

Figure 1 and Figure 2 show typical interference photomicrographs of the two methods approximately five minutes after their preparation at  $-10^{\circ}\text{C}$ . Remembering that even, straight, and parallel interference bands indicate a flat, smooth surface, it can be seen that Figure 1 represents a surface which appears to be flatter and smoother than that of the surface in Figure 2. As previously observed (Itagaki, 1972), Bader's surfaces were always slightly curved, which can be readily seen from the slight curvature of the interference fringes in Figure 2.

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SIR,

### *Origin of rock glaciers*

In a recent letter regarding the origin of ice-cored rock glaciers, Carrara (1973) suggested that the debris at their surfaces may represent a succession of shear moraines formed during glacier retreat. Referring to a photograph of the ice core of the Arapaho rock glacier, Colorado Front Range (Outcalt and Benedict, 1965), he concluded that debris bands in the ice "may well be shear planes", and that shearing "would be one mechanism for obtaining a surficial mantle on the ice body".

Field studies of the Arapaho rock glacier support part, but by no means all, of Carrara's hypothesis. Figure 1 is a photograph of the surface of a debris layer (ablation surface) from the ice exposure in question. Mineral and organic inclusions are arranged in parallel streaks, orientated in a down-glacier direction, and indicating that Carrara is probably correct when he suggests that differential movement has occurred.

There is *no* evidence, however, that shearing has contributed a significant amount of coarse debris to the surface of the rock glacier. During the summer of 1966, erosion by a melt-water stream exposed a discontinuous 220 m long vertical section of buried ice, extending along the axis of the rock glacier from the shallow depression at its rear to a position about 400 m behind its front. The thickness of the exposed ice varied from 1.0 to 9.8 m. Examination of the ice core revealed only a few stones that were larger than 2 cm, and none that was larger than 6 cm. The ice is much too clean and contains stones that are at least an order of magnitude too small to be the source of the thick accumulation of boulders on the surface of the rock glacier. The latter have an average diameter of approximately 1 m (White, 1971) with occasional boulders 15-20 m in maximum dimension.

Along the walls of the melt-water channel, the thickness of the debris mantle ranged from 0.2 to 2.4 m, increasing down-valley. The debris was composed of two units: (1) a poorly sorted basal sand layer containing gravel and a few cobbles; and (2) a surface layer of large open-work boulders. Each layer appears to have originated by a different mechanism.

Boulders in the surface layer are rough and angular. Unlike the smooth, predominantly sub-rounded boulders found on historic moraines a few meters to the north, they show no evidence of modification by glacial transport. I attribute the upper layer of coarse angular debris to rockfall on to the glacier surface, but I am uncertain whether the boulders accumulated gradually through a succession of small rockfall events, or abruptly, as the result of a single catastrophic rockfall avalanche (Mudge, 1965).

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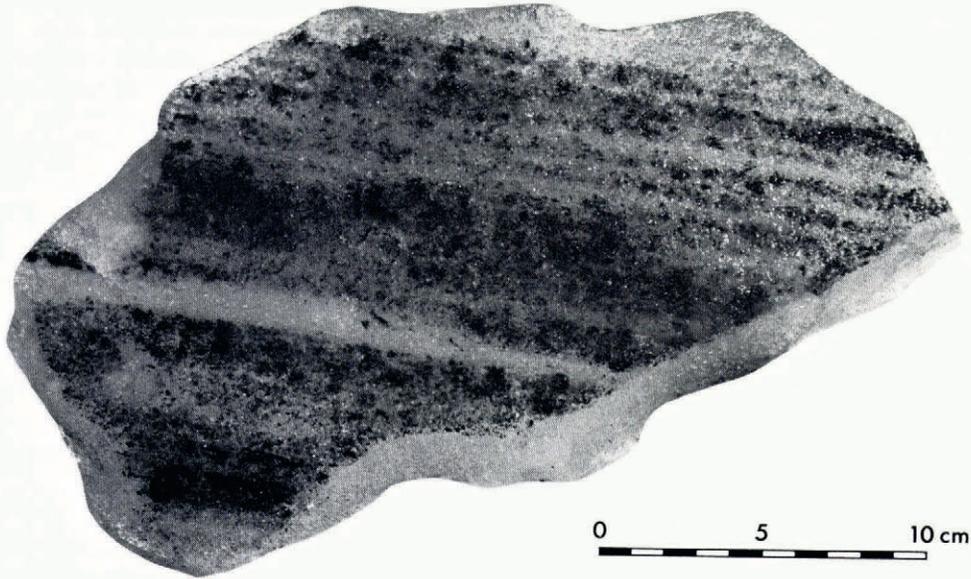


Fig. 1. Plan view of a debris layer in the ice core of the Arapaho rock glacier, Colorado Front Range.

The origin of the basal sand layer is undoubtedly complex. Some of the material may have sifted and washed downward from overlying rockfall debris and some, as suggested by Carrara, may have been brought to the surface of the ice by shearing. Most, however, appears to be ablation till, added to the base of the debris mantle during melting of the underlying ice.

Additional information concerning the ice core of the Arapaho rock glacier may be of interest:

- i. Ablation surfaces dipped up-valley at angles of  $32\text{--}60^\circ$  and showed no systematic variation in dip along the length of the exposure. A strong air-bubble lineation, less steeply inclined, locally intersected ablation surfaces at angles of  $20\text{--}30^\circ$ . Small healed crevasses were not offset where they crossed debris bands in the ice, suggesting that there has been no recent differential movement along the ablation surfaces.
- ii. Thin-section studies by Charles A. Knight (National Center for Atmospheric Research) indicate that the ice is highly modified, and they are consistent with the hypothesis of its glacial origin. Samples from both the rock glacier and the nearby Arapaho Glacier showed a broad range of crystal sizes and shapes, with individual grains as large as 30 mm in diameter. Interlocking grain boundaries were common and air bubbles were distributed throughout the samples with little regard for crystal boundaries. In contrast, samples of recent snow-bank ice from the lateral trough at the south edge of the rock glacier were characterized by smaller equidimensional crystals, a narrower range of grain diameters (0.5–3.0 mm), an absence of interlocking grain boundaries and restriction of air bubbles to the contacts between adjacent crystals.
- iii. Radiocarbon ages of  $1\ 000 \pm 90$  B.P. (I-2562) and  $955 \pm 95$  B.P. (I-3858) were obtained for pollen, plant fragments and insect remains collected from ablation surfaces 310 and 300 m, respectively, from the cirque headwall. The oldest sample was overlain by 90–120 cm of gravelly sand, capped by an additional 120 cm of boulders; the youngest was insulated by 20 cm of sand, beneath a 65–75 cm thick layer of boulders.
- iv. Peter J. Mehringer, Jr (Washington State University) found a predominance of *Artemisia* (45.5%) and *Pinus* (17.5%) pollen in a sample collected from the 1 000 year old ablation surface. Comparison of the *Picea/Pinus* ratio (0.03) with modern ratios determined by Maher (1972) along an altitudinal transect in the Front Range suggests that vegetation zones were depressed only slightly, if at all, at the time of pollen deposition.

In the Colorado Front Range, as in many other mountain areas, the distinction between "rock glaciers" and debris-laden ice glaciers or snow patches is largely artificial. Where modern glaciers are clean, there is a tendency to emphasize the uniqueness of glaciers that are buried beneath thick layers of insulating debris. The significance of the Colorado Front Range rock glaciers is not that they indicate a climate "not quite severe enough to produce or sustain ice glaciers" (Madole, 1972) but rather that the environment at the time of their formation favored both (1) glacierization and (2) extensive rockfall from cirque headwalls.

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SIR,

### *Grain-size characteristics of superglacial dirt*

A large literature exists on superglacial sediment, particularly in relation to the development of dirt cones (Lewis, 1940; Sharp, 1949; Swithinbank, 1950; Lister, 1953; Pirrit, 1953; Streiff-Becker, 1954; McAllister, 1956; Krenck, 1958; Drewry, 1972) but rarely have the grain-size characteristics been described. Figure 1 illustrates the cumulative frequency curves for composite samples of superglacial sediment taken from three localities in the ablation zone of Østerdalsisen, an outlet glacier of the ice cap Svartisen in Norway (lat. 66° 31' N., long. 14° 07' E.). The first sample is from a small dirt-cone field near the south-west margin of the glacier, where the average debris thickness on cone flanks was 10 mm. The largest cone had a basal area of 2.2 m<sup>2</sup> and a height of 0.45 m, and was elliptical in plan, suggesting that the sediment had been deposited originally in a stream channel. The second is from a melt-water channel near the centre of the glacier, where sediment had accumulated in small holes which pitted the stream bed, and the third from the bottom of a shallow depression which was probably part of a former stream course and in which a dirt cone was in the process of formation. The ice core beneath the sediment was only 0.12 m above the surrounding glacier surface.

The similarity of the curves (Fig. 1) suggests that the dirt in the three localities had a common origin and, together with the morphological characteristics of the deposits, that the sites represented different stages in dirt-cone formation. On a glacier such as Østerdalsisen, where the amount of superglacial dirt is small and the dirt is widely distributed, a means of sediment concentration is required if cones are to develop at all. Although there is general agreement that differential ablation of clean and debris-covered ice is the formative mechanism, different modes of dirt concentration have been proposed. Lewis (1940), Sharp (1949) and Swithinbank (1950) favoured deposition in melt-water streams and, although three samples cannot provide an adequate test of the hypothesis, the fact that the size-distribution curves for these sites of variable form and location are not significantly different does suggest a similar mode of concentration on Østerdalsisen. Highly localized deposition within superglacial streams could lead to the development of dirt cones even on glaciers with little surface dirt provided that sediment accumulates initially to a sufficient depth.