4. Sumgin, M. I., and others. "The Thermal Regime of Soils and Grounds in the Permafrost Region," Academy of Sciences, Moscow, 1940. Translation of Chapter V by E. A. Golomshtok.

5. Beskow, Gunnar, "Soil Freezing and Frost Heaving with Special Application to Roads and Railroads," The Swedish Geological Society, Series C., No. 375, 26th Year Book, No. 3, Translated by J. O. Osterberg, Asst. Prof. of Civil Engineering, Northwestern University, Evanston, Illinois.

6. Beskow, Gunnar, " Scandinavian Soil Frost Research of the Past Decade," Highway Research Board, Proceedings of the Twenty-Seventh Annual Meeting, 1947.

7. Berggren, W. P., "Prediction of Temperature - Distribution in Frozen Soils," American Geophysical Union, Transactions of 1943, Part III, p. 71.

8. Hodgeman, Charles D., Editor-in-Chief, "Handbook of Chemistry and Physics," Twenty-Seventh Edition, Chemical Rubber Publishing Co., Cleveland, Ohio, 2553 pp., 1943.

9. "Monthly Weather Review," Weather Bureau, U. S. Department of Agriculture, Printed by the U. S. Government Printing Office.

10. Kersten, Miles S., "Laboratory Research for the Determination of the Thermal Properties of Soils," Comprehensive Report. January 1948. Department of the Army, Corps of Engineers, St. Paul District. Research Laboratory Investigations, Engineering Experiment Station, University of Minnesota, 90 pp.

11. Kersten, Miles S., "Laboratory Research for the Determination of the Thermal Properties of Soils - Final Report," Department of the Army, Corps of Engineers, St. Paul District, September 1948. Research Laboratory Investigations, Engineering Experiment Station, University of Minnesota.

12. American Society of Heating and Ventilating Engineers, "Heating Ventilating Air Conditioning Guide," American Society of Heating and Ventilating Engineers, New York.

13. Baver, L. D., "Soil Physics," John Wiley and Sons, Inc., New York, 370 pp., 1940.

14. Barnes, Howard T., "Ice Engineering," Renouf Publishing Co., McGill College Avenue, Montreal, 366 pp., 1928.

15. Schack, Alfred., "Industrial Heat Transfer," John Wiley and Sons, Inc., New York, 371 pp., 1933. Translated by H. Goldschmidt and E. P. Partridge.

16. New England Division, Corps of Engineers, War Department, Boston, Mass., "Report on Frost Investigation 1944-1945," April 1947.

17. Frost Effects Laboratory, New England Division, Corps of Engineers, Department of the Army, Boston, Mass., "Frost Investigation 1945-1947. Addendum No. 1 to Report on Frost Investigation 1944-1945," June 1948.

INTERPRETATION OF PERMAFROST FEATURES FROM AIRPHOTOS

Robert E. Frost, Joint Highway Research Project, Purdue University

Synopsis

This report describes the use of aerial photography for predicting the presence of permafrost and certain permafrost features in arctic and subarctic regions. The techniques of airphoto interpretation for use in identifying engineering soil conditions and drainage conditions as developed in temperate climates has been expanded to include the application of the principles to the Arctic. These techniques have been used in the far northern regions in connection with highway and airfield location and general soil survey, particularly in Alaska.

Permafrost research at Purdue is being done as a part of the general permafrost program by the St. Paul District under the direct supervision of the Office, Chief of Engineers, Department of the Army. Five field trips to Alaska by members of the Purdue Staff have provided an opportunity to

study frost phenomenon of many types under a wide range of arctic and subarctic conditions.

In permafrost regions engineering problems associated directly with permafrost result from an upset in the thermal balance in those situations where fine-textured soils exist. Influencing factors are topographic position, surface insulation, soil temperature, soil texture, exposure to heat, and moisture. Problems associated with the permafrost can be predicted from airphotos if such items as topographic position, soil texture, cover, and drainage condition can be determined and evaluated in light of the climate, type of permafrost, and exposure to heat.

Many surface features directly associated with natural permafrost phenomena can be seen on airphotos of suitable scale. These are related to such processes as freezing or thawing and are exhibited in a variety of forms. Many of the surface features indicate to a large extent the type of action taking place.

Prediction of engineering difficulties in the "active zone," or the "frost zone" in permafrost regions is done by determination and evaluation of topographic position, soil texture, and drainage in light of climate and depth of seasonal thaw. Because of the usually small areal extent of such features they often can not be seen on small-scale airphotos and they are not predicted directly. It is necessary to determine many of the influencing factors from airphotos by detailed study of soil-permafrost patterns before such features can be predicted and evaluated.

In nonpermafrost areas of the Arctic and Sub-Arctic, frost susceptible soils can be identified from airphoto study by applying certain of the airphoto interpretation principles. Since silty soils are the most susceptible to frost difficulties it often becomes a matter of identifying and separating silt soils from those in other textural classes. One of the most important influencing factors, ground water, must be inferred from an evaluation of such items as topographic differences, parent material structure and texture, and vegetation, since little research has been done in photo identification of ground-water conditions in the Arctic.

Interpretation in temperate regions for predicting frost action is somewhat difficult, particularly in areas having a highly cyclic climate throughout a year. Soil textures can be identified in nearly all climatic belts and the frost susceptible soils determined, but evidences of frost action are not pronounced, particularly from the standpoint of photo interpretation, due to the minute photo scale of the frost phenomenon in an area.

From the standpoint of airphoto interpretation and frost susceptibility of soils it is believed that predictions in the Arctic and Sub-Arctic can be done with a high degree of accuracy. Airphotos can be used to locate and identify adverse permafrost conditions where difficulties of construction and subsequent failure will result. Likewise, the photo method can be used to locate and identify the sites containing the better engineering soils.

This paper is directed toward the identification and interpretation of permafrost and permafrost features using aerial photographs. The purpose of the paper is to present the more general aspects of interpretation of soils and permafrost from airphotos and to present airphotos of some of the peculiar surface configurations of permafrost patterns.

The data were obtained in connection with a study covering the airphoto interpretation of permafrost (1) being prepared by the University for the Office, Chief of Engineers, Corps of Engineers, through a contract between the University and the St. Paul District. Three papers (2, 3, 4) and one progress report (5) have been published covering various aspects of photo interpretation of permafrost regions. The permafrost study is designed to determined procedures for identifying and interpreting engineering soils and permafrost conditions, from aerial photographs of arctic and subarctic regions. The project has been confined to the Territory of Alaska and five summers have been spent in the field gathering data.

This paper does not contain a review of the airphoto interpretation techniques since they are discussed elsewhere (6 to 28 incl.) The paper reports on field observations by the Purdue parties and on observations made by others who have studied the permafrost phenomenon. The more important observations and opinions of others have been referenced in the bibliography.

Figure 1. Dry-Frozen Sand.

Permafrost

Definition - Several definitions of permafrost appear in the literature. Permafrost may be defined as permanently frozen earth materials which include bedrocks having a temperature below freezing and other materials which have become solidlike by low temperatures and have remained in such a state continuously for a long period of time (29, p. 3) (30, p. 1,436). Permafrost may be defined on the basis of temperature exclusively irrespective of degree of induration, water content, or lithologic character (29, p. 3). Permafrost may be defined as permanently frozen subsurface material not subject to seasonal freezing or thawing.

Setting - Permafrost exists in areas where winter freezing exceeds summer thawing as stated by Taber (30, p. 1,505). It occurs where the mean annual temperature is below freezing. Some believe that permafrost areas correspond closely with the unglaciated

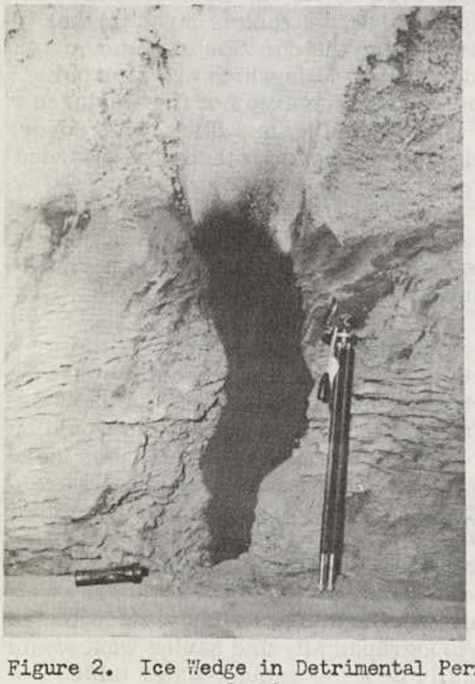

Figure 2. Ice Wedge in Detrimental Permafrost.

Figure 3. Ice Lenses in Detrimental Permafrost.

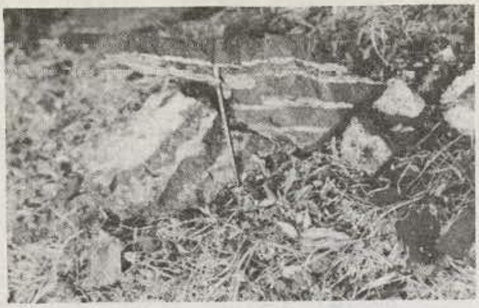

Figure 4. Laminated Ice-Soil Structure.

Figure 5. Ice Crystals.

areas in arctic and subarctic regions. Muller points out that it occurs in almost one-half of the USSR and in most of Alaska and northern Canada (29, p. 1). The depth of the permanently frozen materials varies considerably from just a few feet near the southern limits to nearly a thousand feet in the northern coastal plain of the American Continent.

Mode of Occurrence - Permafrost exists in the following forms: dry frozen or detrimentally frozen.

Active Zone - This is the entire layer of ground above the upper surface of the permafrost layer, most of which freezes and thaws every year. In the Arctic and the SubArctic the thickness of the active zone depends on such factors as soil texture, topographic position, vegetative cover (insulation), and exposure to heat or summer's warmth, as stated by Leffingwell (31, p. 181). In the Arctic Coastal Plain well-drained gravels situated high topographically have an active layer thickness of several feet, often six or more. The finely textured soils which are situated in low topographic positions in the Arctic have an active layer varying in thickness from 12 to perhaps 20 inches. In areas where a thick moss carpet exists the active layer is very shallow - ice can be found beneath the moss in many instances even as late in the season as September. In southern parts of permafrost regions the active zone is much thicker since soil temperatures in the permafrost are warmer and the duration of summer heat is longer than in the Arctic. In well-drained granular soils which are situated high topographically the active zone is much deeper than in the areas of fine-textured soils. Finely textured soils which are relatively unprotected from a thick moss cover or a forest growth may thaw 12 or more feet. However, where protection is afforded seasonal thaw is considerably less.

Frost Zone - This is the top layer of ground subject to seasonal freezing and thawing. Where seasonal freezing penetrates to or below the upper surface of the permafrost layer the frost zone and active zone are identical.

Dry-Frozen Materials - Dry frozen refers to a condition in clastic materials in which the mass is rendered solid by the freezing of interstitial water. In the normal and unfrozen state such soils would be well-drained internally. Ice lenses, ice wedges, or ground-ice areas usually are lacking and such soils can experience thaw without severe settlement. They do not contain free ice as a cementing substance (29, p. 3) (32, p. 1). Such soils are usually confined to granular areas situated high topographically and having what would normally be a low ground-water table.

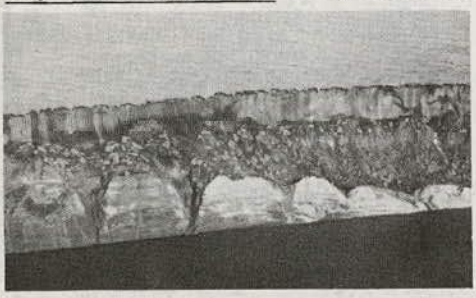

Figure 6. Massive Ground Ice.

Typical soil types are those associated with sand dunes or high sand terraces.

Detrimentally Frozen Materials - This type of permafrost includes: fine-textured soils which contain a large percentage of ice in their mass in the form of crystals, small lenses, or small wedges; soil masses which have been so arranged by segregation of ice and soil particles that they form polygonal blocks of varying size and types; materials situated low topographically and having large masses of ground ice as an integral part of their mass; and large masses of ground ice. In general, the most detrimental permafrost situations may occur on nearly all common landform types provided that soil textures are fine and that the topographic situation is somewhat depressed, very slightly sloping, or exceedingly flat. Thus, such land forms as broad flat plains (level or slightly sloping); valley fill; transition zones; low colluvial slopes; lake beds; backwater flood plains; and others of a similar nature which contain finely-textured soils can be expected to contain detrimental permafrost.

Engineering Significance

With regard to the effect of permafrost on engineering construction, it has been found that both good and bad soils occur in permafrost regions. For the most part the good construction areas contain well-drained granular materials which occur in elevated positions in comparison to the surrounding terrain. The poor areas are those generally low areas which consist of the fine-grained soils having subsurface ice layers and ice wedges.

The engineering problems are contingent on which type of permafrost exists or which type exerts the greatest influence on a structure. Structures confined to the active zone are subjected to seasonal freezing and thawing which will be accompanied by considerable movement if the soils are finely-textured. This is particularly objectionable for such structures as highways, railroads, power lines, buildings, pipe lines, and utilidors. The period of most severe damage is during and shortly following the spring breakup. It is during this period that paved surfaces suffer the greatest distress. Unpaved areas or areas of natural cover in which the soils are silty are rendered non-trafficable for vehicular traffic during and immediately following such a period. Such areas recover rapidly once the frost leaves and the water drains away.

Structures placed on permafrost of the dry-frozen type usually do not experience serious damage from the resulting thaw. Airfields, runways, roads, and buildings have been placed on frozen sands and gravels and have performed satisfactorily not only following construction but throughout the critical breakup seasons as well. There are, however, often local areas containing detrimental permafrost which lie within the bounds of dry frost which should be avoided in engineering construction. Such areas are common in landforms associated with water deposition.

Those structures placed on detrimentally frozen materials experience severe distress almost immediately following construction. Thaw is usually continuous under heated structures which have not been insulated properly from the ground surface. The destruction, or merely disturbance, of the protective natural insulation renders detrimentally frozen areas non-usable for structures and non-trafficable for most vehicles. Recovery of permafrost of the detrimental type in disturbed areas is extremely slow, even after completely abandoning a disturbed site.

Permafrost Pattern Features

On the basis of the field and laboratory work performed to date in connection with the research program designed to develop means of locating various degrees of permafrost in arctic and subarctic regions, it has been found that aerial photographs can be used to distinguish good materials and good site areas from detrimentally frozen materials and unsatisfactory site areas (1). Aerial photographs can be used to identify soil textures and permafrost conditions associated with various arctic and subarctic land forms. By utilizing airphoto interpretation procedures in arctic and subarctic regions,

Figure 7. House Settlement.

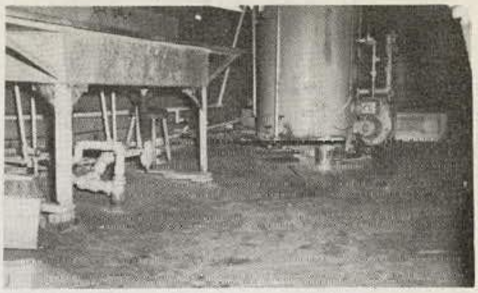

Figure 8. Building Settlement.

engineering problems can be anticipated, feasible site locations can be ascertained, and design practice can be determined with a minimum amount of field work, time, delay, and expense (3).

Basic research on interpretation of soils from airphotos conducted in warmer latitudes is being extended to include the permafrost regions. In arctic regions as in warmer areas the earth's surface features of any general area can be grouped, which grouping is called a pattern. The pattern reflects the surface materials. Detailed study of such features as landform, topographic position, drainage pattern, erosion features, gully characteristics, vegetation, color tone, and others makes it possible to determine the soil parent-material-type and its associated texture, drainage characteristics, and permafrost conditions. Some of the more important elements which exert considerable influence on permafrost are discussed briefly.

Topographic Position - In permafrost regions the topographic position of a deposit or area is one of the most important factors in the occurrence of permafrost, and, therefore, in its identification both from airphoto interpretation and field interpretation practices (3). Since the most detrimental types of permafrost favor certain topographic situations, which are recognizable on photos, permafrost can be predicted in any physiographic arrangement provided such topographic requirements exist. For example, detrimental permafrost can be expected to occur in a limited number of topographic situations in bedrock areas. Such situations are associated with areas of valley filling where sloping terrain allows the accumulation of colluvial material, or in upland depressed situations which would normally contain loose or unconsolidated material. Other elements lend supporting evidence since they are closely related to topographic position, particularly drainage and vegetation.

Landform - Landform as a pattern element is of great importance in identifying the origin of a deposit, in part its erosional history, and in part the texture to be expected. The landform evaluated in the light of climate, vegetative cover, drainage, and topographic position makes it possible to identify permafrost type. In general, landforms are little altered by the presence of permafrost other than in surface detail. Sand dunes, eskers, kames, till plains, terraces and most other landforms, whether frozen or

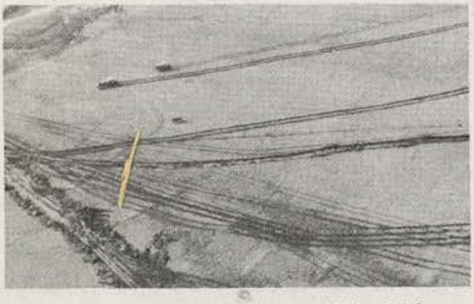

Figure 9. Trafficability Difficulties.

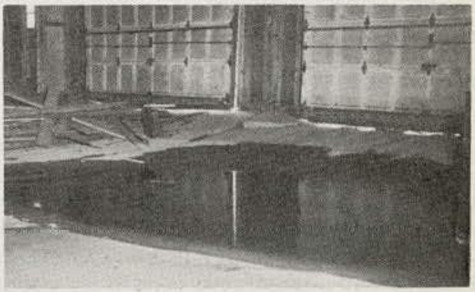

Figure 10. Settlement of Garage Floor.

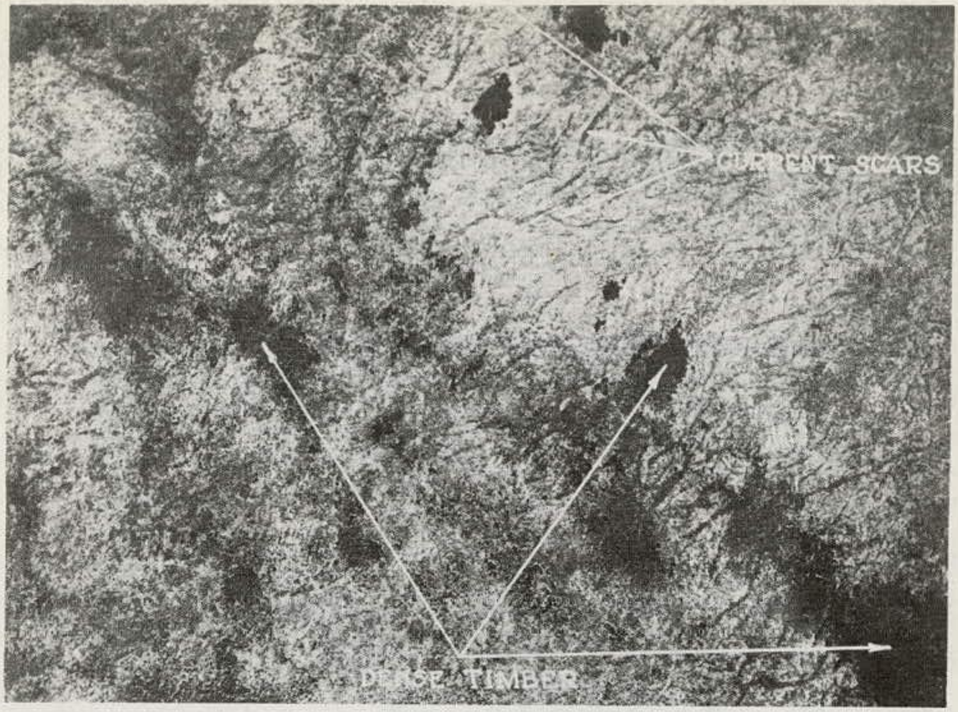

Figure 11. Airphoto Pattern of Well-Drained, Unfrozen Gravel Terrace.

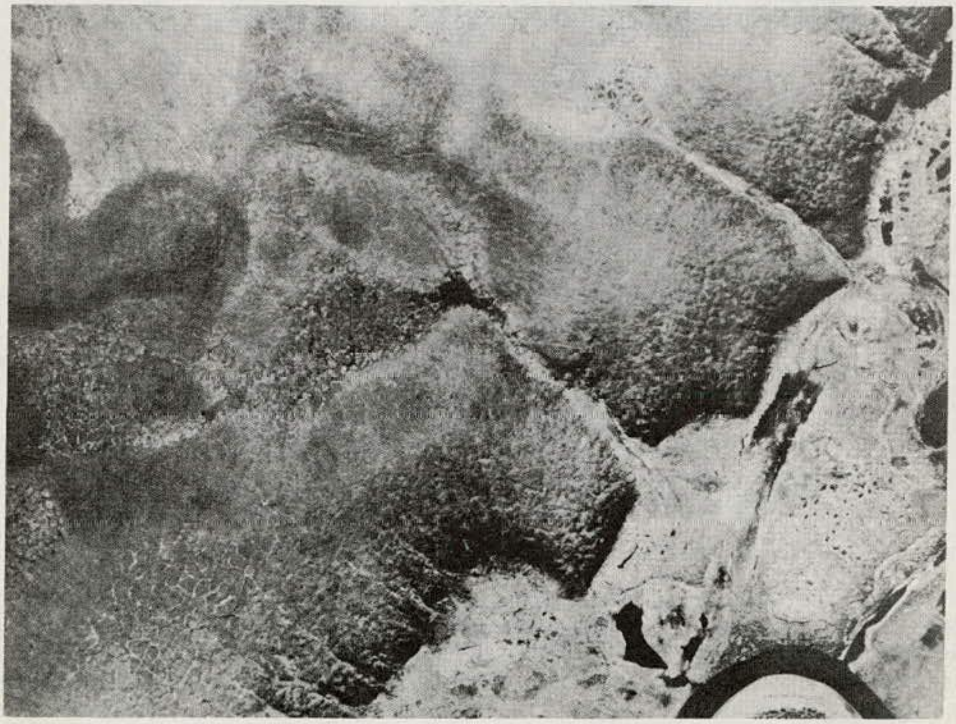

Figure 12. Airphoto Pattern of Detrimentally-Frozen Silt-Covered Terrace.
(NOTE: Bar scale on all photos, where shown, represents 1000 feet.)

unfrozen, have the same respective landform characteristics in any climate. Variations attributed to permafrost are reflected in the macrodetail on the surface such as changes in vegetation, erosional characteristics, color or other features, most of which can be seen on airphotos. Chief among the surface features are soil polygons.

Drainage Pattern - In general, the areal-drainage pattern is little altered by the presence of permafrost. The physiographic arrangement is by far the greatest factor in controlling the major pattern of a watershed. At best, the areal-drainage pattern assists in identifying the major parent-material-type and its structural arrangement (24). Locally, permafrost may exert considerable influence, particularly on the gully characteristics.

Figure 13. Airphoto Pattern of a Detrimentally-Frozen Terrace-Flood Plain Area.

Erosion Features - Frozen soils erode chiefly by thaw, either by running water or by a sudden upset in the thermal balance existing between air-soil temperature as controlled by vegetative cover and exposure to heat.

Erosion by running water is common in upland areas where a gully system will be forced to carry a sudden increase of flow. In such instances if polygons are present the polygon channels become gullies and destruction of the polygon net is rapid. The ice in the channel portion thaws first causing a general subsidence in and adjacent to the polygon channel. This is indicated by overhanging vegetation mats along channels. If thawing is particularly active due to the addition of excess surface water or a particularly warm summer, complete polygons will be destroyed, leaving only isolated mounds of soils as remnants.

When polygonal ground is cleared prior to cultivation, the thermal balance is upset and the ice in the soil melts. If surface gullying does not start or is not allowed to progress, the subsoils will thaw slowly and the water will flow away as ground water. This will result in considerable settlement in areas underlain by ice wedges or other ice masses and will create a topography consisting of a series of domes or mounds of considerable regularity in size and spacing. These features also can be seen on airphotos.

One of the most common types of gully systems in permafrost regions is that associated with button drainage. Inland, and some distance away from the immediate effects of a coast line, or some other erosional base level, thaw in polygon areas usually starts at the intersections of the polygon channels by the formation of small circular pools of water. If any surface flow is established an irregular and angular arrangement to the

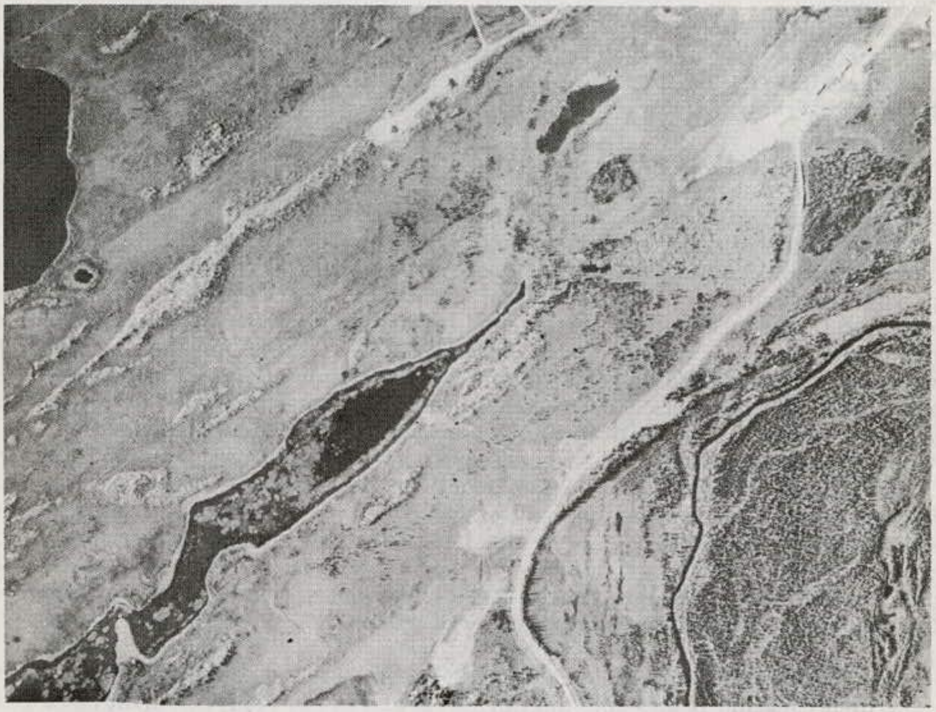

Figure 14. Airphoto Pattern of a Dry-Frozen Sand Terrace.

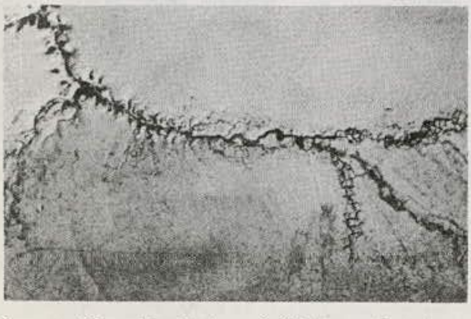

Figure 15. Airphoto of Polygon Erosion,

Figure 16. Polygon Remnants.

Figure 17. Silt Pinnacle of Center of Polygon Remnant.

gully plan is obtained in which a series of connected pools exists. This type of drainage is commonly called button drainage and occurs widespread in the Arctic, particularly in some of the broad gently sloping upland valley-fill situations. Such features are easily discernible on airphotos.

Another of the more common erosional features found in permafrost regions is the occurrence of "caving of frozen banks" along the banks of streams and the shores of large bodies of water. In such instances the under-cutting action produced either by waves or by moving water causes considerable thaw and undermining at the water line which results in caving banks. In areas where timber occurs "leaning trees" accompany the action. Where polygons intersect a waterline or a shore line under-cutting is severe and great blocks of frozen soil break off, usually along the ice-soil contact of the first polygon channel inland. Erosional features of this type are easily discernible on good quality photos.

There are other features which are often exhibited on airphotos in permafrost areas which in one sense may be thought of as part of the erosional pattern. Some of these, such as thermokarst, solifluction, and altiplanation terraces, are discussed under "Special Permafrost Features."

Gully Characteristics - In southern latitudes, or more generally speaking in unfrozen soil areas, gully characteristics such as slope and cross-section, are reliable indicators of soil texture and soil-profile development. This is not true of permanently frozen soils. The full significance of permafrost on gully characteristics has not been completely worked out; however, a few general observations are worthy of mention. Granular soils, both during and after a thaw, exhibit the customary V-shaped cross-section accompanied by a short steep gradient, and textural determinations based on these features are reliable. In finely textured frozen soils, textural predictions based on gully characteristics are unreliable. Melting of the ice in the soil is rapid when in direct contact with running water. This usually allows the "waterfall-type" of gully to occur in which the waterfall rapidly works upstream leaving a vertical U-shaped trench. Where quantities of water are great the trenches are broad, thus allowing the action of the sun's heat to accelerate sidewall thaw. When quantities of water are small the channels are narrow and usually the overhanging mat of moss and vegetation acts as a protector from the sun's heat and may hold a gully in check until the following winter freeze. Such features are of such small magnitude that they are extremely difficult to see on airphotos, even in tundra regions. In timbered areas the screening blanket of vegetation usually obliterates all but the extremely large gullies.

Vegetation - As pointed out by Spurr (13,p194)in his book on photo interpretation of tree species, identification is an ecological problem and the interpreter must have an understanding of the distribution of the species, particularly as correlated with topography and site. The interpreter should have cognizance of complex factors of plant succession, since the vegetation is constantly changing and the factors governing changes are local in effect (33, p. 27). This is particularly true in the Arctic and Sub-Arctic where exposure to light and heat and the location of the timber line with respect to latitude as well as logging operations, fire, and permafrost are

Figure 18. Airphoto of Button Drainage.

important factors governing growth and changes in species. For example, in some situations the north-facing slopes will be mantled with spruce whereas the south-facing slopes will be mantled with aspen and near the limits of timber cover, the east-and-south facing slopes may be timbered while the north-facing slopes are barren.

According to Jenness (34, p. 23), permafrost affects vegetation in two ways. In areas where the active layer is shallow the frozen ground represses all deep-rooted species and limits the growth to those varieties that have shallow roots. In low-lying areas the upper layer is usually waterlogged and all but the most water-loving species are eliminated.

As an example of the permafrost-vegetation relationship in one of the major river valleys of the Sub-Arctic, Stoeckeler says (33, p. 5): "White spruce-paper birch forests occur on both frozen and unfrozen soils, black spruce-tamarack stands grow on frozen muskegs; aspen occurs on dry, unfrozen, south-facing slopes; balsam poplar stands are confined to sites adjacent to active streams having moist, sandy soils unfrozen to a depth of at least ten feet; pure dense willow stands grow on bare river bars which are unfrozen to ten feet or more; and pure alder brush occurs on wet peaty soils frozen at a depth of 30 inches."

Vegetation should not be used alone as a permafrost indicator. Permafrost conditions can be inferred, in many instances, by correlating cover types with soil texture, drainage, and topographic position.

Color Tones - The element color tone has little significance as a direct indicator of soil texture in regions of permafrost. The permafrost is a natural barrier to downward movement of water, hence, surface soils are usually of a high moisture content, often saturated. This condition, of course, renders depressed areas or other waterlogged soils dark in tone regardless of texture. Only on high, unfrozen, well-drained areas, such as terraces or sand dunes, are color tones light. Therefore, for color tones to have any significance it is necessary that they be evaluated in the light of topographic position, landform, and drainage.

Special Permafrost Features

Permafrost patterns range from some of the easiest to some of the most difficult to interpret using aerial photographs. Fortunately the majority of the detrimental types are easily identified on fair-quality photos and engineering evaluation is farily straightforward. The majority of the detrimental patterns contain a variety of configurations or surface features which may be associated with areas of ground ice, unstable thawed zones, severe frost susceptibility, or various types of associated earth movement. Those features creating recognizable patterns include polygons, pingos, altiplanation terraces, thermokarst, certain types of soil flows, mud boils, humpies, and button-type drainage. Some of the features only occur in association with permafrost, others may occur in any region where the requirements of soil texture, moisture, temperature variation, topographic position, and slope exert the correct influence.

Soil Polygons - Soil polygons are one of the chief identifying surface features of permanently frozen ground. In arctic and subarctic regions polygons indicate detrimentally frozen ground, with the one exception being a particular type found in a gravel-soil outwash area. Polygons are geometric configurations which are presumably formed by an adjustment of the frozen earth mass, just beneath the surface, to stresses from seasonal expansion and contraction which are brought about by temperature variations. Leffingwell (31, pp. 205-212), in his discussion on polygons, states that the process of polygon formation is a continuously growingthing, since the summer melt water flows into new cracks and freezes upon contact with the permafrost. Since the ice-soil contact is a plane of weakness the addition of seasonal melt water from the surface snows causes continued ice-wedge growth in the cracks. Leffingwell continues by stating that the wedge ice grows from year to year and that ice may increase until approximately one-fifth a polygon block area will be underlain by ice and that such action could proceed

Figure 19. Airphoto of Raised-Center Polygons.

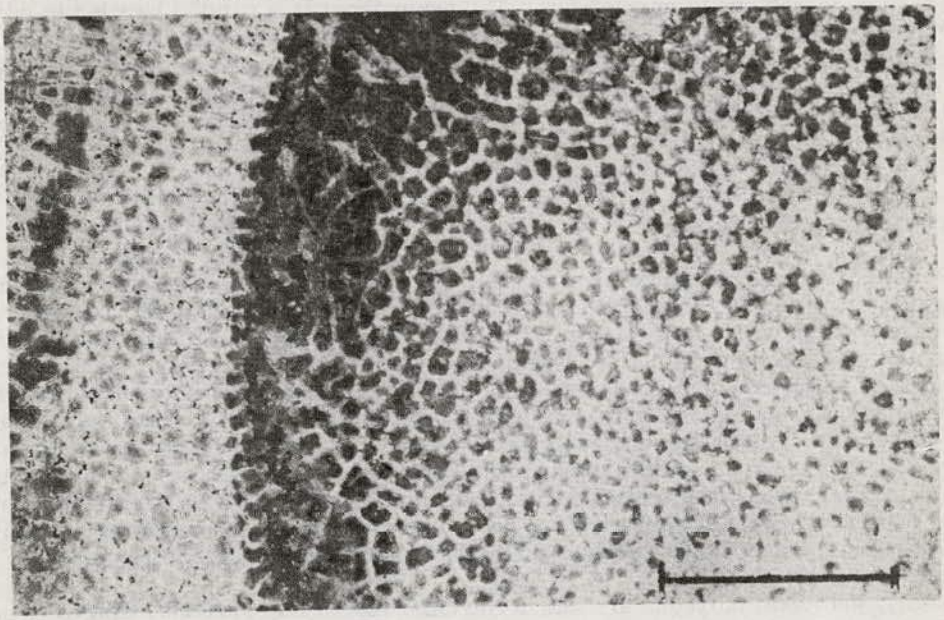

Figure 20. Airphoto of Depressed-Center Polygons.

to such a stage that instead of having ice intruding into the mass of surface earth that ice would be the major material, and it would appear that the earth materials would be intruding into the mass of ice.

There are a variety of sizes, shapes, and types of polygons and descriptions contained in the literature (30, 31, 35, 36). The two most important types associated with permafrost are: (1) those with depressed centers or pans which are inclosed by raised dykes or perimeters and (2) those with raised centers and depressed perimeters as outlining channels. Polygons of both types vary in size from 15 or 20 ft. to perhaps 200 ft. across the polygon. The number of sides varies from four to six with five-sided figures being the most common.

Soil polygons in permafrost areas are confined to unconsolidated materials which have been rendered solid by freezing, and they commonly occur throughout most of the permafrost regions. They do not occur as an integral part of bedrock areas. The only place polygons occur in bedrock areas is in the colluvial materials on the side slopes of hills or in places where the bedrock is overlain by a relatively deep unrelated soil mantle. In the Arctic, polygons abound, being particularly abundant in the Arctic Coastal Plain, where they are easily seen because of the absence of timber cover. In the Arctic, polygons are found on silt and sand and one variation is found on gravel soils. To the south, polygons are more closely associated with silt soils, a low topographic position, and a source of water than are those in the Arctic. This limits their occurrence to those alluvial and colluvial silts which satisfy the requirements of topography and moisture in southern regions.

Raised-Center Polygons - Polygons of the raised type consist, for the most part, of a soil mass in block form which is outlined or surrounded by a perimeter consisting of a series of channels underlain by ice in wedge form. The largest are often over 200 ft. across with the surrounding channels 10 to 15 ft. in width and 4 to 6 ft. in depth. In arctic regions, quite frequently a secondary system of smaller polygons will have formed within the larger polygon outlines. Well-developed polygons of this type are associated with frozen-silt soils, and they usually occur on the level topography associated with high terraces and on the higher areas of the flood plains. Frequently, well-formed polygons occur in bedrock areas, but they are confined either to an unrelated surface mantle or to broad valley-fill situations and to lower and mid-colluvial slopes of hills. Polygons also occur widespread throughout the timbered areas, but they are more closely related to topography, slope, moisture, soils, and vegetative cover than in the arctic regions to the north.

In general, polygons in the southern areas of the Arctic and Sub-Arctic are confined to water deposited materials, to low colluvial slopes in bedrock areas, and in generally depressed situations in glacial drift areas. The polygons are somewhat smaller than those which occur in the north. Shapes and designs vary considerably, but five-and six-sided figures seem to predominate. In water-deposited materials, particularly stream valleys, polygons are confined to low intermediate situations in which the major soil type is silt. They occur both in areas covered with timber and in areas covered with tundra-type vegetation. The depth to permafrost varies considerably; however, in general, the depth of maximum thaw is approximately 24 in. in polygon areas where moss is relatively thick and somewhat less under timber cover and a thick moss.

The depressed-center polygons are most commonly found in the Arctic regions, chiefly tundra. They are associated with a depressed topographic position and occur in such situations as a depression in an old flood plain, a depression of a stream terrace, the bed of an old lake, or in broad and generally depressed areas of coastal plains. Depressed-center polygons are found in association with silt, sandy silt, and fine sands of coastal plain soils. They also occur in back-water or ponded areas of broad flood plains.

This polygon consists of a "pan" or "paddie" surrounded by a raised rim or series of dykes. The centers usually consist of a thick mat of floating grass and roots; often the water is as much as two ft. in depth. A layer of ice, often several feet thick forms the bottom of the pan. The dykes, which completely inclose the polygon, are often 2 ft. above the water level (or the level of the inclosed pan surface) and are covered with grass, moss, lichens and occasionally niggerheads. The dykes, or mounds, have longitudinal cracks or depressions in their centers. The dykes often attain a width at the base of 8 to 10 ft. and at the top 4 to 5 ft. The small channel in the center of the dykes are often as much as a foot below the top surface of the dykes. These channels frequently contain water above the ice and beneath a thick mat of moss.

In general the depressed-center polygons are not as large as the raised-center type. When the two types are found in close association the depressed-center type occupies the lowest topographic position. In transition zones, such as the change between the beach of a lakebed and the adjacent upland, the two types of polygons often merge into one another with geometric regularity.

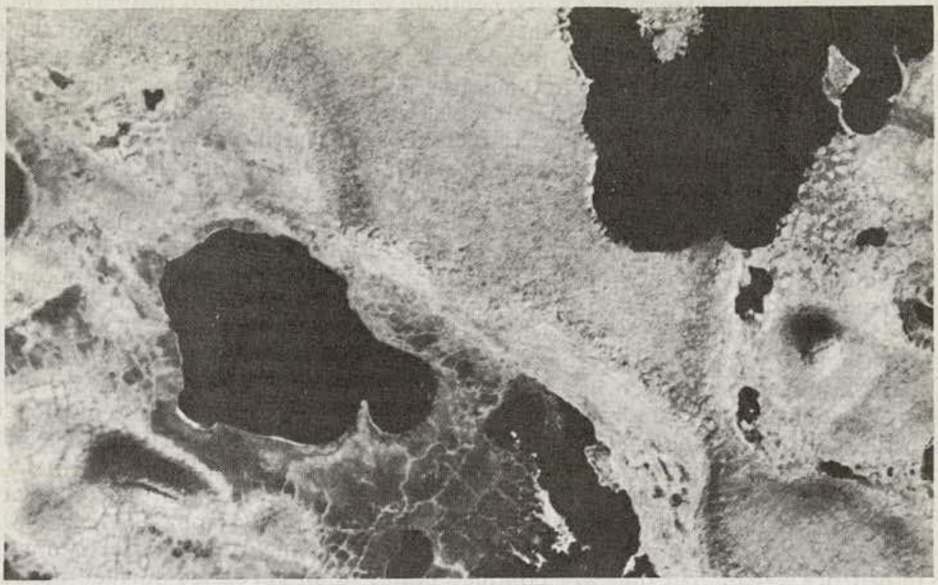

Figure 21. Airphoto of a True Pingo.

Polygons of a different type occur on some of the gravel bars and gravel spits or other low depressed areas adjacent to the coast. For the most part the polygons are rectangular in shape; channels do not always intersect at common corners. Sizes vary considerably as do the depths of the channels. At one location studied channels were as much as 5 ft. in depth and about 8 ft. across; surface water was present in the channels. Some squares were nearly 200 ft. across. In most of these situations the surface of the beach deposit was a matter of a few feet above the water level and soils were gravel or sand. Whether or not ice existed at any depth beneath the polygon markings could not be determined, since sampling was done with a shovel and with a soil auger (dangers encountered with using dynamite in loose gravel precluded its use); however, the patterns, their shapes and arrangements, are believed to be significant even though the full significance is not clearly understood. The only vegetation consisted of lichens and grass, the grass occurring in the channels.

Pingos and Other Mounds - Frost mounds of many types occur at scattered locations throughout the Arctic and Sub-Arctic. In the Arctic the most outstanding mounds are those called "pingos" which occur in the Arctic Coastal Plain. In Alaska they occur in an area extending from the Canadian border generally westward to Wainwright; in the narrow coastal plain region between Pt. Hope and the Seward Peninsula; the coastal plain which forms a fringe around the major part of the Seward Peninsula; to a limited extent in the delta region of the lower Kuskokwim-Yukon valleys; and in the interior of the Seward Peninsula which is in the Kuzitrin-Noxapaga Basin. A few scattered mounds believed to be associated with other frost phenomenon occur in isolated areas in the interior, principally in some of the major stream valleys.

The pingos seem to be of three general types, as far as the writer is able to determine from field observation and literature survey. These are: (1) the true pingos, or frost mounds, which are believed to be the result of upheaval of the earth's crust from pressure of ice from beneath the surface; (2) the isolated dome-shaped terrace remnants, which are the result of peculiarities of arctic erosion and dissection which rendered the mounds conical in shape; and (3) those mounds formed by upward flow of water and/or soils to the surface through an orifice of some type.

Mounds of the dissected-terrace-remnant type occur in stream valley situations and occur topographically on the next highest elevation above the flood plain. Many have steep side slopes and all are usually dome-shaped. When viewed from a distance all appear to have the same general surface elevation. Those studied by the Purdue group showed no signs of having been cracked open or distorted in any way due to pressure from beneath. The soils were sand and gravel. Collier (37, p. 26) and Brooks (38, p. 310) both describe and discuss mounds of this type in the interior of the Seward Peninsula. They say that they are hillocks of stratified gravels, are about 50 ft. high, and are remnants of a former plain left by erosion. They suggest that they resemble haystacks.

Mounds of the type built up from upward flow of water and/or soil occur at many scattered locations in Alaska. One large mud cone occurs in the Cooper Valley near Gulkana and the local people refer to it as the mud volcano. It appears to be rather young, as it is in the process of burying the surrounding trees with soil flowing down the slopes of the cone. Vegetation is not yet established on the side slopes. Mertie and Harrington (39, p. 8) describe a large mound in the Ruby District which they said was 25 ft. high and 75 to 100 yards long and was formed by a spring bringing up from below the material that had formed the mound.

The mounds in the Arctic Plain are distinctively different from those which occur in other parts of the territory. Many writers mention seeing them and have given short descriptions; some have suggested theories of their origin. Porsild (40, p. 46-58) says that the most outstanding types are those which show signs of having been forced upward by pressure from below. Great cracks or fissures occur in the crest of these mounds and radiate downward. He mentions some mounds having hollow craters nestled in the cavity in the top. Some of the largest ones he describes as being 160 ft. high and in one instance he tells of one having a circumference of 2, 700 ft. Of particular interest are his remarks about finding stratified soils in the inside of a particular pingo which consisted of interstratified lacustrine soils-clay and peat.

Leffingwell, in his report on the Canning River region (31 , p. 150 to 155) presents a discussion of what he calls pleistocene and recent gravel mounds. In one instance he cites having seen about 30 mounds from a single point. He has measured mounds which were 230 ft. above the plain. Leffingwell, too, ventures a theory as to the origin of these mounds. He discusses several hypotheses but he believes that the result of hydraulic pressure offers the best explanation. He believes that at the beginning of the arctic climate the ground became frozen progressively downward and formed am impervious layer over a tilted water-bearing stratum, giving rise to conditions favorable to artesian wells. Hydraulic pressure may have acted so slowly as to bulge up and fracture the frozen crust locally without any great outflow of water, or it may have occurred suddenly with a great outflow of water which carried up material from the underlying beds. The coarse material may have been depositied at the outset of the spring, thus building up a mound (31, p. 153).

Smith (41, p. 28), in his report of the Noatak-Kobuk Region, mentions seeing mounds in the Mission Lowland of the Noatak Basin, and he says, ". . . here and there rounded hills one-half mile in diameter at the base rise 100 to 300 ft. above the general surface of this plain. They are symmetrical in shape, and although irregularly distributed over the plain, suggest, when viewed from a distance, giant haystacks. "

It is believed that pingo, or frost mounds, are associated with the elongated lakes of the Arctic Coastal Plain, since many of the mounds occur in the geometric center of

Figure 22. Oblique Photo of a Pingo.

Figure 23. Mud Volcano.

Figure 24. Mud Volcano.

Figure 25. Ground View of a Pingo.

elongated lakes which are either in the process of drying up or which recently have been dried up. Several of these were visited by the Purdue party, and one in particular was studied in detail. The mound in question was situated in the center of an elliptical lake, the longest dimension of which was approximately three-fourths of a mile. The surrounding rim of the lake-bed was situated about 30 ft. above the bottom and was somewhat serrated. The mound was oblong and was estimated to be 85 or 90 ft. in height. At this particular location there appeared to be a series of low benches or shelves between the mound and the highest rim, which formed concentric patterns about the mound. The mound, together with the surrounding lake basin, had the appearance of having been formed recently, since the normal process of erosion had not commenced to destroy or alter the surface features of the mound or the cleft in the mound. The side slopes of the mound were quite steep and were covered with a dense mat of willow. The trees on the mound were much larger than the miniature willow in the surrounding area. Those on the outside of the mound were about 4 or 5 ft. in height and were densely tangled. Situated in the mound was a great V-shaped cleft which extended more than half way down the mound. In the cleft the willows were 6 to 8 ft. in height. The bottom of the cleft contained about 3 ft. of water; ice occurred beneath the water. The soils, as exposed on the sides of the cleft, were horizontally stratified and appeared to be tilted parallel to the outside slope of the mound. In this one instance the surface material consisted of brown peat underlain with 3 or 4 in. of what appear to be volcanic ash, which in turn was underlain by stratified sands of various colors.

From studies made on the ground, studies of airphotos, and studies of a reconnaissance nature from the air of many of these arctic mounds, the following general statements can be made: (1) the mounds are situated in depressions which resemble old lakebeds; (2) the lakebeds are either dried up or contain very little water; (3) the lakebed soils generally contain a peat surface cover on top of stratified lacustrine sands and silts; (4) the mounds are surrounded by a polygon pattern within the confines of the lakebed, which is arranged such that concentric groupings of polygons occur; (5) mounds do not occur in the high coastal plain areas where surface drainage is particularly well developed; (6) some mounds, which appeared to be young in their stage

Figure 26. Elongated Lakes.

Figure 27. Thermokarst Lakes.

of development, were merely "bulged-up" areas, and the polygon nets appeared to cross the bulge portion without any apparent relationship to the axis of the bulge; (7) mounds vary in shape from nearly conical and somewhat symmetrical domes to irregularly-shaped dome-like expressions; (8) for the most part, the mounds in the areas east of the Colville appear to be older, larger, and more irregularly shaped than the mounds west of the Colville, which appear to be young, newly formed, regular in shape, associated with recently drained lakes, and are little altered by erosion. If previous observers are correct in their statements of origin, the significance of such features lies in their indicating sources of ground water.

Figure 28. Thermokarst Lakes.

Elongated Lakes - One of the outstanding features of the almost featureless Arctic Coastal Plain is the presence of a myriad of elongated lakes. Most of the lakes are elliptical in shape, and nearly all have a directional trend a few degrees west of true north. Striking similarity exists between these lakes and the famous and somewhat controversial Carolina Bays of the Atlantic Coastal Plain (42). There is considerable discussion as to the Origin of these lakes (43, 44, 45); some of the theories include meteors, solution, segmented lagoons, and thawing permafrost. It is the theory concerning thaw sinks in permafrost which makes the lakes of significance as far as this paper is concerned.

From the standpoint of photo interpretation, the lakes are one of the features of lower coastal plain patterns, since lakes of this type have not been noted associated with other physiographic arrangements. They occur in sand and silt soils and many are interconnected and form part of the exceedingly sluggish coastal-plain drainage. Those which have been dried up or drained are often marked with concentric rings of polygon nets. Of considerable interest particularly from an engineering standpoint are the elongated sand dunes which occur at right angles to the major axes of the lakes.

Thermokarst - Another condition found in the Arctic and Sub-Arctic associated with permafrost and which creates a definite photo pattern is commonly called "thermokarst." Thermokarst generally refers to lakes or basins in permafrost areas believed to have been formed largely by thawing of large ice masses. The resulting depressions are irregular in shape and contain a volume of water much less than that occupied by ice (32, 46). The lakes appear to be sunken in the land surface and are often easy to differentiate from lakes formed by other means because they are below the general topographic surroundings; they are fringed with leaning trees (46). Such lakes do not have an outlet and are not a part of a water-network in an area. Similar features are described by Hopkins in his discussion of the Seward Peninsula (47) and by Moffit (48, p. 121) in his discussion of the Mentasta Valley. As far as the writer is able to determine, the only significance lies in the belief that a delicate thermal balance exists in permafrost areas where thermokarst occurs. The lakes of this type are usually found in low-lying flat areas in which the soils are predominantly silt.

From the standpoint of airphoto interpretation such features are easily interpreted. For example, thermokarst sinks are irregular in shape, are not connected, appear sunken, and are fringed with leaning trees - all of which can be seen clearly on good quality airphotos. Thermokarst lakes are common in the southern or warmer, permafrost areas. They are also found in the northern regions but not commonly.

Solifluction - One of the characteristic features of hillsides, particularly noticeable in treeless areas, is the lobate surface-flow markings or "earth runs" which occur on the sides of hills. Most of the flow markins seen on airphotos are associated with the processes

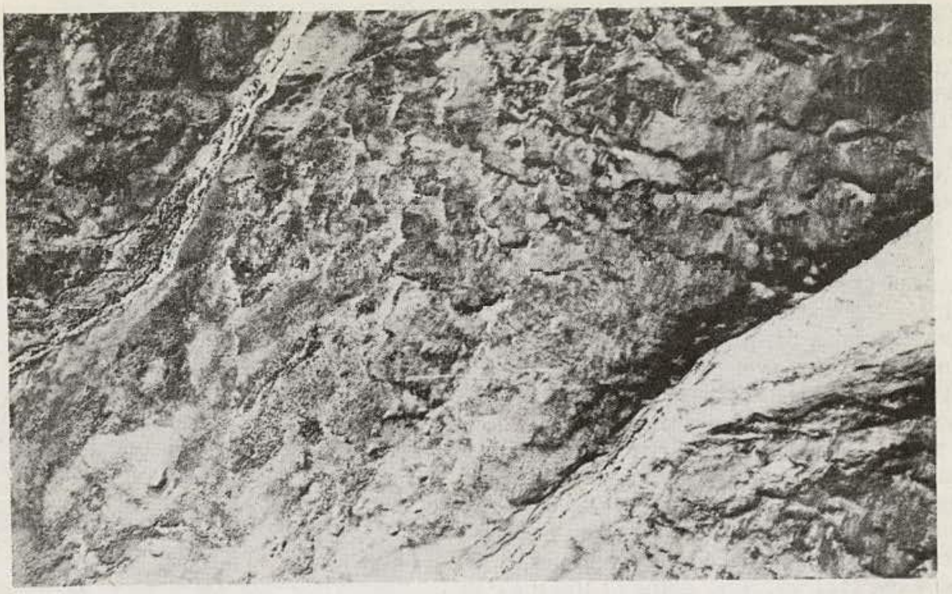

Figure 29. Airphoto of Soil Flows.

of solifluction. In the Arctic and Sub-Arctic the processes of solifluction are active agents of erosion or land destruction. Lobeck (49, p. 83) defines solifluction as "a term applied to the slow imperceptible flowing from higher to lower ground masses of rock and soil saturated with water."

The earth runs or flows consist of nonsorted waste material believed associated with freezing and thawing, slope, gravity, moisture, and vegetative cover (50, p. 97) (51, pp. 66-68). Capps, in discussing soil flow in the Alaska Railroad Region, states that soil flow on the south side of the Alaska Range is not conspicuous, while on the north slopes, where permafrost is present, soil flow is active (52, p. 167-170). It is believed that the process is limited to sloping areas having a shallow surface mantle (52, pp. 76-82).

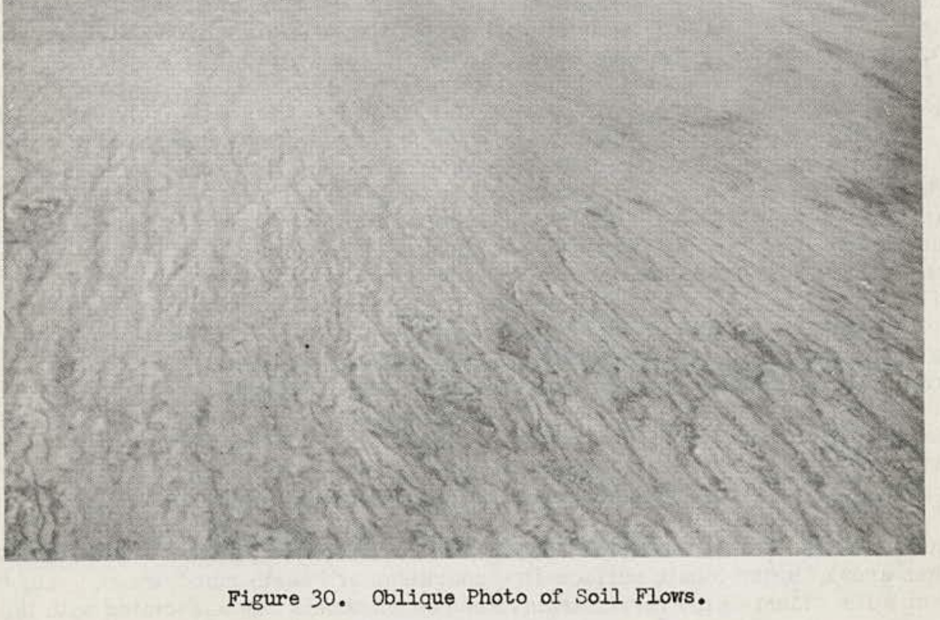

Figure 30. Oblique Photo of Soil Flows.

The action is slow, often requiring years to make a noticeable advance, as stated by Moffit (54, p. 45).

An excellent review of Troll's monograph on solifluction appears in the March 1949 Journal of Geology (55). According to the review, Troll presents a genetic classification of frost-caused earth forms. Solifluction and related phenomena are discussed by many in connection with discussions of various types of earth movement (56, 57, 58).

Figure 31. Ground Photo of Soil Flows.

Solifluction processes create striking airphoto patterns, particularly in tundra regions. Contrasts in vegetation type on parts of a flow area, as well as changes in relief of a hillside which accompany directional features, create this unusual pattern. The features produced by this phenomenon are often on a large scale and in areas of hilly or rolling terrain will be found on nearly all hillsides. Surface markings vary from long "streamers" of rubble which extend parallel down a slope to a series of broken, irregularly shaped flows, which give a scalloped appearance. Entire hillsides appear to be sliding down the slopes.

From the standpoint of the purpose of this paper, such areas indicate unstable soils which should be considered in connection with structures to be placed on hillsides. These unstable soil areas can be identified by photo interpretation procedures.

Altiplanation Terraces - Throughout the Arctic and the Sub-Arctic are many "sloping terraces, sloping benches, or altiplanation terraces." They vary in size from narrow, dissected bench-remnants situated high on the side slopes of a valley to vast tilted surfaces of several square miles in area in large valleys. Because of their unusual surface features and peculiar shape, that of a tilted plain appearing as transition between high and low areas, they create a distinct airphoto pattern. The landform is that of a sloping bench or shelf having a relatively flat to slightly concave surface which ends rather abruptly at the outward and lower face. The areal drainage pattern of such features is parallel, and small streams and gullies seldom deviate from their straight course.

The processes creating such features are believed to be a peculiar type of solifluction, since they contain accumulations of loose rock materials which appear to have been moved by some type of flow (59, p. 78). Harrington believes they are associated with certain types of vegetal growth and confined to areas above the timber line (60, p. 55). Such features occur in areas rather mature in the erosional cycle where topography is well-rounded, smooth, and does not have great differences in elevation.

From an engineering standpoint, areas of detrimental permafrost may be found most anywhere on the surface of these sloping benches. Polygons often exist. Since such areas slope, erosion and thaw are apt to be severe if permitted to develop. Many of the terraces are dotted with minute mounds (53, p. 80) indicating frost activity.

Mud Boils, Hummocks, and Humpies - In some areas south of the permafrost regions, the action of freezing and thawing produces a series of minute mounds or hummocks, some of which can be seen on airphotos, particularly in tundra regions or areas above the timber line. One very curious area of mounds (called humpies by local residents) occurs in the Willow Pass area between Palmer and Willow Creek. Capps (61, 52) and Sharp (62), describe these mounds as appearing to have been furrowed with a plow, because of their

Figure 32. Oblique Photo of Altiplanation Terraces.

Figure 33. Oblique Photo of Mud Boils.

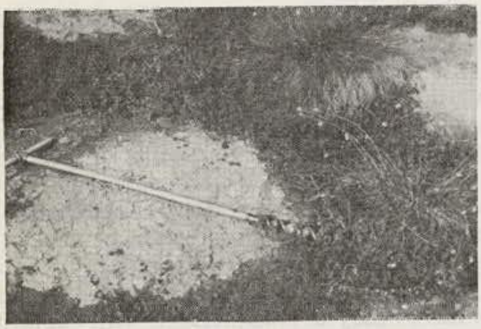

Figure 34. Ground Photo of Mud Boils.

Figure 35. Ground Photo of Humpies.

regularity of size and spacing. These small mounds occur on the upper portion of colluvial slopes, just below the in-place materials of the rocky slopes. Evidence of soil flow, sudden or slow, was not present in the mound areas studied in the Willow Creek Pass. Several were dug into and were found to be composed of silt with a heavy moss and heather cover. There was no evidence of upward or lateral soil flow either within or around the mounds. However, they are believed related to soil texture, moisture, vegetation, frozen ground and/or frost action, and slope.

Mounds of another type were studied on colluvial slopes in the Colville Valley of the Arctic Plateau. There are many areas on the side slopes of hills containing minute circular areas of bare soil which appear to have been formed by frost action processes. On the upper portions of hillsides the mounds examined were circular; down the slope the mounds were elongated, giving the appearance of flow. Samples taken in the centers revealed silt and silty clay and clay shale fragments for considerable depth. The mounds were 30 to 48 in. in diameter and spaced fairly regularly about 5 or 6 ft. apart. Tundra type vegetation separated the mounds. Soils beneath the tundra vegetation were frozen below 12 to 14 in.

Often minute frost boils were studied at many locations in the Arctic Coastal Plain. In each instance silty soils had been forced upward through cracks or holes in the surface and had spread out over the tundra vegetation. Some appeared to have been newly formed, since a wet silty soil was found on the surface in areas where the active layer had not thawed completely. Others were much older, perhaps several seasons, since they were covered with tundra vegetation and were 2 or 3 ft. high.

The significance of such surface features is that they are associated with frost action in surface soils, which suggests unstable conditions as far as engineering use is concerned. Many of the mounds occur in sufficient numbers in an area to create a definite and recognizable pattern on airphotos of fair quality.

Earthen mounds of the frost type and of other types have intrigued researchers in many fields and many have presented theories of origin (63 to 69).

Summary

The following statements summarize the present thinking on airphoto interpretation of permafrost and related phenomena in the Arctic and Sub-Arctic:

(1) Aerial photographs can be used to predict soil textures and permafrost conditions with a high degree of reliability.

(2) In permafrost areas where the frost zone or the active zone is thick, airphotos can be used to differentiate between severe frost-susceptible soils and nonfrost-susceptible soils.

(3) Many surface configurations associated with the existance of permafrost and related phenomena can be seen on aerial photos and indicate instability of soils for potential engineering use.

(4) In nonpermafrost areas, interpretation and evaluation of frost-susceptibility of soils is based on indirect methods, including analysis of soil textures in the light of drainage, climate, exposure, and vegetative cover.

Bibliography

1. Frost, Robert E., "Evaluation of Soils and Permafrost Conditions in the Territory of Alaska by Means of Aerial Photographs," Engineering Experiment Station, Purdue University for the Corps of Engineers, Department of the Army, St. Paul District, June 1950.
2. Frost, Robert E., Hittle, J. E., and Woods, K. B., "Correlation Between Permafrost and Soils as Indicated by Aerial Photographs," Proceedings of the 2nd International Conference on Soil Mechanics and Foundation Engineering, V. 1, Rotterdam, June 1948.
3. Frost, Robert E., and Mintzer, Olin W., "Influence of Topographic Position in Airphoto Identification of Permafrost," a paper presented at the 29th Annual Meeting, Highway Research Board, December 1949.
4. Frost, Robert E. and Cummins, Tom, "Permafrost," Purdue Engineer, Vol. 45, No. 2, p. 10, November, 1949.
5. Frost, Robert E., Hittle, Jean E., and Woods, K. B., "Summary and Statement of Technique Aerial Photographic Reconnaissance Investigation Frozen Soils in Territory of Alaska," Engineering Experiment Station, Purdue University, Appendix No. 3, of "Comprehensive Report Investigation of Airfield Construction in Arctic and Subarctic Regions," Corps of Engineers, St. Paul District, 2nd Revision, May, 1948.
6. Frost, Robert E., Hittle, Jean E., and Woods, K. B., "Photo Interpretation of Vegetation in the Tropical Pacific Area and its Use as an Indicator of Kind of Ground," by U. S. Geological Survey under direction of Office, Chief of Engineers, Military Intelligence Division, Engineering Notes No. 20, August, 1944.
7. Frost, Robert E., Hittle, Jean E., and Woods, K. B., "Pacific Land Forms and Vegetation," Air Intelligence Group, Division of Naval Intelligence, Office of the Chief of Naval Operations, Photo Intelligence Center, Report No. 7, OPNAV-16 VP107, May, 1945.
8. Eardley, A. J., "Aerial Photographs and the Distribution of Constructional Materials," Proceedings, Highway Research Board, 23rd Annual Meeting, November, 1943.
9. Sarason, S. D., "Application of Aerial Mapping to Highway Construction," Proceedings, Highway Research Board, 9th Annual Meeting, December, 1929.

10. Kingery, Robert, "Aerial Mapping Used in Regional Highway Planning," Proceedings, Highway Research Board, 23rd Annual Meeting, November, 1943.
11. Smith, H. T. U., "Aerial Photographs and Their Applications," Appleton Century, 1943.
12. Eardley, A. J., "Aerial Photographs: Their Use and Interpretation," Harper, 1942.
13. Spurr, Stephen, H., "Aerial Photographs in Forestry," Ronald Press Co., 1948.
14. Belcher, D. J., "The Engineering Significance of Soil Patterns, " Proceedings, Highway Research Board, Vol. 23, 1943.
15. Hittle, Jean E., "The Application of Aerial Strip Photography to Highway and Airport Engineering, " Proceedings, 26th Annual Meeting, Highway Research Board, December, 1946.
16. Frost, Robert E., "The Use of Aerial Maps in Soil Studies and Location of Borrow Pits," Proceedings, Kansas Highway Engineering Conference, July 1, 1946.
17. Frost, Robert E., "Identification of Granular Deposits by Aerial Photography," Proceedings, Highway Research Board, Vol. 25, January, 1945.
18. Frost, Robert E., "How Can a Highway Department Use Aerial Photographs, " Proceedings, Mississippi Valley Highway Conference, March, 1949.
19. Frost, R. E., and Woods, K. B., "Aerial Photographs Used as an Engineering Evaluation of Soil Materials, " Proceedings of the 2nd International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, Rotterdam, June, 1948.
20. Hittle, Jean E., "The Use of Aerial Photographs in Identifying Granular Deposits and Other Soils," Proceedings, 29th Annual Purdue Road School, March, 1943.
21. Belcher, D. J., "The Development of Engineering Soil Maps," Proceedings, 29th Annual Purdue Road School, March, 1943.
22. Belcher, D. J., "Identifying Land Forms and Soils by Aerial Photographs, " Proceedings, 30th Annual Purdue Road School, March, 1944.
23. McCullough, Charles R., "An Engineering Soil Map of Indiana Prepared from Airphotos," Proceedings, 35th Annual Purdue Road School, April, 1949.
24. Parvis, Merle, "Development of Drainage Maps from Aerial Photographs," Proceedings 26th Annual Meeting, Highway Research Board, December, 1946.
25. Mollard, J. D., "Airphoto Mapping of Montgomery County Soils for Engineering Purposes," Proceedings, 33rd Annual Purdue Road School, Purdue University, July, 1947.
26. Frost, Robert E., "Prospecting for Engineering Materials Using Aerial Photographs," a paper prepared for the Pan American Engineering Conference, June, 1949.
27. Jenkins, D. S., C. A. A.; Belcher, D. J., Gregg, L. E. and Woods, K. B., Purdue University, "The Origin, Distribution, and Airphoto Identification of United States Soils," Technical Development Report No. 52, C. A. A., Washington, D. C., May, 1946.
28. Frost, Robert E., and Woods, K. B., "The Airphoto Patterns of Soils of the Northwestern United States," Supplement to Technical Development Report No. 52, Civil Aeronautics Administration, Washington, D. C., August, 1948.
29. Muller, S. W., "Permafrost or Permanently Frozen Ground and Related Engineering Problems," Edwards Bros., Ann Arbor, Michigan, 1947.
30. Taber, Stephen, "Perennially Frozen Ground in Alaska: Its Origin and History," Bulletin of the Geological Society of America, Vol. 54, 1943.
31. Leffingwell, Ernest deK, "The Canning River Region, Northern Alaska," U. S. Geological Survey, Professional Paper 109, 1919.
32. Wallace, Robert E., "Cave-in or Thermokarst Lakes in the Nebesna, Chisana, and Tanana River Valleys, Eastern Alaska," U. S. Geological Survey, Progress Report No. 4, Permafrost Program, 1946.
33. Stoeckeler, E. G., "Identification and Evaluation of Alaskan Vegetation from Airphotos with Reference to Soil, Moisture, and Permafrost Conditions," a preliminary paper, Corps of Engineers, St. Paul District, June 1948.
34. Jenness, John L., "Permafrost in Canada," Arctic, Vol. 2, No. 1. 1949.

35. Rozanski, G., "Stone-centered Polygons on the Rock Ledge Bordering the Genessee River at Letchworth Park, N.Y.," Journal of Geology, Vol. 51, 1943.
36. Conrad, V., "Polygon Nets and Their Physical Development," American Journal of Science, Vol. 244, No. 4, April 1946.
37. Collier, Arthur J., "A Reconnaissance of the Northwestern Portion of Seward Peninsula, Alaska," U. S. Geological Survey, Professional Paper, No. 2, 1902.
38. Collier, Arthur, J., Hess, Frank L., Smith, Phillip S., and Brooks, Alfred H., "The Gold Placers of Parts of Seward Peninsula, Alaska, including the Nome, Council, Kougarok, Port Clarence, and Goodhope Precincts," U. S. Geological Survey, Bulletin 328, 1907.
39. Mertie, J. B. Jr., and Harrington, G. L., "The Ruby-Kuskokwim Region Alaska," U. S. Geological Survey, Bulletin 754, 1924.
40. Porsild, A. E., "Earth Mounds in Unglaciated Arctic Northwestern America," Geographical Review, Vol. 24, No. 4, 1934.
41. Smith, Phillip S., "The Noatak-Kobuk Region Alaska," U. S. Geological Survey, Bulletin 536, 1913.
42. Johnson, Douglas, "Mysterious Craters of the Carolina Coast," American Scientist, Vol. 32, No. 1, January, 1944.
43. Cabot, Edward C., "The Northern Alaskan Coastal Plain Interpreted from Aerial Photographs," Geographical Review, Vol. 37, 1947.
44. Black, Robert F., and Barksdale, Wm. L., "Oriented Lakes of Northern Alaska," Journal of Geology, Vol. 57, No. 2, March, 1949.
45. Cooke, C. Wythe, "Elliptical Bays," Journal of Geology, Vol. 51, No. 6, August-September 1943, pp. 419-427.
46. Wallace, R. E., "Cave-in Lakes in the Nabesna, Chisana, and Tanana River Valleys, Eastern Alaska," Journal of Geology, Vol. 56, No. 3, 1948.
47. Hopkins, David M., "Thaw Lakes and Thaw Sinks in the Imuruk Lake Aera, Seward Peninsula," Journal of Geology, Vol. 57, No. 2, March, 1949.
48. Moffit, Fred H., "The Slana District, Upper Copper River Region, Alaska," U. S. Geological Survey, Bulletin 824-B, 1931.
49. Lobeck, A. K., "Geomorphology," McGraw-Hill Book Co., 1939.
50. Smith, Phillip S., "Geology and Mineral Resources of the Solomon and Casadepaga Precincts Seward Peninsula Alaska," U. S. Geological Survey, Bulletin 433, 1910.
51. Capps, Stephen R., "The Kantishna Region Alaska," U. S. Geological Survey, Bulletin 687, 1919.
52. Capps, Stephen R., "Geology of Alaska Railroad Region," U. S. Geological Survey, Bulletin 907, 1940.
53. Eakin, Henry M., "The Yukon-Koyukuk Region Alaska," U. S. Geological Survey, Bulletin 631, 1916.
54. Moffit, Fred H., "Headwater Regions of Gulkana and Susitna Rivers Alaska," U. S. Geological Survey, Bulletin 498, 1912.
55. Troll, Carl, "Strukturboden, Solifluktion, und Frostklimate der Erde," a review of a paper, Journal of Geology, Vol. 57, No. 2, March, 1949.
56. Wahrhaftig, Clyde, "The Frost-Moved Rubbles of Jumbo Dome and Their Significance in the Pliestocene Chronology of Alaska," Journal of Geology, Vol. 57, No. 2, March 1949.
57. Judson, Sheldon, "Rock-Fragment Slopes Caused by Past Frost Action in the Jura Mountains (AIN) France," Journal of Geology, Vol. 57, No. 2, March 1949.
58. Sharpe, C. F., "Landslides and Related Phenomena," Columbia University Press, 1938.
59. Smith, Phillip S., "Areal Geology of Alaska," U. S. Geological Survey, Professional Paper No. 192, 1939.
60. Harrington, George L., "The Anvik-Andreafski Region Alaska," U. S. Geological Survey, Bulletin 683, 1918.
61. Capps, S. R., "The Willow Creek District," U. S. Geological Survey, Bulletin 607, 1915.

62. Sharp, R. P., "Soil Structure in the St. Elias Range, Yukon Territory," Journal of Geomorphology, Vol. 5, No. 4, 1942.
63. Hobbs, W. H., "Soil Flow," Bulletin, American Geographical Society, Vol. 45, No. 4, 1913.
64. Dalquest, Walter W. and Scheffer, Victor B., "The Origin of the Mima Mounds of Western Washington," Journal of Geology, Vol. 50, No. 1, January-February, 1942, p. 68-84.
65. Krinitzsky, E. L., "Origin of Pimple Mounds," American Journal of Science, Oct. 1947. Vol. 247, p. 706-714.
66. Campbell, M. R., "Natural Mounds," Journal of Geology, Vol.14, November, December, 1906, pp. 708-717.
67. Koons, Frederick C., "The Sand Mounds of Louisiana and Texas," Scientific Monthly, Vol. 66, April 1948, pp. 297-300.
68. Price, W. A., "Pocket Gophers as Architects of Mima Mounds of the Western United States," Texas Journal of Science, Vol. 1, 1949, pp. 1-17.
69. Scheffer, V. B., "The Mystery of the Mima Mounds," Scientific Monthly, Vol. 65, 1947, pp. 283-294.
70. Pewe, Troy L., "Origin of the Mima Mounds," Scientific Monthly, Vol. 66, April 1948, p. 293.

COLD-ROOM STUDIES OF FROST ACTION IN SOILS

James F. Haley, Assistant Chief, and Chester W. Kaplar, Engineer
Frost Effects Laboratory, New England Division, Corps of Engineers, U. S. Army

Synopsis

Cold-room studies of frost action in soils are being performed by the Frost Effects Laboratory, New England Division, Corps of Engineers, for the Airfields Branch, Office, Chief of Engineers, Department of the Army, as part of a continuing program of frost investigations aimed toward establishing and improving design and evaluation criteria for roads, highways and airfield runways constructed on soils subject to seasonal freezing and thawing. The present laboratory studies are being made chiefly to determine the quantitative effects of individual factors which influence ice segregation in soils, such as gradation, percent finer than 0.02 mm., percent stone, permeability, capillarity, proximity of water supply, compaction, and the initial degree of saturation in a closed system.

The chief purpose of this paper is to present the testing program and methods and equipment used. The cold-room studies were begun in February 1950 and are currently in progress. The data presented herein are incomplete, and final conclusions must await the completion of the various phases of the investigation.

The data available indicate that percentage finer than 0.02 mm. size is not, by itself, an adequate indicator and that other factors must be considered in recognizing with accuracy a frost-susceptible soil or in predicting the intensity of ice segregation possible in a given soil. Tests have shown the character and distribution of the fines have an important bearing on frost susceptibility.

In some soils the degree of compaction at the start of freezing has a marked effect on the amount of heave which occurs. In other soils the effect may be small. In some a critical degree of compaction may occur at which ice segregation is most intense, with less heaving occurring at densities higher or lower than the critical density.

Closed-system tests on a saturated lean clay indicate considerable ice segregation can occur without water being available from an outside source.