The nearly pure bentonite beds found in this locality are derived from volcanic tuff of Cretaceous age. Some of the characteristics typical of the material making up these beds have been described (*6*); one property that was not mentioned, however, is the unusual ability of this bentonite to imbibe water and swell rapidly. Most bentonites when wetted tend to be self-sealing; that is, they swell rapidly at the point of contact with water, but in swelling they become highly impermeable to water so that it may take several days for a wetting front to advance significantly. Umiat bentonite is different in that even large fragments, when put in contact with water, imbibe and swell rapidly. Undoubtedly the flows shown on the cover are greatly facilitated by this unusual ability of Umiat bentonite to imbibe water, but the degree to which this property governs the occurrence of flows like those shown in the cover photo is as yet unknown.

Earth-flow levees and flow lobes similar in many respects to those observed along the Colville River have been described at Franklin Bluffs (*7*) overlooking the Sagavanirktok River, at Schrader Lake (*8*), and also in the St. Elias Mountains. A survey of the 1948 aerial photography of northern Alaska brought to light numerous other occurrences of slides having the same distinctive morphology of those shown on the cover. In view of the peculiar combination of circumstances required to initiate the slides along the Colville, it is likely that the existence of similar slides in nearby localities is indicative of exposed bentonitic sediments. We believe that smooth-sided, leveed, U-shaped mud-flow channels of the type described may be sufficiently distinctive on aerial photographs to differentiate bentonite debris flows from other debris and mud flows with high reliability. In view of the probability that development of the newly discovered petroleum reserves will stimulate plans for the construction of roads, pipelines, and the like in Northern Alaska, where unstable bentonitic slopes present a widespread construction hazard, the ability to locate and avoid these hazards is likely to become valuable.

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References and Notes

1. E. J. Parizek and J. F. Woodruff, *J. Geol.* **65**, 653 (1957).
2. A. M. Ritchie, *Highway Research Board Spec. Rep. No. 29, NAS-NRC Publ. No. 944* (1958), p. 48.
3. Aerial oblique photo, courtesy of T. Marlar, acquired with the assistance of the Naval Arctic Research Laboratory, Barrow, Alaska.
4. W. P. Brosge and C. L. Whittington, *U.S. Geol. Surv. Prof. Pap. No. 303-H* (1966), part 3, p. 501.
5. The coalescence of tributary sources is in some respects reminiscent of the mud glacier on the Isle of Wight, described by R. F. Moorman [*Nat. Hist. Soc. Proc.* **3**, 148 (1940)].
6. D. M. Anderson and R. C. Reynolds, *Amer. Mineral.* **51**, 1443 (1966).
7. G. S. Anderson and K. M. Hussey, *Iowa Acad. Sci. Proc.* **69**, 310 (1962).
8. G. W. Holmes and C. R. Lewis, *U.S. Geological Survey Bull. No. 1201-B* (1965).
9. R. P. Sharp, *J. Geomorphol.* **5**, 222 (1942).
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Scanning Electron Microscopy of Evaporating Ice

Abstract. *Direct observation of evaporating ice with a scanning electron microscope indicates that the surfaces of single-crystal and polycrystalline ice are markedly different. In specimens of single-crystal ice the crystal planes are revealed by evaporation, whereas polycrystalline ice develops a fibrous surface.*

Odencrantz *et al.* (*1*) have observed fine whiskers on the surface of ice crystals upon examination by a replication technique with a scanning electron microscope. These whiskers, being less than a micron thick, might be expected to fracture as the result of a collision between two ice crystals or an ice crystal and a water drop within a cloud. The small splinters thus produced could act as new ice nuclei. If the observed whiskers are a feature of the surfaces of the ice crystals and not an artifact produced by the experimental technique, the results are important in meteorology. Studies of replicas of ice crystals by means of a scanning electron microscope (*2*) indicate that the structure of the replica produced depends strongly upon the material that forms it, and that faithful reproduction of the ice surface on a microscopic scale is extremely difficult to achieve. The replicating material may either fail to conform to the ice surface or it may severely modify the ice surface. Optical microscopy is unsuited for the observation of such fine structure as that reported by Odencrantz *et al.* because of the limit of resolution and the small depth of field. Therefore I studied the ice surface directly with a scanning electron microscope without the aid of replicas.

The specimen chamber of a scanning electron microscope must be maintained at a pressure of less than 10^{-4} torr, and any specimen must have a surface electrical conductivity that is high enough to prevent charging by the electron beam. Since these two conditions can be fulfilled for an ice specimen, direct observation of the surface of ice is possible. In order to reduce the vapor pressure of the ice sufficiently to achieve the required vacuum, the specimen must be cooled. This was done by mounting the specimens on thermally insulating supports and relying upon the heat of vaporization to lower the temperature (*3*). The revealed surface structure of evaporating ice differs from the surface structure in a saturated environment. Evaporation reveals details of the underlying structure that would not be apparent in a saturated environment. All samples were made from water that had been distilled three times and had an impurity content of not more than 5 parts per million. Polycrystalline specimens were made by freezing water droplets (2 mm in diameter) on the end of glass capillary tubes in a refrigerator maintained at $-20°C$. Single-crystal samples were cut from large crystals grown by the method of Siksna (*4*); crystals of various habits were grown in a diffusion chamber.

Immediately after insertion in the microscope, the cut single-crystal samples exhibit a smooth, although not flat, surface. As evaporation continues, the surface becomes etched, and on the surfaces at an angle to the basal plane steps appear as a result of the more rapid evaporation of the prismatic faces. Figure 1 shows such a surface after evaporation for 30 minutes. The basal plane is the most prominent structural feature of the ice crystal, but prismatic planes are sometimes seen. Surfaces in the direction of the basal plane are generally featureless, although in some samples lines of hexagonal etch pits appear.

A diffusion chamber was used to grow ice crystals of various shapes, including column and plate crystals, from the vapor. Column crystals evaporated in a manner similar to that of single crystals cut from a large sample. The thin plate crystals evaporated with the formation of deep etch pits and holes distributed with roughly hexagonal symmetry (Fig. 2). The ice surface is free from whiskers.

Since polycrystalline ice is a collection of small crystallites, one might expect the surface to show features similar to those of the single-crystal samples. In a few cases such small crystals were seen; however, this appearance of crystals was confined to a small region in a few samples. The characteristic structure of polycrystalline ice consists of a suface with no obvious crystalline features, which gradually develops a fibrous or whiskery appearance as the ice evaporates. This type of surface structure appeared on all polycrystalline samples, including those with regions exhibiting the single-crystal type of surface. This surface structure is very delicate, the fine whiskers or fibers being less than half a micron thick and many times as long. The surface structure most commonly appears as a complex fibrous structure (Fig. 3). In some cases the surface structure first appears as distinct whiskers (Fig. 4). This whisker has a complex structure with fine strands at the end of a shaft about 6 μ wide.

The fragile nature of the strands is indicated by the fact that one has broken from the main structure as the micrograph was taken. This complex surface structure is a feature of all polycrystalline ice. If a single-crystal sample is mechanically polished after being cut from the large crystal, the surface initially develops a fibrous surface; after evaporation for approximately 10 minutes the fibrous surface structure disappears, and the normal single-crystal structure appears. This is in agreement with the observation by Muguruma (*5*) that specimens of polished single-crystal ice have mechanical properties consistent with the existence of a surface layer 10 μ thick with many dislocations.

The fact that the same water was used for polycrystalline and single-crystal samples and that all samples were exposed to the same environment rules out the possibility that the whiskers on polycrystalline ice result from volume or surface contamination. It is unlikely that polycrystalline ice, evaporating in an air stream, would develop such a pronounced whiskery surface; one would expect the air stream to fracture the surface structure and transport the surface elements away as small splinters before the surface structure attained the lengths observed in vacuum. In the case of pellets of polycrystalline hail, such small splinters would be liberated in subsaturated regions where the hailstone evaporates; it is therefore unlikely that such splinters would be found in the supersaturated region of the cloud where they could act as ice nuclei.

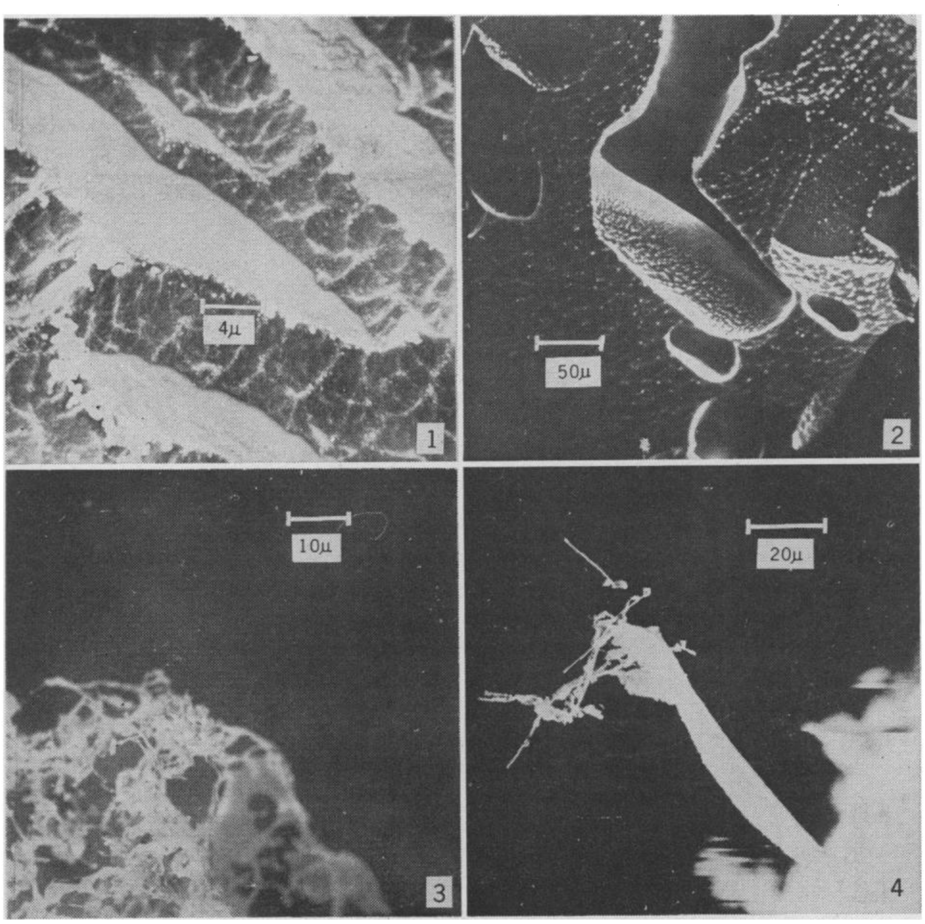

Fig. 1. Surface of single-crystal ice evaporation for 30 minutes [instrumentation magnification (I.M.), × 2500]. Fig. 2. Etch pits on planar ice crystal (I.M., × 240). Fig. 3. Surface structure on polycrystalline ice (I.M., × 1200). Fig. 4. Whisker on surface of polycrystalline ice (I.M., × 750).

The fragile surface structure of polycrystalline ice could, however, be responsible for the charging of ice by evaporation (*6*). Electrostatic forces between an ion and the ice surface in which it is embedded are too great to be overcome by the evaporation process. Therefore, no loss of charge from a smooth evaporating surface is expected, even though an evaporation current has been observed for evaporating polycrystalline ice. If the ice develops a fibrous surface during evaporation in an air stream, the fracturing and transporting away of the fine structure could produce electrical charging in the same manner as that observed (*7*) for frost deposits exposed to an air stream.

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References

1. F. K. Odencrantz, W. S. McEwan, P. St. Amand, W. G. Finnegan, *Science* 160, 1345 (1968).
2. J. D. Cross, unpublished work.
3. ——— and P. M. Cross, *J. Sci. Instrum.*, in press.
4. R. Siksna, *Arkiv Fys.* 11(43), 495 (1957).
5. J. Muguruma, paper presented at the International Symposium on Ice, Munich, 1968.
6. J. Latham and C. D. Stow, *J. Atmos. Sci.* 22, 320 (1965).
7. J. Latham, *Quart. J. Roy. Meteorol. Soc.* 89, 265 (1963).

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