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E. PENNER

ICE-GRAIN STRUCTURE AND CRYSTAL ORIENTATION IN AN ICE LENS FROM LEDA CLAY

Abstract: The long axes of ice grains were oriented parallel to the direction of heat flow. A random *c*-axis orientation, determined by an etching technique, appeared to exist. In some adjacent crystals the *c*-axes were as much as 45° apart. This disorder seems to be consistent with the disorderly distribution of clay particles in the ice lens.

Marked differences have frequently been observed in the character of frozen soil and the disposition of ice and soil resulting from the ice-segregation process in different soil types (Czeratzki and Frese, 1958). The soil structure and the related features that consistently occur when remolded Leda clay is frozen (Pl. 1) are in sharp contrast to the regular soil strata, well-ordered ice lenses, and flat freezing fronts so common in coarser frost-susceptible soils.

The main purpose of this preliminary investigation was to determine whether there is some well-defined regularity in the ice structure both with respect to the crystal orientation and the form and orientation of the ice grains despite the apparently random occlusions of clay in the ice and the undulating soil–ice interface. Such regularity is common for ice produced from bulk water in a container by one-dimensional cooling.

A block sample of Leda clay was obtained from a depth of 20 feet in a freshly dug excavation. It was thoroughly remolded at its natural moisture content of about 60 per cent and consolidated in a 6-inch-diameter mold to a dry density of 1.58 gm/cm^3 (101 lb/ft^3). The resultant moisture content of this saturated specimen was about 26 per cent. Grain size was determined using the hydrometer method. The clay content ($<$0.002 mm) and silt content (0.002 to 0.2 mm) were 69 and 25 per cent respectively. Some details on the origin and geotechnical properties of this soil are given by Eden and Crawford (1957).

A cylindrical specimen 6 inches in diameter and 2 inches high was frozen unidirectionally in the frost-cell apparatus described by Penner (1960). The pre-freezing temperature gradient was 1.16°F/inch with the cold side of the specimen close to 32°F. After a constant heat flow was achieved the cold end was supercooled to about 31°F, and crystallization of the soil water was easily induced by rubbing the top of the soil with a previously inserted steel wire. The cold-side temperature of the conditioning plate was set, and freezing was allowed to proceed without any changes in the temperature of the conditioning plates. A moderate rate of heat removal from the specimen insured that only a part of the specimen would be frozen in a period of a week. At the same time a slowly penetrating frost line was needed to build up an ice lens with some soil inclusions. A heave of 0.59 inch was achieved over a period of 174 hours giving an average heave of about 0.08 inch/day. The rate of heaving at the beginning was nearly 0.1 inch/day and after 7 days slowed down to 0.0605 inch/day.

After the freezing period the specimen was removed from the frost cell and taken into a cold (15°F) room. Half of the sample was cut in about 1/8-inch slices with a band saw to permit examination of the vertical section of the ice lens. The other half was cut horizontally for examination of the horizontal section.

The etching procedure used to determine the *c*-axes orientation was essentially that described by Higuchi (1958) and was carried out at a cold-room temperature of 15°F. Samples were prepared by polishing the surface of the ice lens in the cut slices. A 1 per cent solution of polyvinyl formal in ethylene dichloride was applied to the surface of the ice lens directly after polishing. After evaporation of the solvent the surface was examined microscopically (mag. 40 ×) under transmitted light for the appearance of etch pits. It took up to 30 minutes for mature pits to develop.

A vertical slice of the specimen is shown in Plate 1. The heat flow during freezing was unidirectional from the bottom to the top. All the soil below the ice lens was unfrozen when removed from the frost cell. To preserve the sample it was rapidly frozen and kept at a

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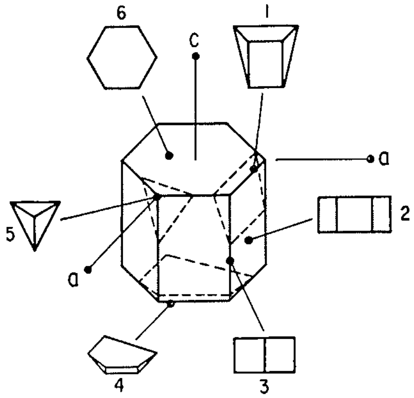

Figure 1. Schematic diagram of possible types of etch pits on an ice crystal (after Higuchi, 1958)

regular boundaries. The orientation of the long axes of the ice grains seems to be the same as that reported by Gold (1960) when water in a tank is frozen by one-dimensional cooling in the direction normal to the water surface.

The etch pits developed on the surface of horizontal and vertical sections of the ice lens are shown in Plates 3 and 4. The diagram by Higuchi (1958) showing the *c*-axis orientation of an ice crystal in relation to the type of etch pit is reproduced in Figure 1. A résumé of all these results is given in Table 1.

The disorder in the optic axes of the ice grains appears to be consistent with the disorderly nature of the clay and ice distribution in the frozen layer and the uneven character of the ice-soil interface at the freezing front. How much the two are related is still a matter for conjecture.

TABLE 1. ETCH PITS OF ICE LENS FROM LEDA CLAY

Illustration	Plane of ice surface with reference to direction of heat flow	Type of etch pit*	Orientation of *c*-axes with reference to direction of heat flow
Pl. 3, fig. 1	Parallel	Between type 1 and type 2	Nearly perpendicular
Pl. 3, fig. 2	Parallel	Between type 1 and type 2	Nearly perpendicular
Pl. 4, fig. 1 lower half	Perpendicular	Type 6	Parallel
Pl. 4, fig. 1 upper half	Perpendicular	Type 1	About 45°
Pl. 4, fig. 2 lower half	Perpendicular	Type 1	About 45°
Pl. 4, fig. 2 upper half	Perpendicular	Between type 4 and type 6	Nearly parallel

*Type of etch pit refers to the various types shown in Figure 1.

room temperature of 15°F. The random fissures visible in the soil below the ice lens developed as a result of the quick freeze.

Plate 1 clearly shows the concoidal shape of the soil fragments, the undulating or uneven soil–ice interface, and the discontinuous ice-lens formation. Some soil fragments have been rotated during the ice lensing.

Vertical sections (+1 mm thick) of the same specimen, placed between crossed polaroids and viewed in transmitted light, show that the long axes of most ice grains are in the direction of the heat flow (Pl. 1, fig. 2b). Not all ice-grain boundaries, however, are exactly vertical. In many cases the grains extend the full distance across the ice lens and terminate in soil at both ends.

Horizontal sections show the short-axes ice-grain pattern which is normal to the heat flow (Pl. 2). The grains range in size and have irregular boundaries.

The disorderly nature of the clay distribution may be related to nonlinear heat flow and uneven moisture supply at local sites at the freezing front where the ice is formed. Uneven shrinkage at the interface is almost certainly involved in breaking away the clay fragments at the freezing front.

The rotation of the soil particles could be caused by the differential rates of growth of two adjacent ice crystals with different optical orientations since the rate of crystal growth depends on its orientation (Hillig, 1958). The random orientation in the c-axes of ice crystals found in the ice lens studied may result from random nucleation. In ice produced from bulk water the orientation changed with depth (Perey and Pounder, 1958). In these studies the ice lens was too thin to permit study of the

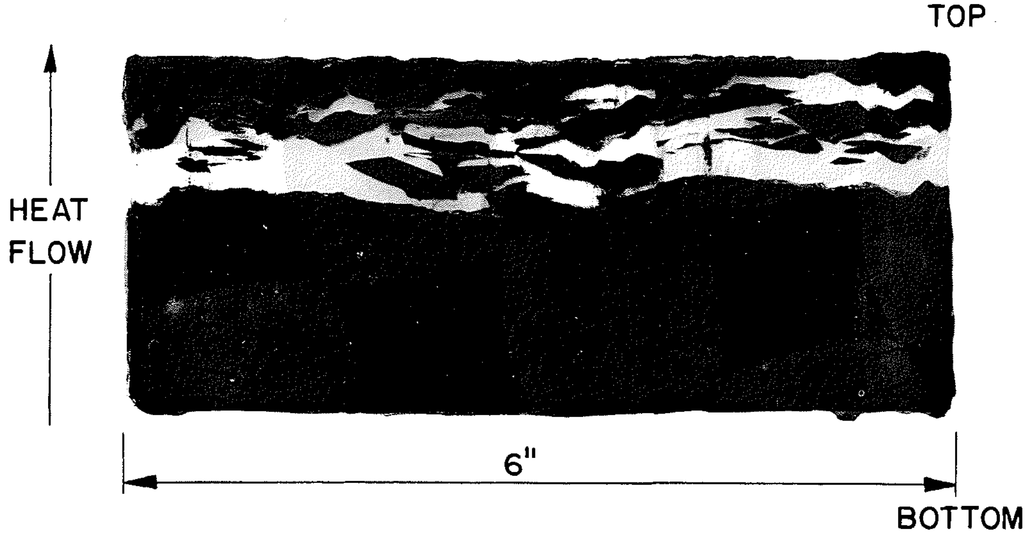

Figure 1. Normal photograph of specimen showing soil structure, ice lens, shape of freezing front, and occluded clay. Note rotation of large soil fragment to left of center and near bottom of ice lens.

Figure 2. Ice lens showing ice-grain boundaries in vertical section. (a) Normal photograph of specimen; (b) specimen photographed from same location as in (a) but with transmitted light between crossed polaroids. Note grain boundaries are not exactly vertical and mostly extend full distance between soil particles.

VERTICAL SLICE OF SPECIMEN AFTER FREEZING

ENLARGED VIEW OF HORIZONTAL SECTION OF ICE LENS (MAG. 10 ×)

Heat flow normal to plane of photograph. Note irregular grain boundaries and uneven grain sizes.

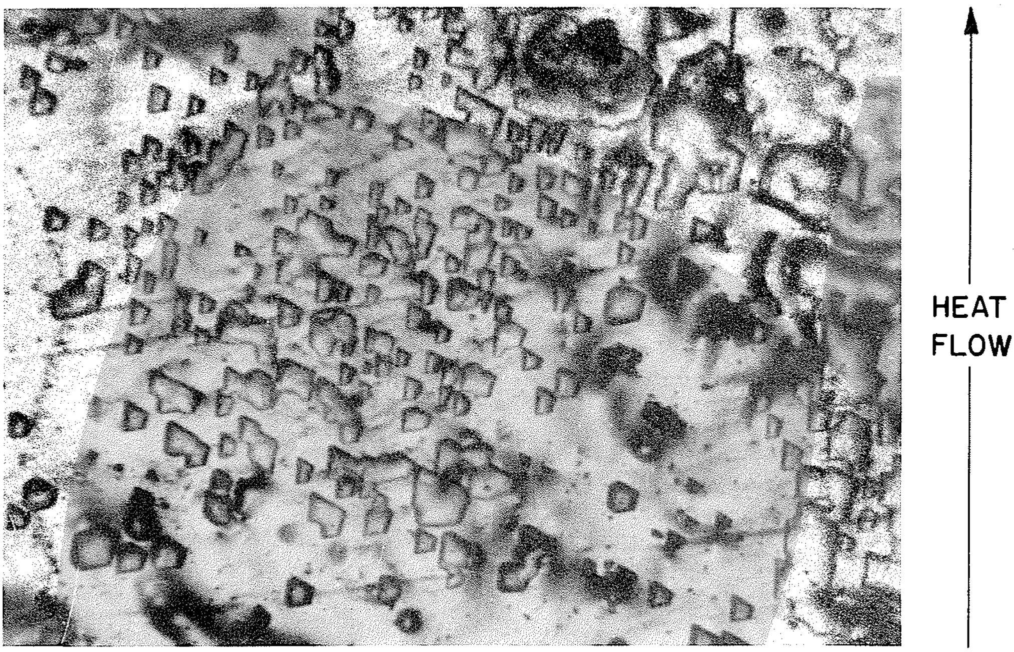

Figure 1

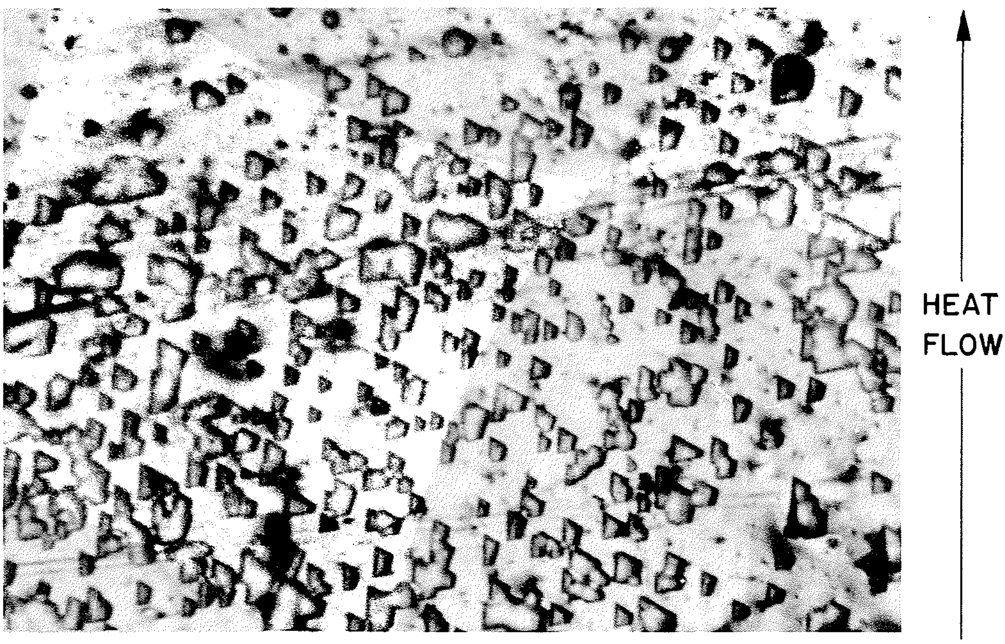

Figure 2

ETCH PITS DEVELOPED ON VERTICAL FACE OF ICE LENS
IN TWO LOCATIONS (MAG. 180 ×)

Shape of pits are between type 1 and 2 (Fig. 1 in text), *i.e.*, the *c*-axis is nearly perpendicular to direction of heat flow; consequently, growth direction of crystals was normal to *c*-axes.

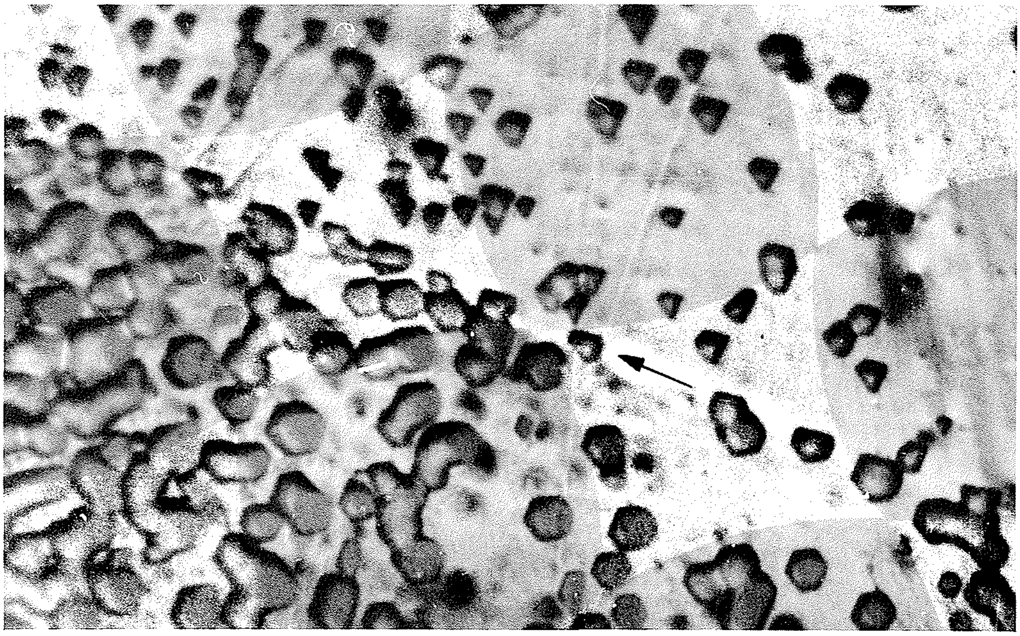

Figure 1. Note crystal boundary running diagonally from bottom right to top left. In lower crystal c-axis nearly parallel to heat flow, and is type 6 (Fig. 1 in text). Upper crystal is oriented at about 45° to lower crystal and is type 1.

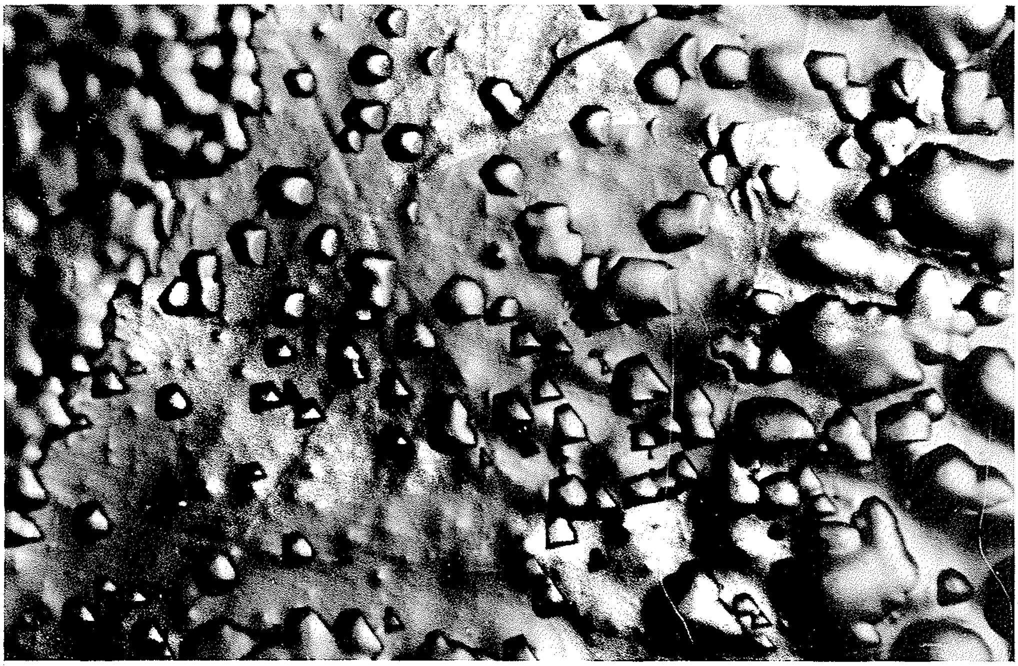

Figure 2. Crystal in bottom half belonging to type 1 indicating c-axes at about 45° to direction of heat flow. Crystal upper half is oriented between types 4 and 6; thus c-axes nearly parallel to heat flow.

ETCH PITS DEVELOPED ON HORIZONTAL FACE OF ICE LENS

Heat flow and long axes of grains normal to plane of paper change of orientation with depth; this should be checked in future studies.

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