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PALEOCLIMATIC SIGNIFICANCE OF FOSSIL ICE WEDGES

Abstract

Fossil ice wedges (ice wedge casts, fente en glace remplie, etc.) have been described from temperate latitudes (Illinois, Poland, Germany, etc.) for decades but interpretations of their paleoclimatic significance are not strictly reliable because of lack of knowledge of the present day climatic significance of existing ice wedges in polar areas. It has been agreed, however, that fossil ice wedges indicate the former presence of permafrost.

Present work indicates that although permafrost will form in areas that have a mean annual air temperature of about 0°C or colder, it is thought that ice wedges form only when the mean annual air temperature is —6 to −8° or colder many years, although in certain local environments ice wedges may form at slightly warmer temperatures.

Ice wedges may exist in an inactive state after climatic warming for thousands of years as long as permafrost remains. In general, permafrost thaws and ice wedges melt when mean annual air temperature warms to more than 0°C. Large areas of the subarctic contain dormant ice wedges.

INTRODUCTION

Ice wedges, large masses of foliated ground ice in permafrost, are currently widespread in polar and subpolar regions and were formerly extensively distributed in many regions of the temperate latitudes. Their former existence in the middle latitudes has long been known (Soergel 1936), and many inferences have been made concerning their past distribution and climatic significance. To interpret the meaning of former ice wedges in now-temperate latitudes, it is necessary to study existing ice wedges.

EXISTING ICE WEDGES **

The most conspicuous type of ground ice is that of the large ice wedges or masses characterized by parallel or subparallel foliation structures. The foliation planes are marked by films of organic or inorganic matter, air bubbles, and boundary surfaces between ice layers of different composition.

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** This section has been condensed from Pewé (in press).

Most foliated ice masses occur as wedge-shaped, vertical or inclined sheets or dikes 1 cm to 3 m wide and 1 to 10 m high when seen in transverse cross section. Some masses, when seen on the face of frozen cliffs, may appear as horizontal bodies a few centimeters to 3 m in thickness and $^1/_2$ to 15 m long. The true nature of the form of ice wedges can be seen only in three dimensions. The ice wedges are parts of a polygonal network of ice enclosing polygons or cells of frozen ground 3 to 30 m or more in diameter.

The most striking field relationship between the vertically foliated ice masses and the enclosing sediments is the almost universal appearance of upturning of the strata adjacent to the wedge. The upturning may affect the sediments $^1/_2$ to 3 m on either side of the wedge, being the greatest at the top of the wedge.

The network of foliated ice in the ground generally causes a microrelief pattern on the surface of the ground, generally called polygonal ground or tundra polygons. The troughs which delineate the polygons are generally underlain by ice wedges 1 to 2 m wide at the top. The polygons 3 to 30 m in diameter are not to be confused with the small-scale polygons or patterned ground produced by frost sorting (Black 1952; Washburn 1956).

The origin of large ground-ice masses in perennially frozen ground of North America has been discussed in print since Kotzebue recorded ground ice at a spot now termed Elephant's Point in Eschscholtz Bay of Seward Peninsula (1821). The origin of ground ice was discussed earlier in Siberia (Leffingwell 1915). The general theory of the origin of the ice wedges now accepted is the termal contraction theory of Leffingwell (1915, 1919), which has been recently analyzed by Lachenbruch (1962, in press).

CLASSIFICATION OF ICE WEDGES

Ice wedges may be classified in many ways, such as origin, size, shape, and age. The following classification is based on their degree of activity and history, and permits aerial mapping and geographical subdivision of the types in a general way. The following classification is suggested: (1) active ice wedges, (2) inactive ice wedges, and (3) fossil ice wedges.

There is a complete gradation from active to inactive to fossil ice wedges, both in position on the scale and in aerial distribution (fig. 1).

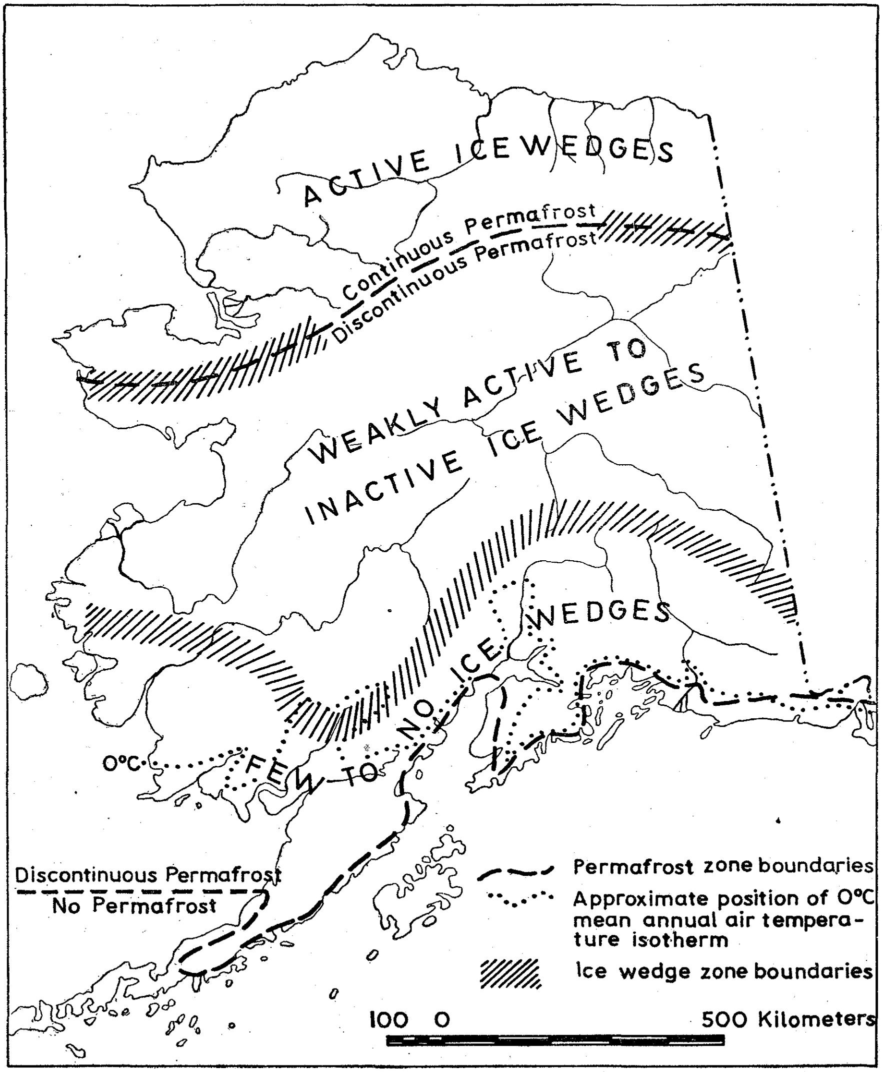

Fig. 1. Distribution of ice wedges and permafrost in Alaska

(Compiled by Troy L. Péwé)

ACTIVE ICE WEDGES

Active ice wedges are defined as those which are actively growing. The wedge may not crack every year, but during many or most years, cracking does occur and an increment of ice is added.

The area of active ice wedges appears to roughly coincide with the continuous permafrost zone. In this area, active cracking into ice wedges has been observed more often than elsewhere; low-center polygons are widespread and well developed; the meager thermal data available indicate that the temperature of the ground at the top of permafrost in this zone is about −15 °C or colder. This area is limited almost entirely to the tundra. Active ice wedges occur in silt, sand, and gravel (pl. 1).

The area of active wedges in Alaska, for example, has a rigorous climate. The mean annual air temperature in this area ranges from about −6 °C or −8 °C on the south to −12 °C at Barrow on the north. The mean annual degree (°C) days of freezing ranges from 2800 to 5400.

The winters are very cold, and the summers are cloudy and cool. Both rainfall and snowfall are light — about 20 cm annual rainfall and less than 150 cm of snow annually. Snowfall is light and accumulation is thin enough to permit great cooling of the ground, especially since much snow is blown by the winds to prowide an uneven cover and packed by drifting to provide better heat transfer.

Permafrost in the area of active ice wedges is classed as continuous, is actively forming, and has a temperature of −5 °C or colder at the level of zero amplitude (depth of 20 to 30 m).

INACTIVE ICE WEDGES

Inactive ice wedges are defined as those which are no longer growing. The wedge does not crack in winter and therefore no new ice is added. There is of course, a gradation between active ice wedges and inactive ice wedges represented by those wedges which crack rarely. For purposes of this paper, wedges which crack rarely will be grouped with the inactive wedges.

Inactive ice wedges in Alaska, for example, have been described only from frozen silt (Taber 1943; Péwé 1948, 1957, 1958, 1962); none are known to exist entirely in sand or gravel.

The area of inactive ice wedges has a mean annual air temperature ranging from about −2° C on the south to about −6° to −8° C on the north. The degree (C°) days of freezing range from 1700 to 4000. The climate is maritime on the west and continental in central and eastern Alaska. Snow fall ranges from 100 to 200 cm. Permafrost in the area of inactive ice wedges is classed as discontinuous and it is forming only in favorable localities. Temperature of permafrost at the level of zero amplitude ranges from −0.5° C to −4° C. Minimum winter temperatures at the top of permafrost are less than −10° to −15° C. Such ground temperatures probably rarely permit thermal cracking of the ice wedges; therefore, no or little ice is added to existing ice wedges and they can be considered dormant, relic, or inactive.

In this zone the permafrost of some areas of permeable sand and gravel has been thawed by heat supplied, in part, from moving groundwater. Ice wedges formerly existing in such sediments are, therefore, no longer present.

FOSSIL ICE WEDGES

Fossil ice wedges are defined as sedimentary structures formed as a result of an ice wedge melting and the space formerly occupied by the ice wedge subsequently being filled with some type of sediment. Many terms have been used to describe these features besides fossil ice wedge: Ice wedge pseudomorph, ice-wedge fill, ice-wedge cast (Wright 1961), fente de glace remplie (Hamelin 1962), frost wedge (Sekyra 1961), and others. They also have been erroneously termed ice wedges by Johnsson (1959, 1962), Filipiuk (1960), and by Galloway (1961).

Fossil ice wedges are generally described as wedge-shaped fillings of sediment, and a voluminous literature exists, mainly in Europe. Much confusion exists concerning true and false fossil ice wedges as well as their paleoclimatic significance. The filling is derived from both the sediment on the sides and from the overlying material. The fill generally has a bimodal mechanical analysis curve (Church, Péwé, and Andresen,

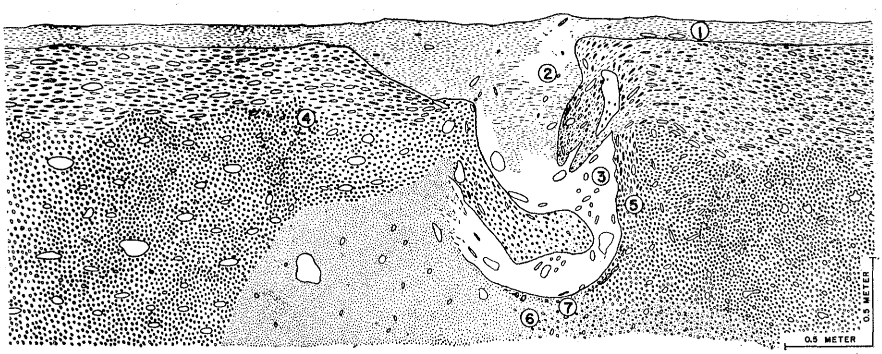

Fig. 2. Diagrammatic sketch of a fossil ice wedge, Donnelly Dome area, Alaska. (From Church, Péwé, and Andresen 1965, fig. 10)

Circled numbers indicate the types of sediment: 1. silt mantle; 2. fill of upper part of wedge; 3. fill of middle and lower part of wedge; 4. undisturbed outwash gravel; 5. disturbed outwash gravel; 6. sand; 7. iron-stained sediments. No vertical exaggeration

1965) if the fossil ice wedges are in gravel, but may also be unimodal or multimodal. The shape of the fill is not always wedge-shaped but may be very irregular (fig. 2).

Fossil ice wedges may be reflected by a poorly to well-developed ground pattern (Dimbleby 1952; Wilson 1958; Shotton 1960), an inheritance of the ice-wedge microrelief polygon pattern (pl. 2). The pattern is similar to ice-wedge polygons except that it is less well preserved and not associated with beaded drainage, thaw gullies with angular courses, thaw lakes, or pingos.

Fossil ice wedges originate when the ice wedges melt. Melting of the wedge occurs when the permafrost thaws, generally from the top down, commonly in response to a warming of mean annual air temperatures to a level of 0 °C or warmer.

It appears that in areas of permeable sand and gravel having active ground water circulation, permafrost and ice wedges may disappear with subsequent formation of fossil ice wedges when the mean annual air temperature is at or above 0 °C for a shorter time than in areas where ice wedges are in perennially frozen silt. In the discontinuous permafrost zone of central Alaska, for example, few ice wedges in perennially frozen silt have been completely thawed but many ice wedges that existed in permeable gravel are gone and the voids filled with sediment, forming fossil ice wedges.

It is agreed that fossil ice wedges indicate the former presence of permafrost, and, therefore, that the mean annual air temperature must have been 0 °C or colder in the past. However, most workers have not singled out the difference between the type of climate necessary to induce permafrost and that necessary to permit ice wedges to form in the permafrost. It has long been stated that the presence of fossil ice wedges indicate that the mean annual air temperature in that region at the time the ice wedges formed was about 0° C to —2° C. Such an interpretation is the result of not realizing that there is a difference between a „permafrost" environment and an "ice wedge" environment.

Based on a study of actual ice wedges, the author believes that the mean annual air temperature of a region at the time extensive ice wedges form is at least —6° C to —8° C. In central Alaska, for example, the mean annual air temperature at the time the current ice wedges formed probably was as cold as —6° C or —8° C, a temperature 3 to 4 degrees C colder than today. Based on the belief that fossil ice wedges are present in central Europe, the mean annual air temperature there during Wisconsin time could have been 15 to 17 degrees C colder than now. The fossil ice wedges of central England may indicate a mean annual air temperature 16 to 18 degrees C colder than now.

SUMMARY

It requires a particular environment to produce permafrost, and an even more rigorous environment to produce ice wedges. Yet, once ice wedges are formed, they may exist in an inactive state in a relatively "weak" permafrost environment.

If ice wedges can be proven to have existed in the geologic past in a particular area, it can be broadly assumed that, at the time of ice wedges formation, a rigorous permafrost environment existed with a mean annual air temperature in the vicinity of $-6°$ C to $-8°$ C, or colder.

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DISCUSSION

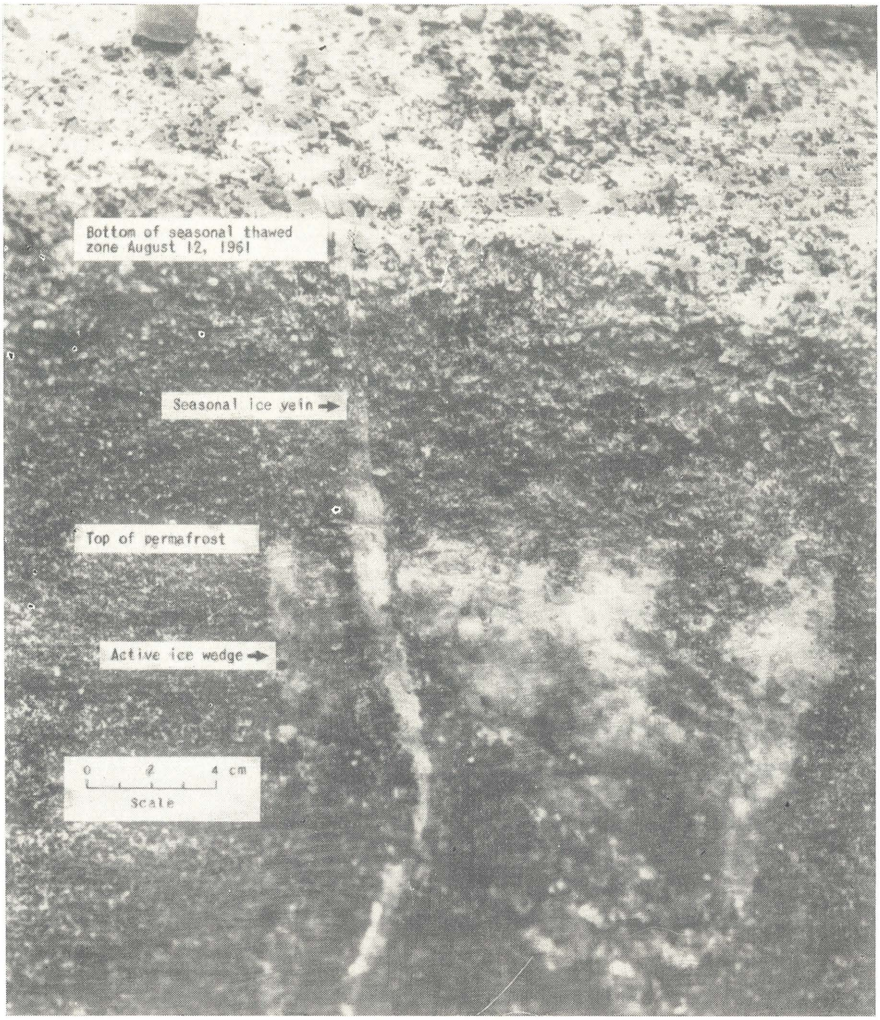
Mr Andrews — In north central Baffin Island with a mean annual temperature of —12° to —14° C the majority of polygons are high-centred. Does this indicate that they are active and if so how do they form? I cannot believe that erosion along the frost cracks is the principal reason for their appearance.

Professor Cailleux referred to Antarctic examples and observed that there were fewer ice wedges at the Bunger oasis with a mean annual temperature of c. —9° C than in the more rigorous climate at McMurdo (mean ann. temp. c. —20° and mean min. temp. c. —36° C). On the other hand, there were polygons in Lapland where the climate was much less cold (mean ann. temp. c. —3° C) than would seem to be required by Professor Péwé.

Professor Rudberg commented on the development of polygons in S. Sweden in Younger Dryas time and also referred to his observations in Axel Heiberg Island where both high-centred and low-centred polygons exist together.

Photograph by T. L. Péwé, July 14, 1961

Pl. 2. Oblique aerial photograph of the large-scale polygonal ground of the Donnelly Dome area, Alaska. Vegetation cover consists of mixed evergreen-deciduous scrub and shrub



Photograph by T. L. Péwé, August 12, 1961

Pl. 1. Small active ice wedge in gravel at Point Barrow Spit, Alaska

Professor Péwé replied that in his experience flat-topped, high-centred polygons were either very young features or they were indicative of erosion, by water washing, keeping pace with uplift.

Mr Jennings — Though a frost fissure polygon origin for mima mounds at Seattle seems not impossible, the climatic demands of applying the same explanation to the mima mounds of the Texas coastal plain and Prairie Terrace of S. Louisiana seem so great as to make it unlikely. Would Professor Péwé extend his suggestion so far? The mima mounds in S. Louisiana which I have seen seem to be very similar in dimensions to those illustrated from Seattle.

Professor Péwé — There are at least 30 different theories for the origin of the Seattle mima mounds!

Professor Dylik — The palaeogeographical significance of so-called ice wedges is a very important question, and Professor Péwé is to be congratulated on his geographical method of presentation. However, some problems remain. First, a distinction must be made between frost fissures containing fissure ice and the so-called sand wedges which you have described from Antarctica. The palaeogeographical significance of these two types is not quite the same. Secondly, there is the question of the climatic conditions under which the fossil structures, caused by infilling after ice meting, were formed. Probably if we find upturned layers and sharp walls we must infer that the infilling took place during conditions of severe cold. What are the manifestations of former ice wedges which were filled by sediments after they melted in the quite different conditions in the interglacials or in Holocene time? Quite clearly there are two different types of ice-wedge pseudomorph.

Professor Péwé — If the edges of fossil wedges are sharp and the adjacent bedding upturned, the ice wedges may have melted under cold conditions. This is possible provided water can get in. But if we find a wide distribution of fossil wedges, all with sharp walls and upturned edges, I believe we can still assume that melting occurred during warm conditions if we consider the type of sediment. In gravel there is a tendency for the sides to slough in; but in loess or organic-rich bedded silt or bedded retransported loess the wedge structure is likely to be maintained.