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ICE WEDGES IN PERMAFROST, LOWER YUKON RIVER AREA NEAR GALENA, ALASKA **

Abstract

Foliated ground-ice masses exposed in vertical banks of the Yukon River occur as wedges or vertica or inclined dikes 4 mm to 3 m wide and 1 m to 5 m high. Individual wedges are part of a polygonal network of ice enclosing polygons or cells of frozen ground 1 m to 30 m in diameter. The dominant foliation or lineation of bubbles and minute soil particles is subparallel to the sides of the ice masses. Some sharp--walled, clear, white ice-filled veins 1 to 5 mm wide trend parallel to or cut across the prominent foliation. Many of the planes of foliation are faulted, sheared, bent, or otherwise deformed by minor movement and adjustments within the ice mass.

The ice crystals are 1 to 100 mm in diameter, colorless, and rather equidimensional. The tops of the wedges have ice nipples or projections 10 to 150 mm wide extending upward 50 to 300 mm into the overlying frozen sediments. Extending upward 50 to 600 mm from these ice projections are ice-filled fissures 2 to 10 mm wide, some of which extend to ground surface.

The sediments adjacent to the wedges are pushed up, and in many places overturned. The upturning may affect the sediment 1/2 to 3 m on either side of the masses. Foliated ice masses cross-cut other ground--ice and sediment layers.

Ice-filled cracks extending from the surface downward into the ice wedge, the cross cutting of sediments and older ice masses by ice wedges, and the foliation support Leffingwell's hypothesis that ground--ice masses form in seasonally recurring thermal contraction cracks in permafrost — cracks produced by great seasonal temperature changes.

INTRODUCTION

Ice is widespread in the frozen ground of the world. Although some ice forms annually in the seasonally frozen ground layer in both middle and high latitudes, most ice in the ground exists in the permafrost of the polar and subpolar lands. Permafrost can be hundreds of feet thick, and contains bodies of ground-ice that range in size from those filling pores in sediment to large masses of ice 1 to 30 m in diameter. Ice in the perennially frozen ground is an important constituent of the rock, both from the standpoint of geology and engineering.

The most conspicuous, important, and controversial type of ice in perennially frozen ground is the large ice wedges or masses that have

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a marked foliated appearance (Péwé 1958, fig. 2) caused by a multitude of parallel or subparallel layers of air bubbles and of minute inclusions of organic and inorganic matter. The term *foliation* as used here has no genetic implication and follows that used by Turner & Verhoogen (1951, p. 278) in their discussion of metamorphic rocks. They state that foliation surfaces are „parallel surfaces determined... by segregations of particular minerals in alternating streaks and bands". This type of ground-ice forms the largest ice masses in central Alaska and elsewhere in the world.

PHYSICAL SETTING OF AREA

The Pleistocene geology and physiography of the Galena area are described and mapped in Péwé (1948); Galena is on the north bank of the Yukon River in a deeply alluviated lowland 55 km wide at the junction of the Yukon and Koyukuk Rivers in west central Alaska (fig. 1).

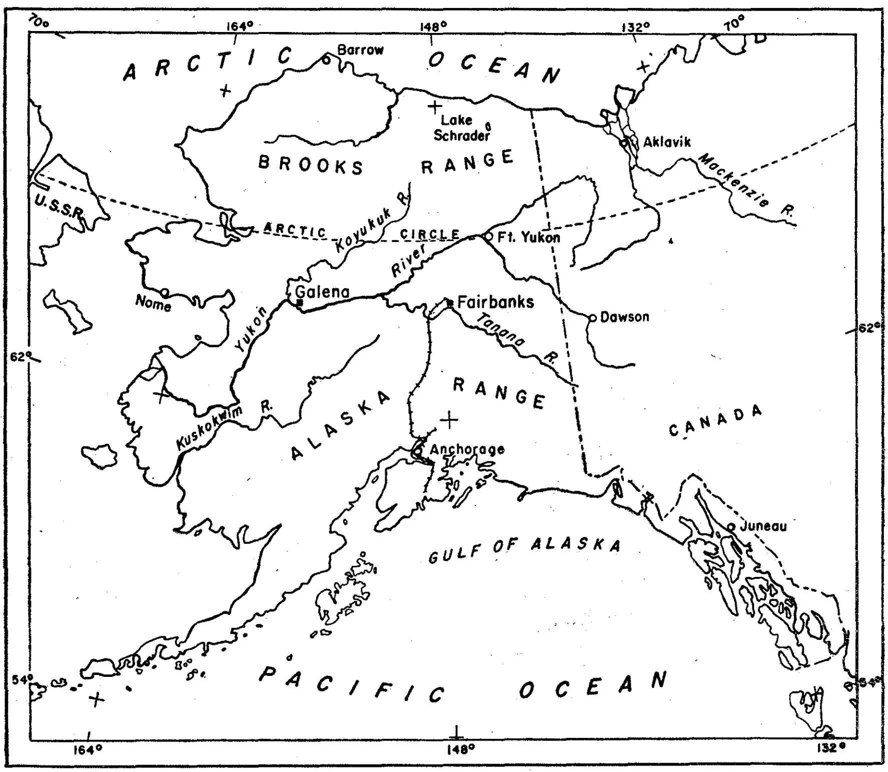

Fig. 1. Index map of Alaska

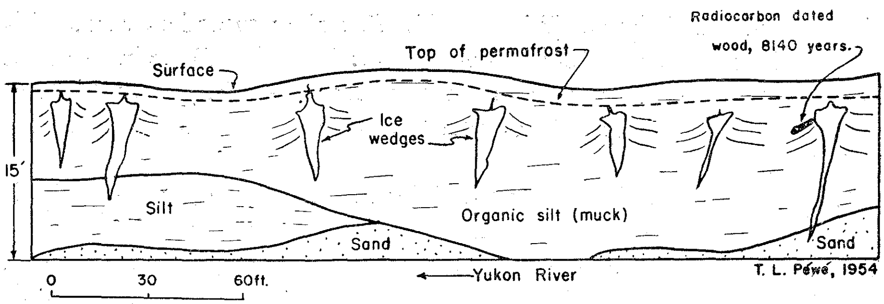

Fig. 2. Diagrammatic section of Quaternary deposits along the Yukon River near Galena, Alaska

The lowland contains numerous terraces 3 to 50 m high and a wide irregularly-shaped flood plain. In most places, the terraces are carved from thick silt deposits in the valley. The flood plain of the Yukon River ranges in width from less than 1 km to about 30 km and is a complicated series of sloughs, meander scars, oxbow lakes, swamps, creeks covered by a mo-

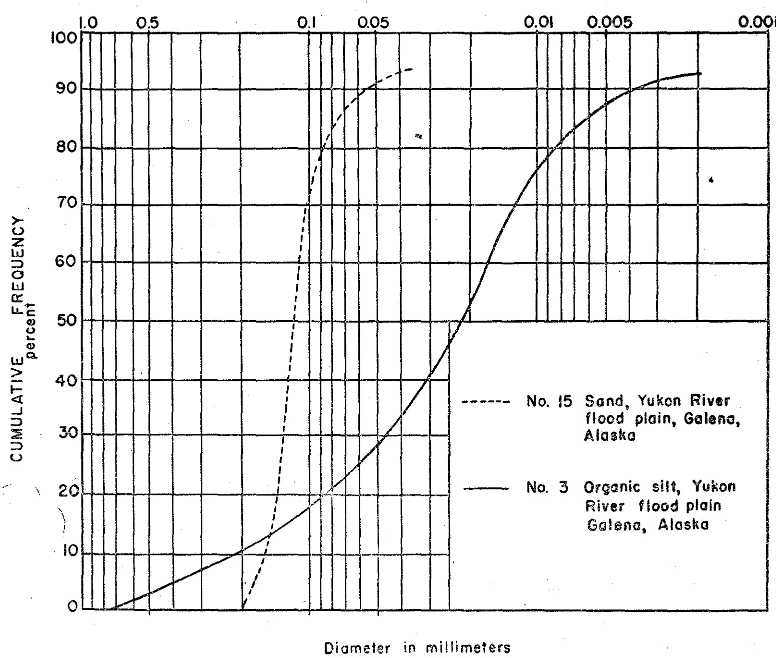

Fig. 3. Cumulative-frequency curves of sediment from Quaternary deposits along Yukon River near Galena, Alaska

saic of tundra and forest (Péwé 1947). The river meanders across this flood plain modifying older features. Eardley (1938) estimates that the river is cutting laterally across the meander belt at the rate of 8 to 15 m a year. Péwé (1948, p. 44) estimates 8 to 9 m of annual lateral erosion at Galena.

The Quaternary sediments of the Galena area that are pertinent to this discussion are flood-plain deposits exposed along the Yukon River 3 to 13 km upstream from Galena on the north side of the river, and 2 to 3 km downstream on the south side. A layer of organic-rich, black, fetid silt (muck) 2 to 5 m thick crops out in the cutbank of the river (fig. 2), and overlies disconformably well-sorted medium grained sand that is locally cross bedded (fig. 3). Only 0,3 m to 1 m of sand is exposed above river level. In some places a relatively inorganic gray, poorly bedded silt layer is exposed between the muck and the sand. The ice wedges are limited to the muck, although the „tails" of some ice wedges extend 0,3 m to 1 m downward into the sand layer.

The muck is in part, if not all, post-Wisconsin in age. Small sticks adjacent to ice wedges in the muck were radiocarbon-dated by the U. S. Geological Survey to be 8 140 ± 300 years (W—472), and 7 740 ± 200 years (W-736) old (written communication, Meyer Rubin 1956, 1959).

CLIMATE

The Galena area has a continental climate, characterized by an extreme range between summer and winter temperatures. The following climatic data are based on an 8 year record from 1948 to 1956: the absolute minimum recorded temperature is —53,3 °C (—64 °F); the absolute maximum is 31,6 °C (89 °F). The mean annual number of days with freezing temperatures is 228. The annual mean temperature at Galena is —4,7 °C (23,5 °F); the annual mean maximum temperature is 0,2 °C (32,4 °F), and the annual mean minimum temperature is —9,4 °C (15,0 °F) (fig. 4).

The mean annual precipitation is 31 cm (12,2 in.). Most of the precipitation falls during the summer season in light showers; thunder-storms are not frequent. August is the wettest month, with a mean precipitation of 6,4 cm (2,52 in.). The mean annual snowfall is 120 cm (47,3 in.), and the amount of snow on the ground in the winter is approximately 60 to 75 cm (23,5 to 30 in.) excluding drifts.

There are 125,4 mean annual days with more than 0,025 mm (0,01 inch) of precipitation. Again, most of these days are in the summer.

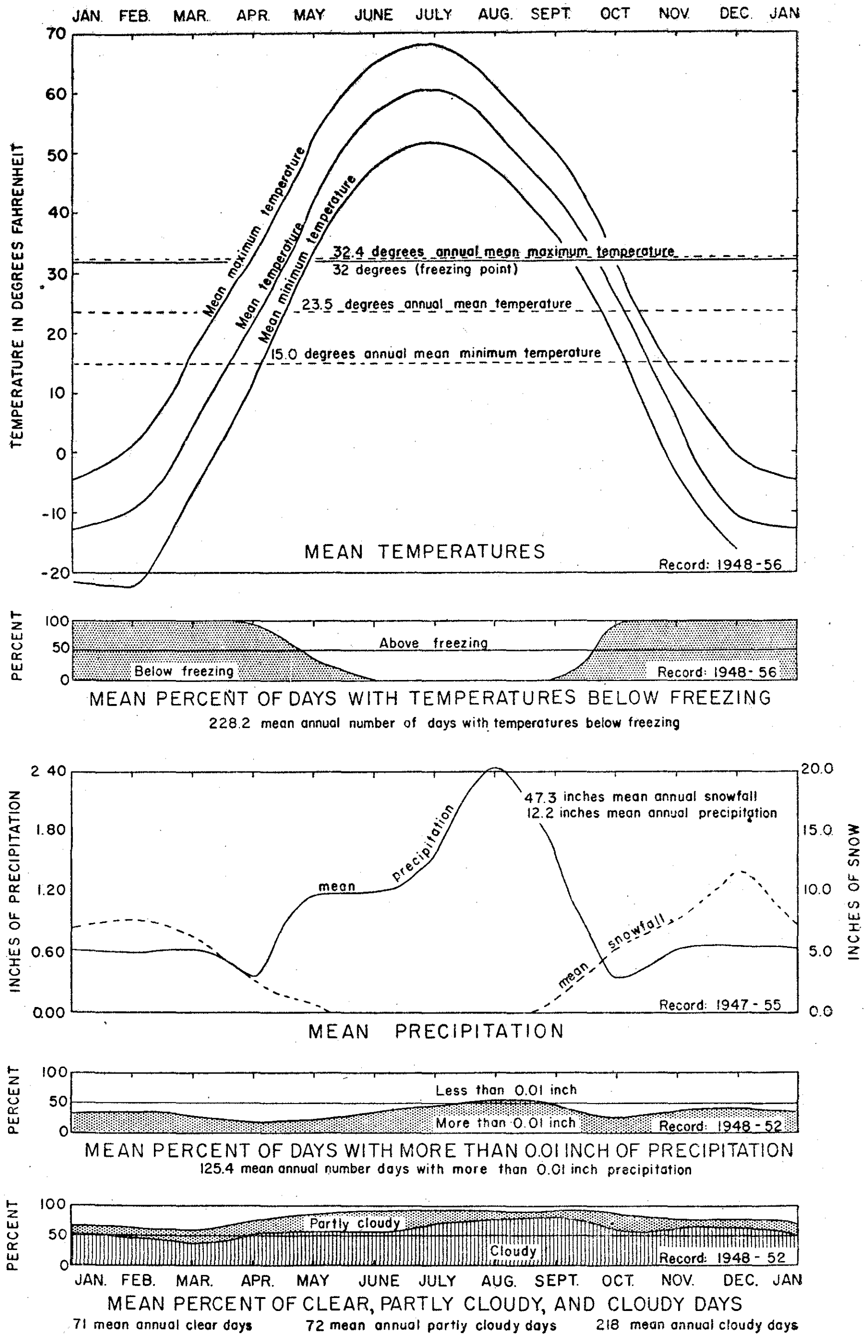

Fig. 4. Climatic data for Galena, Alaska

The area is quite cloudy, with only 71 mean annual clear days, 72 mean annual partly cloudy days, and 218 mean annual cloudy days. The summers are considerably more cloudy than the winters.

DESCRIPTION OF ICE WEDGES

Most foliated ice masses are wedge-shaped, vertical, or inclined sheets or dikes 4 mm to 3 m wide and 1 to 5 m high as seen in a vertical section. Some masses, when seen in the face of a frozen silt cliff, expose only the top part of coalesced wedges or longitudinal sections of ice wedges forming a horizontal mass 0,3 to 3 m thick and 10 m long.

The true form of foliated ice masses can be seen only when they are observed in three dimensions. Individual wedges are revealed to be part of a polygonal network of ice enclosing polygons of frozen ground 1 m to 30 m in diameter. In cross-section, a wedge may be 0,2 m to 1,5 m wide at the top, and taper down to a feather edge. In three dimensions, the axis of the wedge may extend laterally 10 to 15 m without a change in direction.

The two-dimensional form of foliated ice masses depends upon the complexity of the ice polygon network and the particular view or transect formed by the exposure. A cut parallel to the axis of an ice wedge reveals a broad sheet of ground-ice; a cut transverse to the axis reveals a wedge-shaped mass of ice.

The dominant or gross foliation or lineation of bubbles and particles is parallel to subparallel to the sides of the wedges or ice dikes and horizontal ice masses. A plan view of an ice polygon or plan view of a single wedge shows foliation parallel to the axis of the ice mass.

Although the tops of most ice wedges in central Alaska are flat, most of the tops of wedges in the Galena area have ice nipples or projections.

DETAILS WITHIN THE ICE WEDGE

Foliation

The most conspicuous feature within the ground-ice mass is the foliation. Although the ice may contain a few large 25 cm to 30 cm diameter masses or inclusions, most of the inorganic and organic particles are minute, and comprise a thin film of silt less than a millimeter thick when viewed in three dimensions. These films or layers form a line on a two-dimensional face of the wedge, and are spaced 1 to 10 mm apart.

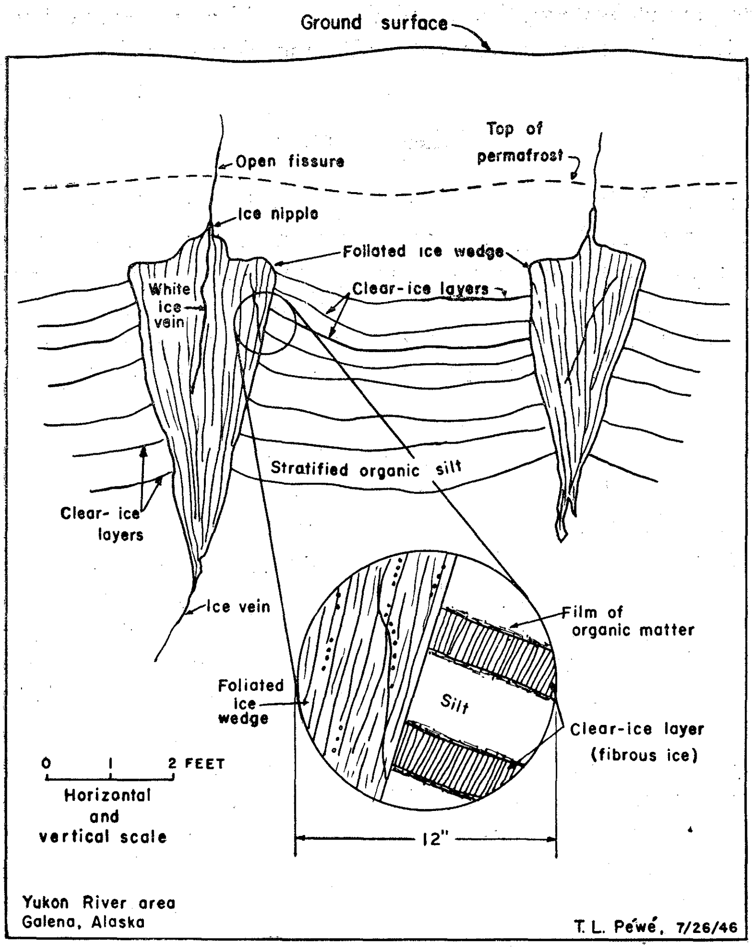

Fig. 5. Sketch of foliated ice wedges cutting stratified organic silt and clear-ice seams, Galena, Alaska

Some foliation lines are due to sharp-walled clear, white, ice-filled veins 1 to 5 mm wide trending parallel to or cutting across the prominent dark foliation (fig. 5). These ice veins are younger than the rest of the ice, and have a thin film of silt particles along a plane in the center of the vein. In the Galena area these young ice-filled veins extend to the top of the wedge and continue upward into the ice nipple, and in some places continue farther into the frozen ground above the wedge.

Bubbles are ubiquitous in foliated ice masses. Most bubbles are 1 to 12 mm in diameter and approximately equidimensional. Some bubbles, however, are elongate vertically and about 1 to 12 mm long and 1 to 4 mm wide. Some bubbles are concentrated along clear-ice veins.

Other structures

Many of the folia or silt traces are faulted, sheared, bent, or otherwise deformed or displaced by minor movements and adjustments within the ice mass. The trace of a silt film cropping out on an ice wedge face may be displaced in steps or by echelon breaks 1 to 10 mm wide or greater. This adjustment within the wedge also may cause recrystallization such as has been reported in wedges at Barrow by Black (1951).

Ice crystals

Ice crystals in the foliated ground-ice masses in the Galena area range in size from less than 1 to 100 mm, and are mostly equidimensional. They are anhedral or subhedral with smooth borders. Because the crystals are mostly equidimensional and of the same size, a rather granular neve-like material forms on the ice mass surface upon melting and separation of the crystals. Individual ice crystals are colorless when viewed in absence of the ubiquitous silt particles that give the overall nature of the ice mass a gray or dirty appearance. Small ice crystals exist in the younger, white, 1 to 5 mm wide ice veins in the foliated ground-ice masses. The crystals in these craks within the wedge are about 1 to 4 mm in diameter, and roughly equidimensional. In the younger ice-filled cracks that extend from the upper end and out of the wedge, the crystals are somewhat needle-like, 1 to 5 mm long, either unoriented or horizontal, and at right angles to the wall of the vein.

FIELD RELATIONS

The most striking field relationship between the vertical foliated ice mass and the sediment through which it passes is the almost universal appearance of deformed strata adjacent to the ice mass. The sediment has the gross appearance of having been pushed aside. The origin of this deformation will be considered under the discussion of the origin of the foliated ice. The strata or sediments adjacent to the wedge are deformed upward and in many places overturned. The upturning may affect the sediment 0,3 m to 3 m on either side of the wedge. The amount of deformation is greatest at the top of the wedge, and diminishes toward the base of the ice dike. Such deformation can only be seen if bedding is present; in homogeneous silt, the deformation is difficult, if not impossible, to notice.

In many wedges, the contact of the enclosing sediment and the ice mass is in the form of minute, regular to irregular steps, depending upon the regularity of the thickness of strata and size of the wedge. Each succeeding stratum upward is stepped inward to the ice wedge (fig. 6). Some strata have the appearance of having been pushed into the ice wedge. Fo-

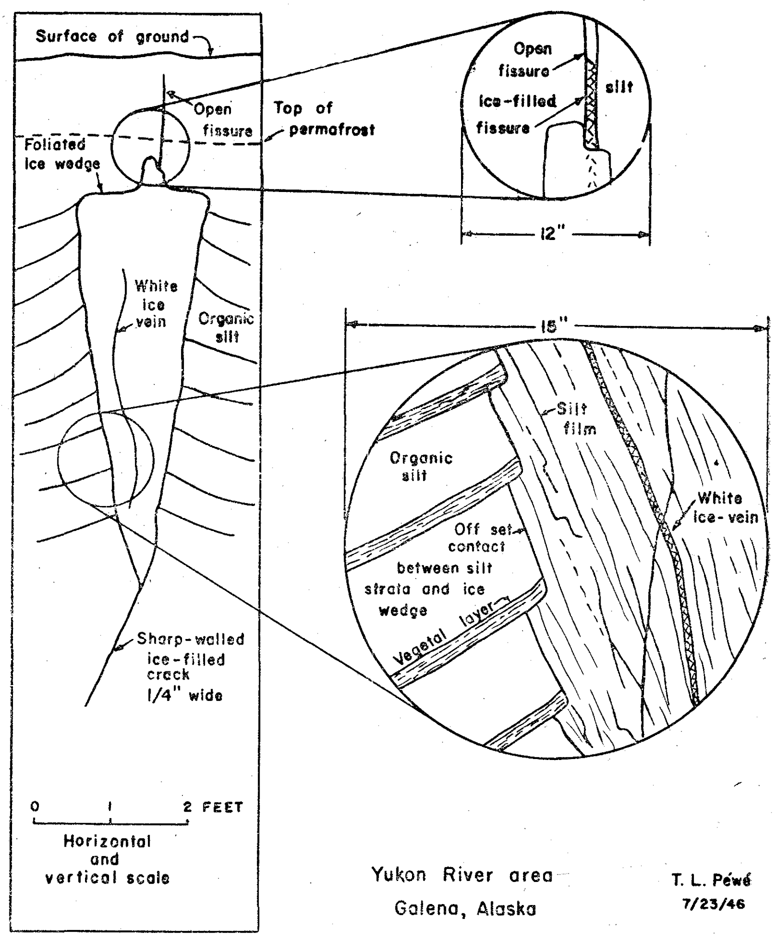

Fig. 6. Sketch of foliated ice wedge showing offset contact with frozen silt, Galena, Alaska

liated ice masses crosscut non-foliated ground-ice as well as sediment (pl. 1; fig. 5).

Ice wedges in the Galena area have ice nipples or projections 10 to 150 mm wide extending upward from the top of the ice wedge 50 to 300 mm into the overlying sediments. Also extending 50 to 600 mm upward from the top of many, if not most, wedges are 2 to 10 mm wide fissures in both the ice and sediments. Most of these cracks are filled with ice in the wedge, and in some places the extensions of the cracks into the sediment are filled with ice.

ORIGIN

The origin of large ground-ice masses in the perennially frozen ground of North America has been discussed in print since Kotzebue (1821, pp. 219—222) recorded ice at Elephant Point in Eschscholtz Bay of Seward Peninsula. Discussions of ground-ice origin appeared earlier in Siberia (Leffingwell 1919, p. 215). During the last 100 years, various ideas for the origin of large ground-ice masses have been suggested, including buried icebergs, buried glacial ice and ice growth in thermal contraction cracks in permafrost (Leffingwell 1915). These and others are thoroughly summarized by Maddren (1905, pp. 36—117) and Leffingwell (1919, pp. 179—243). The only new suggestion since 1915 was made by Taber (1943, pp. 1522—1527) who stated that the large ground-ice masses in permafrost segregated as the ground froze, and water was supplied by the moisture drawn through small soil capillaries.

Ice wedges in the Galena area support Leffingwell's hypothesis that foliated ground-ice masses form in seasonally recurring thermal contraction cracks in the perennially frozen ground — cracks which are produced by the great changes in temperature from summer to winter. The intense stresses generated by a drop in ground temperature (Lachenbruch 1959, p. 1796) result in the formation of a polygonal network of contraction cracks. Hoarfrost, ice crystals, and snow melt water periodically fill, or partly fill, the cracks to produce a narrow vein of ground-ice in the permafrost. This ice vein is not destroyed by the expansion of the ground in summer, and provides a zone of weakness for repeated cracking and ice growth in subsequent winters. Eventually a polygonal network of massive foliated ice masses (wedge) is developed in the ground.

Evidence in the Galena area to support the Leffingwell's hypothesis for the origin of foliated ground-ice can be marshalled as follows:

1. Cracks 2 to 10 mm wide extend from the surface of the ground

downward into some ice masses. Some cracks are filled with ice. The ice masses with ice-filled cracks extending to the surface are actively growing.

2. According to Leffingwell's hypothesis, minute particles of inorganic and organic debris can enter the contraction cracks with the melt water. Such particles should outline the length and direction of the periodic cracks in the ice mass and would give rise to a series of parallel or subparallel lines in a wedge. Examination of the ice wedges in the Galena area reveals excellent foliation outlined by minute organic and inorganic particles.

3. Leffingwell's hypothesis indicates that foliated ice masses may occur in various kinds of sediments. In the Galena area the ice wedges, although occurring mostly in muck, in some places extend 30 to 60 cm into an underlying sand layer.

4. The ice masses cut across sediments that contain vegetal matter including logs, and also cut across older layers of ice from 2 mm to 50 mm thick.

5. If the ground contracts in winter, it must expand in summer. This readjustment to the stress may take place by deforming the ground on either side of the ice wedge, or deforming the ice itself. In the Galena area, one of the most conspicuous features observable in the field is the upturning of the ground adjacent to the ice wedges; the strata are pushed up, and in many places become vertical or even overturned. Structures within the ice wedges, such as offset folia, shearing and other deformation, also attest to the pressure set up by the expanding frozen ground as it warms in the summer and presses against the ice mass.

CONCLUSIONS

Foliated ground-ice masses (ice wedges) in the Galena area occur mainly in organic silt, silt that is less than 10 000 years old. The ice masses grew in seasonally recurring thermal contraction cracks as outlined by Leffingwell (1915). A few of the ice wedges in the area are growing today.

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Pl. 1. Foliated ice wedge crosscutting clear-ice seams in organic silt, Galena, Alaska