lenses diagrammatic. Vertical exaggeration × 4.*
B. *Diagrammatic cross-section through rock glacier near upper end.*

fragments that overlie rock mixed with finer-grained debris. Stream-bank exposures and pits dug in
active and fossil rock-glacier debris indicate that the material beneath the boulder cap is a diamicton that
contains a large amount of relatively small, angular rock fragments and considerable sand and silt but
without sufficient fine-grained sediment to fully fill the spaces between the larger fragments. If interstitial
ice cements the fragments together, as the term "ice-cemented rock glacier" implies, the mass might
creep slowly down a steep slope, but the internal friction would be great.

Whalley (1974) believes that all rock glaciers must have a core of glacial ice. He computed shear
strengths of debris–ice mixtures, and concluded that they are too great to allow many of the thinner rock
glaciers to flow. Even though Wahrhaftig and Cox (1959) calculated a viscosity for Alaskan rock
glaciers that was not much greater than that of glacial ice, on theoretical grounds I shall have to agree
with Whalley that the 10° to 15° gradient of most rock glaciers is not sufficient to overcome the shear
strength of a debris–ice mixture within the body of a rock glacier unless there is enough excess ice to
separate the rock fragments. A similar conclusion was reached by Smith (1973). Washburn ([ᶜ1979])
regards some excess ice to be present in most active rock glaciers. This requires, then, that active rock
glaciers contain some kind of clear core or ice lenses, deformation of which results in movement down-
slope, carrying the debris above it and creating the structures observed on the surface. The manner of
formation of the ice core or lenses, however, remains in question.

Avalanching of snow and rock debris onto rock-glacier surfaces or rock falls on snow masses or icings
may result in some aggradational ice lenses in rock glaciers, but they are unlikely to be the major source
of debris-free ice masses within all rock glaciers that do not have glacial ice at their heads. The Balch
process may account for near-surface ice in rock glaciers and undoubtedly aids in maintaining low

temperatures at the base of the boulder veneer, but it would be unlikely to produce lenses of debris-free ice. Another source, mentioned by Thompson (1962), Barsch (1977[a], [b], 1978), and Washburn ([ᶜ1979]), but little stressed, seems reasonable, however. In regions of both active permafrost and seasonal frost, segregation of clear ice masses on a small scale is a common occurrence, particularly in sediments that contain considerable silt. Mackay (1971, 1973) reported on the nature, distribution, and extent of several hundred massive icy beds in the Canadian Arctic that he regarded to be large-scale examples of ice segregation. Most of the examples he studied showed that the massive icy beds occurred in close association with coarse-grained, porous sediments that could serve as an aquifer to supply water to the freezing plane or zone in aggrading permafrost. He considered water expulsion during freezing of the sediments to be the main source of the ice in the massive beds.

A similar process might readily explain the masses of segregated ice found in rock glaciers, and the fact that the volume of active rock glaciers is considerably greater than that of their fossil remains. Where a talus accumulates a few meters thick in an environment cold enough to produce permafrost within a thermal regime of $-5°C$ or lower and becomes saturated by the flow of melt water from snow banks above it, a body of perennially frozen ground will begin to form in the upper part of the talus. As soon as a layer of permafrost exists, water circulating through the talus below the frozen layers and above the bedrock (Fig. 1A) should be confined under enough hydrostatic pressure to keep it in contact with the base of the aggrading permafrost. Both the top and sides of most rock glaciers are exposed to the sub-freezing atmosphere, so the permafrost body should be mound-shaped in cross-section with the freezing front penetrating downward in a concentric manner (Fig. 1B). In this type of open system, as long as underflow of water through the talus beneath the frozen layer is maintained by melt water from snow banks, conditions are similar to those described by Mackay (1971, p. 411–12) and Washburn ([ᶜ1979], p. 68–70) for ice segregation to take place at the freezing front. Such development of ice lenses, each a few centimeters or tens of centimeters thick, would heave the talus surface upward and form the kind of ridges commonly found at the head of lobate and small linguoid rock glaciers. Additional small ice lenses may exist near the top of a rock glacier where they formed beneath boulders whose upper surfaces are within the active layer and are being or have been heaved upward to the surface. These ice lenses would be preserved if they remain below the permafrost table.

Such an explanation would account for the clear ice lenses reported by Barsch (1977[a], [b]), all of which were associated with porous layers. Successive seasons of surface snow-melt and downward migration of the water should increase the volume of segregated ice as the permafrost layer grows in thickness, particularly in the headward part of a rock glacier. Growth of such ice lenses would also help explain the apparent upward growth of the surface of a rock glacier in its headward reaches. Once layers of massive ice, however thin, had formed, shearing forces exerted down the slope by gravity and the weight of the rock debris should overcome the shear strength of the ice, and flowage could begin in a rock glacier with approximately the same gradient as that required for glacial ice. Deformation would take place within one or more beds or lenses of massive ice a few meters beneath the surface.

The existence of lenses of clear ice in rock glaciers that have no connection with glacial ice has been documented, but little is yet known about the nature of that ice. The crystal fabric, air bubbles, and content and distribution of sand in segregated ice lenses differ sufficiently from those found in icings and the ice resulting from buried avalanches that these characteristics should aid in determining the manner of ice-lens development in rock glaciers (Corte and Blanca, 1963). Unfortunately, samples of ice from rock glaciers that might be examined to determine their crystallinity and composition are difficult to obtain because most rock glaciers are in remote areas and hand excavation to an adequate depth is difficult and often not possible. It will be necessary, however, to obtain and study samples of ice from several rock glaciers, particularly those that have no connection with glacial ice, past or present, to provide a satisfactory answer to the question of the origin, nature, and distribution of the ice in rock glaciers.

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