Research Report 159

ORIGIN AND ENVIRONMENTAL SIGNIFICANCE OF LARGE-SCALE PATTERNED GROUND

Donnelly Dome Area, Alaska

by

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PREFACE

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SUMMARY

Large-scale patterned ground in the Donnelly Dome area of central Alaska consists of polygons 25 to 46 m in diameter bounded by shallow troughs 1 to 2 m wide that form the sides of the polygons. The troughs are underlain by wedge-shaped masses of sediments that extend downward 2 to 3 m. Texture of the sediments of the wedges is distinct from that of the poorly stratified glacial outwash gravel that the wedges transect.

Sediments of the wedge vary texturally along the strike and vertically within a given wedge. The coarsest material in the wedge is about 75 mm in diameter, which is the same size as the coarsest material in the outwash. The fine material in the wedges is silt, the same as that which blankets the area.

The patterned ground of the Donnelly Dome area originated during Wisconsin time when the mean annual air temperature was at least 3C colder than now. A polygonal network of large-scale thermal contraction cracks formed in the gravel during the winters and ice wedges grew in the permafrost.

With the warming of the climate in post-Wisconsin time most of the perennially frozen gravel thawed and the ice wedges melted. The voids created by the melting of the ice wedges were filled with sediment that was washed from the surface or collapsed from the thawed sides of the voids. The troughs bounding the polygons are now, however, no longer underlain with ice wedges but with ice wedge pseudomorphs ("fossil" ice wedges).

Frontispiece. Oblique aerial photograph of the large-scale polygonal ground on the Donnelly Dome area, Alaska. Vegetation cover consists of mixed evergreen-deciduous scrub and shrub. (Photo by T. L. Péwé, 14 July 1961).

LARGE-SCALE PATTERNED GROUND, DONNELLY DOME AREA, ALASKA

by

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INTRODUCTION

Preliminary statement

Perennially frozen ground, like glaciers, can be regarded as an historian of climates or of changes in environmental conditions. Changes in the amount of ice in the perennially frozen ground are among the best indicators of climatic changes.

Ice in perennially frozen ground exists in various sizes and shapes which can be grouped into five main types (Péwé, in press): (1) interstitial or pore ice, (2) segregation or Taber ice, (3) foliated or ice-wedge ice, (4) pingo ice, and (5) ice masses derived from buried ice or snow. One of the most conspicuous types is foliated or ice-wedge ice. Most such ice masses are wedge-shaped vertical or inclined sheets or dikes 1 cm to 3 m wide and 1 to 10 m high. The true form of ice wedges can be seen only in three dimensions and is revealed to be part of a polygonal network of ice enclosing polygons or cells of frozen ground 2 to 30 m in diameter. A polygonal network of foliated ice in the ground generally causes a polygonal microrelief pattern on the surface called polygonal ground. The trough which delineates the polygons is usually underlain by ice wedges 1 to 2 m wide at the top. These large polygons are not to be confused with the small-scale polygons or patterned ground produced by frost-sorting (Black, 1952a; Washburn, 1956).

In central Alaska and elsewhere in the subarctic and Arctic a microrelief pattern of large-scale polygons also occurs in glacial outwash sediments that are not now perennially frozen (Frontispiece). The edges of the polygons are marked by shallow troughs underlain by "wedges" of sediments, but not by ice wedges. This polygonal pattern has been mistaken for ice-wedge polygonal ground and it has been erroneously stated that such areas, therefore, are underlain by ice-rich, fine-grained perennially frozen ground. Such an interpretation results in incorrect views of the engineering geology and past environmental conditions.

A study was made of the well developed large-scale polygonal ground in the Donnelly Dome area, central Alaska (Fig. 1), to try to find solutions to the following problems: (1) Are the polygons an inheritance from ice-wedge polygons, or (2) are they primary features? (3) If they are primary, are they forming today or are they products of a past climate? (4) Knowing their origin, what environment was present when they were formed?

Methods of study

Large-scale polygons in gravel have been reported from several areas in Alaska (Black, 1952b; Hopkins, Karlstrom and others, 1955; Péwé and Church, 1962; and Péwé and Holmes, in press). The Donnelly Dome area was selected for the present study because: (1) the polygons are well developed, (2) the surficial geology has been studied in detail (Péwé and Holmes, in press), (3) the environment of the area, including climate and vegetation, has been studied in considerable detail, (4) the area is easily accessible, and (5) it is near logistic facilities of Fort Greely.

Two areas of patterned ground, designated site 1 and site 2 (Fig. 2), were mapped with an alidade and plane table. Three locations were selected for excavating so that the polygons could be studied in vertical section. Trenches approximately 3 m wide and 3 m deep were cut across the polygons and normal to the edges. Additional studies were made of sediment wedges exposed in road cuts and gravel pits in the Donnelly Dome area.

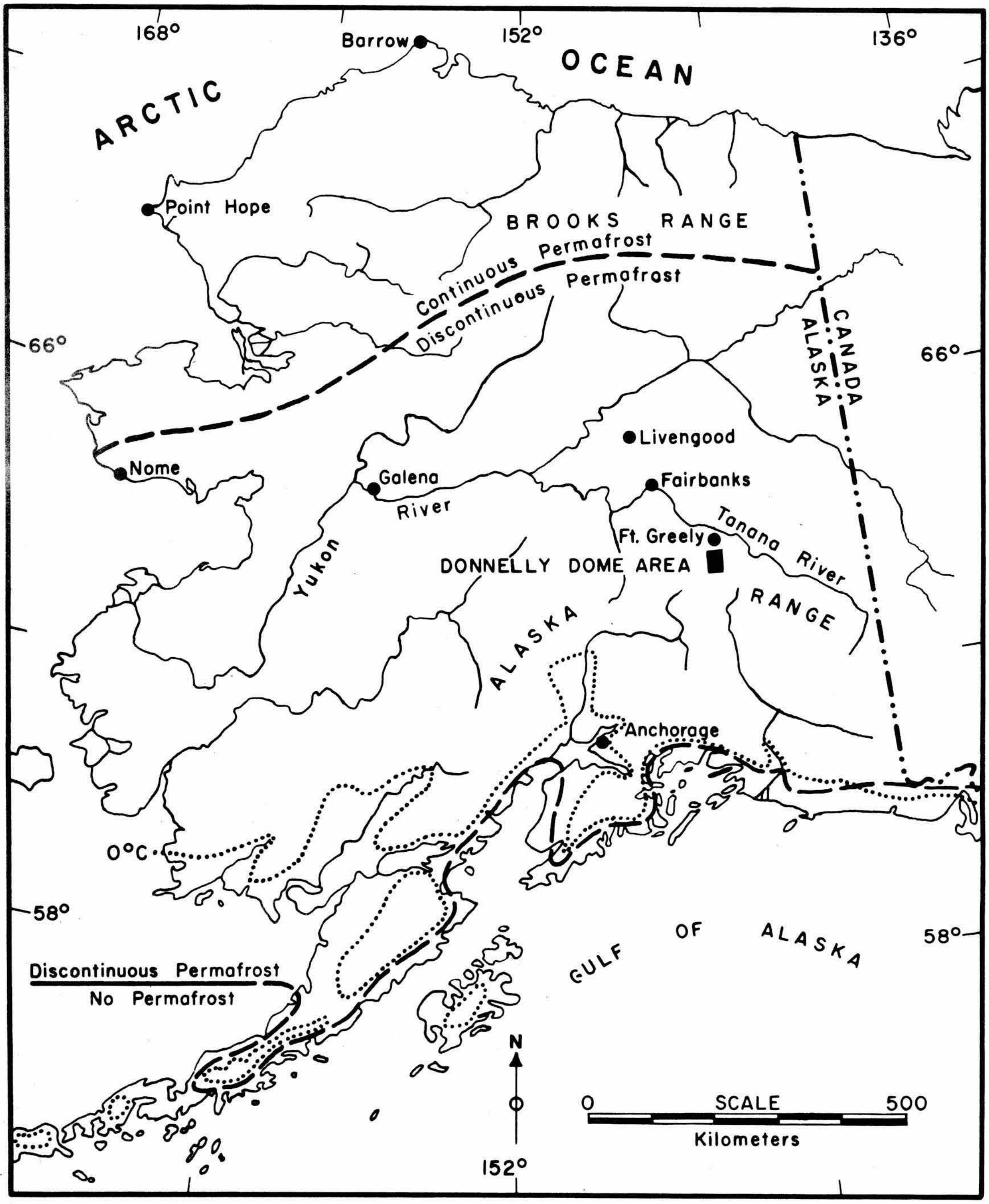

Figure 1. Index map of Alaska showing the location of the Donnelly Dome area, permafrost zones, and the approximate position of the 0C mean annual air temperature isotherm.

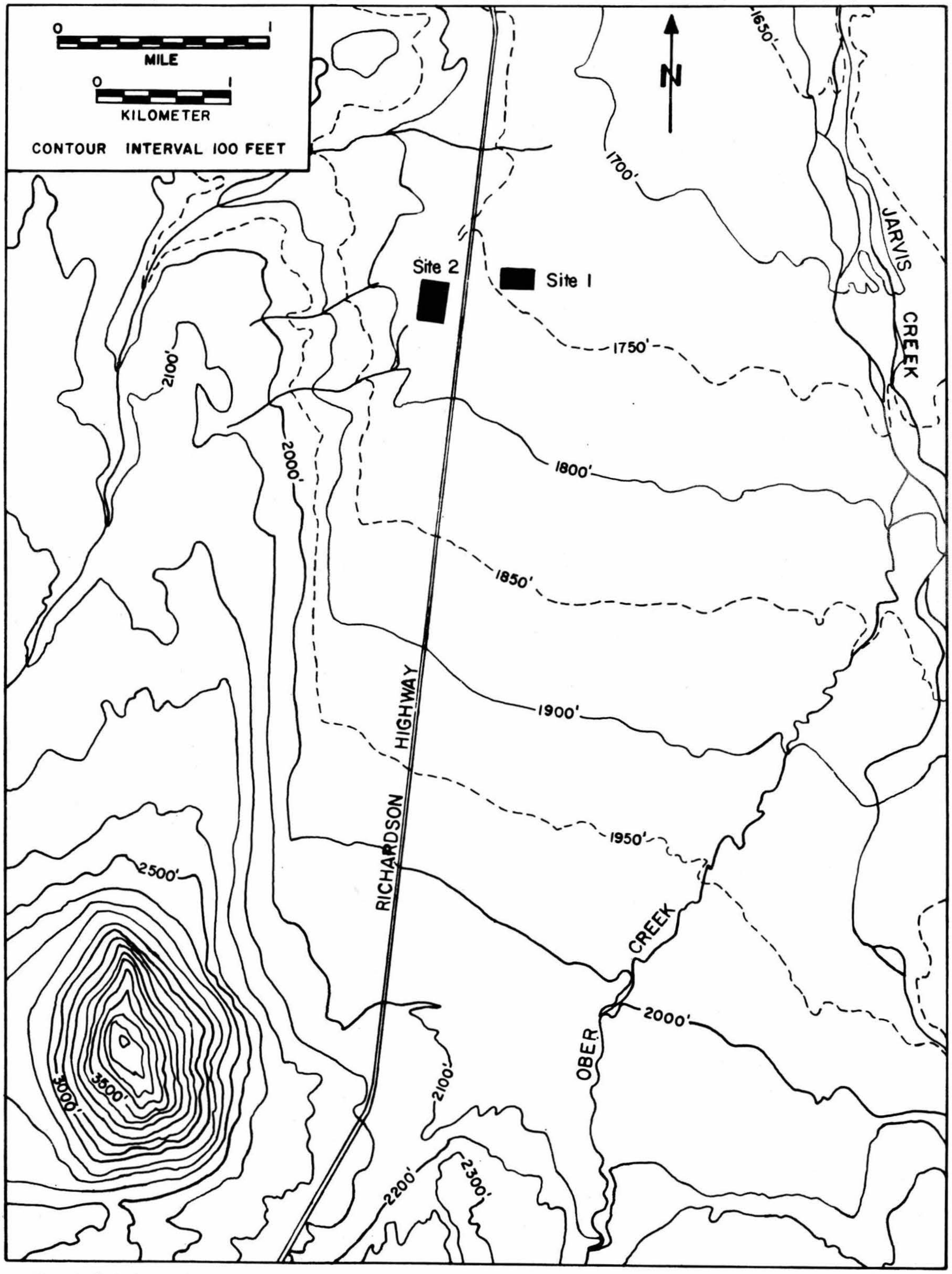

Figure 2. Topographic map of the Donnelly Dome area, Alaska. Polygons were mapped in detail at Sites 1 and 2 (Fig. 6, 7).

In order to investigate ice wedges actively growing in gravel in a known environment, the polygonal pattern and wedges on the spit at Point Barrow, Alaska, were studied (Péwé and Church, 1962).

Definitions

Several terms dealing with permafrost and sedimentation may be unfamiliar to some readers, and others have not been clearly defined in previous papers. The writers' usage of these terms is given below.

Active ice wedge - ice wedge which is growing today. An increment of ice is added during most winters.

Active layer - layer of ground which freezes in the winter and thaws in the summer. The active layer may extend down to the permafrost table but does not do so in areas where permafrost is absent or deep-seated.

Buried ice - ground ice in permafrost which was once at the surface and is buried stream ice, lake ice, aufeis, snow, or glacier ice.

Degree-day - each degree in any one day that the average daily air temperature varies from 0C. The difference between the average daily temperature and 0C equals the degree-days for that day. The degree-days are minus when the average daily temperature is below 0C and plus when above (Linell, 1953, p. 19).

Foliated ground ice - ice which has subparallel to parallel planes marked by films of organic or inorganic matter, air bubbles, and boundary surfaces between ice layers of different composition. Ice wedges are composed of this type of ground ice. (See ice wedge.)

"Fossil" ice wedge - structure formed as a result of an ice wedge thawing and the space formerly occupied by the ice wedge subsequently being filled with some type of sediment. Some synonyms are ice wedge cast or frost wedge.

Freezing index - the number of degree-days between the highest and the lowest points on the cumulative degree-days time curve for one freezing season. The index determined for air temperature for 4.5 ft above the ground is commonly designated as the air freezing index, while that determined for temperatures immediately below the surface is known as the surface freezing index (Linell, 1953, p. 19).

Frost action - a general term for freezing and thawing of moisture in materials and the resultant effect on these materials and on structures of which they are a part, or with which they are in contact (Hennion, 1955, p. 107).

Grains - detrital mineral particles larger than .03 mm in diameter.

Ground ice - ice in seasonally or perennially frozen ground. The term generally is not applied to buried ice.

Ice wedge - wedge-shaped, vertical, or inclined sheets or dikes of foliated ground ice typically 1 cm to 3 m wide and 1 to 10 m high. Ice wedges are commonly arranged in a polygonal network. (See foliated ground ice.)

Inactive ice wedge - ice wedge which is not actively growing today.

Kurtosis - the state of peakedness or curvature of a frequency curve.

Latent heat of fusion - quantity of heat to change a unit mass of material from solid to liquid with no change in temperature.

Leptokurtic - the character of a frequency curve more peaked than the curve of a normal distribution. Indicates excess material in the center of the distribution.

Mesokurtic - the character of a normally distributed population when plotted as a frequency curve.

Normal grain size distribution (normal distribution) - a sample distributed exactly according to the laws of probability is said to have a normal grain size distribution.

Permafrost - a thickness of soil or other surficial deposits or even of bedrock at a variable depth beneath the surface of the earth in which the temperature below freezing has existed continuously for many years (Muller, 1945, p. 219).

Permafrost table - upper limit of permafrost.

Phi scale - the class limits of the classical Udden - Wentworth grain-size grade scale can be expressed as powers of 2. Krumbein (1934) proposed the phi scale (phi = $-\log_2$ grain diameter in mm) to simplify statistical computations. A simplified conversion table is as follows:

mm	ϕ
16.0	-4
8.0	-3
4.0	-2
2.0	-1
1.0	0
1/2	1
1/4	2
1/8	3
1/16	4

Midpoints of classes in the phi scale always can be expressed as rational numbers, e.g., 4.25ϕ, -4.5ϕ, etc.

Pingo ice - mass of more or less clear ground ice existing in a pingo.

Platykurtic - the character of a frequency curve flatter than the curve of a normal distribution. Indicates a paucity of material in the center of the distribution and excess material in the extreme ends or tails of a distribution.

Polygonal ground - ground with a polygonal surface pattern caused by the subsidence of the surface over ground ice, that is, over ice wedges arranged in a polygonal network. Also caused by raised edges around actively growing ice wedges or sand wedges. Also called tundra polygons or Taimyr polygons. Not to be confused with small scale polygonal surface markings (Black, 1952a).

Pore ice - ground ice which occurs in the pores or interstices of soil or rock.

Sand wedge - a wedge of sand in frozen or unfrozen ground or ice. It is not an ice wedge replacement, but a primary feature. Occurs in a polygonal network similar to ice wedges.

Seasonally frozen ground - frozen ground that forms in winter and thaws in summer.

Seasonal frost crack - thermal contraction crack in seasonally frozen ground.

Segregated ice - ground ice which occurs as more or less horizontal seams or lenses in fine-grained sediment. Formed by the drawing in of water to the growing ice crystal as the ground is frozen. A synonym is Taber ice.

Skewness - the asymmetry about the mean of a frequency curve. In grain-size distributions, positive skewness indicates an excess of coarse material in an essentially fine-grained sediment and negative skewness indicates an excess of fine material in an essentially coarse-grained sediment. Skewness values near 0.00 indicate high degrees of symmetry.

Sorting - a measure of the spread or dispersion of a distribution about an average. In grain-size distributions, sorting describes the variability in size of the material comprising the sample; that is, are the grains all about the same size (good sorting) or is there great variability (poor sorting)?

Sorting coefficient - a mathematical measure of the degree of sorting of a sediment (Trask, 1932, p. 26).

Taber ice - see segregated ice.

PHYSICAL SETTING

Location

The Donnelly Dome area (Fig. 1) (63°50'N ; 145°45'W) is in southeastern interior Alaska approximately 145 km southeast of Fairbanks. The area is 19.5 km south of Fort Greely, Alaska, and lies partly within the military reservation.

Physiography

The Donnelly Dome area is in the Tanana Lowland physiographic province. The southern part of the area abuts the foothills of the Alaska Range physiographic province. The Tanana Lowland province, drained by the Tanana River, is a long, irregularly shaped depression trending northwest which separates the Yukon-Tanana Upland to the north from the Alaska Range to the south.

Landforms present within the Donnelly Dome area include bedrock foothills, moraines, outwash fans and plains, alluvial fans, terraces, and flood plains.

The elevation of the outwash plain on which the patterned ground study was carried out ranges from 515 m to 600 m (Fig. 2).

Geology

Areal geology. The oldest rocks exposed in the Donnelly Dome area are units of the Birch Creek schist of Precambrian age. These rocks, and the granodiorite bodies intruded during Mesozoic time (Péwé and Holmes, in press), are mapped as undifferentiated bedrock (Fig. 3). They are exposed only in the foothills of the Alaska Range in the southern part of the area and on Donnelly Dome.

Quaternary deposits consist of glacial moraines, glaciofluvial deposits, colluvium, and flood-plain and low river-terrace deposits.

Morainal deposits of the Delta Glaciation occur in the central and western part of the area. They are characterized by subdued knob and kettle topography (Fig. 3). Moraines of the Donnelly Glaciation cover much of the area. Their knob and kettle topography is much more rugged than the topography of the moraines of the older Delta Glaciation, and more lakes are present. Extensive outwash fans and outwash plains occur along the margins of the moraines of the Donnelly Glaciation. It is on one of these outwash plains that the areas of polygonal ground occur and that wedge exposures designated B, C, D, and E are located (Fig. 3). The outwash gravel in which the wedges occur is composed of a variety of rock types, most of which have their origin in the Birch Creek schist. Pebble counts were made on the sieved fraction of pebbles in the 5 to 25 mm diameter range by Mr. Noel Horlocker, Dept. of Geology, University of Alaska. Analyses of 100 pebbles from each of 10 samples indicate the following compositional percentages: quartz, 31; quartzite, 22; quartz mica schist, 19; micaceous quartzite, 12; green schist, 9; gneiss, 2; greenstone, 2; granite, 1; phyllite, 1; and traces of granodiorite, limestone, coal, and rhyolite.

Windblown silt, loess, forms a surficial cover over all but the bedrock hills and flood plains. The cover becomes thicker northward toward the Tanana River and westward toward the Delta River (Péwé and Holmes, in press).

Quaternary history. The Quaternary history of the Donnelly Dome area is characterized by advances of glacier ice from the Alaska Range. According to Péwé (1952b, p. 1289), the earliest glacial advance was the Darling Creek Glaciation; however, no deposits of this glaciation remain in the Donnelly Dome area.

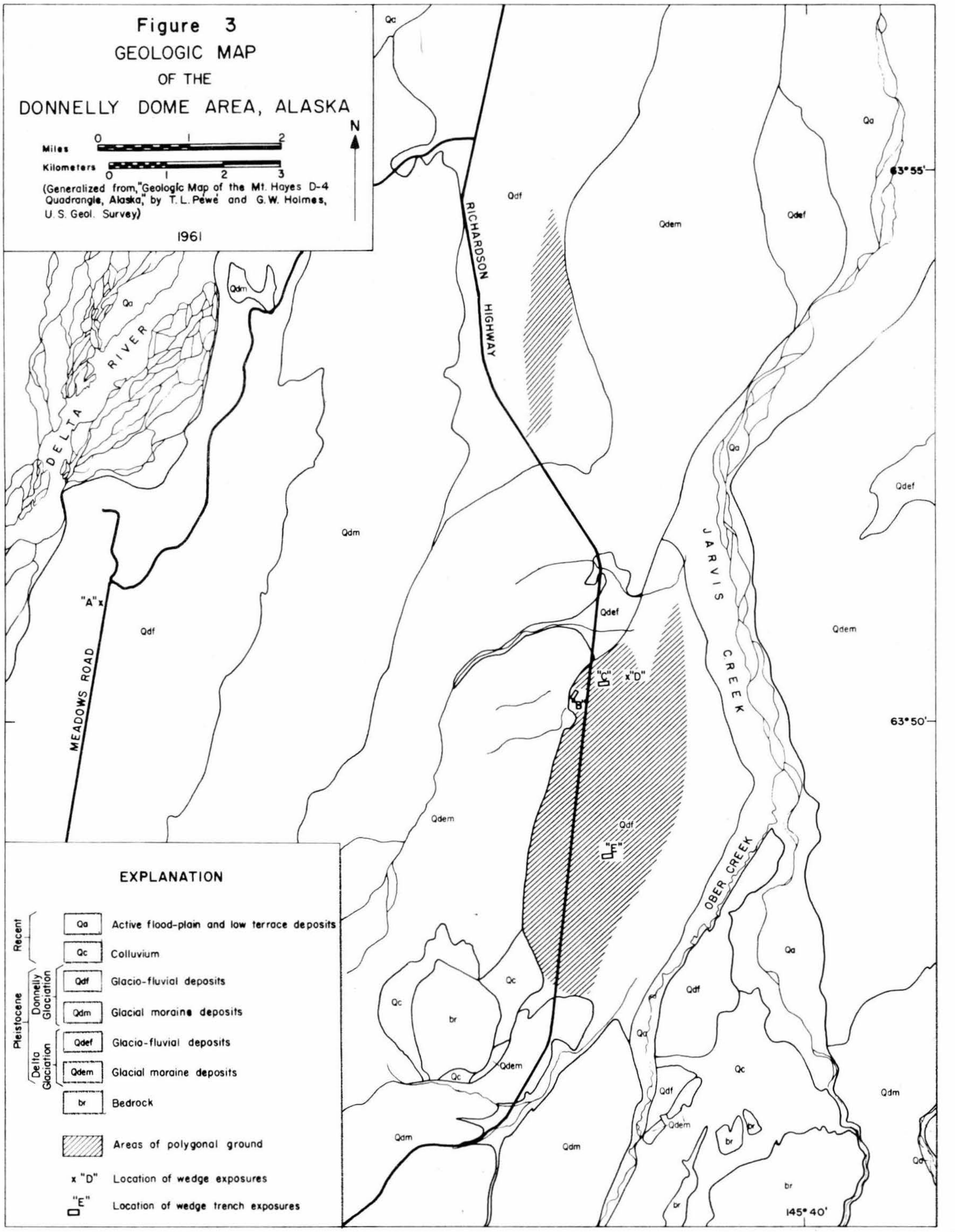
Figure 3
GEOLOGIC MAP
OF THE
DONNELLY DOME AREA, ALASKA
Miles
0
1
2
Kilometers
0
1
2
3
N
(Generalized from, "Geologic Map of the Mt. Hayes D-4 Quadrangle, Alaska," by T. L. Péwé and G. W. Holmes, U. S. Geol. Survey)
1961
DELTA RIVER
RICHARDSON HIGHWAY
MEADOWS ROAD
JARVIS CREEK
OBER CREEK
"A"x
"B"
"C"
x"D"
"F"
63°55'
63°50'
145°40'
Qa
Qc
Qdf
Qdm
Qdef
Qdem
br
EXPLANATION
Recent
Qa
Active flood-plain and low terrace deposits
Qc
Colluvium
Pleistocene
Donnelly Glaciation
Qdf
Glacio-fluvial deposits
Qdm
Glacial moraine deposits
Delta Glaciation
Qdef
Glacio-fluvial deposits
Qdem
Glacial moraine deposits
br
Bedrock
Areas of polygonal ground
x "D"
Location of wedge exposures
"E"
Location of wedge trench exposures

During the succeeding glacial advance, ice of the Delta Glaciation (Péwé, 1952b, p. 1289) covered all the area except the top of Donnelly Dome which protruded as a nunatak.

The Donnelly Glaciation, the latest major ice advance (Péwé, 1952b, p. 1289), was not as extensive as the earlier advances and one lobe terminated near Donnelly Dome (Fig. 3). Sand and gravel of the outwash plain, in which the polygonal ground is developed, were deposited during this advance.

The glaciers then withdrew to the south so that subsequent advances and retreats are not recorded in this area. During and after glacier withdrawal and terrace formation, silt was picked up from the floodplains of the Delta River and Jarvis Creek and deposited as loess over much of the adjacent terrain. This process is continuing today (Péwé, 1951).

Age. The outwash gravel in the area is broadly interpreted to be Wisconsin* in age (Péwé, Hopkins and Giddings, in press). The gravel was deposited when the glacier of Donnelly age stood at a position of maximum advance.

The Delta River has cut a broad valley through the major glacial moraine of Donnelly age. This occurred since the withdrawal of the glacier from the immediate area and since the formation of the outwash plain in which the sediments here investigated were deposited. Subsequently, large gravel alluvial fans extending into the Delta River valley have formed, and a veneer of loess 1.5 to 20 m thick has accumulated on top of these fans. A large number of buried forest beds exist in the loess, and it has been possible to obtain radiocarbon age determinations. A date of 7000 ±275 (I-462) years has been obtained from a piece of spruce log at the base of the 15-m thick loess section on the east side of the Delta River directly west of Donnelly Dome (Péwé and Holmes, in press). Upstream from this location 14.5 km a date of 5900 ±250 (I-646) years has been obtained from a piece of wood at the base of the loess on a gravel fan near the junction of Ruby Creek and the Delta River (Reger, et al., in press). A date of 8040±190 yr (GXO 255) has been obtained on charcoal at the base of loess overlying sand dunes adjacent to the Tanana River 45 km downstream from Donnelly Dome.

From these data it is readily apparent that the outwash gravel is at least 7,000 years old. The loess veneer on the outwash gravel is of post-Wisconsin age.

Ground water. Information is sparse on the distribution and depth to ground water within the boundaries of the Donnelly Dome map area (Fig. 2). Much of the water is derived from mountain streams that recharge the gravel in the higher parts of the plains along the mountain fronts to the south. Ground water issues from springs at the north end of an outwash plain near the Big Delta area (Péwé, 1955, p. 130).

Two wells drilled in outwash sediments of Donnelly age approximately 0.4 km east of wedge trench exposure E (Fig. 3) encountered the water table at depths of 20.6 and 21 m, respectively. One of these wells also encountered a perched water table at a depth of 3.6 m. A well drilled 400 m south of wedge exposure D intersected the ground water table at a depth of 14.9 m and a perched water table at a depth of 7.3 m (Péwé and Holmes, in press). During excavation of wedge trench exposure B (Fig. 3) a perched water table was noted at a depth of 3 m.

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*The meaning of the term Wisconsin used here is that outlined by Flint (1963), i.e., the last 70,000 years.

Seasonally frozen ground. In wells drilled in the outwash sediments in which the large scale polygons are formed, thicknesses of seasonally frozen ground have been reported to be as great as 6 m (Péwé and Holmes, in press). The outwash gravel presents ideal conditions for maximum penetration of seasonal ground freezing as it has a sparse vegetation cover, is covered with a thin blanket of snow in winter, and has a low moisture content and a high coefficient of thermal conductivity.

Permafrost. Permafrost, perennially frozen ground, is widespread in northern North America and in northern Asia. It has been estimated to underlie one-fifth of the land surface of the earth (Muller, 1945, p. 1). It is present throughout most of Alaska and, as might be expected, is more widespread and extends to greater depths in the north than in the south. Alaska can be divided into two generalized permafrost zones: the continuous and discontinuous (Fig. 1).

Perennially frozen ground has been the object of considerable research near Fairbanks, Alaska, 145 km northwest of the Donnelly Dome area (Fig. 1). In the Fairbanks and Donnelly Dome areas, permafrost conditions are probably typical of those existing in the discontinuous zone (Péwé, 1954; 1958a, p. 13). Permafrost is found nearly everywhere near Fairbanks except on hilltops and steep southward-facing slopes. Maximum observed depth of permafrost is 81 m in the flood plain of the Tanana River which is underlain by zones of perennially frozen ground interspersed and interstratified with zones of unfrozen sediments (Péwé, 1958b). The temperature of permafrost below the zone of seasonal fluctuations is - 0.5C to -1.0C.

Data on permafrost in the Donnelly Dome area are scarce and few reliable measurements have been made to determine the distribution and temperature. Till, colluvium, silt and peat deposits are perennially frozen. Depth to permafrost is 30 cm to 1 m in these ice-rich sediments; however, permafrost thickness is unknown (Péwé, 1955; Péwé and Holmes, in press).

A number of test holes and wells were drilled on the outwash plain during military construction activities. Wells were drilled about 0.4 km east of wedge trench exposure E (Fig. 3), and no permafrost was encountered. In two wells near wedge exposure D, however, permafrost was encountered. In one well, frozen ground occurred in gravelly, silty sand at a depth of 11.7 m and extended to the bottom of the hole at a depth of 13.4 m. In the second well permafrost was encountered in gravelly, silty sand between depths of 9.9 m and 14.3 m. A thermal cable was subsequently installed in this hole by the Corps of Engineers, U. S. Army, and the temperatures recorded five times, the last time being in July, 40 days after installation. Ground temperatures of -0.55C to 0C substantiated the presence of perennially frozen ground.

No permafrost was encountered during excavation of the wedges on the outwash plain. It is believed that permafrost, where present in these outwash sediments, is relict and is restricted to lenses containing a high percent of silt. The lower permeability of the silt restricts meteoric and ground water movement through the sediments—water which would have otherwise entirely degraded the frozen ground. Frozen silty sediments have a higher ice content than gravelly sediments; therefore, thawing was retarded in the silt-rich gravel because of additional energy required to overcome latent heat of fusion.

Because of the minor amount present, and the depth at which it occurs, perennially frozen ground does not affect the present environment of the polygonal ground.

Climate

The Donnelly Dome area has long, extremely cold, dry winters; and short, sunny, mild summers.

The nearest weather station at which observations have been made over a number of years is the Federal Aeronautics Administration installation at Big Delta airfield, approximately 15 km north of the Donnelly Dome area (Fig. 1). Records from this station were used to compile Figure 4.

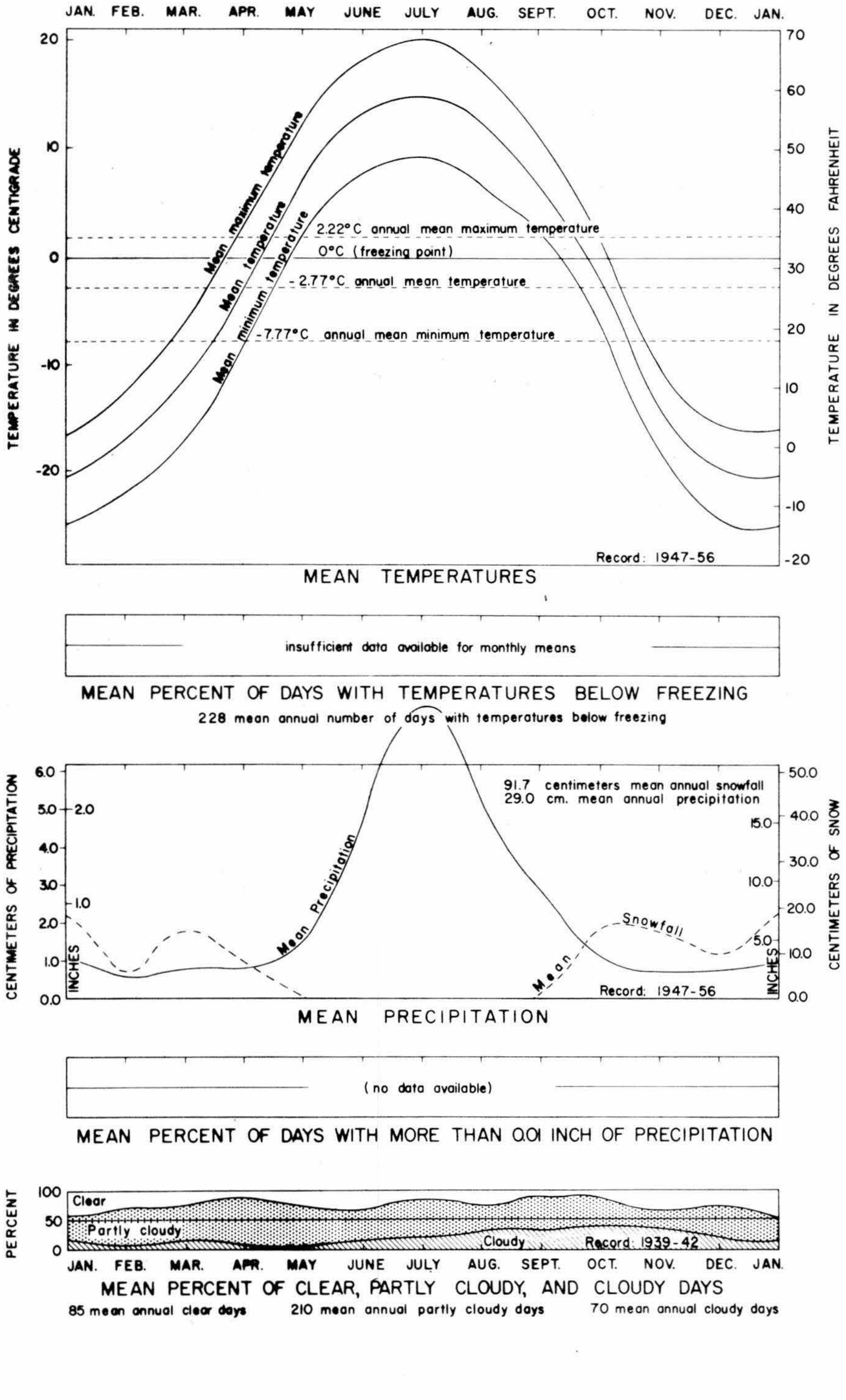

Figure 4. Mean monthly climatic data for Big Delta FAA station at Ft. Greely, Alaska, 15 km north of the Donnelly Dome area.

The annual range of temperature between extremes (absolute maximum to absolute minimum) is usually from 70C to 83.5C at Big Delta. The lowest recorded temperature is -54.4C and the highest is 32.2C. The mean summer temperature is 13.5C. Temperatures at or below -40C may be expected to occur on an average of 3 to 4 days each month during December through February. The freezing index is 2950 degree-days (C).

The mean annual precipitation at Big Delta is 29.2 cm, most of which falls as rain in June, July, and August (de Percin, Falkowski, and Miller, 1955, p.3). The mean average snowfall is 86 cm.

The wind pattern in the Donnelly Dome-Big Delta region is complex and unique. During the winter months winds are predominantly from the east-southeast. These winds, which occur 38% of the time from November through February, are the result of a topographically induced convergence of the flow of air from the Tanana Valley which occurs at times of south-easterly gradient winds aloft (Mitchell, 1955, p.1). The high winds common in the area blow away or pack much of the snow that falls.

Vegetation*

The vegetation of the outwash plain in which the polygons are developed, can be divided into three mappable vegetation units (Frontispiece, Fig. 5). The first unit (LB), which shows up very distinctively as a light gray area on aerial photographs (Fig. 5), consists of lichen barrens with patches of mixed evergreen-deciduous scrub and shrub vegetation. The lichens grow where there is little or no silt cover. Most of the mixed evergreen-deciduous scrub and shrub vegetation grows in the troughs at the edges of the polygons where the silt is thicker. It is the difference in vegetation types between the center of the polygons and the troughs at the edges that delineates the polygonal pattern so well in this area.

The lichen-barrens unit grades into a second unit (MS) composed of mixed evergreen-deciduous scrub and/or shrub vegetation (Frontispiece). The polygonal pattern is outlined by the taller shrub members and trees growing in the trenches at the wedges of the polygons where the silt cover is thicker (Frontispiece).

The third unit (DS) is mapped as deciduous scrub and shrub vegetation (Fig. 5). The taller members of this plant community grow in the troughs of the polygons and thus aid in delineating them. The polygons are not, however, as readily distinguishable from the ground in this unit or the previously described one as they are in the lichen-barrens unit.

The difference in vegetation types on the same outwash plain is probably due to differences in thickness of the silt cover. Holmes and Benninghoff (1957, Chap. 9) suggest that the light gray areas of lichen were the sites of melt-water channels during the time of the Donnelly Glaciation. Since then little or no silt has accumulated on this outwash plain so the ancient melt-water channels are almost silt-free.

DESCRIPTION OF THE LARGE-SCALE POLYGONAL GROUND

Plan view

The large-scale polygons in the Donnelly Dome area are outlined by a network of intersecting trench-like depressions 30 cm to 1 m deep and 1 m to 2 m wide. These

* This section is mainly from Holmes and Benninghoff, 1957, Chap. 9, supplemented by observations by the writers.

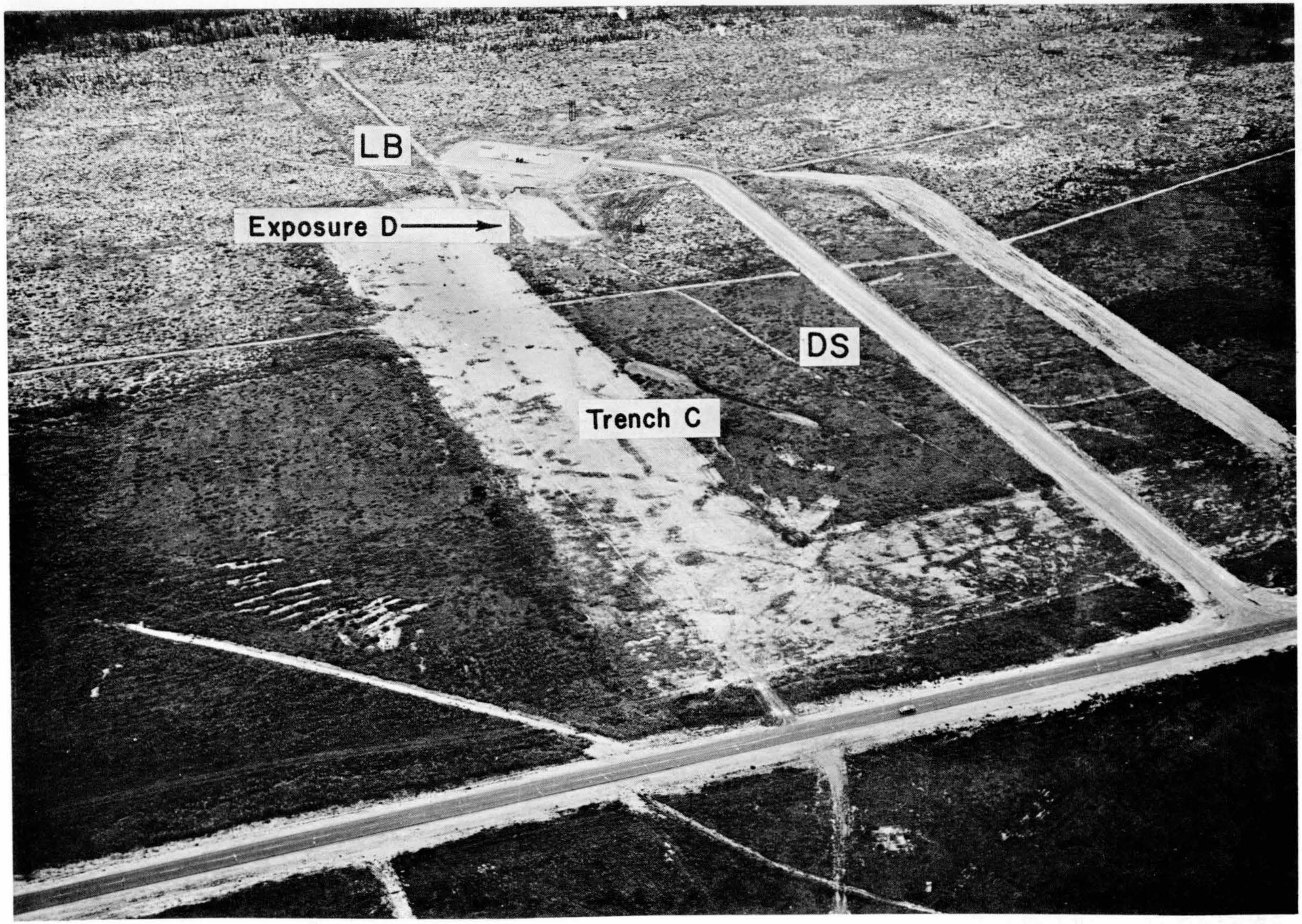

Figure 5. Low angle oblique aerial photograph of large-scale polygonal ground in the Donnelly Dome area, Alaska. Vegetation symbols: LB - lichen barrens; DS - deciduous scrub and shrub. (Photo by T. L. Péwé, 14 July 1961).

troughs are underlain by wedge-shaped masses of material of different texture than the outwash sediments in which they occur. The polygons are accentuated by differences in vegetation between the centers of the polygons and the trenches.

Some of the polygons are approximately equidimensional, but most have a long and a short axis. The equidimensional polygons generally vary from 25 to 30 m on a side. Most of the inequidimensional polygons are 25 to 30 m wide and 30 to 46 m long (Fig. 6, 7). The maximum length of any polygons measured was 61 m. The long dimensions of the polygons have no apparent systematic orientation. Smaller polygons with a maximum dimension of 25 m also occur and in many cases they appear to be subdivisions of large polygons.

The polygons are 3-to 6-sided, but the greatest number have 4 sides. Numerous 5-sided polygons also occur. The sides are not always straight, some are slightly curved and some bend sharply (Fig. 6, 7).

At Site 1 (Fig. 2, 5, 6), most of the troughs which form the sides of the polygons intersect obliquely. At Site 2 (Frontispiece, Fig. 2, 7), however, the trenches tend to intersect orthogonally, although oblique intersections are also common.

Vertical section

The sediments exposed in the sides of the excavations which cut representative polygons have grossly similar textural and structural characteristics. Wedge-shaped masses of relatively fine-grained sediments underlie the slight surface depressions which mark the polygon boundaries (Fig. 8). These wedge-shaped masses, or wedges, crosscut poorly stratified glacial outwash gravel. The outwash gravel maintains its identity in an undisturbed form to a zone within approximately 3.5 m of a wedge. In this zone on either side of the wedge, the character of the outwash is texturally and/ or structurally distinct from the parent outwash material. The material in this zone is also quite distinct from the wedge-fill sediments.

Wedge geometry

The individual sediment wedges of fine-grained material, locations given in Figure 9, vary greatly in size and shape although most are composed of three segments which can be recognized in the field (Fig. 10 to 20). These segments are a wide upper part, a narrow middle section, and an extremely irregularly shaped lower part. The wedges extend from 1 to 3 m below the ground surface and all bend and curve to varying degrees. Some of the wedges widen and narrow again (Fig. 13); many of them terminate in a sharp hook (Fig. 10, 11, 13, 17); and some terminate in a large foot-like mass or bulge (Fig. 14, 15, 16).

Wedges E2, E3, and E4 (Fig. 9) are somewhat smaller than wedge B3 (Fig. 12, 18, 19, 20). The former vary from 0.6 to 1.2 m in width at the top and narrow rapidly downward so that below the upper segment (at a depth of about 1 m below the ground surface) the wedges are generally 15 to 60 cm wide (Fig. 18, 19, 20). Often however, the wedges widen again at a greater depth and may actually be wider at their basal terminations than at the top.

The gross shape of some wedges varies markedly along the wedge trend (compare Fig. 10 and 12). In a lateral distance of 3 m, the width of an excavation, a wedge may decrease in size from a well-defined entity 2 m deep and terminating in a sharp hook to an indistinct veinlet of fine-grained material which extends only 0.6 to 1.0 m below the surface. A photograph (Fig. 21) of sediment wedge illustrates the field appearance in black and white. It is the light gray to tan silt lying next to the brown or reddish gravel that so strikingly outlines the wedges in the field.

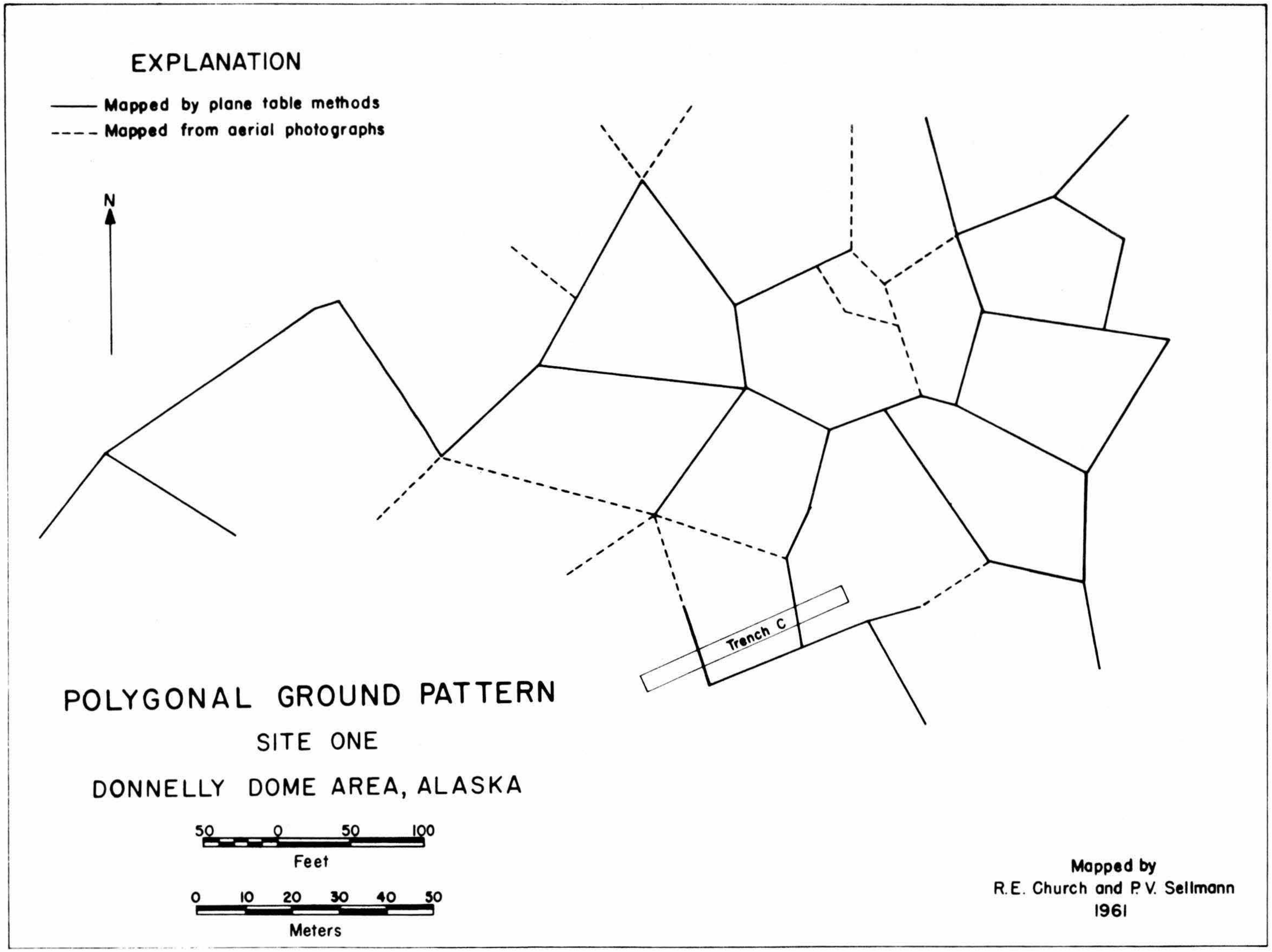

Figure 6. Plane table map of large scale polygons, Site 1, Donnelly Dome area, Alaska. See Figure 5 for photograph.

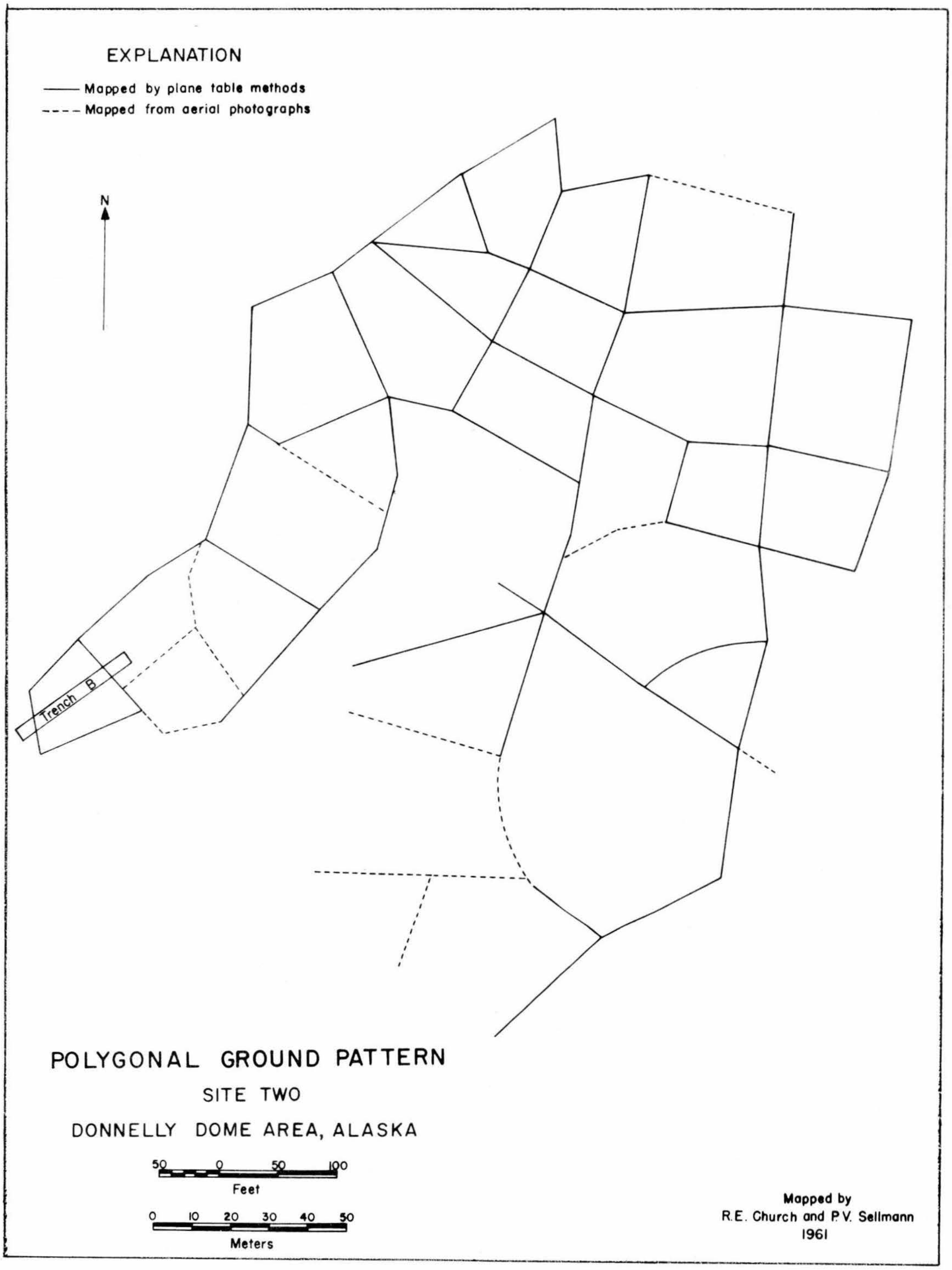

Figure 7. Plane table map of large-scale polygons, Site 2, Donnelly Dome area, Alaska. For photograph see Frontispiece.

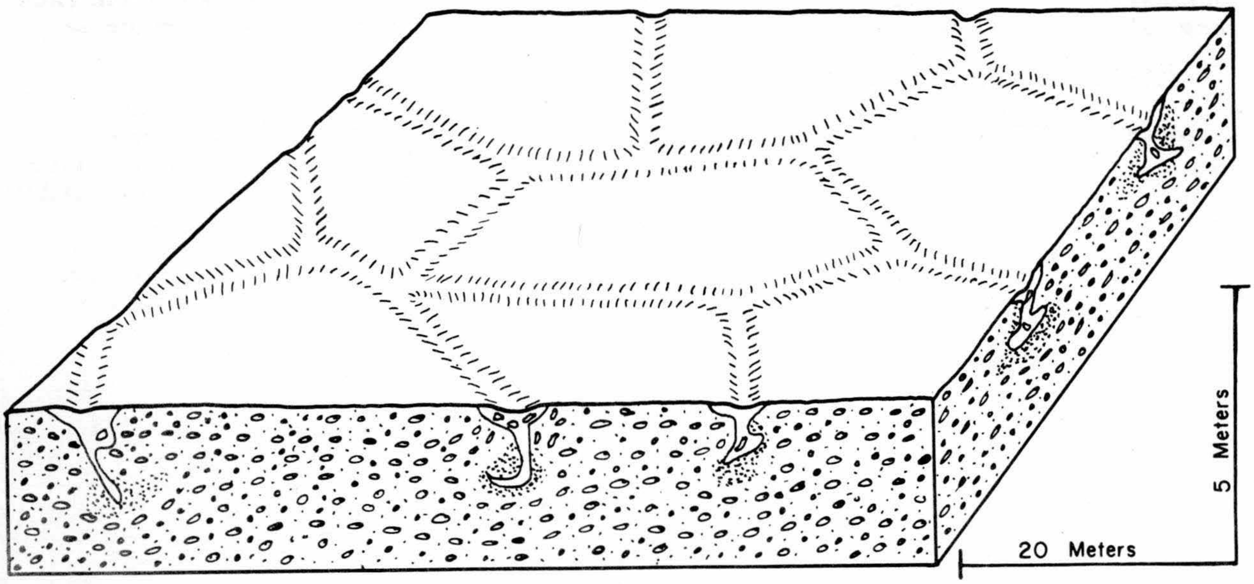

Figure 8. Relation of large-scale polygonal ground to sediment wedges, Donnelly Dome area, Alaska.

Classification of the sediment types

The sediment wedges, locations given in Figure 9, are highly variable in size and shape, but they also possess a number of common details of structure and texture. Similarly, the materials in which the wedges occur, the outwash gravel, and the modified outwash material adjacent to the wedges, also exhibit definitive textural characteristics.

Seven types of sedimentary material are recognized in connection with wedge occurrence and are: (1) silt mantle overlying all other materials in the area, (2) fill comprising the upper part of the wedge, consisting of silt with some cobble-sized grains, (3) fill comprising the middle and lower parts of a wedge consisting of silt with abundant grains coarser than sand size, (4) undisturbed outwash gravel of Donnelly age, (5) disturbed outwash gravel in a zone adjacent to the wedge, (6) sand "envelope" enclosing the lower part of the wedge, and (7) iron-stained disturbed outwash sediments adjacent to the wedge-fill material. The iron-stained material described above as type (7) is differentiated on the basis of color and does not occur as an independent textural type; therefore, no grain-size analyses were made. The six sediment types and the iron-oxide stained gravel are indicated on Figures 10 to 20, and the positions from which sedimentological samples were taken are marked.

Description of the sediments

The ranges in the proportion of gravel*, sand, silt, and clay-sized material in each of the textural types defined above are given in Figure 22. The grain size parameters are those developed by Folk and Ward (1957) which are described in detail in Appendix A. Table AI in the appendix gives the grain-size data from which the

*The following size-grade classification is used in this report: gravel, >2.00 mm; sand, 0.0625-2.00 mm; silt, 0.005-0.625 mm; and clay, <0.005 mm.

parameters are derived, and the parameters are given in Table AII. These data are summarized in Figure 23. It must be noted that the number of samples taken from each textural type is relatively small and that only general interpretations can be made.

Features of the sediments in the wedges.

Texture: The upper segment of all the wedges, with the exception of the artificially truncated wedge at exposure D (Fig. 16), consists of unstratified brown to red-brown, gravelly, very silty sand containing various quantities of roots and other organic debris. The sediment of the upper wedge, textural type 2, grades imperceptibly into the thin brownish silt which mantles the area (textural type 1). It also grades down imperceptibly into the greenish-gray sediment which fills the middle and lower segments of the wedges (textural type 3). Two samples from the upper segment were examined and the respective statistical parameters calculated for this material are all within the wide range of those for the rest of the wedge fill (Table AII: Fig. 23). Even though the number of samples examined is small, it appears that the materials of the upper wedge can be recognized in the field on the basis of color and position in the wedge. The material is not distinct texturally from the materials found in the middle and lower wedge segments, however.

The sediment which constitutes the middle and lower segments of the wedges, textural type 3, varies from unconsolidated greenish-gray to tan, very sandy silt to gravelly, very silty sand of the same color. Material of sand size is most abundant in the wedges. There is no systematic variation with depth in the proportions of gravel-, sand-, silt-, and clay-sized particles in the wedges, or in the various grain-size parameters derived from the sediment distributions. The smallest mean or median size may occur in the top, middle, or bottom segment of a particular wedge. Similarly, the best size-sorted material may be in any position. All but two of the wedge samples have negatively (coarse) skewed distributions. Coupling this fact with the mean size values (Fig. 23) indicates that wedge fill is essentially a fine-sized material to which coarse grains have been added. The kurtosis of the grain-size distribution in each sample has been calculated (Table AII), but the values are virtually meaningless so they are not presented in Figure 23.

The respective statistical parameters were plotted against depth for each of the investigated wedges to see if any trends were present, but the general conclusion reached is that there is textural chaos in the wedge-fill materials. Some faint trends do appear in a given wedge, but the reverse trend is likely to occur in the next wedge. It seems that the wedge filling is the result of very local conditions; this idea is supported when one notes that wedge geometry changes rapidly in just a few meters.

A minor amount of iron-staining occurs in the wedges at exposures C1 and E3. The wedges in the rest of the exposures are free of staining, although sediments adjacent to a wedge fill are rust-stained at locality C2.

Moisture content: The wedge-fill sediments were frozen when the polygons were excavated in early June, 1961. The moisture content of this frozen sediment at a depth of 1 m varied from 16.7 to 21.9% by dry weight (Table AIII).

Structures: The only apparent structural feature within the wedges is the preferred orientation of elongate pebbles and cobbles in the middle and lower segments of some wedges. There is no apparent preferred orientation in the upper segment. In the middle part of the wedges a high proportion of the stones are oriented with their long axes vertical or nearly vertical (Fig. 14, 15). Many of the stones near the contact between the wedge and the surrounding sediments are oriented parallel to the contact (Fig. 15).

In the lower segment of the wedges many of the cobbles and pebbles are oriented with their long axes vertical or nearly vertical, but many of them near the edges are oriented with their long axes parallel to the contact with the adjacent material. Thus, in wedges having lateral enlargements at their respective termini, the preferred orientation near the contact of the wedge with subjacent sediments may be nearly horizontal (Fig. 15, 19).

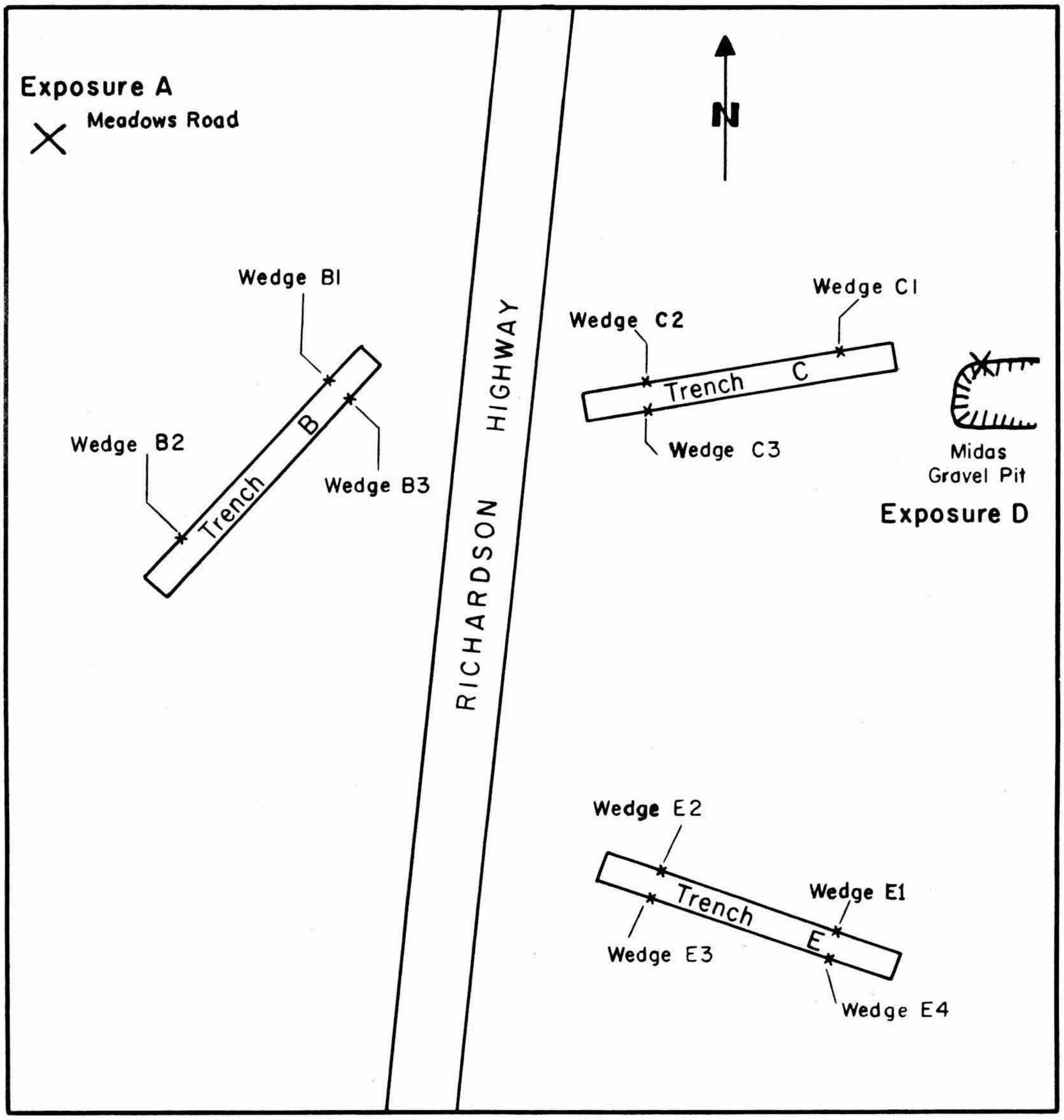

Figure 9. Relative locations of sediment wedge exposures, Donnelly Dome area, Alaska (not to scale). See Figure 3 for exact locations.

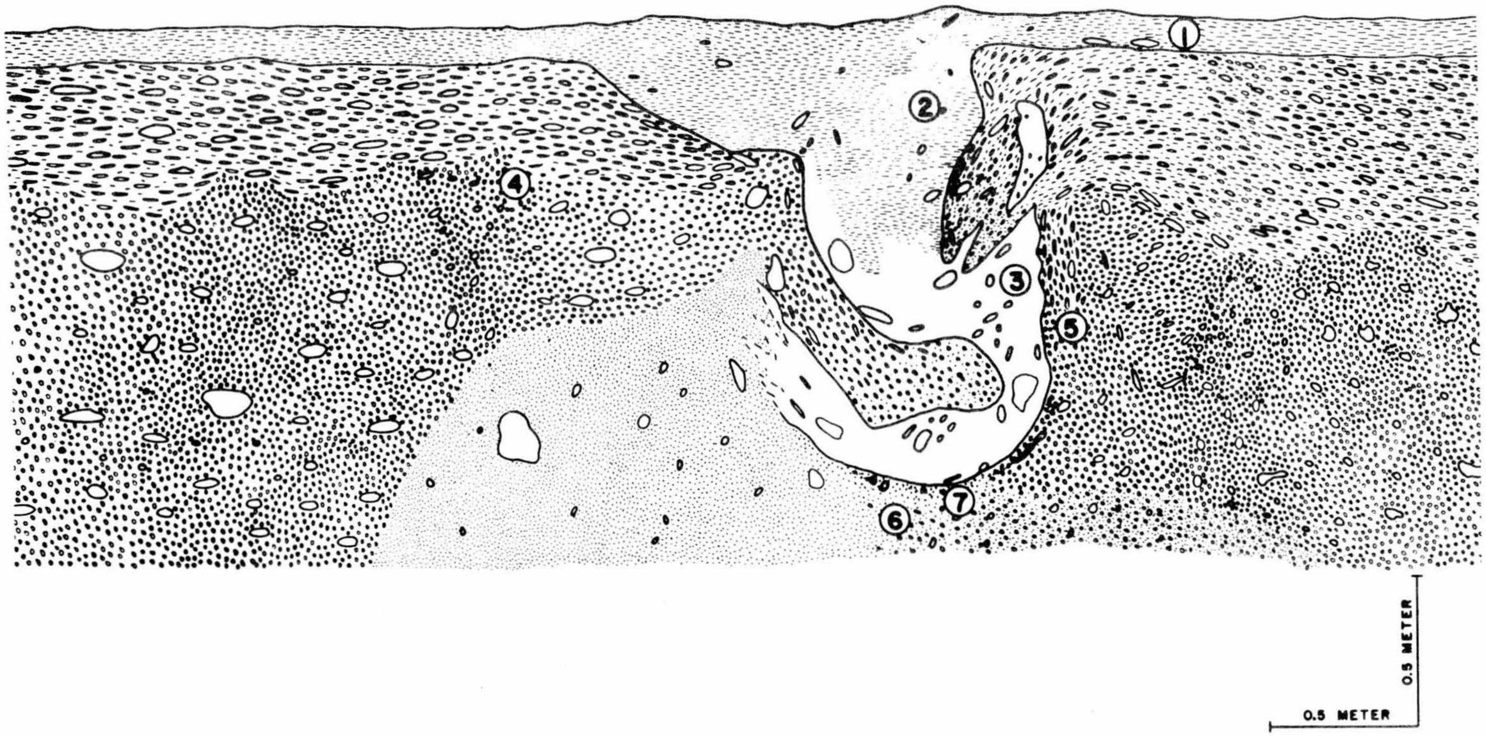

Figure 10. Wedge B1. Circled numbers indicate sediment type: (1) silt mantle, (2) fill of upper part of wedge, (3) fill of middle and lower part of wedge, (4) undisturbed outwash gravel, (5) disturbed outwash gravel, (6) sand, and (7) iron-stained sediments. See Fig. 9 for location.

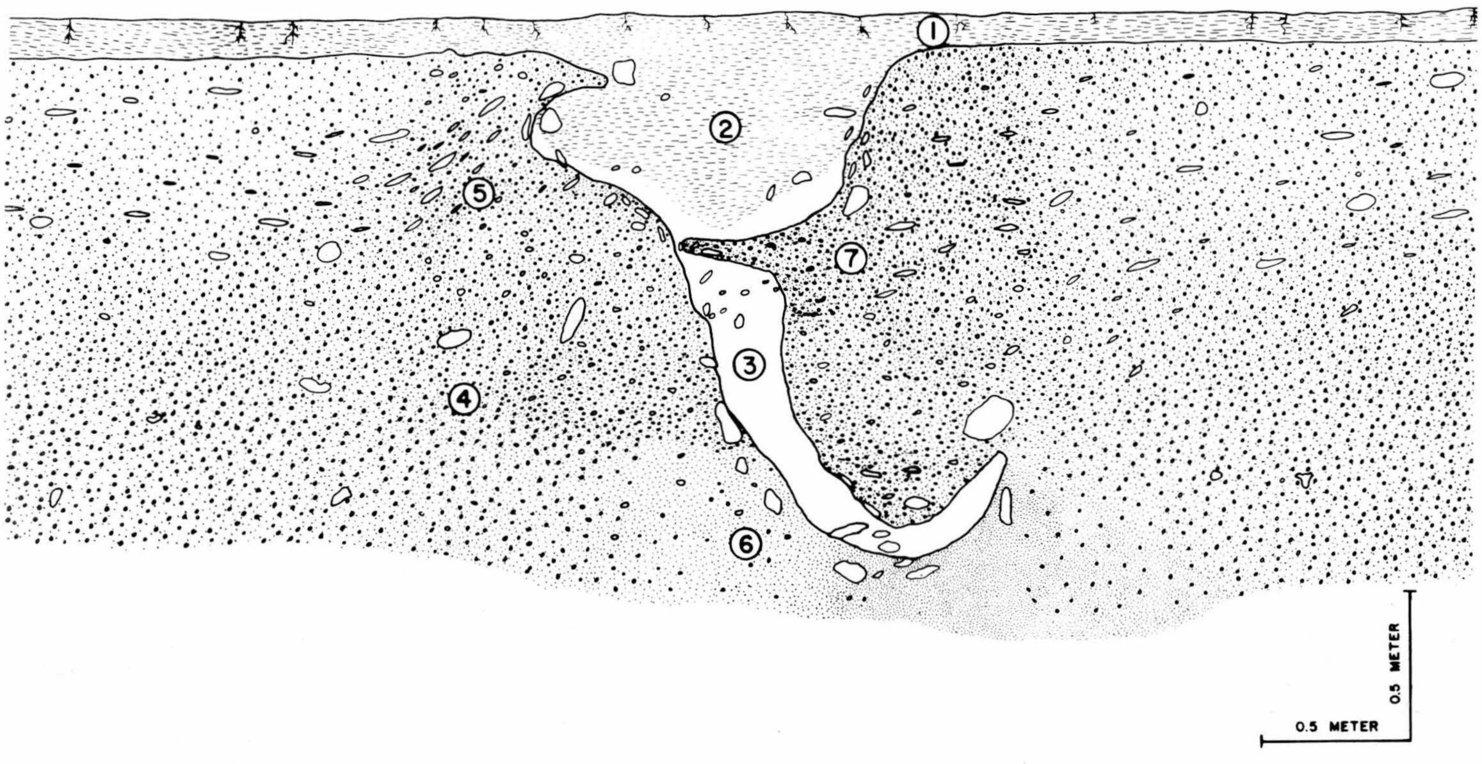

Figure 11. Wedge B2. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

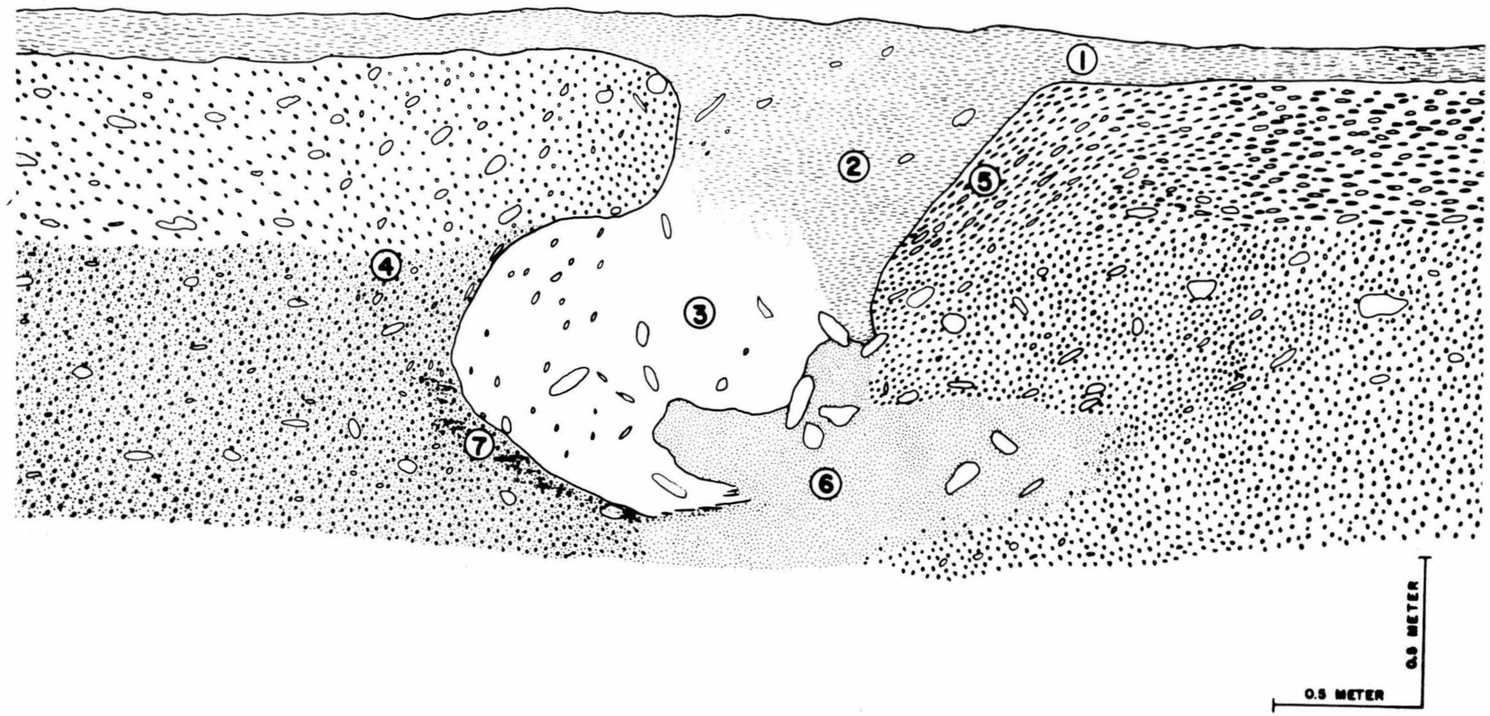

Figure 12. Wedge B3. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

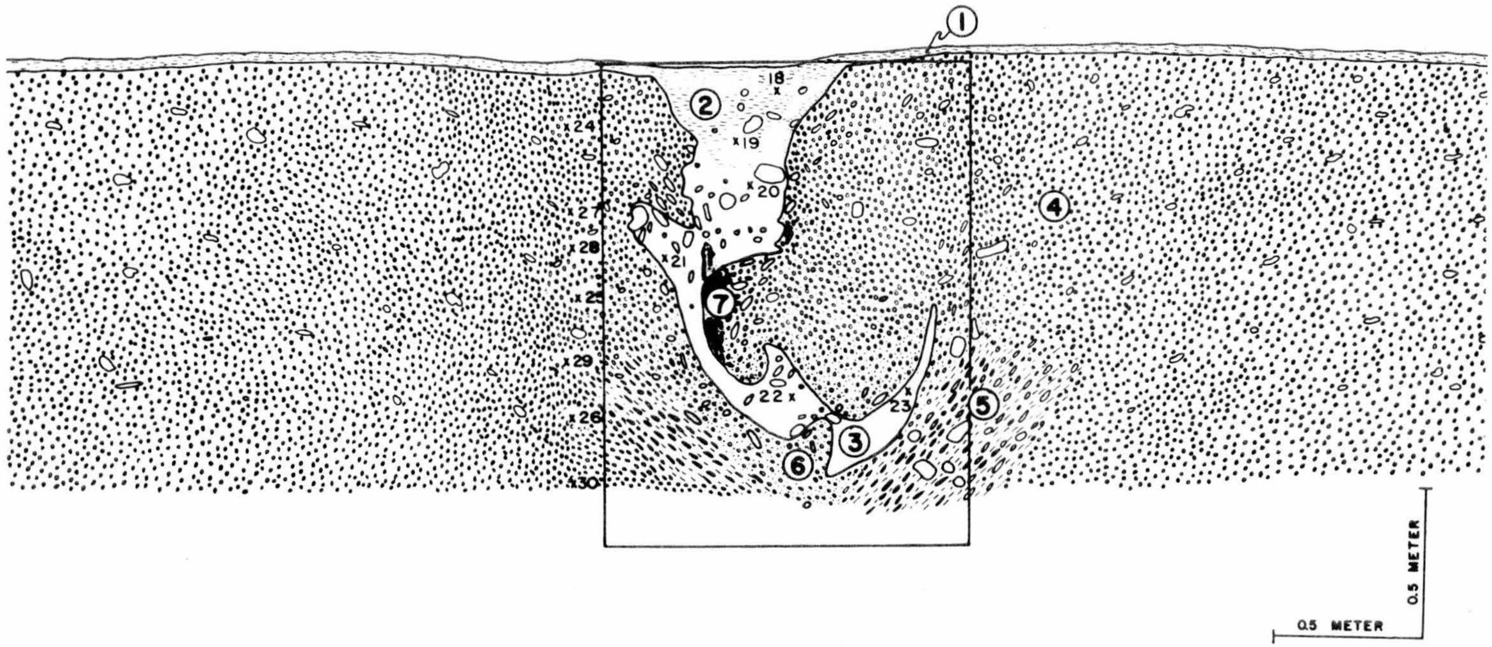

Figure 13. Wedge C1. Small numbers indicate location of sediment samples. Area within the rectangle is shown on Fig. 21. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

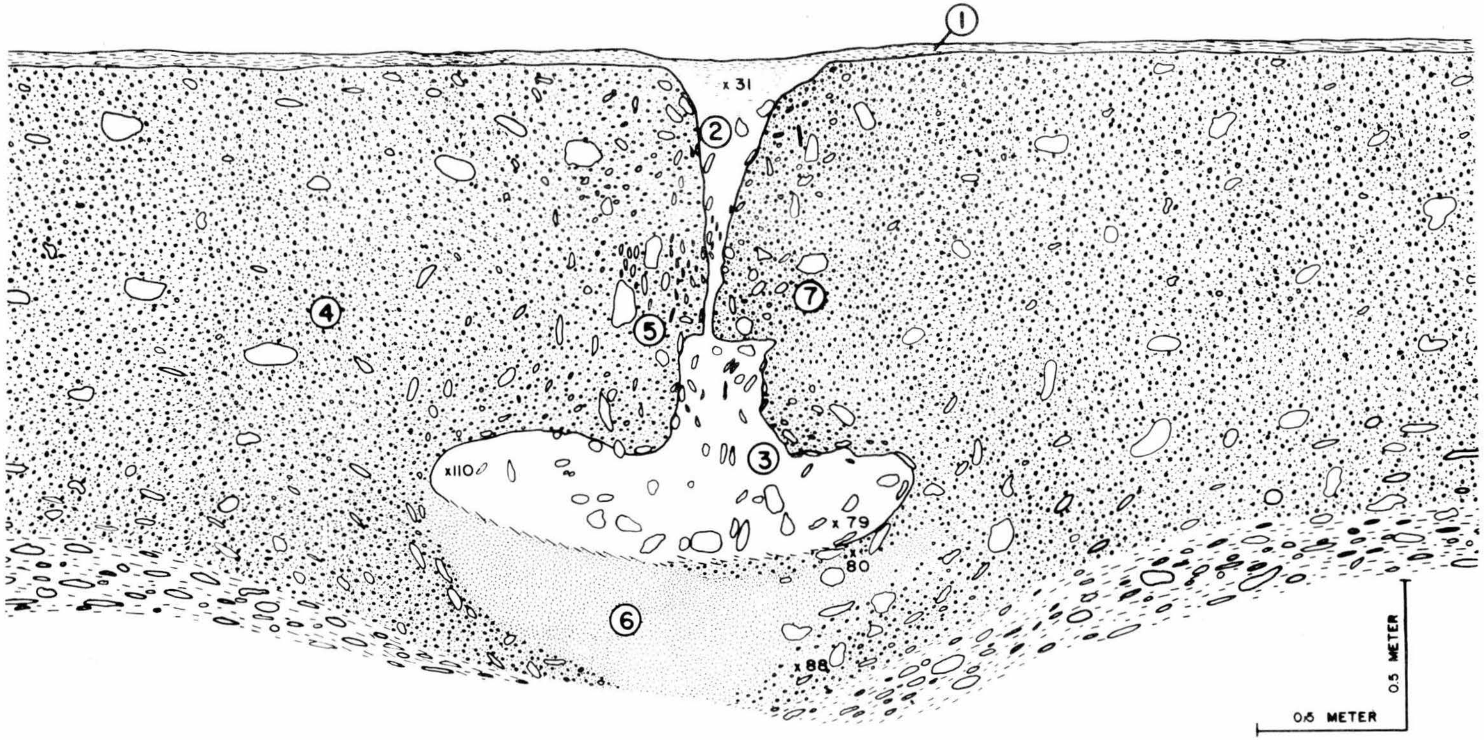

Figure 14. Wedge C2. Small numbers indicate the locations of sediment samples. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

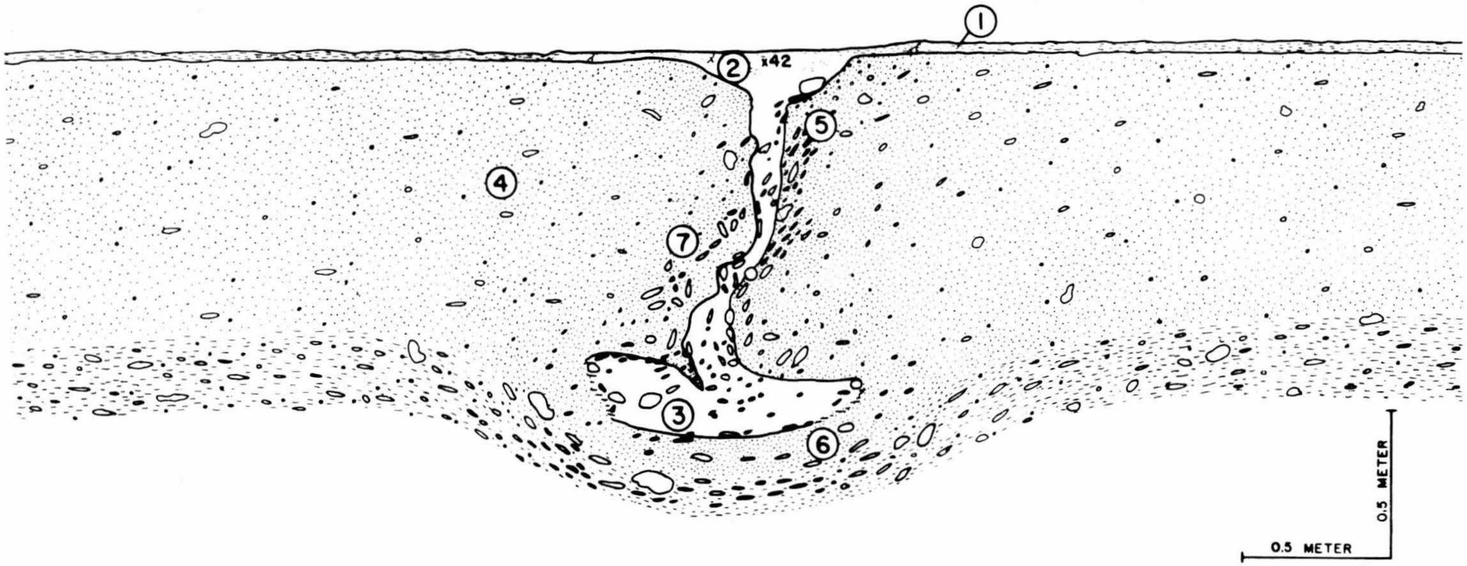

Figure 15. Wedge C3. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

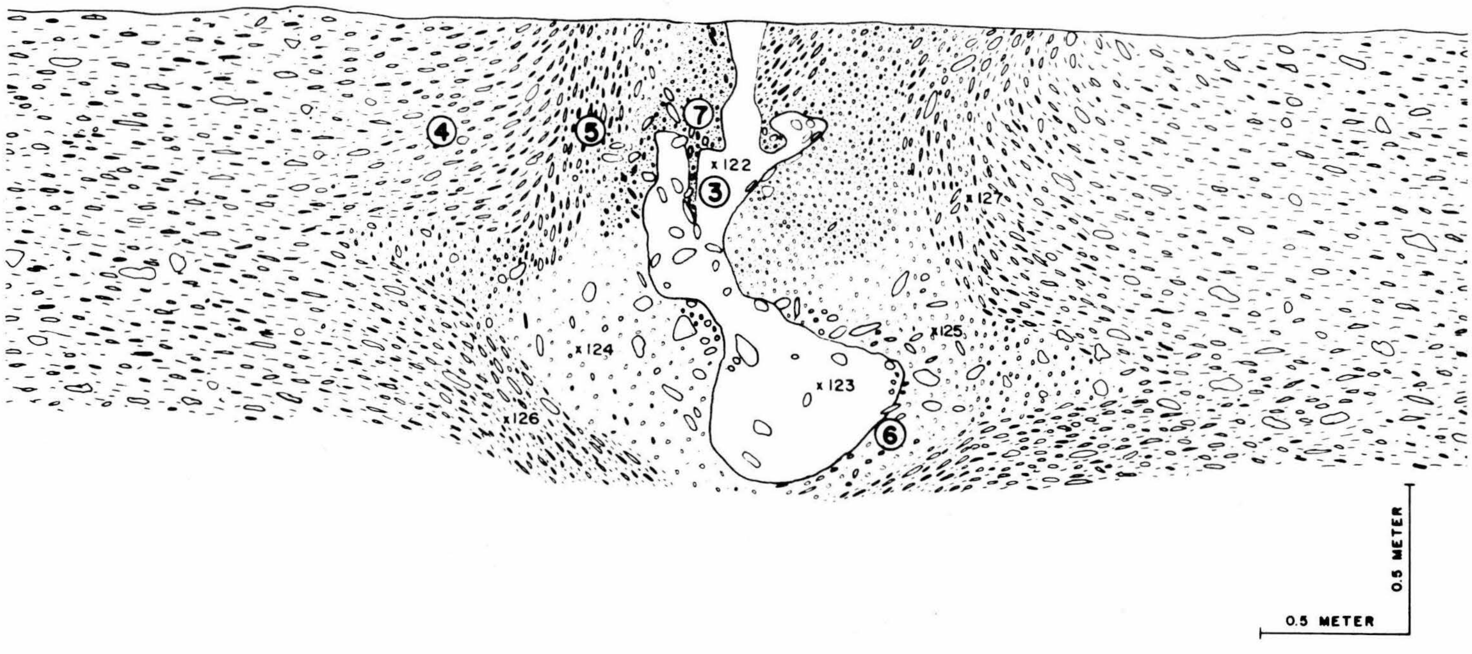

Figure 16. Wedge at exposure D. Small numbers indicate locations of sediment samples. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

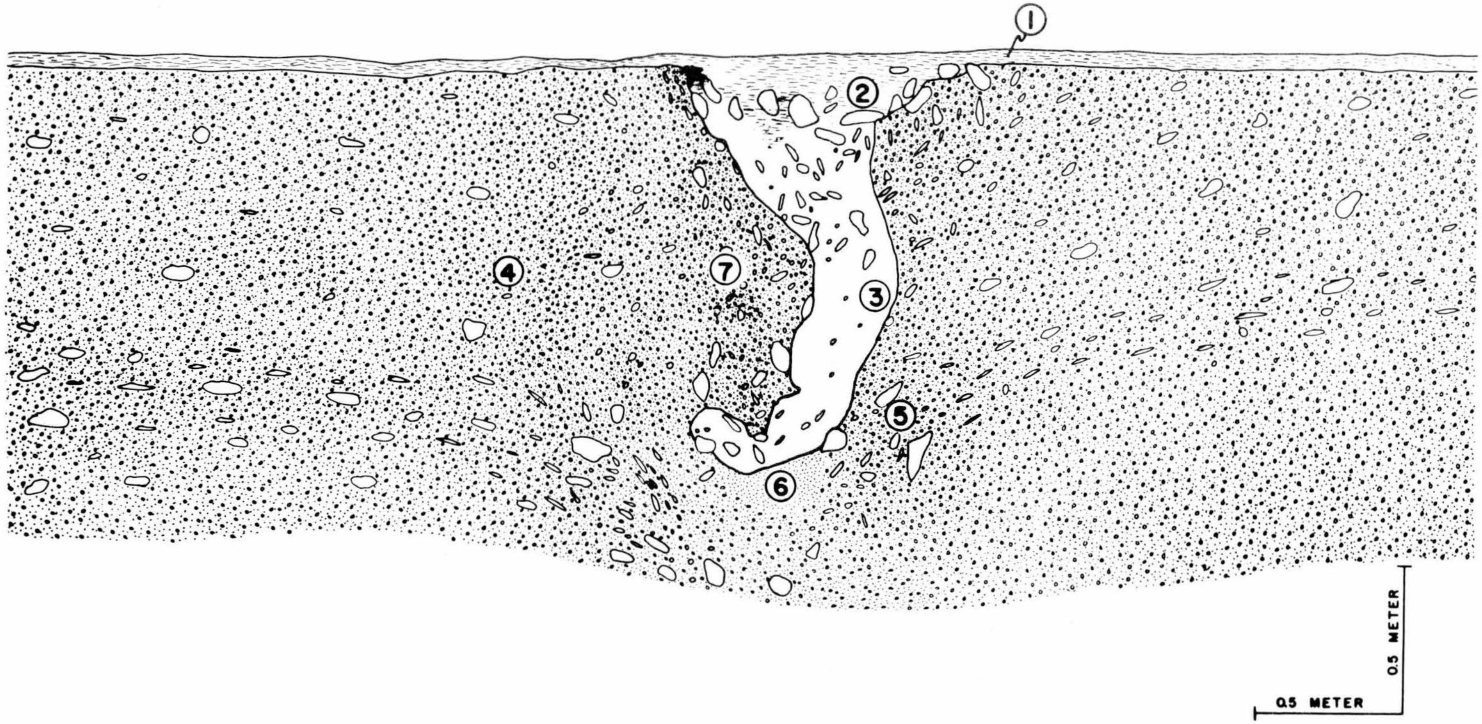

Figure 17. Wedge E1. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

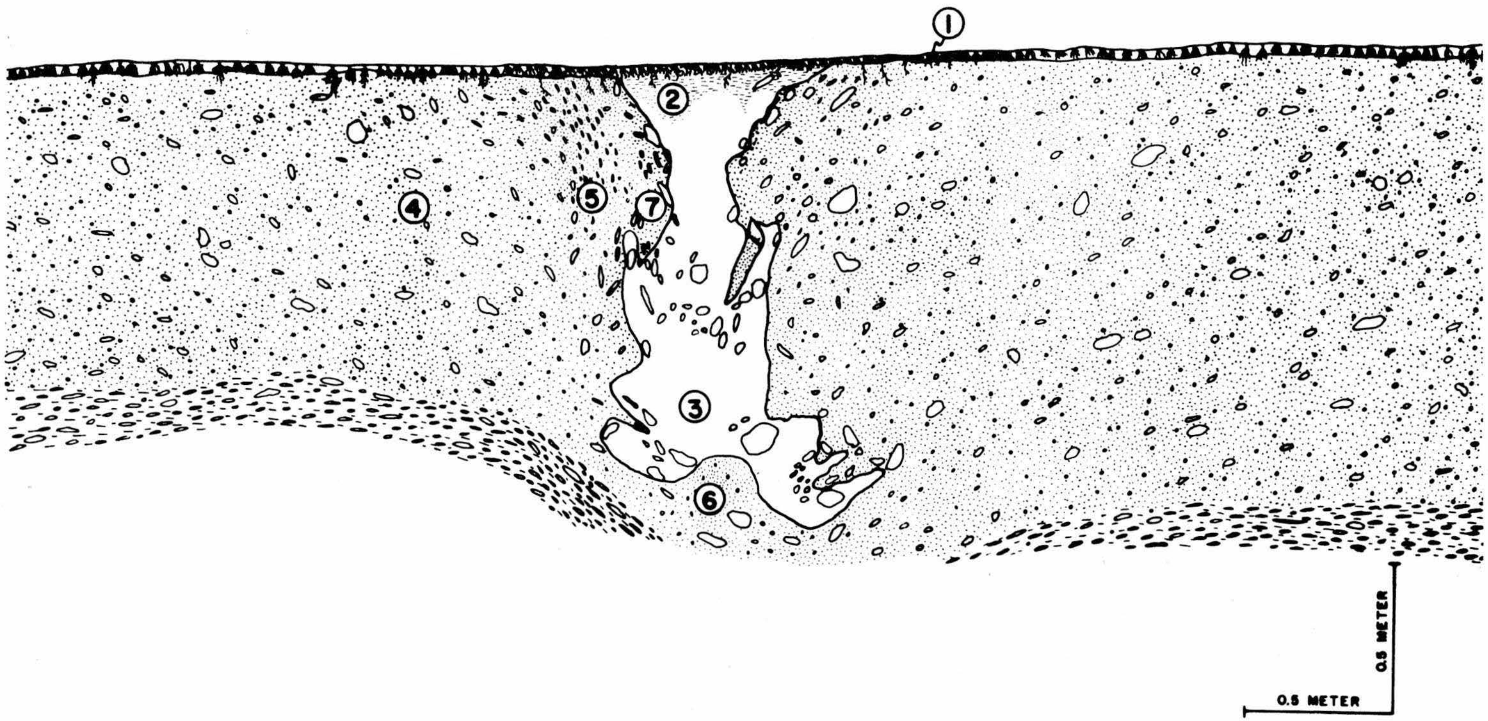

Figure 18. Wedge E2. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

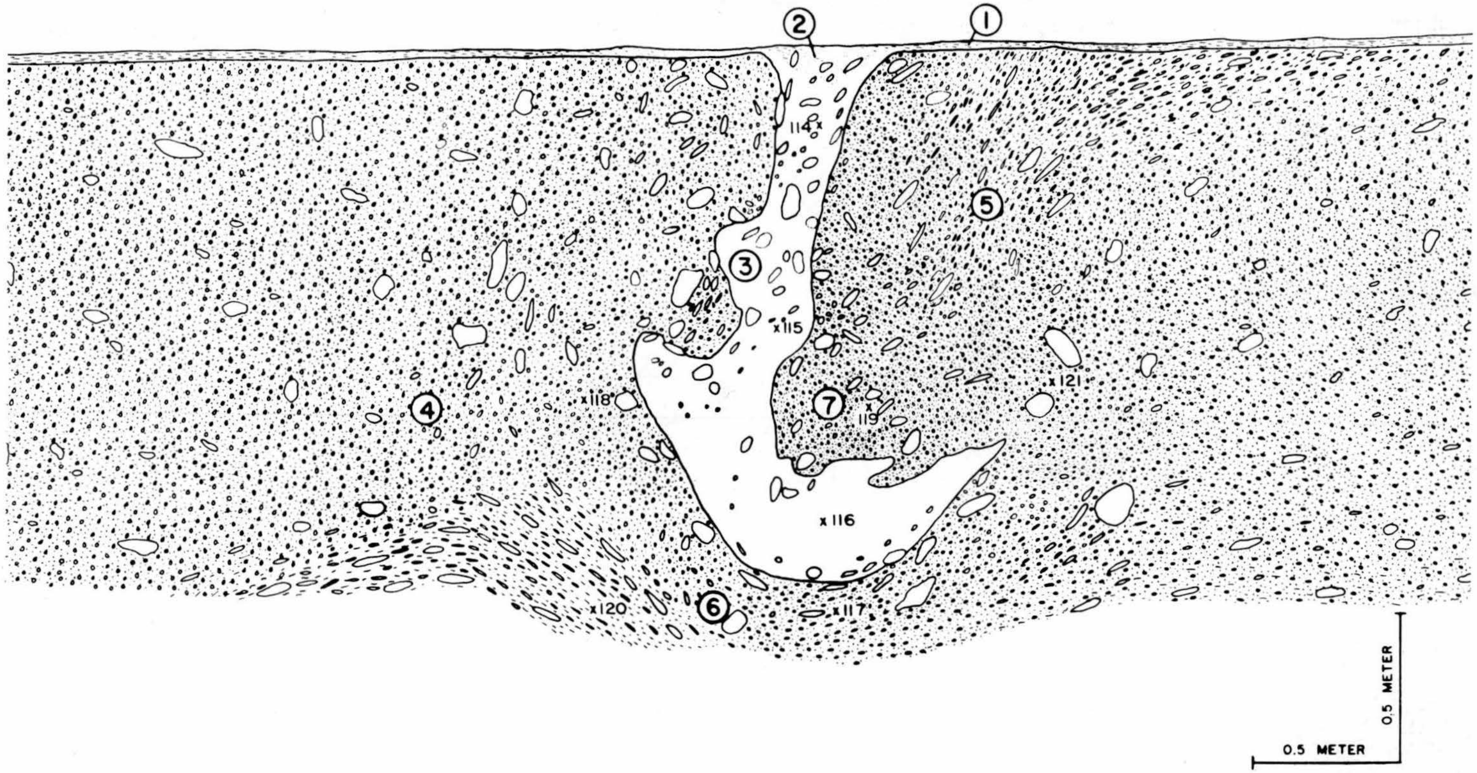

Figure 19. Wedge E3. Small numbers indicate locations of sediment samples. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

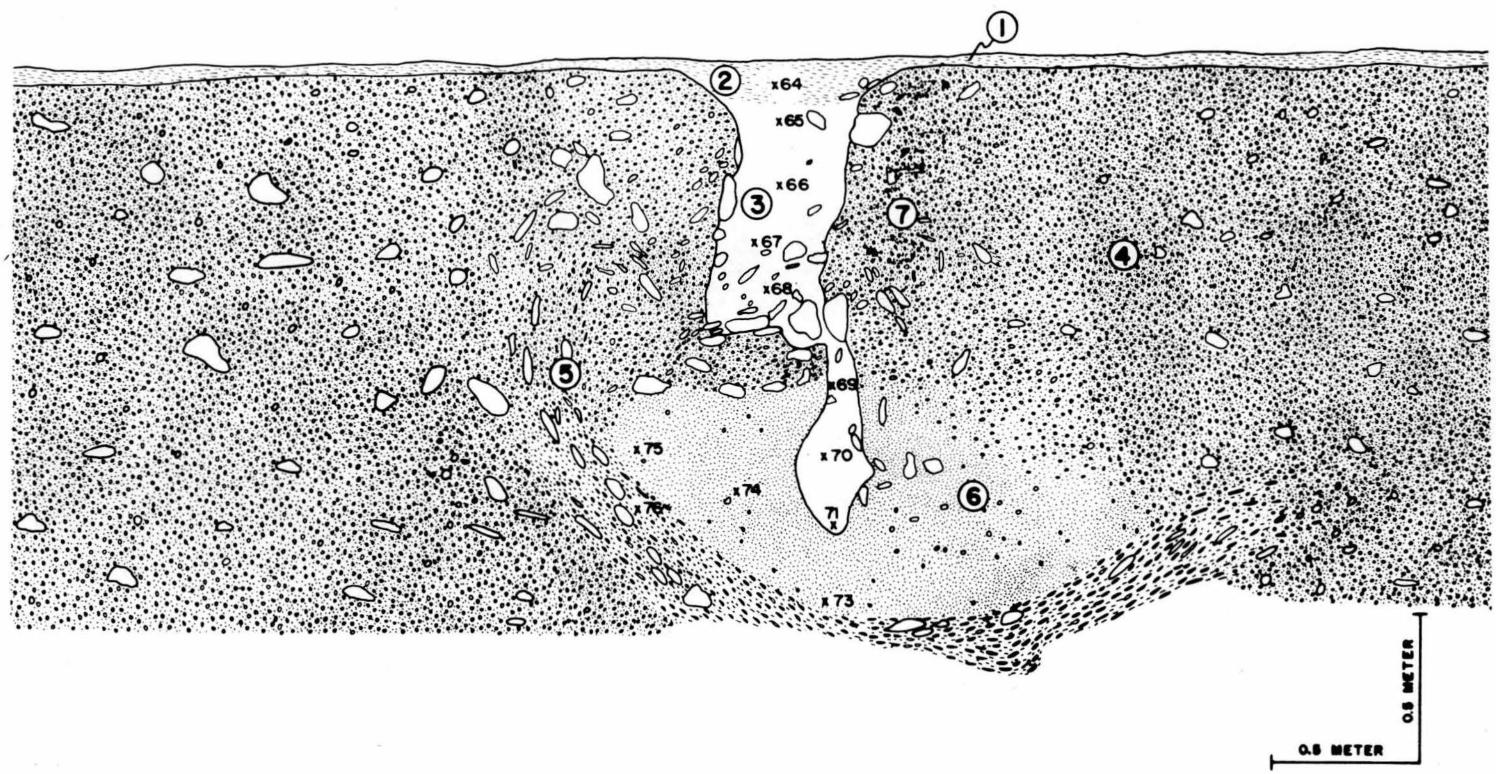

Figure 20. Wedge E4. Small numbers indicate locations of sediment samples. See Fig. 9 for location and Fig. 10 for explanation of circled numbers.

Figure 21. Wedge C1. See Fig. 13 for diagrammatic sketch. (Photo by T. L. Péwé, 14 July 1961).

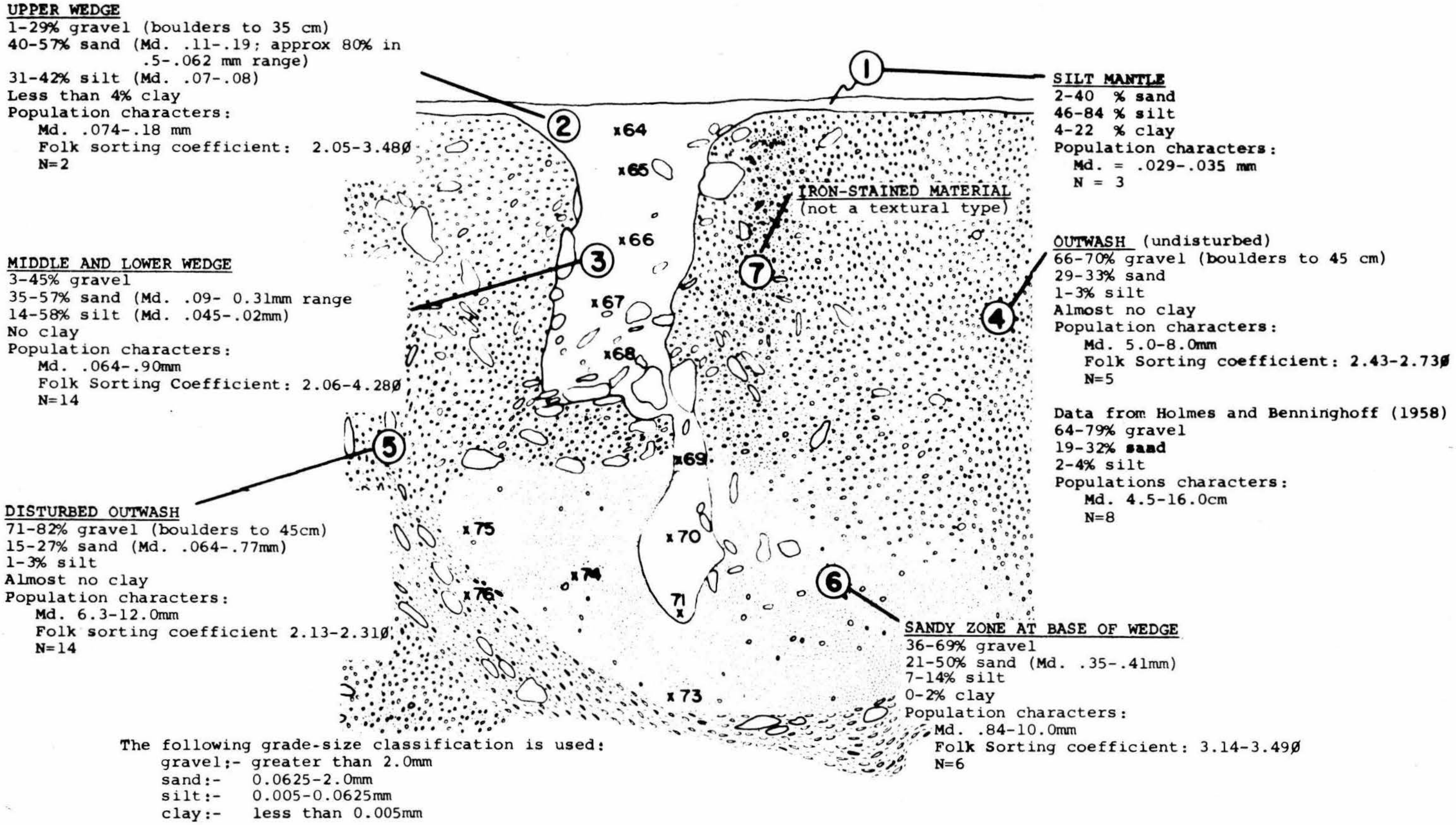

Figure 22. Summary of grain size characteristics of the textural types associated with sediment wedges in the Donnelly Dome area.

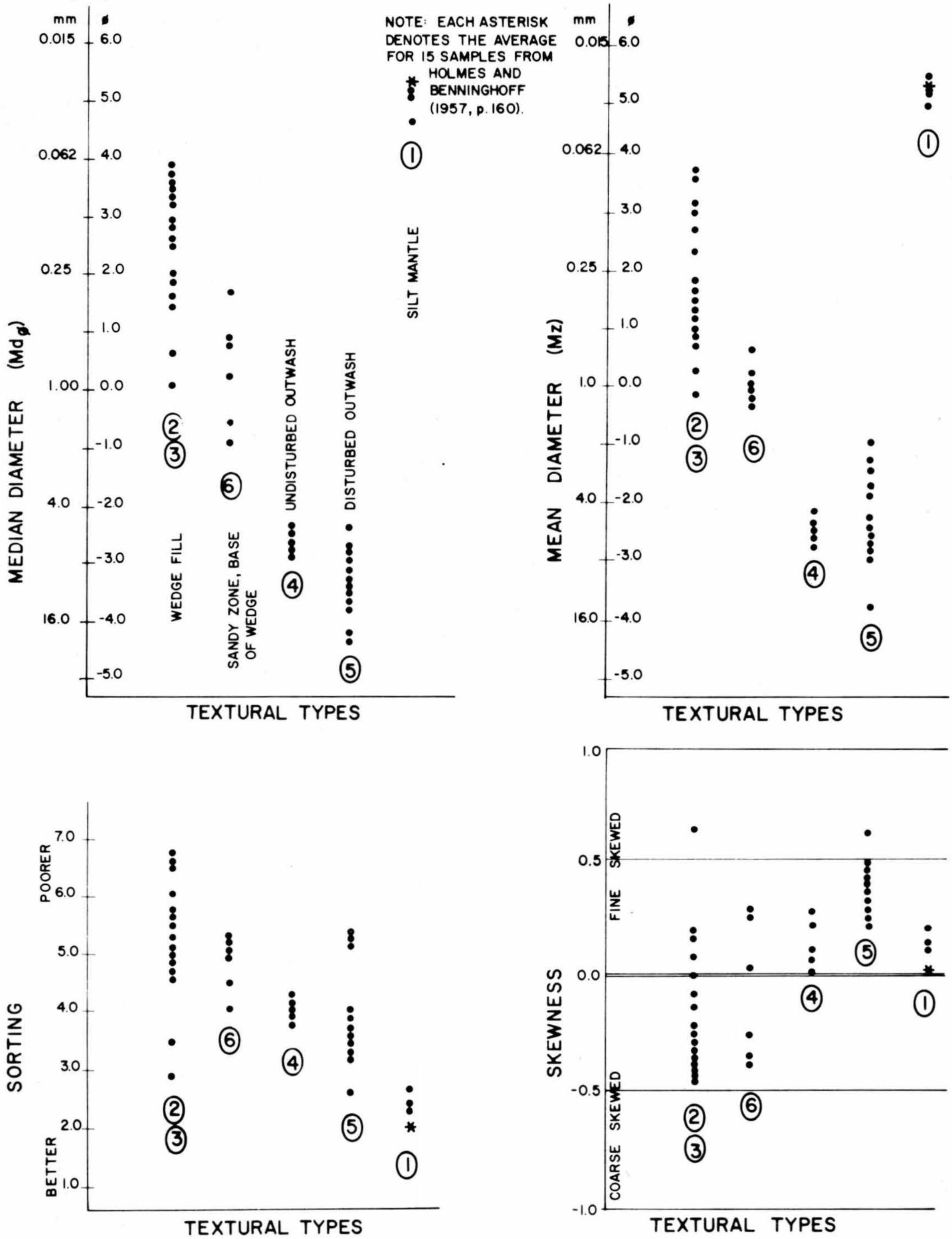

Figure 23. Folk and Ward grain size parameter data. See appendix for raw data and explanation of each parameter.

Features of the sediments near the wedges.

Texture: The sediments of the zone near the wedges contain two texturally and structurally distinct types of material: textural type 6, the sandy zone at the base of the wedge, and textural type 5, structurally altered sediments which have approximately the same textural appearance in the field as the undisturbed outwash gravel.

Type 6 materials vary in color and in texture from gray to brown, unconsolidated, very sandy, cobble gravel to gray to brown, silty, very gravelly, medium sand. The gravel-size materials range from pebbles to boulders. The range in proportions of gravel-, sand-, silt-, and clay-sized materials is given in Figure 22.

Six samples of material of this textural type were analyzed. The statistical parameters for each sample and for the group are intermediate between those for the wedge-fill and the outwash materials (Fig. 23). Type 6 material appears to be a textural phase transitional between the outwash gravel and the wedge-fill material. The sandy zone materials range in median diameter from 0.25 mm to approximately 2.0 mm which is equivalent to the coarser half of the median-diameter size range for the wedge-fill materials. The mean grain-size of type 6 material ranges from 0.5 mm to slightly larger than 1.0 mm; again, this is equivalent to the range in mean diameter values for the coarser part of the wedge fill (Fig. 22).

The sorting of the type 6 materials occurs in the middle of the range for the wedge fill, but is not nearly so good as that for the outwash. The materials comprising the sandy zone at the wedge base are very poorly size-sorted. This material has skewness values grouped around 0.00 (Fig. 23), indicating a nearly symmetrical distribution about the mean although some values are positive indicating slight excess of fine-sized material, and some values are negative, indicating a slight excess of coarser-sized grains. As with the deposition of the wedge-fill materials, local conditions must have been quite variable. The kurtosis values support this since they are extremely variable and show no trend (Table AII).

In summary, textural type 6 material appears to be equivalent in grain-size character to the coarser, better size-sorted wedge-fill materials. The statistical parameters chart (Fig. 23) seems to show that this material is intermediate in character between wedge fill and outwash, with gross character being more like that of the wedge-fill materials.

Textural type 5 sediments differ from the undisturbed outwash gravels primarily in structural appearance, consisting of gray to brown, unconsolidated, slightly silty, very sandy cobble gravel. The only difference between the two materials is that there has been some slight textural modification of the disturbed materials. The undisturbed outwash is quite regular and constant in its textural character (Fig. 22, 23). The slope and shape of the zones in which all the cumulative frequency curves occur for the two textural types (Fig. 25) are identical except that the width, or variability within the zone defined by the occurrence of all the curves of modified outwash material is much greater than that for the undisturbed outwash. Generally, fine material appears to have been added to the disturbed outwash since the skewness values for this material are larger than those for the parent material, the undisturbed outwash (Fig. 22).

Moisture content: Moisture samples were collected from textural type 6 sediments when the polygons were excavated in June, 1961. The material in the wedges was still frozen, but the material adjacent to them was not. The moisture content of these sediments at a depth of 1 m varied from 8.5 to 12.3% by dry weight. The moisture content of the type 5 sediments varied from 3.1 to 5.9% by dry weight at a depth of 1 m.

Iron staining: Extensive iron staining occurs in the silty altered sediments adjacent to the wedge borders (type 6). The staining generally occurs in a zone 30 to 60 cm wide on one side of the wedge, usually the concave side. The zone of staining is widest at the top and narrows downward.

Structures: The most prominent structures in the sediments which immediately surround the wedges are stone orientations adjacent to the wedges and the distortion of the normal bedding adjacent to and beneath the wedges (Fig. 14-20).

Many of the stones adjacent to the upper and central segments of the wedges are oriented with their long axes vertical or inclined at a steep angle (Fig. 10, 14-16).

The sediments in the structurally disturbed zone are thin-bedded, with beds less than 35 cm thick. The bedding consists of alternating beds of sand-sized and gravel-sized sediments. The bedding is often quite distinct but tends to become obscure as it passes into the zone of silt-rich sediments (type 6).

Near the upper segment of the wedges the bedding, which is normally almost horizontal in the unaltered outwash, is generally warped downward, becoming very steeply inclined as the wedge is approached. In some cases it is vertical or even overturned (Fig. 16, 19). The overall effect is for the bedding to become parallel to the wedge borders. The inclined stones begin to occur at a distance of 3 to 5 m from the center of the wedges.

The bedding is generally indistinct immediately adjacent to the middle segment of the wedges. Where the bedding is distinct adjacent to the terminal segments of the wedge, it dips downward under the wedges in nearly all exposures and is not broken by the wedge as is the bedding near the upper segments (Fig. 13-16, 18-20).

Features of the undisturbed outwash sediments.

Texture: The undisturbed outwash sediments underlying the polygon centers, textural type 4, are gray to brown, unconsolidated, slightly silty, very sandy cobble gravels. The gravel-sized grains are subangular to subrounded, range in size from pebbles to boulders, and have a maximum diameter of 45 cm. There is marked uniformity of this sediment type throughout the study area (Fig. 23; Holmes and Benninghoff, 1957, p. 154).

Moisture content: Moisture samples were collected in April 1962 when the sediments were seasonally frozen. At a depth of 50 cm below the ground surface the moisture content averaged 8.5% by dry weight.

Structures: The only structure shown by the undisturbed outwash sediments is a horizontal stratification of beds 35 cm or less thick. This stratification dips gently northward and is indicated by alternation of thin beds of cobbles and boulders with beds of sand and pebbles. The quality of the stratification is quite variable; the coarser sediments are generally distinctly bedded, but bedding in the finer-grained materials is indistinct and often not readily apparent.

The bedding tends to be lenticular and sand units pinch out within 30 m or less. The coarser materials show a distinct imbrication, reflecting the source area to the south.

Features of the silt mantle.

Texture: The silt mantle, textural type 1, consists of unstratified brown to red-brown, dominantly silt- and clay-sized material with a small proportion of material in the sand-size range. The material contains an appreciable amount of roots and other organic debris. It is the best size-sorted sediment type here investigated, and has the smallest mean and median diameters (Fig. 23). It has a unimodal grain-size distribution that is only slightly positively (fine) skewed and is of very uniform character throughout the study area. Three samples were analyzed for this investigation, one from above each of the three trenches dug to expose the wedges in vertical section, and each sample is within the range in character for 17 samples from the area described by Holmes and Benninghoff (1957, p. 160).

The silt mantle is present virtually everywhere on outwash of Donnelly age and ranges in thickness from a few cm to a few meters (Péwé and Holmes, in press).

Moisture content: No samples were analyzed for moisture content.

Structures: There are no apparent structures in this material in this study area.

Summary. Grain size parameters indicate that several different textural types of material occur in connection with wedge formation and that there may be transitional types between the obviously distinct textural types (Fig. 23). Typical cumulative frequency curves of the various distinct textural types: (1) silt mantle, (2) and (3) wedge filling, (4) outwash gravel, and (5) modified outwash gravel, graphically portray the individuality of the respective textural types except in the case of the outwash sediments, types 4 and 5 (Fig. 24). The differences in character of the two types of outwash sediments are shown in Figure 25. The range of occurrence of cumulative frequency curves of both textural types have the same general form, but much greater variability in the size of the modified outwash material is indicated. Also, the modified material is generally less well sorted and generally is more positively skewed (Fig. 23), indicating a greater amount of fine-sized material in an essentially coarse-grained sediment distribution.

The coarsest material in the wedge fill is of the same magnitude as the coarsest material available in the glacial outwash of the area (Fig. 24, 25). Also, the finer materials in the grain-size distributions of the wedge fill are of the same size as the fines in the silt mantle (Fig. 24, 25).

The grain-size distributions of the wedge fill are distinctly and characteristically bimodal, having a smaller mode in the coarser-sized fraction and a much larger mode in the finer-sized fraction. The grain size distributions of the outwash, textural types 4 and 5, and of the silt mantle, type 1, are unimodal (Fig. 24, 25).

ORIGIN

Introduction

The large scale polygonal pattern is not a primary phenomenon formed by the agencies which deposited the outwash gravel, but is instead a feature superimposed on the outwash sediments by outside controls, as indicated by the occurrence of structurally disturbed outwash.

Aerial photographs and maps of the Donnelly Dome area (Frontispiece, Fig. 5, 6, 7, and 8) reveal that the polygonal pattern displayed on the surface of the outwash plain is the pattern characteristic of "contraction-crack polygons," the name applied to a reticulate system of intersecting contraction cracks on the surface of a body (Lachenbruch, 1960a, p. B406). Contraction-crack polygons are formed by tensional stresses resulting from a decrease in volume as a result of desiccation or cooling and are developed in diverse media on a variety of scales from a few millimeters in diameter on cooling ceramic ware to 50 meters in diameter in permafrost and even larger in dry lake beds. Contraction-crack polygons include mud cracks, columnar basalt joints, frost cracks, and shrinkage cracks in concrete. Lachenbruch (1960a, 1960b, 1961, 1962) discusses in detail the mechanics of thermal contraction cracks.

The following hypotheses are considered in an evaluation of the origin of the large-scale polygonal ground in the Donnelly Dome area:

- Desiccation-crack hypothesis
- Thermal contraction-crack hypotheses
  - Seasonal frost crack hypothesis
  - Ice wedge hypothesis
  - Sand wedge hypothesis.

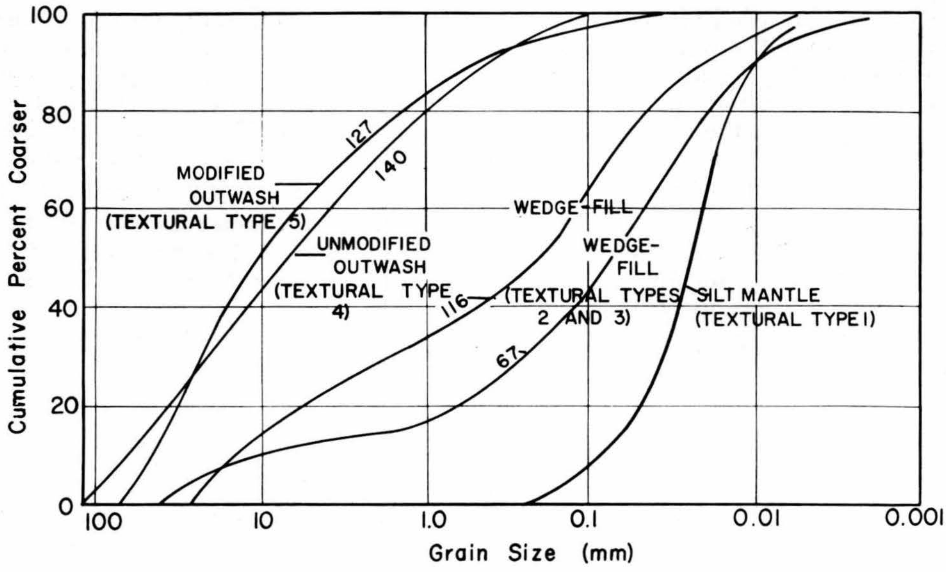

Figure 24. Typical cumulative frequency grain-size curves for textural types occurring in the Donnelly Dome area, Alaska (silt mantle data from Holmes and Benninghoff, 1957, p. 160); Numbers on each curve are sample numbers used in Table AI and AII.

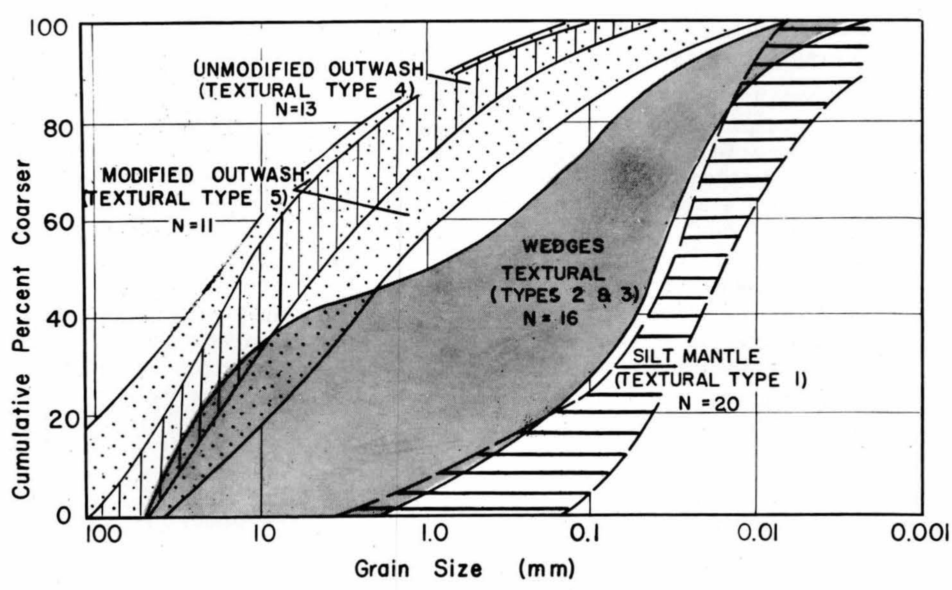

Figure 25. Composite cumulative frequency grain-size curves showing range of grain size distribution within each textural type. N is the number of samples analyzed in each group.

Desiccation-crack hypothesis

Preliminary statement. The similarity in size and appearance of the polygons in the Donnelly Dome area to large-scale desiccation-crack polygons elsewhere suggests the possibility that the polygons in the Donnelly Dome area are the result of shrinking of the ground by drying at some time in the past. Desiccation-crack polygons of the same order of magnitude have been described from a number of areas of western United States by Willdren and Mabey (1961), Knechtel (1951, 1952), and Land (1943). Knechtel (1951) and Black (1952a) have noted the similarity of desiccation-crack polygons to thermal contraction-crack polygons formed in the Arctic and subarctic.

Theory of origin. The desiccation-crack polygons described in the literature result from tensional stresses produced by shrinkage of fine-grained sediments, generally lake clays, due to water loss. In the Black Rock and Smoke Creek Deserts in Nevada the fissures produced in this manner intersect to form orthogonal networks that may be as much as 30 to 76 m across (Willdren and Mabey, 1961, p. 1359). The fissures range from less than 2.5 cm to about 60 cm in width and some are open to depths in excess of 1.2 m. Willdren and Mabey believe that the polygons are the results of a long-term decrease in the supply of surface and ground water to the playas on which they are developed, due to a period of dry climate beginning between 1910 and 1920.

Assuming that the Donnelly Dome polygons formed as a result of desiccation during a period of extremely dry weather, the cracks could have filled with a combination of slump material and eolian silt and sand to form the sediment in the wedges.

Evidence. There appears to be little evidence in support of the theory that the polygons in the Donnelly Dome area are the result of desiccation, aside from their similarity in appearance in plan view. The outwash gravel has an extremely low percentage of clay-sized material (Fig. 25) and complete desiccation of the gravel would not result in any significant volume reduction. In addition, even if there were sufficient volume reduction, it is extremely doubtful that the dry material would be cohesive enough to transmit the tensional stresses.

Finally, there is no paleoclimatic evidence to support any assumption that such a period of extreme dryness existed since deposition of the outwash sand and gravel in Wisconsin time.

In summary, although the polygonal ground in the Donnelly Dome area is similar to that of some known large-scale dehydration cracks, there is no evidence to support a desiccation-crack hypothesis for its origin.

Hypotheses of thermal contraction-crack polygons

General statement. "Thermal contraction-crack polygons" refers to any polygonal pattern produced by cooling, and as used here will refer to the large-scale polygonal networks resulting from tensional cracking of the ground in winter as a result of volume reduction due to contraction of ice-cemented sediments. Active and inactive thermal contraction-crack polygons are widespread in the Arctic, subarctic, and Antarctic and have been described from numerous localities in Russia, Greenland, Canada, Antarctica, and Alaska. In addition, features that have been interpreted as "fossil" thermal contraction-crack polygons have been described from temperate latitudes in North America and Europe.

Included in the category of thermal contraction-crack polygons are two classes of polygons: "seasonal frost-crack polygons" and "ice-wedge polygons." These two types, both of which are reported to be present elsewhere in Alaska, are similar in plan view, have somewhat similar origins, and can be considered as genetically related phenomena but have formed under different environmental conditions.

Seasonal frost-crack hypothesis.

Preliminary statement: Seasonal frost-crack polygons, also known as frost polygons or frost-cleft cracks, are reported in Russia (Pataleev, 1955) and New Hampshire (Washburn, Smith, and Goddard, 1963). Although they have been reported to be present in Alaska (Black, 1952b; Hopkins, Karlstrom and others, 1955) there have been no studies made to determine if these seasonal frost-crack polygons are active or are "fossil" features. In the opinion of the authors the features reported as seasonal frost-crack polygons in Alaska are in reality probably "fossil" ice wedge polygons.

Theory of origin: Thermal contraction and cracking of the ground occurs during the winter when the sediments are frozen. Vertical fissures a few millimeters to 2 cm in width and perhaps 1 or 2 m deep form a polygonal pattern. Hoarfrost and snow accumulate in the cracks during the winter, but melt during the spring and summer as the seasonally frozen ground thaws. During the spring melting, before the ground thaws, melt water carries silt and sand from the surface downward into the cracks, partly filling them (Danilowa, 1956). Some melt water may freeze in the crack and thaw later. Slumping probably occurs at the edges of the crack during thawing. During subsequent winters these silty or sandy veinlets may act as zones of weakness so that reopening occurs and additional increments of silt and sand are added in the subsequent spring. This process, repeated over hundreds or perhaps thousands of years, results in a wedge-shaped mass of sediment 1 to 3 m deep and 60 cm or 1 m wide at the top. During propagation of the cracks they may be deflected by boulders, changes in stratigraphy, changes in ice content of the ground, or by some combination of the latter two, with the result that the wedges may bend, hook, or even split.

Melt water running into the cracks in the spring is believed to carry clay-, silt-, or fine sand-sized particles into the surrounding porous and permeable outwash gravel.

Evidence. Direct evidence that seasonal frost cracks do occur is provided by the observations of Pataleev (1955) made in Khabarovsk and Amur provinces, U. S. S. R.; by Washburn, Smith, and Goddard (1963) in New Hampshire; and by Péwé in the Fairbanks area. Seasonal frost cracking in interior Alaska occurs only in certain restricted environments at present. It occurs in central Alaska, as far as the authors know, only in areas that are vegetation-free and/or that are kept snow-free during the winter, such as roads and pathways near Fairbanks. The cracks in seasonal frozen ground which traverse the roads and paths narrow rapidly and disappear as they pass into adjacent areas covered with vegetation and unpacked snow.

The only polygons in Alaska known to have been outlined by such cracks were those reported to have formed one winter in the broad asphalt-capped runway of an airfield near Fairbanks (oral communication, Joe Smith, Corps of Engineers, Fort Greely). Under natural conditions, no such polygons are forming today in the permafrost-free areas near Fairbanks or Fort Greely.

It is apparent that the lack of snow and vegetation cover permits the rapid and great cooling of the seasonally frozen ground to cause thermal contraction and cracking of the ground. Such cracking in interior Alaska occurs during certain cold periods when the air temperature drops to -40 to -50C. No quantitative data are available to permit comparison of ground temperatures in snow-covered vs snow-free areas where cracks form. Also, no air temperatures are available for such localities during the period when cracking occurs.

Detailed studies in the Donnelly Dome area indicate that frost cracking is not occurring at present on the outwash plain, under normal vegetation and snow cover. A thorough search was made for cracks on the surfaces of the outwash plain during the winter of 1961-1962. A previous search was made by Péwé in the winter of 1954-1955, under the auspices of the U. S. Geological Survey, during which explosives were used to make pits over the polygon trenches in an effort to reveal cracks. At neither time was there evidence of cracks or torn vegetation of the surface or torn roots in the vertical sections such as would be expected if cracking were active, nor was there any evidence of seasonal cracks in the wedge sediments.

Although seasonal frost cracks are not forming in the Donnelly Dome area today it is conceivable that the polygons are "fossil" seasonal frost-crack polygons formed in the past under different environmental conditions than now exist.

It would appear that, for the contraction cracks to have formed under natural conditions of snow and vegetation in the past, the ground must have become colder. This could have been accomplished by reducing the insulating value of the vegetation, or by decreasing the thickness of the snow cover, or by lowering of the mean annual air temperature. No evidence is available to support the first two points but evidence is available to support a lowering of mean annual temperature as well as shorter and cooler summers in the interior of Alaska during Wisconsin time (Péwé and Hopkins, unpublished manuscript). It is apparent that, with lowering of the mean annual air temperature, permafrost would form more rapidly and be more widespread than it is today in central Alaska; and it is thought that permafrost would exist in most of the present-day non-permafrost areas, including the outwash gravel deposits of the Donnelly Dome area. The presence of relic permafrost today in these outwash gravels supports this suggestion.

A climate that would cause thermal contraction and cracking of the seasonally frozen ground under natural conditions of vegetation and snow cover would also produce permafrost, thermal contraction, cracking of the permafrost, and subsequent formation of ice wedges. Therefore, thermal contraction cracks that formed in the ground during Wisconsin time would have been not only in seasonally frozen ground, but would have extended into the underlying permafrost. Conventional ice wedges would have formed in these contraction cracks in permafrost upon the running of spring melt water into the cracks.

In summary, although the surface configuration of the polygonal ground in the Donnelly Dome area is similar to that of features reported to be polygons in seasonally frozen ground, and seasonal frost cracks are known to form locally in interior Alaska, evaluation of conditions reveals that the polygons in the Donnelly Dome area are not due to cracking of seasonally frozen ground. Such cracks are not forming in the area today under natural conditions. If they had formed in Wisconsin time permafrost would have been present and ice wedge polygons would have formed instead of frost crack polygons in seasonally frozen ground above.

Ice wedge hypothesis.

Preliminary statement: The similarity in size and gross geometry of the polygons in the Donnelly Dome area to active ice-wedge polygons suggests that they may have an ice-wedge origin. Since no ice wedges were found beneath the edges of the polygons in the Donnelly Dome area they are certainly not active or inactive ice-wedge polygons (Péwé, 1964), but instead may be "fossil" ice-wedge polygons.

After an evaluation of the polygons in the Donnelly Dome area and observations of ice-wedge polygons and "fossil" ice-wedge polygons in various parts of the world, the writers conclude that the polygons in the Donnelly Dome area are "fossil" ice-wedge polygons.

The origin of ice-wedge polygons has been discussed in the literature for about 100 years, and numerous hypotheses have been presented to explain their origin. The thermal-contraction crack hypothesis will be followed here. It is now subscribed to, with minor variations, by most serious investigators (Bunge, 1884, 1902; Leffingwell, 1915, 1919; Black, 1952a, 1954; Péwé, 1952a, 1958b, 1959; Popov, 1955; Hopkins, Karlstrom et al., 1955; Washburn, 1956; Britton, 1958; and Lachenbruch, 1959, 1961, 1962). In additon, Lachenbruch (1960a; 1960b; 1961; 1962) has offered proofs based on the physical properties of frozen soils that, mechanically, such an origin is possible. Today only a few works (Taber, 1943; Ducker, 1951; and Schenk, in press) doubt the general validity of the contraction crack origin of ice-wedge polygons.

Theory of origin: It is postulated that large scale patterned ground formed in the Donnelly Dome area in the past when the outwash sediments were perennially frozen, and when thermal contraction of the frozen sediments during cold periods in the winter caused cracks to form. Nearly vertical fissures a few millimeters in width and 1.5 to 3 m deep developed in the perennially frozen sediments when sufficient contraction had occurred to overcome the tensile strength of the firmly ice-cemented outwash sand and gravel. After the initial crack (Fig. 26A) it is thought that cracks in subsequent winters initiate at the top of the ice wedge (Lachenbruch, oral communication, 1962). Lachenbruch (oral communication, 1962) states that although the relations that determine whether or not an ice wedge cracks are extremely complex, a single simple criterion that takes account of many of the factors is the minimum winter temperature at the top of permafrost. He suggests that, when it is below -15 to -20C, the active cracking of ice wedges might be expected in many permafrost materials. During the spring, melt water may have run into the fissures and been frozen to produce, in combination with hoarfrost accumulated in the crack in winter, a near vertical veinlet of ice penetrating the perennially frozen sediments. During the following winters, renewed thermal contraction resulted in reopening of the ground in, or near, the ice-filled crack and in the spring addition of melt water, which when frozen, added another increment of ice. This process, repeated over a period of hundreds of years, but not necessarily every winter, produced wedge-shaped masses of "foliated" ice (Péwé, 1958b) 2 m deep and $\frac{1}{2}$ to 1 m wide. The polygon pattern resulted as a natural consequence of the contraction origin (Lachenbruch, 1960b, 1962).

Horizontal expansion of the interwedge perennially frozen ground as it warmed during the summer resulted in up-turning of the frozen sediments near the ice wedges. Most up-turning was at the widest segment of the wedges; there was less deformation of the sediments in the depth where the wedges were narrower.

The cracks, during downward propagation, may have been deflected by boulders, changes in stratigraphy of the outwash gravel, changes in ice content of the sediments, or by a combination of the latter two. This resulted in irregularities in the shape of the wedges in the form of bends and hooks and perhaps bulges at the termini of some wedges as the result of deflections of the cracks in more than one direction during growth of the wedge. Such has been noted in ice wedges near Fairbanks (Péwé, unpublished manuscript).

In summary, it is theorized that ice-wedge polygons formed in the perennially frozen outwash gravels of the Donnelly Dome area during the Wisconsin glacial stage as the natural result of thermal contraction of sand and gravel and subseqent filling of cracks with ice.

Evidence: The theory that the polygons in the Donnelly Dome area are "fossil" ice-wedge polygons hinges primarily on the ability to demonstrate that the outwash sediments were perennially frozen in the past and had an ice content sufficient to permit the ground to crack, and, further, that the ice wedges formed in the crack in the manner described. These factors in turn rest on presentation of evidence that the climate was more rigorous in the past and that the permafrost would have subsequently degraded in the outwash sediments. The theory next rests on the ability to demonstrate that the shape of the wedges, the structures associated with them, and the textural relationship of the wedge-filling material and the undisturbed sediments could have been developed during the growth and subsequent melting of the ice wedges.

It is generally accepted that, on a world-wide basis, the mean annual temperature during the glacial epoch was on the order of several degrees centigrade colder than today (Flint, 1957, p. 487). It can be assumed that the mean annual temperature changed in the Donnelly Dome area, particularly as there is extensive evidence of former widespread glaciations in the area. Evidence for a lower tree line during Wisconsin time has been found in the Fairbanks area (Péwé, unpublished manuscript) and in the Manley Hot Springs area (Repenning, Hopkins, and Rubin, unpublished manuscript) and suggests that the summers must have been cooler during Wisconsin time than at present (Hopkins, 1959, p. 216).

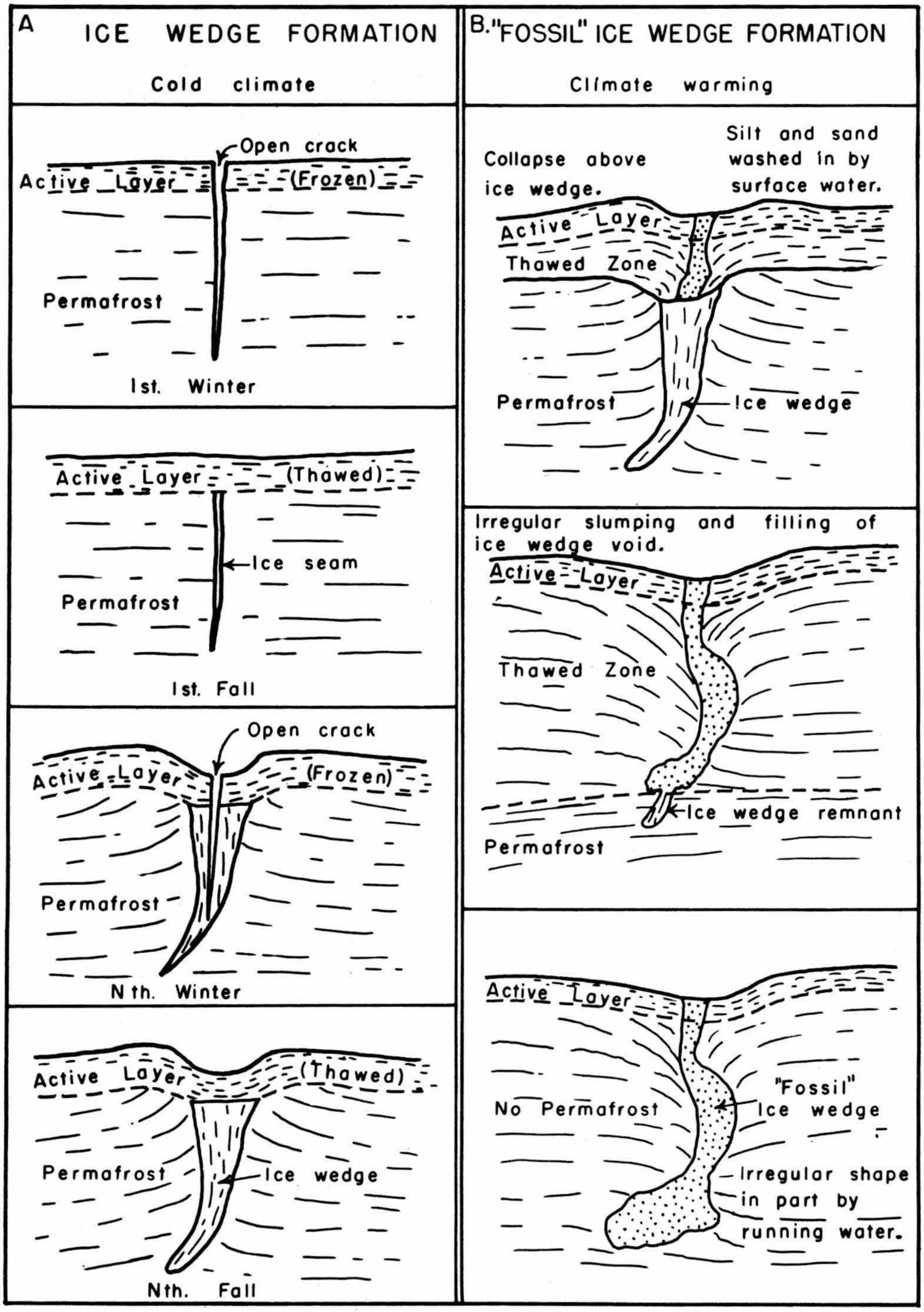

Figure 26. Schematic diagram illustrating the origin of ice wedges (after Lachenbruch, 1960) and the subsequent formation of "fossil" ice wedges.

It has been noted that the present climate in interior Alaska is apparently quite critical with respect to the formation of permafrost and that in some environments perennially frozen ground is actively forming (Péwé, unpublished manuscript). This leads one to speculate that even a slight decrease in mean annual temperature as the result of increased summer cloudiness, such as may have occurred in Wisconsin, time, would result in a more widespread distribution of perennially frozen ground and therefore formation of permafrost in the Donnelly Dome outwash sediments. This thesis is considerably strengthened by the fact that relict permafrost exists in the outwash sediments today, as proven by the two drill holes near exposure "D" (Fig. 3). The permafrost lies below the depth of penetration of seasonally frozen ground. This seems to be direct evidence that the outwash sediments were perennially frozen in the past, and that the permafrost has subsequently been extensively degraded. It is unlikely that permafrost could selectively form in small, deeply buried lenses like these.

Corté (1962) reports that ice-wedge polygons are formed in outwash gravel near Thule, Greenland. These polygons range in size from 3 to 30 m in diameter, and the troughs are underlain by ice wedges up to 1 m wide at the top. The median diameter of the gravel in which the ice wedges are formed varies from 4 to 5 mm and the sediment contains an average of less than 1% silt and clay-sized sediment. These parameters are in the same range of values as those of the outwash gravel in the Donnelly Dome area.

It is to be expected that the change in environment which has occurred since the last glacial epoch could cause degradation of the permafrost in the outwash gravel. The Donnelly Dome area is in the central part of the zone of discontinuous permafrost where temperatures of the perennially frozen sediments are $-\frac{1}{2}$ to -1C. It would take little environmental change to cause degradation of the permafrost in outwash gravel. The gravel is porous and permeable so that meteoric water could penetrate the thawed active layer readily, carrying heat which would aid in melting the ice in the underlying perennially frozen sand and gravel. Entrenchment of Jarvis Creek, which apparently controls the level of the water table, may have greatly aided this process by inducing downward percolation of meteoric water.

Inactive ice wedges are presently widespread in interior Alaska (Péwé, 1958b; in press), but are known only in fine-grained sediments. In the past, however, when conditions were more rigorous, it is to be expected that they were also present in coarse-grained sediments—sediments which were not as favorable for their preservation when the climate warmed slightly and ground water circulation improved. Ice wedges do form in gravel in Alaska in the proper environment (Péwé and Church, 1962). The large-scale polygonal ground developed in the beach gravel of the Barrow spit, near Barrow, Alaska, was investigated by drilling a number of holes centered over the trench-like depressions which outlined the polygons. Active growing ice wedges composed of multiple ice veins and totalling 15 cm to 60 cm wide at the top and extending downard 2.4 m to 3 m were found to underlie the troughs (Fig. 27 and 28). They occur in beach gravel having a median diameter ranging from 1 to 5 mm, a Folk's sorting coefficient of .59-.84 ϕ units, and a moisture content of 17.7% water by dry weight. Both the size and shape of these polygons are similar to the size and shape of the polygons in the Donnelly Dome area.

In summary, the assumption that the large-scale polygons in the area originated as ice-wedge polygons is supported by the following facts: (1) the mean annual temperature during Wisconsin time was colder than at present, (2) relict permafrost exists in the outwash sediments in the area today, (3) ice wedges do form in similar gravel deposits , and (4) degradation of the permafrost in the outwash gravel as the climate ameliorated and as ground water circulation improved is plausible.

Figure 27. Actively growing ice wedge in gravel at Barrow, Alaska, exposed in 1-m diam borehole. (Photo by T. L. Péwé, 12 August 1961).

Figure 28. Closeup of actively growing ice wedge in gravel at Barrow, Alaska, exposed in 1-m diam borehole. (Photo by T. L. Péwé, 12 August 1961).

Theory of ice wedge replacement: Fossil ice wedges* are known elsewhere in Alaska (Péwé, in press) but few have been described. Only a few examples are known from temperate United states (Denny, 1936; Horberg, 1949; Schafer, 1949; Wilson, 1958). Fossil ice wedges have long been known from Europe (Harrassowitz, 1921; Kessler, 1925; Lotze, 1932; Soergel, 1932, 1936). Since World War II, a voluminous literature has developed, mostly from Europe. A few representative descriptions are as follows: Kunsky (1944, 1945, 1954); Zahalka (1947), Cailleux (1948a, 1948b), Poser (1948), Büdel (1951), Dylik (1951), Jahn (1951), Dimbleby (1952), Dylikowa (1956), Fitzpatrick (1956), Sekyra (1956, 1960), TePunga (1956), Johnsson (1958, 1959), Maarleveld (1960) and Wright (1961).

After the ice wedge polygons had formed, there was a change in at least one of the environmental parameters to permit melting of the ice wedges. It is known that there was a rise in the mean annual temperature (Péwé and Hopkins, manuscript); however, an increase in early and total snowfall, a decrease in mean winter temperature, a change in the vegetation cover, or a combination of these changes would also discourage ice wedge growth and favor melting.

Permafrost began to thaw, perhaps both from above and below; however, it is the thawing or degrading of permafrost from the top down that is important in this study.

As the permafrost table was lowered, the top of the ice wedges melted down, allowing a gentle collapse of the overlying sediments. As soon as a pronounced polygonal pattern of shallow trenches appeared on the surface, water would be channeled in these furrows and would percolate down into the melting ice wedge, supposedly carrying fines (silt and sand) downward. As the ice wedge surface was further lowered and the surrounding sediments thawed, losing their cementing material (ice), they would tend to collapse toward and into the area formerly occupied by the ice wedge. This is especially true in coarse sandy gravel. In loess, the walls may stand and the fill originate only from above. Collapse of the bordering material plus downwashing of fines would result in a mixture of fine-grained and coarse-grained sediments.

As sediment from the sides slumped into the position of the former ice wedge, the outwash gravel farther away may have been moved slightly, disturbing the original outwash bedding. The upbending of the outwash gravel bedding near the wedge during the ice-wedge growth, plus the disturbance created by the collapse of the adjacent sediments as the ice wedge melted, would give rise to a rather chaotic structure near the wedge border.

Downward percolating surface water probably thaws the ice wedge irregularly. That is, the water can thaw its way down along the contact between the ice wedge and the adjacent gravel and even erode large cavities in the side of the ice wedge. Thawed gravel probably would slump into such cavities producing further disturbances of the outwash gravel adjacent to the original ice wedge.

It must be remembered that modern ice wedges exhibit irregular shapes when viewed in two dimensions: bent, curved, hooked wedges or even ice masses which connect with each other passing under the polygon (Fig. 29, 30, 31). The irregular shape of the original ice wedge, plus slow unequal collapse of sediment over and adjacent to the melting ice wedge, would result in greatly disturbed structures in the

*Many terms have been used to describe these features besides "fossil" ice wedges: ice wedge pseudomorph; ice wedge fill; ice wedge cast (Wright, 1961); fente de glace remplie (Hamelin and Clibbon, 1962); frost wedge (Sekyra, 1961, fig. 4). They also have been erroneously termed ice wedges by Johnsson (1959, 1962), Shotton (1960) and by Galloway (1961).

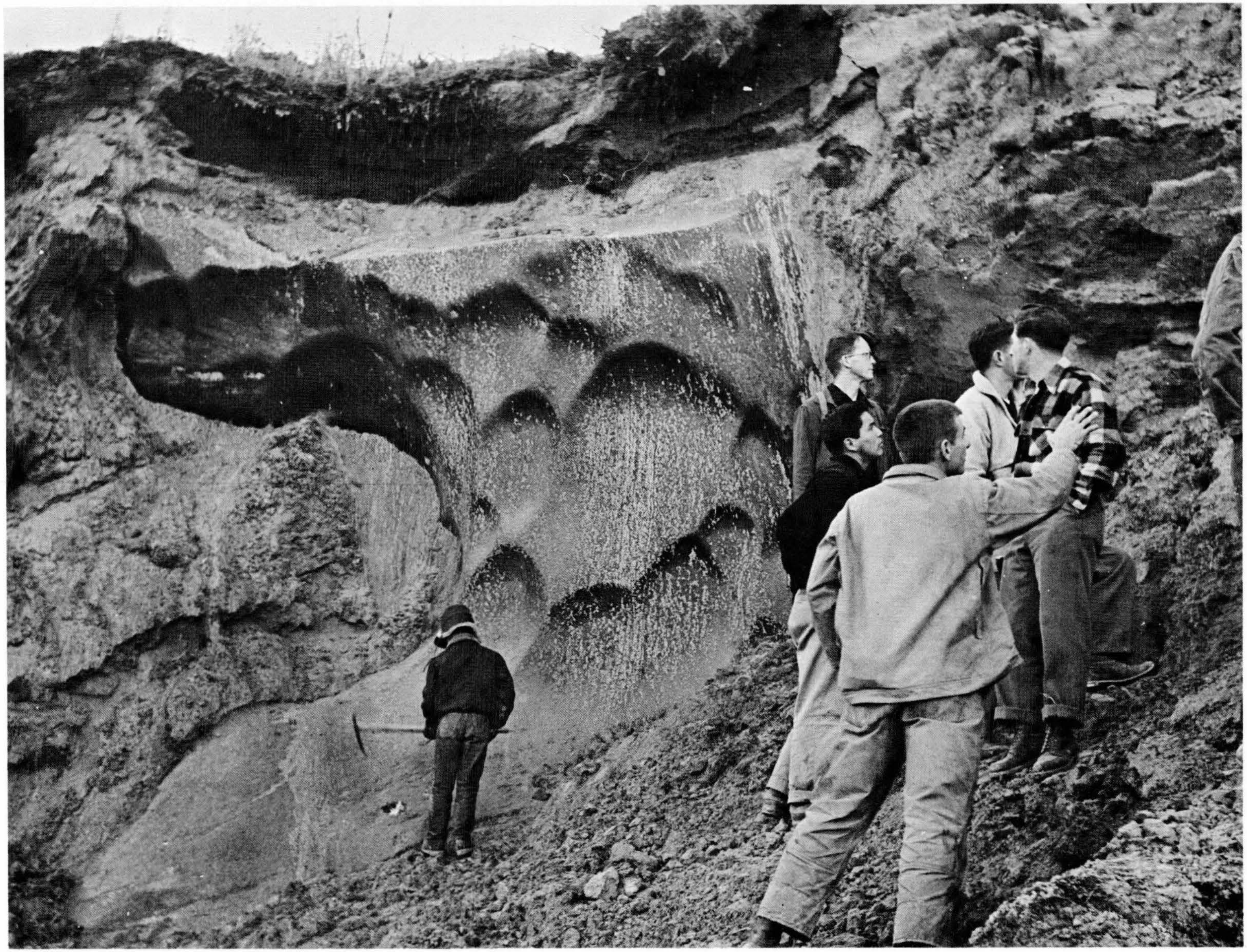

Figure 29. Inactive ice wedge in silt exposed by placer mining operations at Fairbanks Creek, near Fairbanks, Alaska, 1953. (Photographer unknown).

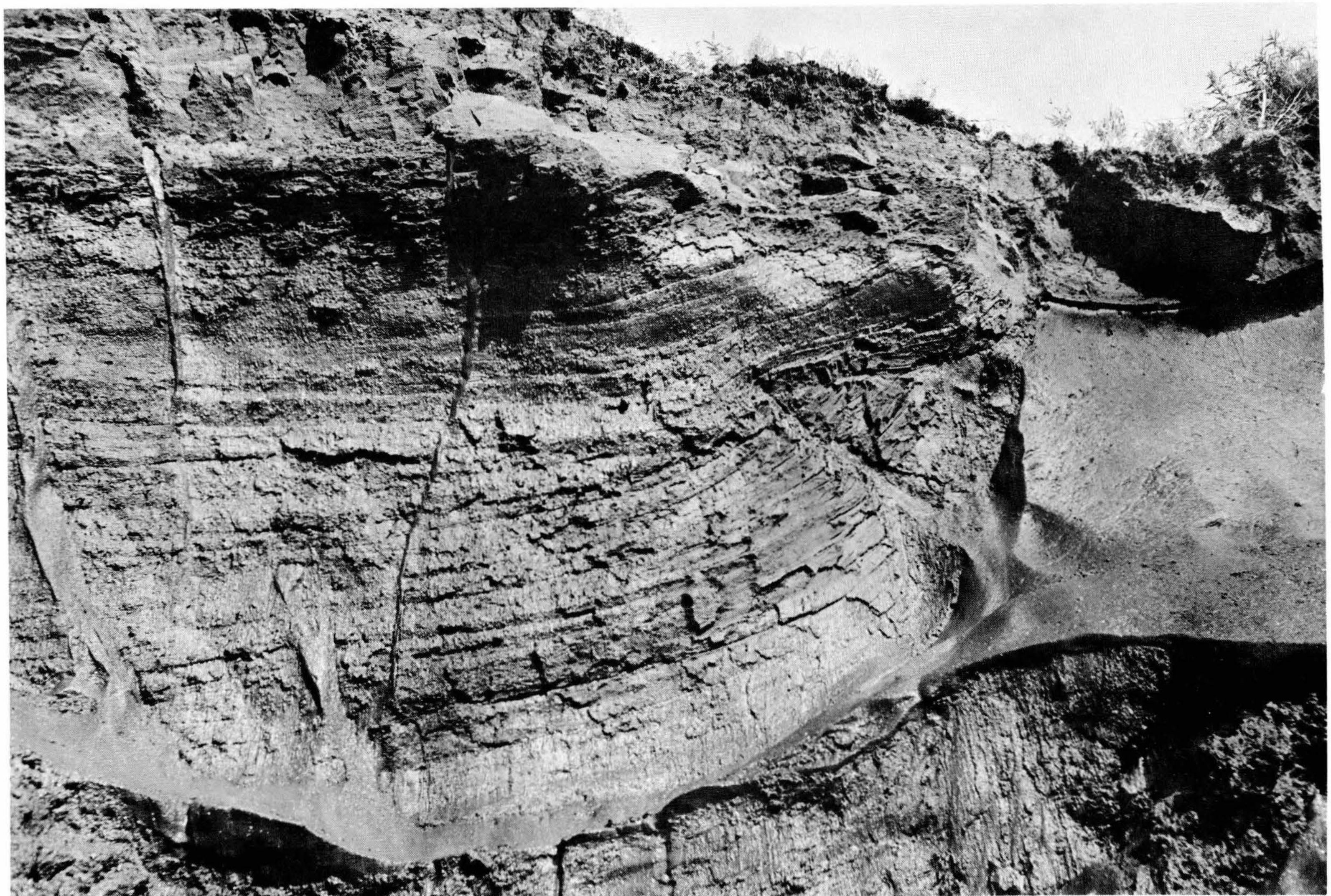

Figure 30. Inactive ice wedge in silt exposed by placer mining operations at Amy Creek near Livengood, Alaska. (Photo by T. L. Péwé, 16 July 1948).

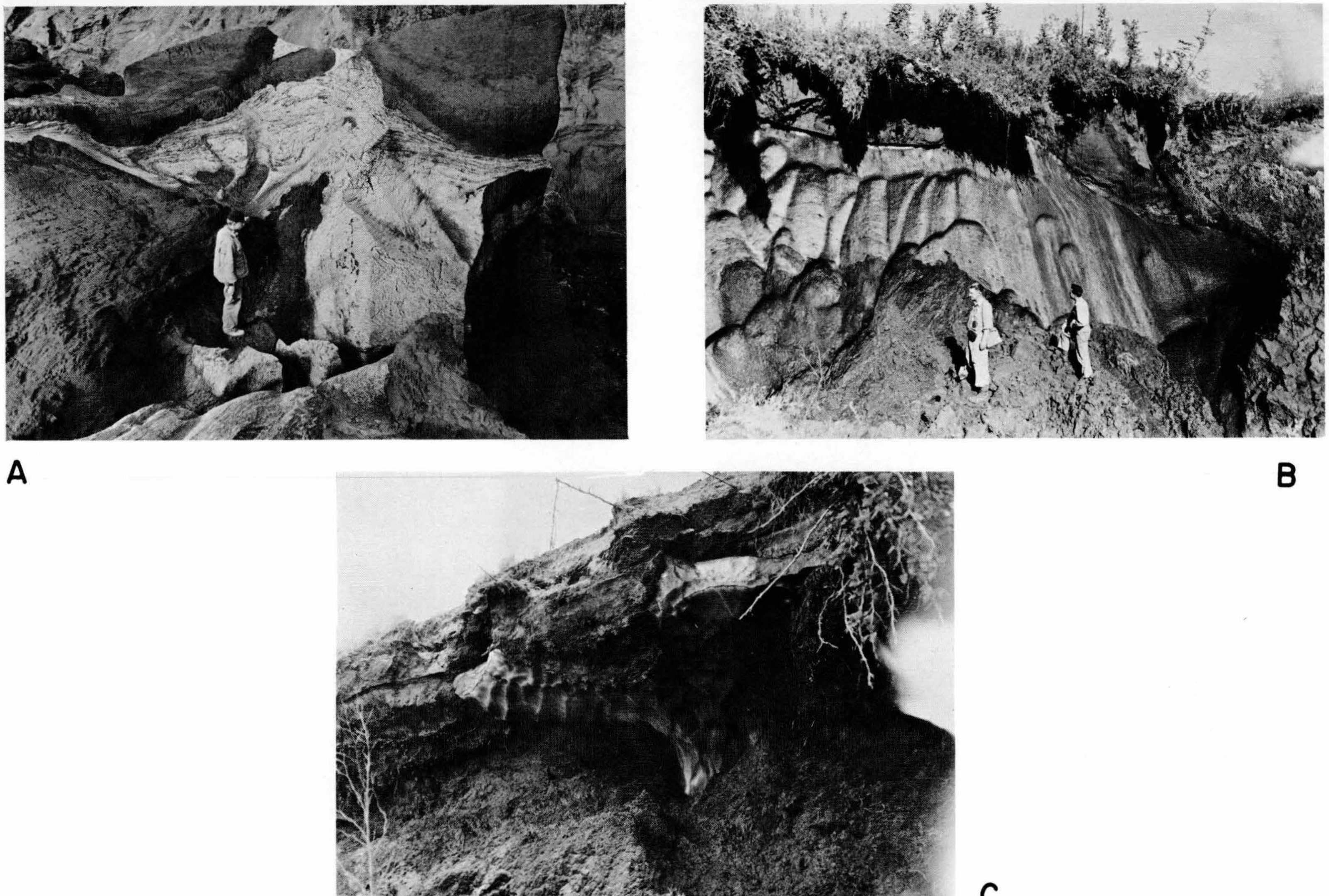

Figure 31. Inactive ice wedges exposed by placer mining operations. A, Sheep Creek, near Fairbanks; B, Dome Creek near Fairbanks; and C, on the Yukon River near Galena, Alaska. (Photography by T. L. Péwé; 25 Sept 1955, 16 Aug 1954, and 3 Aug 1954, respectively).

sediment. Such original and secondary conditions result in abrupt changes in form of fossil ice wedges along the strike.

Melt water from the ice wedges and from surface runoff would carry clay, silt and very fine sand outward from the fossil ice wedge into the surrounding porous and permeable outwash gravel. The gravel next to the wedge, therefore, would have a larger percentage of fines than would the undisturbed outwash gravel several meters away. Such dispersing of fines would tend to obliterate the original textural bedding of the sediments near the fossil ice wedges.

When the permafrost had thawed down below the level of the wedge, or even before this time, downward percolating water channeled into the area of fossil ice wedges could carry the fines into the gravel at or near the base of the wedge forming a gravelly area rich in sand and silt. Observations that wedges are an excellent channel for percolating ground water have been recorded in Poland (Golab, 1956).

To complete the events related to the formation of fossil ice wedges it is necessary to mention that channelized ground-water movement may cause a concentration of iron-oxide staining on the gravel adjacent to the wedge. Such a concentration could come from ground water percolating downward along the side of the wedge, or from laterally moving ground water which was stopped and deflected by the fine sediments of the wedge which acted as a permeability barrier.

Evidence for ice-wedge replacement: The following evidence supports the theory of ice-wedge replacement outlined above: (1) the deformed bedding in the sedimentary material adjacent to the sediment wedges, (2) the bends and bulges in the sediment wedges, (3) the textures of the sediment wedges, and (4) the textures of the sediments adjacent to the wedges.

The downwarped, distorted, and often completely destroyed bedding found in the outwash gravels and other sediments near the wedges is the expectable result of compression during the time of ice-wedge forming and subsequent collapse during and after the melting of the ice wedges. Similar collapse features can now be seen over ice wedges in the Fairbanks area that have not yet completely melted (Péwé, unpublished manuscript).

Similarly, the bends, bulges, and hooks displayed by the sediment wedges in the Donnelly Dome area are like those seen in exposures of some inactive ice wedges in the Fairbanks area (Fig. 30, 31).

The texture of the material comprising the sediment wedges indicates that this material was deposited in a much different way than the surrounding sediments, and also permits the conclusion that the wedges were filled by a combination of washing in of material from above and collapsing from the side. These statements are supported by the following: (1) The grain-size distributions of the sediment wedges are negatively skewed, indicating they are essentially fine distributions to which coarse material has been added, (2) cumulative frequency curves of wedge-fill sediments are bimodal suggesting a dual source, (3) the size of the coarsest material in the sediment wedges is the same as that in the outwash gravels in which they are developed, and the finest material in the sediment wedges is the same size as the finest material in the loess-soil blanket of the area, (4) the wedge fill materials are not bedded and are very poorly sorted, indicating that they were not deposited in a fluid medium like a stream, and (5) the wedge-fill materials show no systematic variation in texture from bottom up or along the strike of a wedge, indicating that extremely local conditions (such as those during differential ice-wedge melting) were responsible for this deposition. The sediment wedges are the result of washing in of material from above and collapse from the side as outlined in the theory of origin.

The textures of the sediments adjacent to the wedges show modification of the grain-size distributions. The structurally modified outwash, for example, looks no different in places than the parent outwash gravel on a textural basis, but it has been shown that there are differences (Fig. 23, 25). The modified outwash has had fine material added to it in places and washed out of it in other places. This must have been accomplished by ground water percolation. The samples collected closest to a sediment wedge have the highest proportion of fines. The median and mean diameters of these sediments are much smaller than those for the parent outwash, (Fig. 23). Some of these fines may have been removed from modified, outwash, but most must have come from the wedge-fill materials. Most of the modified outwash has higher skewness values than the unmodified outwash, indicating that in most cases fine material was added to the modified outwash rather than removed.

Thus, the chaotic structures found along the wedge borders and the textures of the sediments in and surrounding the wedges support the theory that the present polygons were formed by degradation of the ice in ice-wedge polygons, and subsequent filling by inwash of surficial eolian sediment combines with material caved from the wedge borders.

Sand-wedge hypothesis. It has been suggested (Péwé, 1959, p. 550) that fossil ice wedges in many parts of the world could perhaps be "sand wedges" and the associated polygonal patterns would therefore be sand-wedge polygons (Péwé, 1959) or tesselations (Taylor, 1922).

Sand wedges are primary features formed in polygonal thermal-contraction cracks in permafrost. The method of origin is the same as ice wedges except that the thermal contraction crack is filled with eolian sand from the surface rather than by water. Such wedges have been observed actively forming in the McMurdo Sound area of Antarctica (Péwé, 1959; 1962), and Péwé suspects that they may also occur in northern Greenland. Sand wedges form in extremely arid, vegetation-free, windy areas where little or no spring melt water is available to enter the cracks and no hoarfrost forms in the cracks in the winter. Sand wedges do not indicate a time of permafrost degradation and sediment-wedge formation by replacement of ice.

To completely support the fossil ice wedge hypothesis for the origin of the wedges in the Donnelly Dome area it is necessary to demonstrate that the wedges are not "sand wedges" as described above. They cannot be active sand wedge polygons because of the absence of continuous permafrost in the area. The possibility that they are fossil sand wedge polygons is considered below.

The outwash plain could have been vegetation-free, and sand could have been blowing over the surface during Wisconsin time. However, if the sediment fills had originated by eolian sand dribbling down a narrow crack, the fill would be well sorted and would contain few, if any, cobbles. Diagrams (Fig. 10 to 20) and sediment analyses (Fig. 24, 25) show that the sediment in the wedges does not meet these qualifications. Also, inasmuch as the sediment in the sand wedges is from one source, the sorting would be unimodal and not bimodal as in the wedge fillings in the Donnelly Dome area (Fig. 24). Caution must be used, however, because some outside sediment could be incorporated, perhaps during growth of sand wedge.

If the Donnelly Dome wedges were sand wedges, the sediment adjacent to the wedges should show upturning. Collapse features would be absent because, upon thawing of the permafrost, no "empty" space is created such as is formed when an ice wedge melts. Examination of the Donnelly Dome wedges shows no well-formed, upturned strata adjacent to the wedges but abundant evidence of collapse of the sediments bounding the wedges.

The sand-wedge hypothesis is not supported by field evidence.

ENVIRONMENTAL SIGNIFICANCE

Environment when ice wedge polygons formed

To state what the environment was in the Donnelly Dome area when the ice wedges originated, it is necessary to examine an environment where ice wedges are actively growing today. Two examples may be given: Ice wedges are only weakly active in organic-rich silt near Galena, in interior or subarctic Alaska (Péwé, 1962) but ice wedges are actively forming in gravel as well as silt near Barrow (Péwé, in press, Fig. 3) in Arctic Alaska.

Climatic environment today in areas of active ice wedges

Galena, Alaska. The Galena area is in the zone of discontinuous permafrost (Fig. 1) and has a continental climate characterized by an extreme range between summer and winter temperatures. The mean annual temperature is -4.7C; other climatic data are listed in Figure 32 and Table I.

Table I - Summary of climatic characteristics at Barrow, Galena, Fairbanks, and Fort Greely, Alaska (U. S. Weather Bureau data).

		Barrow	Galena	Fairbanks	Fort Greely
Mean annual temperature	(°C)	-12.2	-4.7	-3.3	-2.8
Maximum mean annual temperature	(°C)	- 8.9	0.2	2.1	2.2
Minimum mean annual temperature	(°C)	-15.6	-9.5	-9.3	-7.8
Absolute recorded maximum temperature	(°C)	25.5	31.6	37.1	32.2
Absolute recorded minimum temperature	(°C)	-48.9	-53.3	-54.4	-54.4
Mean temperature of coldest month (Jan)	(°C)	-27.1	-23.8	-24.0	-20.6
Mean temperature of warmest month (July)	(°C)	4.4	15.5	15.5	15.0
Mean summer temperature	(°C)	2.8	14.4	14.3	13.5
Mean annual freezing days		321	228	233	228
Mean freezing index (in degree-days °C)		4600	3080	2940	2950
Mean annual precipitation	(cm)	11.0	31.0	29.7	29.0
Mean annual snowfall	(cm)	83.3	120.1	169.2	91.7
Mean annual wind velocity	(kmph)	18.9		7.8	

The mean annual precipitation at Galena is 31.0 cm, most of which falls during the summer. August is the wettest month, with a mean precipitation of 6.4 cm (Péwé, 1962). The annual mean snowfall is 120.1 cm and the amount of snow on the ground in the winter is approximately 60 to 75 cm.

No ground temperatures are available at the top of permafrost.

Barrow, Alaska. Barrow, Alaska is in the zone of continuous permafrost (Fig. 1) and is characterized by a cloudy, cold, dry, windy climate. The mean annual air temperature is -12.2C; other climatic data characteristic of this rigorous Arctic climate are listed in Figure 33 and Table I.

The mean annual recorded precipitation at Barrow is 11.0 cm, about half of which falls as rain in July, August, and September. The mean annual recorded snowfall is 83.3 cm. Black (1954, p. 206) states, however, that the actual precipitation at Barrow is greater than recorded and may be two to four times as great. Mean annual cloud cover is 56%.

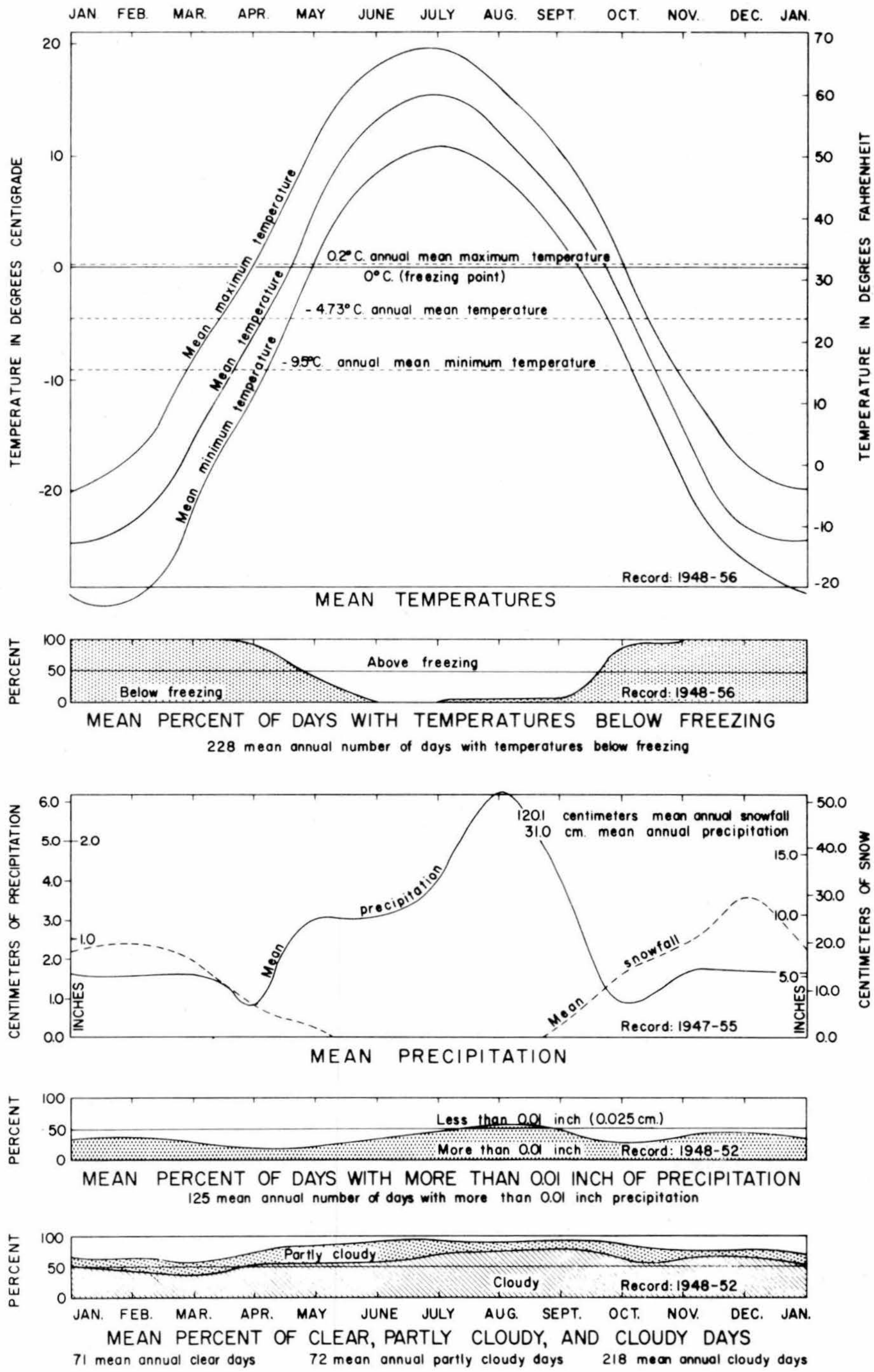

Figure 32. Mean monthly climatic data for Galena, Alaska.

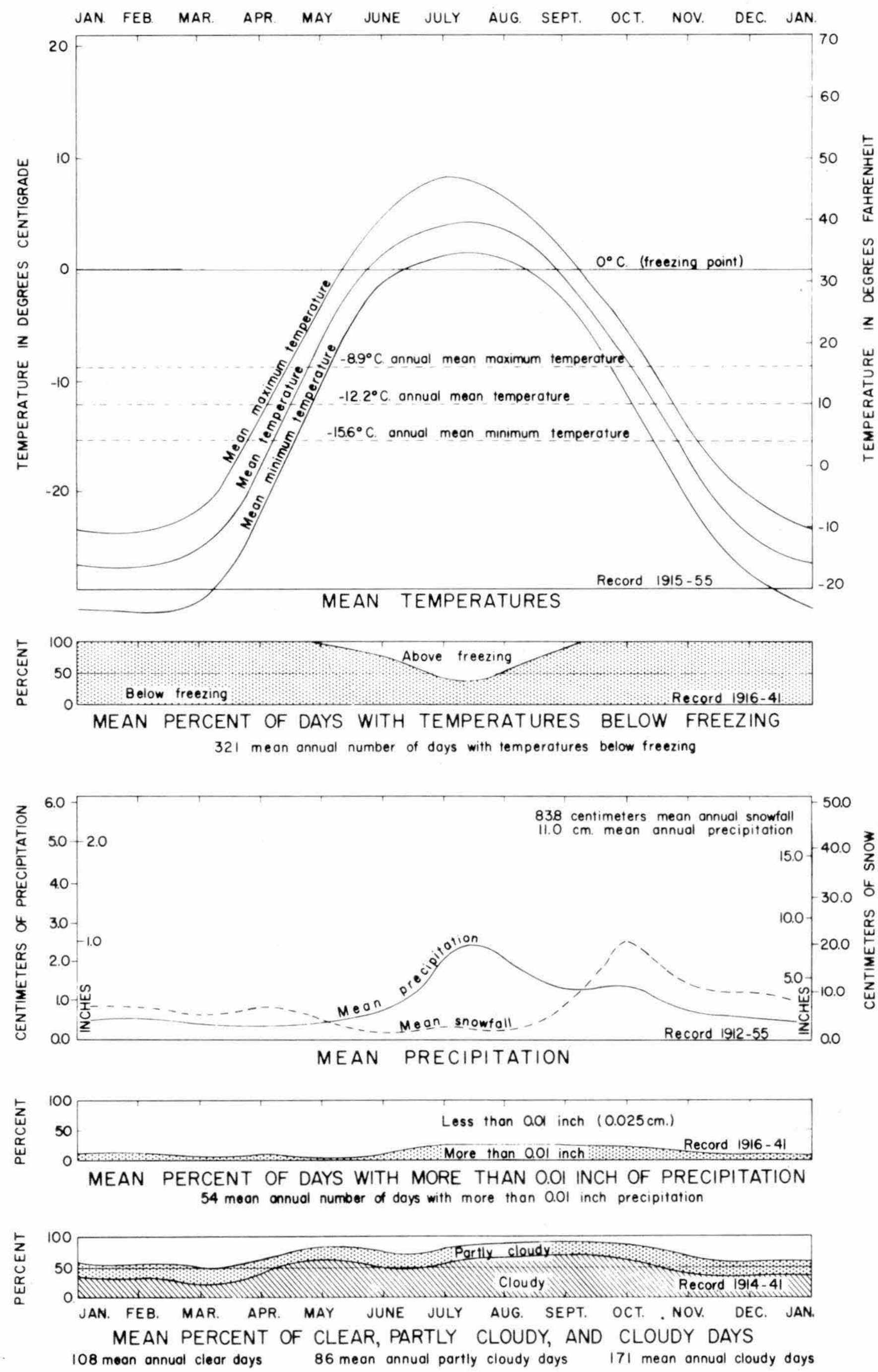

Figure 33. Mean monthly climatic data for Barrow, Alaska.

Ground temperature measurements made at Barrow show that minimum winter temperatures at the top of the permafrost vary from -15 to -25C (Lachenbruch, 1962, Fig. 8).

Comparison of environments of active ice wedge growth with the environment in the Donnelly Dome area

The present climatic environment in the Donnelly Dome area, as recorded at nearby Fort Greely (Fig. 4), is slightly less rigorous than the climate at Galena (Table I) and much less rigorous than the climate at Barrow. The mean annual air temperature, for example, at Fort Greely is -2.8C, at Galena it is -4.7C, and at Barrow it is much colder, -12.2C. The differences in environment are also well reflected by the other climatic parameters (Table I).

Because of the windiness at Barrow and Fort Greely, snow cover on sparsely vegetated areas such as the outwash plain at Fort Greely or on unvegetated areas such as the spit at Barrow is thin.

Data are not available for minimum winter temperatures at the top of permafrost at Galena and Fort Greely. However, data from the nearby Fairbanks area, where inactive ice wedges are common and the environment is similar to Fort Greely (Table I), show that the minimum temperature at the top of permafrost in silt recorded in 1962, an extremely cold winter, was -3.3C at a depth of 1 m in an area of natural spruce forest and -2.2C at a depth of 1.3 m in an area of natural cover near the edge of the spruce forest (Kitze, Chief, CRREL Alaska Field Station, oral communication, 1962). Minimum ground temperatures recorded at Fort Greely on March 2, 1957 (Table II) in an area of forest cover where there is no permafrost was -5.1C at a depth of 120 cm in gravel. Minimum ground temperatures at the top of permafrost are much warmer than those recorded at Barrow.

Table II - Ground temperatures in wooded area at Fort Greely, Alaska (Data from U. S. Army Corps of Engineers, Alaska District, Anchorage, Alaska).

Depth in meters	Temperature (°C) March 2, 1957	Temperature (°C) April 5, 1957
0.0	-	-3.2°
0.6	-	-2.9°
1.2	-5.1°	-3.2°
1.8	-2.9°	-2.9°
2.4	-1.7°	-2.7°
3.0	-0.5°	-2.3°
3.7	-0.1°	-1.6°
4.3	-0.4°	-0.8°
4.9	-0.4°	-0.3°
5.5	-0.3°	0.0°
6.1	-0.4°	0.5°
7.6	-0.4°	0.4°
9.2	0.0°	0.4°
10.7	0.4°	0.4°
12.2	-0.3°	0.4°
13.7	0.3°	0.4°
15.3	0.8°	0.3°

Summary of environmental conditions when ice-wedge polygons formed

The climatic environment at Fort Greely when the large-scale contraction-crack polygons formed was considerably different from the climate today. The climate was colder and more rigorous. Floral and faunal evidence from adjacent areas in interior Alaska indicate that the summers were cooler and shorter. The tree line was 450 to 600 m lower than at present so that the Donnelly Dome area was covered by tundra vegetation rather than the forest which now covers most of the area. Glacial melt-water streams crossing the outwash plains kept most of it free of vegetation. Winds blowing over the vegetation-free area blew sand and silt, polishing and carving the rocks on the nearby moraines (Péwé, 1953), and depositing loess to the leeward.

Two methods are available to obtain a suggestion as to what the mean annual air temperature in the Donnelly Dome area was at the time of ice-wedge growth. One is based on the lowering of snowline in the area during Wisconsin time and the other on the knowledge of climatic conditions requisite for ice-wedge growth.

The snowline in the general area today is about 1800 m. In Wisconsin time the snowline, as determined from the base of cirques on Granite Mountain adjacent to the Donnelly Dome area, was about 1350 m, a difference of 450 m. Using the lapse rate (vertical temperature gradient) of 0.68C per 100 m, as determined from Fairbanks in the region of 1450 to 2000 m elevation, the Wisconsin depression of mean annual air temperature was -3.0C. This would give a mean annual air temperature of -5.8C for the Donnelly Dome area in Wisconsin time in contrast with the mean annual air temperature of -2.8C today.

Lachenbruch (oral communication, 1962) suggests that, when minimum winter temperatures at the top of permafrost are about -15 to -20C, active cracking of permafrost might be expected in most permafrost materials. Therefore, it is suggested that the former climate of the Donnelly Dome area must have been cold enough to produce such minimum winter ground temperatures at the top of permafrost. Such temperatures are 7 to 12C lower than those which now occur in winter at the top of permafrost in the Fairbanks and Donnelly Dome areas.

Areas in Alaska where ice wedges are actively growing have a mean annual air temperature colder than about -6 to -8C (Péwé, in press); it is assumed from these data that the mean annual air temperature of the Donnelly Dome area was at least -6C in Wisconsin time when the ice wedges grew, in contrast to the mean annual air temperature of -2.8C present today.

Comparison of the present environment of the Donnelly Dome area with that of Galena, where ice wedges are now weakly active only in areas of optimum conditions for their growth, and with the environment at Barrow, where ice-wedge polygons are forming in almost all environments, indicates that ice-wedge polygons in gravel in the Donnelly Dome area developed during a time when the climate was more rigorous than the environment now present at Galena and perhaps nearly as rigorous as the environment at Barrow. Snowline and treeline were about 500 m lower and the mean annual air temperature was about 3C to 4C colder than today.

Environmental changes since formation of ice wedges

Preliminary statement. It has been demonstrated that a climate more rigorous than that of today existed in the Donnelly Dome area to permit the formation of ice wedge polygons. The next question is: What were the environmental changes that permitted the formation of fossil ice wedges? These are two possibilities: (1) The mean annual air temperature warmed to 0C or above and all the permafrost, as well as the ice wedges, disappeared, or (2) there was less of a climatic amelioration and a selective thawing of permafrost and melting of ice wedges occurred.

Hypothesis of major climatic warming. The almost universal concept of fossil ice wedges is that they formed when the mean annual air temperature of the region rose to 0C or above and permafrost disappeared. This concept is based upon investigations of fossil ice wedges in temperate latitudes. Such an interpretation for the Donnelly Dome area would mean that the mean annual air temperature of the region warmed from -6C or colder at the time of ice wedge formation, to 0C or warmer for a long enough time to permit the ice wedges to melt. Since then, the mean annual air temperature of the region has dropped to -2.8C and permafrost is forming in favorable localities.

It is felt that this hypothesis is not tenable because, if the climate had ameliorated in such a fashion for a long time, the ice wedges of Wisconsin age present today in the nearby Fairbanks area would have disappeared.

Hypothesis of selective ice wedge melting. Inasmuch as some ice wedges of Wisconsin age still exist in central Alaska, a hypothesis must be presented which permits melting of ice wedges and thawing of permafrost only in selected areas. Such a hypothesis could have two variants: (1) The climate warmed only enough to become similar to the present conditions [mean annual air temperature -2.8C], or (2) the climate warmed enough to have a mean annual air temperature of at least 0C but only for a short time.

First variant: Under this hypothesis rise of the mean annual air temperature to -2.8C plus the heat transferred to the ground through the improved circulation of ground water in the permeable gravel was enough to cause thawing of permafrost and melting of ice wedges in the Donnelly Dome area.

While it cannot be disproved that such an air temperature and active ground water circulation may have caused the degradation of permafrost in permeable gravel, we know that this hypothesis is not entirely plausible. The partial melting of ice wedges and lowering of the permafrost table in the silt near Fairbanks (Fig. 34) is thought to require a mean annual air temperature of 0C or above, a temperature not possible under this variant. Permafrost and ice wedges in the Fairbanks Area are not thawing under present climatic conditions.

Second variant: This hypothesis states that in post-Wisconsin time the mean annual air temperature remained at 0C long enough to thaw almost all permafrost and melt all ice wedges in the permeable gravel near Donnelly Dome. At the same time only partial thawing and melting of permafrost and ice wedges occurred in the perennially frozen silt near Fairbanks. After this warm period the climate cooled to its present condition.

This hypothesis is supported by abundant evidence in the nearby Fairbanks area which indicates the existence of a warm period about 3,000 to 7,500 years ago, a time when the permafrost table was lowered slightly and when ice wedges melted (Péwé, 1952a; 1958a, b). This post-Wisconsin warming period is recorded world wide (Flint, 1957). The flat tops of ice wedges in the Fairbanks Area are the result of down-melting in post-Wisconsin time and no ice wedge growth since then (Fig. 34). Since this time, permafrost has re-formed in the thawed sediments and is forming today in newly deposited sediments under the present climatic environment.

It is believed that, in areas of perennially frozen permeable gravel with little vegetation cover (Fig. 5) such as the outwash plain in the Donnelly Dome area, the warming of climate during this interval not only caused the permafrost to degrade and some ice wedges to melt, but permitted downward percolating ground water to travel more widely and add enough heat to almost completely thaw the permafrost and to completely melt the ice wedges. Although the climate has cooled slightly since and permafrost has re-formed in silt, it is thought that the improved ground-water circulation plus vegetation conditions prevents permafrost formation in the gravel in the Donnelly Dome area despite a mean annual air temperature of -2.8C.

In summary, ice wedge polygons formed under the rigorous climate of Wisconsin time; the climate ameliorated 3,000 to 7,500 years ago to provide a mean annual air temperature of probably 0C or above; and this period was followed by a cooling to the present conditions. Warming caused thawing of the permafrost and

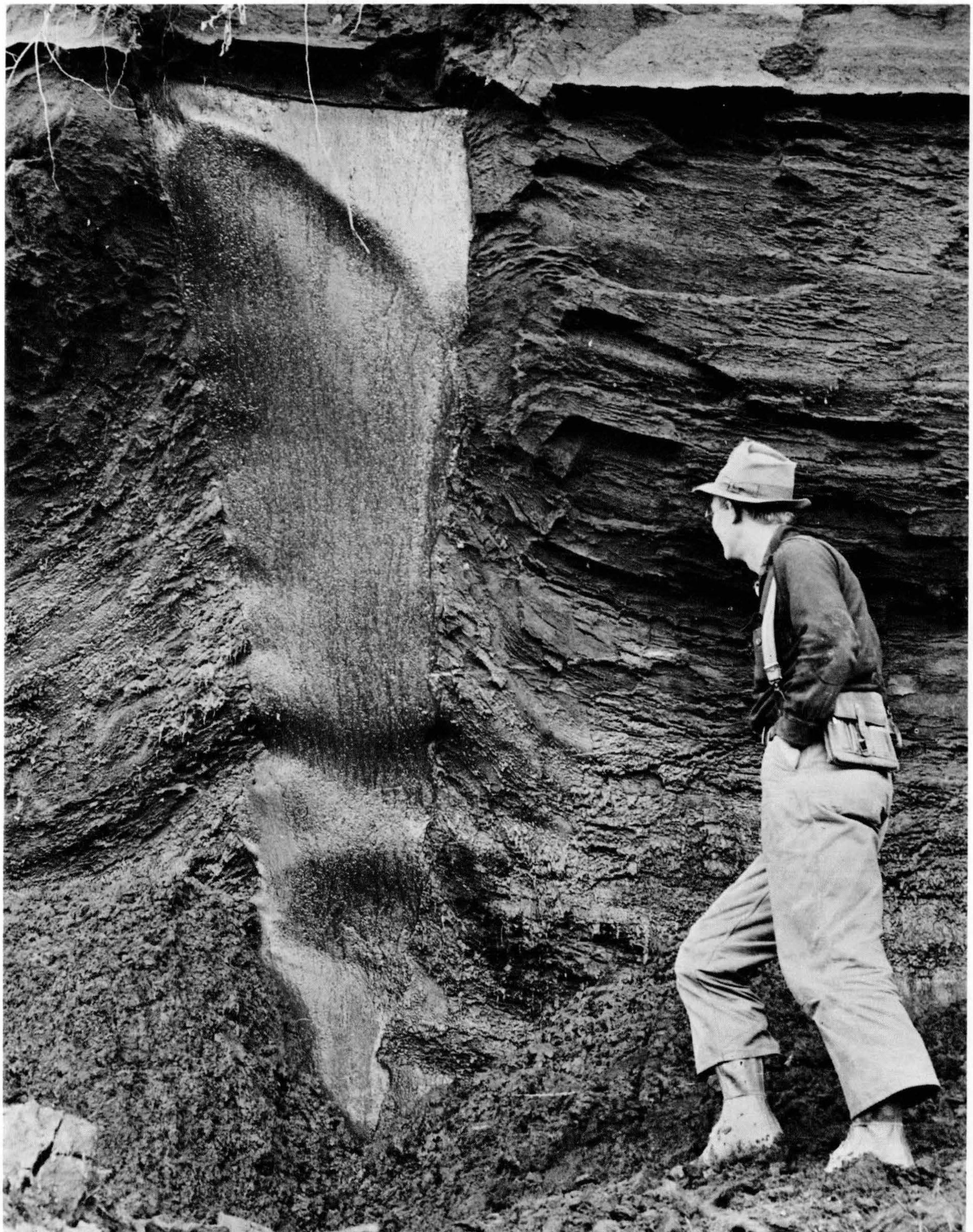

Figure 34. Inactive ice wedge exposed by placer mining operation at Wilbur Creek, near Livengood, Alaska. (Photo by T. L. Péwé, 19 Sept 1949).

melting of ice wedges. Collapse of sediments overlying the ice wedges formed fossil ice wedges with associated fossil ice wedge polygons.

CONCLUSIONS

It is believed that the large-scale polygons in the Donnelly Dome area are fossil ice wedge polygons which formed as a result of melting of ice wedges and subsequent filling of the void with sediments. This suggestion is supported by the fact that there is deformed bedding in the sedimentary material adjacent to the sedimentary wedge. This deformation occurred as material collapsed into the void. The material in the sediment wedge was derived primarily from fine material (silt mantle) overlying the outwash gravel and secondarily from the outwash gravel on the side of the wedge. Bimodal grain size frequency curves indicate this dual source. The size of the coarsest material is the same in the wedge as the outwash gravel, and the size of the finest material is the same as the overlying windblown silt. The mean grain size and skewness of wedge samples indicate that they are essentially fine-grained deposits to which some coarse material has been added. Ground water percolation into the melting ice-wedge area carried fines into the wedge and into the pore space of adjacent outwash gravel. This resulted in a textural modification of the outwash gravel adjacent to the wedge fill as indicated by the skewness values of modified outwash and unmodified outwash.

The climate in the Donnelly Dome area at the time the large scale contraction crack polygons formed was colder and in general more rigorous than today. Tree line was 450 to 600 m lower and snowline was 450 m lower. Based on the lowering of snowline, the Wisconsin mean annual air temperature was 3C lower. Based on a comparison with areas where ice wedges are actively growing today the mean annual air temperature of the Donnelly Dome area at time of ice-wedge growth was at least -6C in contrast to the mean annual air temperature of -2.8C today.

After formation of the wedges the climate warmed to 0C or above and ice wedges as well as most of the permafrost in the Donnelly Dome outwash gravel disappeared. This interval of warmer climate was evidently rather short, inasmuch as the permafrost and ice wedges in silt in adjacent regions were only partially thawed. After this thawing the weather cooled and frozen ground started to re-form and is still forming today.

It has been generally accepted that large-scale patterned ground in the Arctic and subarctic indicates ice wedges and permafrost, generally in fine-grained sediments, even though such polygonal patterns have been reported from temperate latitudes and demonstrated to be fossil ice wedge polygons. The validity of sucn an assumption is especially important in the location and construction of engineering facilities and interpretation of present and past climates.

Study of the large-scale patterned ground in the Donnelly Dome area has demonstrated that extensive areas of fossil ice wedge polygons can occur in coarse-grained sediments in regions where permafrost is actively growing, such as in central Alaska, and where large ice wedges are still present in fine-grained sediments. Such an association supports the suggestion that the permafrost and ice wedges thaw more rapidly in coarse-grained sediments than in ice-rich fine-grained sediments. This is especially true where percolating ground water modified the thermal regime of the ground, such as in outwash plains, alluvial fans, and river flood plains.

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APPENDIX A. SEDIMENTOLOGICAL DATA

The samples for the sedimentological and moisture analyses were collected from the Donnelly Dome area during summer 1961 and April 1962. In all, 110 random samples of approximately 3000 g each were taken, and are representative of textural types 1 through 6, which were defined on pages 19-28.

Sieve analyses were made of 83 selected samples. A $\frac{1}{2}$ phi* interval was used between successive screens, and the samples were run for 10 min in a Ro-Tap automatic shaking machine. Of the 83 sieved samples, 13 have less than 4% material finer than 0.037 mm ($4\frac{3}{4}\phi$), the smallest screen opening available, and required no further analysis. The fine fractions of 39 of the remaining 70 samples were examined for their respective grain size distributions to the practical lower limit diameter of 0.008 mm (7ϕ) using a pipette and settling tube. The samples were weighed dry, moistened, and suspended in individual 1-liter settling tubes containing 0.10 N $Na_2C_2O_4$. Each sample was stirred and 20-ml withdrawals were made at specified time intervals. The 20-ml withdrawals were placed into separate evaporating dishes and the pipettes were rinsed into the appropriate dish with 20 ml of distilled water after each withdrawal. The samples were oven-dried and weighed to 0.0001-g accuracy on an electronic balance. The weights of the empty dishes were recalculated after each use.

The results of the grain size analyses are given in both phi and millimeter values at the 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentile values as determined on the cumulative grain-size frequency curve of each sample (Table AI). The phi values at these percentiles are used in calculating the respective statistical parameters of the distribution and for reconstructing the cumulative frequency curve of any of the samples here described.

Cumulative frequency curves were drawn for each of the analyzed samples. Visual comparing and contrasting of such curves is inexact and subjective, and generally does not allow the investigator to make truly meaningful interpretations. Quantitative expressions of the grain-size distributions such as those developed by Trask (1930, 1932), Inman (1952), and Folk and Ward (1957) are much more useful in objective description and interpretation, and therefore are used in this report. Visual analysis of the curves is also used.

Different formulas are available for calculating each of the four distribution moments (see below), but only the Folk values are used in making interpretations in this report. Folk values are based on 90% of a given distribution whereas other parameter calculations are based on as little as 50%. The derived Folk parameters for each sample and the others calculated for comparison purposes are presented in Table AII.

First Moment Central tendency

Median $Md = \phi 50$ (This is read as the ϕ value occurring at the 50th percentile on the cumulative frequency curve of the grain-size distribution).

Mean (Folk and Ward, 1957)

$$Mz = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

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*Phi (ϕ) is defined as $-\log_2$ of the diameter of the screen opening in millimeters (Krumbein, 1934). Phi values are readily converted to mm values by using the tables given by Page (1955, p. 284-292).

Second Moment Dispersion or sorting

Phi quartile deviation $QD_\phi = \frac{\phi 75 - \phi 25}{2}$

(This is the analog of the Trask (1930, 1932) sorting coefficient:

$So = \sqrt{mm\, 25 / mm\, 75}$

but adapted for the ϕ scale.)

Graphic standard deviation (Inman, 1952) $\sigma_G = \frac{\phi 84 - \phi 16}{2}$

Inclusive graphic standard deviation (Folk and Ward, 1957)

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} .$$

An explanation of values derived in using the formula is as follows:

σ_I Range	Verbal expression of sorting
.00-.35	Very well sorted
.35-.50	Well sorted
.50-.70	Moderately sorted
.70-1.0	Moderately poorly sorted
1.0 -2.0	Poorly sorted
2.0 -4.0	Very poorly sorted
> 4.0	Extremely poorly sorted

Third Moment Skewness or lateral symmetry of the distribution

Phi quartile skewness (Adapted from Trask, 1930, 1932)

$$QSk_\phi = \frac{\phi 25 + \phi 75 - 2(\phi 50)}{2}$$

Graphic skewness (Inman, 1953)

$$Sk_G = \frac{\phi 16 + \phi 84 - 2(\phi 50)}{\phi 84 - \phi 16}$$

Inclusive graphic skewness (Folk and Ward, 1957)

$$Sk_I = \frac{\phi 16 + \phi 84 - 2(\phi 50)}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2(\phi 50)}{2(\phi 95 - \phi 5)}$$

Again, the Folk formula was used in making interpretations and the following remarks indicate the significance of SK_I values:

A symmetrical distribution has $Sk_I = 0.00$. Positive skewness indicates a tail to the fine-grained side of the distribution. The upper limit is 1.00. Negative skewness indicates an excess amount of material in the coarse-grained portions of the distribution. The lower limit is -1.00.

Table of Sk_I values:

Sk_I	1.0 to 0.30	Strongly fine skewed
	0.30 to 0.10	Fine skewed
	0.10 to -0.10	Nearly symmetrical
	-0.10 to -0.30	Coarse skewed
	-0.30 to -1.00	Strongly coarse skewed

Fourth Moment   Kurtosis or peakedness of the distribution

Graphic kurtosis (Folk and Ward, 1957) $K_G = \frac{\phi 95 - \phi 5}{2.44\,(\phi 75 - \phi 25)}$

Absolute mathematical limits of K_G are 0.41 to infinity, but most values are in the range 0.60 to 5.0. A normal distribution has $K_G = 1.0$.

Table of graphic kurtosis values	
.67	Very platykurtic
.67 to .90	Platykurtic
.90 to 1.11	Mesokurtic
1.11 to 1.50	Leptokurtic
1.50 to 3.0	Very leptokurtic
3.0	Extremely leptokurtic

To treat K_G statistically (e.g., calculate the mean of a population) one must normalize the distribution using the formula:

$$K'_G = \frac{K_G}{(1 + K_G)}$$

Table AI. **Grain size values in millimeters and ϕ* at selected percentiles as derived from cumulative frequency curves, Donnelly Dome area, Alaska.**

Sample no.	Location (see Fig. 9)	Textural type+		ϕ and mm values at selected percentiles 5th	16th	25th	50th	75th	84th	95th
18	C1	(2)	ϕ	0.31	1.47	1.69	3.32	5.01	6.38	6.96
			mm	0.8	0.36	0.31	0.1	.031	0.12	.008
19	C1	(3)	ϕ	-5.43	-4.32	-0.77	2.94	4.40	5.51	6.79
			mm	43	20	1.7	.13	.047	.022	.009
20	C1	(3)	ϕ	-4.64	-2.66	51	3.77	5.44	5.97	6.96
			mm	25	6.3	0.7	0.73	.023	.016	.008
21	C1	(3)	ϕ	-5.39	-4.46	-2.68	1.69	3.47	3.74	4.72
			mm	42	22	6.4	.31	.09	.075	.038
22	C1	(3)	ϕ	-4.09	-3.06	-.93	2.56	4.13	4.92	6.79
			mm	17	8.3	1.9	.17	.057	.033	.009
23	C1	(3)	ϕ	-5.32	-4.39	-3.32	1.47	4.08	5.16	6.96
			mm	40	21	10	.36	.059	.028	.008
24	C1	(5)	ϕ	-6.57	-5.32	-4.46	-2.26	.28	2.12	4.68
			mm	95	40	22	4.8	.82	.23	.039
25	C1	(5)	ϕ	-5.28	-4.91	-4.52	-3.32	-.84	.38	1.64
			mm	39	30	23	10	1.8	.77	.32

* ϕ is defined as the $-\log_2$ diameter in mm (Krumbein, 1934, p. 65-77).

\+ Textural types are defined fully on p. 16 and are as follows: (1) silt mantle, (2) and (3) wedge-fill material, (4) undisturbed outwash gravel, (5) disturbed outwash gravel, and (6) sandy zone at base of sediment wedge.

Table AI (Cont'd)

Sample no.	Location (see Fig. 9)	Textural type		∅ and mm values at selected percentiles						
				5th	16th	25th	50th	75th	84th	95th
27	C1	(5)	∅	-	-	-5.70	-2.63	3.68	1.84	3.94
			mm	>100	>100	52	6.2	.78	.28	.065
28	C1	(5)	∅	-6.65	-6.07	-5.67	-4.31	-2.07	-.77	2.32
			mm	100	67	51	19.8	4.2	1.7	.2
29	C1	(5)	∅	-	-	-6.0	-4.17	-1.68	0	2.64
			mm	>100	110	64	18	3.2	1.0	0.16
30	C1	(5)	∅	-6.32	-5.64	-4.95	-3.17	-0.49	+.51	2.32
			mm	80	50	31	9	1.4	.7	.2
64	E4	(2)	∅	-4.17	-3.0	-1.59	2.64	4.61	5.50	7.00
			mm	18	8	3	.16	.041	.022	.0078
65	E4	(3)	∅	.32	1.47	1.79	3.74	not run		
			mm	.8	.36	.29	.075			
66	E4	(3)	∅	-5.29	-.38	1.69	3.72	5.16	5.80	6.80
			mm	39	1.3	.31	.076	.028	.018	.009
67	E4	(3)	∅	-5.0	-.38	1.29	3.97	5.26	5.72	7.38
			mm	32	1.3	.4	.064	.026	.019	.006
68	E4	(3)	∅	-4.53	-2.41	-1.0	1.60	not run		
			mm	23	5.3	2	..33			
69	E4	(3)	∅	-4.17	-1.26	-.49	1.89	4.0	4.76	6.38
			mm	18	2.4	1.4	.27	.062	.037	.012
70	E4	(3)	∅	-0.14	2.0	2.83		not run		
			mm	1.1	.25	.14	.053			
71	E4	(3)	∅	-2.46	-1.0	.51	2.94	not run		
			mm	5.5	2.0	.7	.13			
75	E4	(6)	∅	-4.86	-3.59	-2.04	1.69	2.94	3.84	5.88
			mm	29	12	4.1	.31	.13	.07	.017
76	E4	(5)	∅	-5.13	-4.39	-3.70	-2.66	-1.0	0	1.73
			mm	35	21	13	6.3	2.0	1.0	.3
114	E3		∅	-5.5	-4.9	-4.3	.15	3.62	4.57	6.5
			mm	46	31	20	.9	.081	.042	.011
115	E3		∅	-4.9	-2.25	-1.25	.7	3.9	4.75	6.5
			mm	30	3.8	2.4	.6	.065	.037	.011
116	E3		∅	-4.4	-3.5	-2.3	2.05	3.7	4.6	6.25
			mm	21	11	4.8	.24	.075	.041	.013
117	E3		∅	-5.9	-5.5	-5.2	-3.3	-.5	1.65	4.9
			mm	58	45	36	10	1.4	.32	.033
118	E3		∅	-5.6	-5.2	-4.8	-3.7	0	2.0	5.4
			mm	51	36	28	13	1.0	.25	.024
119	E3		∅	-5.1	-4.7	-4.6	-2.7	1.15	2.55	5.4
			mm	35	26	24	6.5	.45	.17	.024
120	E3		∅	-	-5.1	-4.6	-3.6	-1.5	-.7	1.2
			mm	>100	34	25	12	29	1.6	.43
121	E3		∅	-5.4	-4.9	-4.5	-3.25	-1.3	0	1.8
			mm	42	30	23	9.4	2.5	1.0	.43
122	D	(3)	∅	0.4	1.84	2.64	3.56	5.21	5.88	6.97
			mm	.76	.28	.16	.085	.027	.017	.008
124	D	(5)	∅	4.81	-3.24	-2.0	.25	2.56	3.74	5.97
			mm	28	9.5	4	.84	.17	.075	.016

Table AI (Cont'd)

Sample no.	Location (see Fig. 9)	Textural type	ø and mm values at selected percentiles						
			5th	16th	25th	50th	75th	84th	95th
125	D	(5)	ø -4.60	-3.46	-2.70	-.93	2.08	3.32	5.97
			mm 25	11	6.5	1.9	.22	.1	.016
126	D		ø -5.79	-5.6	-4.86	-3.46	-1.08	-.13	1.73
			mm 55	36	29	11	2.1	1.1	.3
127	D		ø -5.59	-4.91	-4.46	-3.14	-1.08	-.49	1.32
			mm 48	30	22	8.8	2.1	1.4	.4
138	C	(4)	ø -5.75	-5.0	-4.46	-2.74	-0.68	+0.44	2.47
			mm 54	32	22	6.7	1.6	.74	.18
139	C	(4)	ø -6.34	-5.41	-4.64	-2.41	-0.38	+0.52	1.84
			mm 81	42.5	25	5.3	1.3	.70	.28
140	C	(4)	ø -6.5	-5.55	-4.75	-2.85	-0.49	+0.29	1.89
			mm 92	47	27	7.2	1.4	.82	.27
141	B	(4)	ø -5.64	-4.91	-4.32	-2.35	-0.38	+0.36	1.74
			mm 50	30	20	5.1	1.3	.78	.30
142	B	(4)	ø -5.43	-4.70	-4.17	-2.59	-0.14	+0.97	2.64
			mm 43	26	18	6.0	1.1	.51	.16
201	B	(1)	ø 1.8	3.15	3.85	5.2	6.6	7.6	9.7
			mm 0.29	0.11	0.655	0.027	0.015	0.0052	0.0095
202	C	(1)	ø 1.85	3.18	3.85	5.25	6.6	7.6	10.0
			mm 0.28	0.10	0.0655	0.026	0.015	0.0052	0.0097
203	E	(1)	ø 1.0	2.6	3.13	4.62	6.52	7.65	10.0
			mm 0.5	0.166	0.115	0.045	0.011	0.005	0.0097

Table AII. Statistical grain-size parameters derived from ø values at selected percentiles on cumulative frequency curves of sediment samples, Donnelly Dome area, Alaska.

Sample no.	Location (see Fig. 9)	Statistical parameters*								
		Mz	Md	QD_ϕ	σ_G	σ_I	QSk_ϕ	Sk_G	Sk_I	K_G
18	C1	3.72	3.32	1.66	2.45	3.46	.03	.25	.170	.82
19	C1	1.38	2.94	2.59	4.92	6.77	-1.13	-.48	-.42	.97
20	C1	2.36	3.77	2.47	4.32	4.67	-.80	-.49	.63	.96
21	C1	.32	1.69	3.08	4.10	5.63	-1.30	-.50	-.45	.67
22	C1	1.47	2.56	2.53	3.10	5.64	-.96	-.41	-.32	.88
23	C1	.75	1.47	3.70	4.78	6.64	-1.09	-.23	-.17	.68
24	C1	-1.81	-2.26	-	3.72	3.56	-	.31	.206	.82
25	C1	-2.62	-3.32	1.84	2.65	3.69	.64	.40	.42	.77
27	C1	-.88	-2.63							
28	C1	-3.72	-4.31	1.80	2.65	4.01	.44	.34	.41	1.02
29	C1	-1.39	-4.17				4.17			
30	C1	-2.77	-3.17	2.23	3.08	1.77	.45	.20	-.50	.79

* The respective statistical parameters are defined and explained on p. 65 - 67.

Table AII (Cont'd)

Sample no.	Location (see Fig. 9)	Statistical parameters								
		Mz	Md	QDϕ	σ_G	σ_I	QSk$_\phi$	Sk$_G$	Sk$_I$	K$_G$
64	E4	-2.77	-3.17	3.10	4.25	6.05	-1.13	-.33	-.24	.78
66	E4	3.05	3.72	1.74	3.09	4.92	-.30	-.33	-.41	1.43
67	E4	3.10	3.97	1.99	3.05	4.93	-.70	-.43	-.44	1.28
69	E4	1.80	1.89	2.25	3.01	4.60	-.14	-.04	-.10	.96
75	E4	.65	1.69	2.49	3.72	5.34	-1.24	-.42	-.32	.88
76	E4	-2.35	-2.66	1.35	2.20	3.23	.31	.21	.25	1.04
79	C2	2.69	3.64	2.48	3.59	5.13	-1.16	-.40	-.37	.84
80	C2	-.03	-.59	2.04	3.07	4.47	.56	.28	.29	.93
88	C2	-.04	.91	3.52	3.88	5.20	-1.49	-.37	-.33	.51
110	C2	1.17	2.83	2.60	4.87	6.72	-1.00	-.51	-.44	.96
112	C2	.05	.89	3.22	4.02	5.53	-1.27	-.32	-.24	.64
114	E3	-.06	.15	3.96	4.74	6.55	-.49	-.07	-.004	.62
115	E3	1.07	.70	2.58	3.50	5.23	.63	.16	.09	.91
116	E3	1.05	2.05	3.00	4.05	5.66	-1.35	-.37	-.29	.73
117	E3	-2.38	-3.30	2.35	3.58	5.21	.45	.38	.45	.94
118	E3	-2.30	-3.70	2.40	3.60	5.27	1.30	.58	.62	.94
119	E3	-1.62	-2.70	2.88	3.63	5.22	.98	.45	.50	.75
120	E3	-1.20	-3.60				3.60			
121	E3	-2.72	-3.25	1.60	2.45	3.54	.35	.33	.36	.92
122	D	3.76	3.56	1.29	2.02	2.92	.37	.15	.15	.95
124	D	.25	.25	2.28	3.49	5.12	.03	-.00	.03	.97
125	D	-.36	-.93	2.39	3.39	4.99	.62	.25	.28	.91
126	D	-3.06	-3.46	1.89	2.74	3.87	.49	.22	.30	.82
127	D	-2.85	-3.14	1.69	2.21	3.26	.37	.20	.24	.84
138	C	-2.43	-2.74	1.89	2.72	3.97	.17	.17	.22	.89
139	C	-2.43	-2.41	2.13	2.97	4.20	-.10	-.01	.01	.79
140	C	-2.70	-2.85	2.13	2.92	4.19	.23	.08	.10	.81
141	B	-2.30	-2.35	1.97	2.64	3.75	-.00	.03	.07	.77
142	B	-2.11	-2.59	2.02	2.84	4.06	.44	.26	.28	.82
201	B	5.3	5.2			2.30			.108	
202	C	5.35	5.25			2.335			.115	
203	E	4.92	4.62			2.62			.199	

Table AIII. Water content by percent of moisture samples, Donnelly Dome area, Alaska.

Sample no.	Location (see Fig. 9)	Textural type*	Textural description	Water content (by wt. percent)
M1	C3	(3)	Light blue gravelly clayey silt	21.9
M2	C3	(5)	Reddish brown silty sandy gravel	9.1
M3	C3	(5)	Gray brown silty gravelly sand	5.9
M4	C3	(5)	Brown gravel-sand-silt mixture	12.3
M5	C3	(4)	Grayish brown gravel	3.5
M6	E1	(3)	Light blue gravelly clayey silt	16.7
M7	E1	(5)	Brown sandy gravel	3.1
M8	E1	(6)	Tan gravelly silty sand	10.6
M9	E1	(6)	Brown gravelly sand	8.5

*Textural types are defined fully on p. 16 and are as follows: (1) silt mantle [loess-soil], (2) and (3) wedge-fill material, (4) undisturbed outwash gravel, (5) disturbed outwash gravel, and (6) sandy zone at base of sediment wedge.