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SOME ASPECTS OF AIRPHOTO INTERPRETATION OF PERMAFROST IN CANADA

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ABSTRACT

Aerial photography is an indispensable tool in the investigation of permafrost and the terrain in which it exists, particularly in the Far North where large-scale topographic map coverage is sparse. Its use in interpreting permafrost conditions in northern Canada has assumed steadily increasing importance since the Second World War as the region undergoes expanding resource development. Vertical or trimetragon photographic coverage from 20,000 or 30,000 ft altitude for the entire country, including the permafrost region, has been available for twenty years and many areas are now covered by airphotos from lower altitudes. This paper deals only with black and white panchromatic aerial photographs and their application to problems of interpreting permafrost conditions in northern Canada. Much has been written in Canada, the United States and the U.S.S.R. on this subject and some of the major references are listed.

QUELQUES ASPECTS DE L'ÉTUDE DU PERGÉLISOL AU CANADA À L'AIDE DE LA PHOTOGRAPHIE AÉRIENNE

SOMMAIRE

La photographie aérienne est un outil indispensable dans l'étude des sous-sols gelés en permanence, surtout dans la Grand Nord, dont on ne possède qu'un nombre restreint de cartes topographiques à grande échelle. Depuis la Seconde Guerre mondiale, la photographie aerienne occupe un place de plus en plus importante dans l'étude du pergélisol dans le Nord canadien, où l'exploitation des ressources naturelles est en plein essor. Depuis une vingtaine d'années il existe, pour l'ensemble du pays, y compris la région du pergélisol, des photographies verticales et trimétrogones prises à une altitude variant de 20,000 à 30,000 pieds. Il existe également, pour plusieurs régions, des photographies aériennes prises à une altitude plus basse. Le présent article traite seulement des photographies aériennes panchromatiques en noir et blanc et de leur application aux problèmes d'interprétation des conditions du pergélisol dans le Nord canadien. Plusieurs publications sur ce sujet ont paru au Canada, aux Etats-Unis et en URSS; l'auteur énumère quelques-unes des plus importantes.

NATIONAL RESEARCH COUNCIL OF CANADA
DIVISION OF BUILDING RESEARCH

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PREFACE

The Division of Building Research has been carrying out investigations for many years on the distribution of permafrost in Canada in connection with its continuing studies of northern construction problems. An important aspect of this work is the use of aerial photographs in interpreting permafrost conditions in the field. This paper was prepared originally as a chapter in a book on airphoto interpretation in Canada. Publication of the book has been delayed and the Division is now making this material available in the form of a Technical Paper. It is intended that the material will be included in the book as originally planned when it is published.

Ottawa
February 1974

N.B. Hutcheon
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SOME ASPECTS OF AIRPHOTO INTERPRETATION OF PERMAFROST IN CANADA

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Aerial photography is an indispensable tool in the investigation of permafrost and the terrain in which it exists, particularly in the Far North where large-scale topographic map coverage is sparse. Its use in interpreting permafrost conditions in northern Canada has assumed steadily increasing importance since the Second World War as the region undergoes expanding resource development. Vertical or trimetragon photographic coverage from 20,000 or 30,000 ft altitude for the entire country, including the permafrost region, has been available for twenty years and many areas are now covered by airphotos from lower altitudes.

This paper deals only with black and white panchromatic aerial photographs and their application to problems of interpreting permafrost conditions in northern Canada. Much has been written in Canada, the United States and the U.S.S.R. on this subject and some of the major references are listed. Particularly noteworthy is the work of J.D. Mollard and his associates who are among the leaders in airphoto interpretation in Canada (Mollard, 1961, 1966). The author is indebted for continued assistance and advice through the years. In the United States, R.F. Frost and his colleagues have published many valuable papers and guides on this subject (Frost, 1952, 1960, 1966). Airphoto interpretation in permafrost regions is also being studied actively in the U.S.S.R. where I.V. Protas'eva is one of the leading workers (Protas'eva, 1959, 1961, 1967). It is the author's present plan merely to cite examples of airphoto interpretation of permafrost features in Canada, some of the problems associated with this technique, and future possibilities.

The use of standard black and white aerial photographs lies within the larger context of the entire field of remote sensing of the environment. Colour and infra-red (false colour) aerial photographs, infra-red thermal scanners, radar systems, radio phase techniques (both ultra low frequency and in the broadcast band) are being tried to detect and delineate bodies or islands of permafrost. These sensors are sensitive to various portions of the electromagnetic spectrum within and outside the visible range. Much information on their potentialities is being obtained but the use of these methods lies beyond the scope of this paper.

NATURE AND DISTRIBUTION OF PERMAFROST

Permafrost or perennially frozen ground is defined exclusively on the basis of temperature, regardless of water content or degree of induration, and refers to the thermal condition of earth materials such as soil (including clay, silt, sand, gravel and peat) and rock when their temperature remains below 32°F (0°C) continuously for a number of years.

All water in the ground does not freeze at 32°F. Although freezing implies a change of state, the presence of unfrozen water in the soil at temperatures below 32°F causes semantic difficulties in the use of the term. Despite these problems, it is generally agreed that defining permafrost solely on the basis of temperature is the most workable arrangement.

Ice can be an important component of permafrost and occurs in the ground in various forms. It may take the form of layers or lenses ranging from hairline, scarcely visible to the naked eye, to several feet in thickness. The layers are mostly horizontal, but diagonal and vertical layers can also occur. These ice formations are normally observed in fine-grained soils. Others form as coatings or films on small particles, stones or boulders, or as individual ice crystals or inclusions in the cavities in the soil. Such occurrences are usually found in coarse-grained deposits such as sands and gravels. Some of the more spectacular ice deposits are found as random or irregularly oriented layers tens of feet thick, vertical wedges, and variable blocks or chunks sometimes ten to hundreds of feet in horizontal and vertical extent.

Permafrost includes ground that freezes in one winter and remains frozen through the following summer and into the next winter, although it may be only a few inches thick. This is the minimum limit for the duration of permafrost. At the other end of the scale, permafrost exists that is thousands of years old and hundreds of feet thick. The mode of formation of such old and thick permafrost is identical to that of permafrost only one year old and a few inches thick. With the former, even a small negative heat imbalance at the ground surface each year results in an additional thin layer annually. After several thousands of years this process, repeated annually, can produce a layer of permafrost hundreds of feet thick. Permafrost does not increase in thickness indefinitely, however. Rather, an equilibrium is eventually reached whereby the heat loss causing downward penetration of frozen ground is balanced by heat from the earth's interior.

Above the permafrost a so-called active layer exists, a surface layer of soil or rock that thaws in summer and freezes in winter. Its thickness depends on the same climatic and terrain features that affect permafrost.

The permafrost region is divided into two zones, a discontinuous one in the south and a continuous one in the north (Figure 1). In the discontinuous zone, frozen and unfrozen masses and layers of ground occur together but, on the southern fringe of this zone, permafrost occurs in scattered islands a few square feet to several acres in size and is confined to certain types of terrain, mainly peatlands. Other occurrences are associated with either north-facing slopes of east-west oriented valleys or isolated patches in forested stream banks, apparently in combination with increased shading from summer thawing and reduced snow cover. Northward it becomes increasingly widespread in a greater variety of terrain types.

Permafrost varies in thickness from a few inches or feet at the southern limit to about 200 ft at the boundary of the continuous zone, with unfrozen layers sometimes occurring between layers of permafrost. The depth to the permafrost table (top surface of the permafrost) ranges from about 2 to 10 ft or more, depending on local climatic and surface terrain conditions. The bottom of the active layer may be separated from the permafrost table by a layer of ground that remains thawed throughout the year. This situation occurs in areas where the permafrost table lies some distance below the depth of seasonal frost penetration. The temperature of the permafrost in the discontinuous zone, at the depth at which annual fluctuations become virtually imperceptible (i.e., less than about 0.1°F) and known as the level of zero annual amplitude, generally ranges from a few tenths of a degree below 32°F at the southern limit to about 23°F at the boundary of the continuous zone.

In the continuous zone permafrost occurs everywhere beneath the ground surface except in newly deposited, unconsolidated sediments where the climate has just begun to impose its influence on the ground thermal regime. The thickness of permafrost is about 200 ft at the southern limit of the continuous zone, increasing steadily to more than 1,000 ft in the northern part of the zone in the Arctic Archipelago. The active layer generally varies in thickness from about $1\frac{1}{2}$ to 3 ft and usually extends to the permafrost table. The temperature of the permafrost in this zone at the level of zero annual amplitude generally ranges from about 23°F in the south to about 5°F in the extreme north.

SURFACE FEATURES

Surface features associated with permafrost in the discontinuous zone are most prominent in peatlands and peat bogs where low hills or knolls of peat about 10 ft or less in height, designated by the Swedish term "palsa," occur as permafrost islands. They form by the combined action of peat accumulation and ice segregation in the underlying mineral soil. These mounds grow and coalesce to form ridges and plateaux that are particularly widespread in the northern part of the discontinuous zone.

Many features of the ground surface in the continuous zone are indicative of underlying conditions. They become increasingly distinctive towards the north in response to the more severe climatic conditions and the decrease in the masking effect of surface vegetation. These features are also found in the northern part of the discontinuous zone, but they are generally less distinctive. The reader is directed to the extensive North American and Russian literature and to the review by Stearns (1966). Only a few references are cited here, including some notable Canadian contributions.

A comprehensive classification of patterned ground and a review of suggested origins was presented by Washburn (1956). This was followed by a more recent publication presenting an approach to a genetic classification of patterned ground (Washburn, 1970). Washburn considered patterned ground as a collective term to include polygons, circles, nets, steps, stripes, and mounds. These features are not restricted to permafrost regions but they attain their best development in such regions particularly in the continuous zone.

Polygons occur in many forms and sizes, furnishing a pattern that is widespread throughout the cold regions. Washburn classified them as either raised- or high-centre (borders are cracks or fissures) or depressed-centre (raised borders) polygons in which the surface materials may be sorted or non-sorted. They may be of all sizes up to 100 ft in diameter. In some places primary polygonal networks are divided by secondary, internal polygons. The existence of permafrost is not essential for their formation, but the largest are found in the permafrost regions. They are particularly well developed in the continuous zone where tundra polygons (both raised-centre and depressed-centre), whose boundaries are underlain by ice wedges, are widespread.

Circles may be sorted or non-sorted. This patterned ground has a mesh with circular elements 2 to 12 ft in diameter and sometimes larger. The sorted circles or stone rings have clean stone borders surrounding fine-grained soil, sometimes with gravel or pebbles. Non-sorted circles also have a circular mesh but the stone border is absent. They include stony earth circles with centres of silt and some sand and gravel that form from plugs of soil in the active layer. Both sorted and non-sorted circles form above the permafrost, but permafrost is not essential for their existence.

Steps and stripes vary in width from a few inches to several feet, occur on moderate to steep slopes, and may be sorted or non-sorted. The steps are parallel to the contour; the stripes extend downslope. The non-sorted steps consist of an earth core covered by moss and other plants, and the difference in elevation forms the steps. Non-sorted stripes are alternating parallel lines of vegetation and bare ground. Solifluction stripes, lobes, and scars can be noted where soil is moving slowly downslope under the combined forces of frost action, gravity, and fluid flow. Frost boils are also a common pattern caused by intense frost action in the active layer that brings fine-grained soil to the surface in concentrated circular deposits. Mounds caused by intense frost heaving in the active layer also form microrelief of 3 to 4 ft.

The most spectacular landforms associated with permafrost are pingos. More than 1000 of these conical hills, which may grow through several centuries or thousands of years to more than 100 ft in height and one-quarter mile in diameter, have been mapped in the Mackenzie Delta (Stager, 1956). They also occur in northern Alaska, northeast Greenland, and Siberia. They have ice centres covered with soil and vegetation, are often cracked diametrically at the top, and become widely cratered later in their lifespan. Two types of pingos classified according to origin have been described. Closed-system pingos occur in the continuous zone in flat, poorly drained terrain such as old lake bottoms or river deltas where water in the underlying thaw basins is forced towards the surface by the surrounding aggrading permafrost (Mackay, 1962). Open-system pingos form in the discontinuous zone where groundwater in unfrozen zones between permafrost layers is forced to the surface and an ice mass accumulates (Müller, 1959).

The thawing of permafrost also forms distinctive landforms in both the discontinuous and continuous zones. "Thermokarst" is the term used for uneven land subsidence caused by the melting of ground ice. The resulting ground surface is very hummocky and uneven, resembling the karst topography found in limestone areas where sink holes provide a landscape of many small, circular, oblong and elliptical lakes. Tilted trees, known as "drunken forests," along the margins of such lakes are indicative of active caving. In treeless areas active caving may be indicated by tension cracks parallel to the banks of lakes. Beaded streams are particularly prevalent in the continuous zone where blocks of massive ground ice melt in the stream bed, forming enlargements along its course. The thawing of ice wedges of polygonal ground gives a distinctive pattern of regular hillocks termed "baydzherakhi" (cemetery mounds) in the U.S.S.R. Caving of frozen cutbanks around lakes and along streams frequently gives these banks a serrated appearance. Massive slumps may occur on the hillsides where large masses of ground ice are exposed to melting by the disturbance of the surface vegetation. Disturbance of the surface vegetation by man in areas of ground ice concentration can also cause slumping.

PERMAFROST INTERPRETATION FROM AERIAL PHOTOGRAPHS

Because permafrost is a temperature condition of the ground and is separated from the ground surface by the active layer, it cannot be recognized directly by photographs but must be interpreted from secondary features usually associated with terrain. Because it occurs sporadically in the discontinuous zone, airphoto interpretation in this region is directed toward mapping or elucidating its distribution, and toward evaluating permafrost conditions and parameters including geometry: thickness of active layer, depth to permafrost table, areal extent of bodies of permafrost, thickness of permafrost; type of soil or rock; temperature; and ice content. In the continuous zone permafrost is known to exist everywhere beneath the land surface except in newly deposited unconsolidated deposits; airphotos are used primarily to evaluate permafrost conditions.

As permafrost itself does not exist at the ground surface, there are no landforms except pingos and palsas that have developed exclusively over perennially frozen ground; in the discontinuous zone no indicators except palsas can be considered absolutely reliable. Features such as smaller frost mounds are commonly formed by annual rather than perennial ice accumulation. Patterned ground, including polygonal forms, when visible on photographs may be formed by seasonal frost or be relics from a cooler epoch, and features such as thaw lakes indicate degraded permafrost rather than confirm its existence. These features cannot be used to delineate the distribution of permafrost, but they do provide clues to the characteristics of the active layer and ground ice content. In the future, remote sensing methods such as infra-red thermal imagery and radio phase may be used for permafrost mapping. At present the application of these techniques is in an experimental stage; they have not been developed to the point where they can be used to detect and delineate bodies of permafrost reliably.

In the discontinuous zone, vegetation (trees, shrubs, moss and lichen ground cover) is the most useful factor indicating the existence and distribution of permafrost, particularly in the southern fringe. Peat acts as an insulator and aids in the development and preservation of permafrost conditions. Thus the identification of peatlands and peat bogs provides the first step in locating the most probable areas of permafrost occurrence. Within this particular terrain type permafrost may be restricted to microrelief features such as peat plateaux. Permafrost may also occur locally in areas of dense tree growth due to more intensive shading and on some north-facing slopes. Further north in the discontinuous zone permafrost extends into mineral soil terrain and becomes more common on north-facing slopes. An indication of its presence is local thaw slumping of cliffs and leaning trees.

Vegetation is dynamic and vegetation-permafrost relations are subject to continual change. Although vegetation alone should not be used as an indication of permafrost conditions, some observations may be noted that are especially valuable when carrying out field investigations (Stoeckler, 1948). The recognition of shallow-rooted species on aerial photographs aids in delineating areas where permafrost is most likely to occur at shallow depth, and recognition of deep-rooted species helps delineate areas least favourable for the formation or preservation of permafrost. Pihlainen (1951), reporting on permafrost studies along the upper reaches of the Mackenzie River in the discontinuous zone, observed that; aspen poplar will not grow on frozen ground; jackpine indicate reasonably well drained soils and a low permafrost table; willows indicate a very low permafrost table and the likelihood of underground water; balsam, poplar and birch indicate a low permafrost table and well drained subsoils; and white moss, tundra vegetation and stunted spruce suggest poorly drained subsoils and a high permafrost table.

The interpretation of soil conditions from landform identification can assist in predicting subsurface permafrost conditions, particularly with regard to thickness of active layer and ground ice situation. Other factors being equal, the active layer is thicker in well drained sandy and gravelly soils than in poorly drained fine-grained materials. Landforms composed of fine-grained organic and inorganic waterlaid and glacial icelaid materials are very susceptible to frost action and the development of segregated ice layers in the active layer. Examples of landforms noted for their association with adverse permafrost conditions are low coastal plains, extensive delta plains, former lakebeds, former alluvial flood plains, the less steep lower slopes on colluvial deposits and alluvial fans and landforms composed of silty and clayey till. This applies also to any poorly drained depressional area in coarse-grained landforms. Noteworthy examples are backswamp and slackwater areas on granular terraces, kettleholes in granular morainic areas, and fossil channels in glacial outwash deposits. In these instances a relatively thick layer of organic, fine-textured soils commonly overlies the coarse-grained substratum and the water table is usually near the ground surface. On the other hand, elevated, well drained landforms composed of coarse-grained materials are either unfrozen or contain virtually no ice near the ground surface. Examples of this group of landforms are the upper slopes and crests of sand dunes, eskers and kames, the outer (riverward) portions of sand and gravel terraces, and the more elevated portions of outwash plains. Large masses of ground ice have been encountered, however, in such landforms in the continuous zone and even in the northern portions of the discontinuous zone.

Solifluction, the downslope mass movement of earth material over a permafrost surface, can usually be observed in aerial photographs. Its various manifestations depend on slope, thickness of the affected layer, and the volume and distribution of ice in the affected layer. Solifluction is rarely seen in temperate climates, except for alpine regions, because slopes in these areas are usually well drained above the capillary fringe. Asymmetrical stream valleys occur, especially in the Arctic, where a greater degree of thawing and downslope movement has occurred on south-facing slopes than on adjacent north-facing slopes. A whole series of downslope flow markings and terracettes may develop along the sides and lower slopes of hills. Depending on their form and the soil-instability processes that shaped them, these microforms are called soil terraces and soil lobes, lobate terraces, and tundra mudflows by Sigafoos and Hopkins (1952). Other workers use such terms as flow markings, earth-flow markings, earth runs, stepped and striped ground to describe a variety of frost-induced mircoforms (Frost, 1952; Sager, 1951; Washburn, 1956; U.S. Army, Corps of Engineers, 1950). In the continuous permafrost zone an impervious sheet of frozen ground prevents percolation of water and promotes surface run-off. Slopes underlain by all but the most durable rock types tend in time to be smooth and rounded owing to long-continued downslope migration of fine to coarse rock waste.

Gullies, often used as indicators of soil type and permeability in temperate regions, must be viewed with considerable caution in permafrost areas. In impermeable gravel deposits cemented by ice, for example, they will not necessarily display the same form as gullies in impermeable unfrozen soils.

Depressed-centre polygons, one of the most dependable indicators of permafrost, are commonly found in poorly drained areas. Pools of water in the centres of some polygons are a diagnostic recognition feature and it is common to find these polygons expressed on aerial photographs as dark-toned centres surrounded by light-toned marginal ridges. Raised-centre polygons occur in slightly better drained areas than those in which the depressed-centre polygons are found; generally, the centres are relatively level, although they may be domed where frost action is extremely active. In contrast to depressed-centre polygons, drainage round raised-centre polygons is commonly concentrated in marginal trenches and pools of water are present at trench intersections. Because of their high centres these polygons are commonly expressed on aerial photographs as light-toned centres surrounded by dark-toned margins. Frost-crack polygons may be difficult to distinguish on aerial photographs because they are similar to high-centre polygons; they may be present in some areas where permafrost is absent.

The airphoto observer can also often detect a range of diagnostic mound forms having varying sizes, shapes, origin and occurrence. Among these forms are so-called "earth hummocks," peat mounds, frost mounds and pingos. The last mentioned are readily distinguished on aerial photographs by their distinctive landforms although they may be confused with erosional knolls or hills.

AIRPHOTO INTERPRETATION IN THE PERMAFROST REGION OF CANADA

The discontinuous and continuous zones in Canada's permafrost region can each be considered to have three subdivisions for purposes of airphoto interpretation (see Brown, 1967a and 1970b for a description of the discontinuous and continuous permafrost zones). In the discontinuous zone the three subdivisions are:

1. southern half of discontinuous zone (southern fringe) where permafrost occurs mainly as scattered islands in peatlands;
2. peatlands in northern half of discontinuous zone (widespread subzone) where permafrost is widespread, i.e., 50 per cent or more;
3. mineral terrain in northern half of discontinuous zone (widespread subzone) where permafrost is widespread, i.e., 50 per cent or more.

In the continuous zone the three subdivisions are:

1. Forested band along southern boundary;
2. Tundra;
3. Polar desert.

A stereoscopic pair of aerial photographs from each of these subdivisions is presented with selected low level and ground photographs to illustrate various features of permafrost as they relate to aerial photographs. Locations are shown on Figure 1.

Discontinuous Zone

Permafrost in Peatlands. The identification of features in peatlands containing permafrost is not always as straightforward as the two subdivisions indicate. Most palsas are relatively small features and cover very small areas on all but aerial photographs flown at low levels. Peat plateaux are more extensive and thus more easily discernible. Where peat micro-relief features are absent the existence of permafrost can only be inferred in relation to visible terrain factors such as drainage. These terrain relations have to be considered in the broad framework of climate and location in the permafrost region. For example, permafrost will seldom be found in wet peatland in the southern fringe of the discontinuous zone, but is quite common in similar terrain conditions in the northern portion.

Attempts have been made to correlate the distribution of permafrost in peat terrain with the occurrence of lichen. It has been suggested that lichen (termed the "H factor" in Radforth's muskeg classification) is an indication of permafrost in peatlands (Radforth, 1962, 1963a, 1963b, 1966), and it can be used effectively in identifying the presence of permafrost in peatlands on aerial photographs (Korpijaakko and Radforth, 1966). These suggestions have been considered in the investigations of permafrost occurrence in Canadian peatlands and have proved to be invalid (Brown, 1966). Lichen is indeed widespread in Northern Canada, but it proliferates in many peat areas where no permafrost exists and is absent from many areas where it occurs.

1. Peatlands in southern half of discontinuous zone

Figure 2 shows a typical stereo pair of aerial photographs from the southern fringe of the discontinuous zone in Northern Ontario about 30 miles west of James Bay (Brown, 1968, 1970a). The entire area is peatland in which three main patterns are evident:

(A) Medium grey with smooth texture covering the north-central and south sides of the stream which flows from west to east. This is a low, wet, poorly-drained flat sedge area. The black pepper-like flecks are small pools of water less than 100 ft in diameter. No permafrost occurs in this pattern.

(B) Fine network of closely spaced dark grey to black flecks in a light grey mesh-like matrix in the northwest corner of the photographs. This is a low, wet, poorly-drained and flat area consisting of shallow pools up to 200 ft in diameter separated by 1- to 2-ft-high narrow sedge- and moss-covered peat ridges.

(C) Light grey circular and irregularly shaped areas with white patches adjacent to the stream and in the southeast portion of the photographs. These areas are large mature palsas 10 to 15 ft high and high peat plateaux and coalesced palsas (photographs Nos. 1 and 2). The light grey tone is caused by the dense cover of Labrador tea (Ledum groenlandicum) growing on the lichen cover of the palsas. The white patches are lichens (Cladonia sp.). Permafrost occurs in these features. The peat is about 5 ft thick, overlying grey silty clay with sand and small stones. The permafrost table is about $2\frac{1}{2}$ ft below the ground surface and the permafrost is probably about 20 to 30 ft thick.

Some typical aerial photographs of other areas in the southern fringe of the discontinuous permafrost zone are described for Thompson, Manitoba (Johnston et al, 1963), northern Alberta (Brown, 1964), northern Saskatchewan (Brown, 1965) and northern British Columbia (Brown, 1967b).

2. Peatlands in northern half of discontinuous zone

In some localities the features with permafrost are quite distinct from those with no permafrost. Such a situation exists in the northern portion of the discontinuous zone in northern Manitoba on the Nelson River 10 miles east of Gillam and about 100 miles west of Hudson Bay (Brown, 1970b). The peatland in this region is a mosaic of peat plateaux interspersed with wet depressions. The stereo pair and photographs Nos. 3 and 4 in Figure 3 show the two main patterns clearly.

(A) Dark grey with small black circular and elongated areas. These are low, flat, wet, grass- and sedge-covered depressions with shallow pools of water. Tree growth is virtually non-existent. On the oblique aerial view this pattern comprises most of the dark grey smooth-textured lower half of the photograph. In the ground view the low wet area in the foreground is typical of this terrain type. Test borings indicate that no permafrost occurs under these wet depressions and pools.

(B) Light grey with small white irregular shaped areas. These are peat plateaux, rising 3 to 4 ft above the level of Pattern (A), covered with dense spruce forest and groundcover of hummocky thick Sphagnum and other mosses, lichens and Labrador tea. On the oblique aerial view this pattern comprises the coarse-textured upper third of the photograph. In the ground view the forested peat plateau in the background is typical of this terrain type. Test borings indicate that permafrost exists in the peat plateaux to a depth of about 80 ft. The active layer varies from about $1\frac{1}{2}$ to 2 ft.

3. Mineral terrain in northern half of discontinuous zone

This subdivision presents the greatest difficulties for the interpretation of permafrost and it is difficult to select one aerial photograph representative of the diverse conditions. The permafrost is discontinuous but widespread, occurring in mineral terrain as well as in peatland. Few surface manifestations such as polygons and thaw slumps exist and they are frequently masked by vegetation. Thus the existence and distribution of permafrost has to be mainly inferred.

This situation exists at Schefferville, Quebec, located in the centre of the Labrador-Ungava peninsula where large-scale open-pit mining or iron ore has been carried out for more than 15 years. Elevations in this portion of the Labrador Trough vary from about 1,500 ft above sea level in valley bottoms to more than 2,500 ft on ridge summits. Permafrost is discontinuous, occurring in the form of small scattered islands below the treeline (about 2,300 ft) and it is widespread with measured thicknesses in excess of 300 ft above this elevation. Several accounts of permafrost conditions in the area and associated mining problems are described by Ives (1962) and Thom (1969a, 1969b).

A typical stereo pair from this area, 15 miles northwest of Schefferville, is shown in Figure 4. Two main patterns are evident:

(A) White to light grey areas with closely spaced black flecks in the west half of the aerial photographs. This is lichen-spruce woodland which occurs in valley bottoms up to about 2,300 feet above sea level (photograph No. 5). The black flecks are white and black spruce up to 50 ft high. The white and light grey tones are caused by a continuous lichen mat (mainly *Cladonia sp.*) up to 8 in. thick. Little or no permafrost occurs in this pattern.

(B) Medium grey, smooth textured area in east half of aerial photographs. This is lichen-heath tundra on ridge summits and slopes above 2,300 ft (photograph No. 6). Lichen and tundra plants predominate. A few scattered stunted trees, mainly spruce, grow only in sheltered locations. Permafrost is widespread to continuous throughout this pattern. The active layer is 5 to 10 ft thick and permafrost varies in thickness to 300 ft and more. No surface features are visible to indicate the existence of permafrost.

Continuous Zone

1. Forested band along southern boundary

Virtually all of the continuous permafrost zone lies north of the treeline, but this smallest of the six subdivisions occurs where the boreal forest extends northward along the Mackenzie River almost to the Arctic coast. Here, as in the previous subdivision, features associated with permafrost are frequently obscured and it is difficult to select one representative aerial photograph. Because this division lies in the continuous zone, permafrost exists everywhere beneath the land surface. Ground surface features would be expected to reflect the characteristics of both the active layer and underlying permafrost. Tree growth is somewhat sparse and stunted, being near the treeline, although vigorous growth exists in the forested portion of the Mackenzie Delta itself and its immediate vicinity and along the Mackenzie River. Some surface evidence of permafrost exists in the Delta, including polygons and some lake and riverbank slumping where thawing of frozen ground is occurring (Mackay, 1963). Away from the Delta, patterned ground and thermokarst appear in areas where tree growth is particularly sparse. Some typical aerial photographs of areas in the forested band of the continuous zone are described for the alluvial fans west of the Mackenzie Delta (Legget et al, 1966) and the Mackenzie Delta region (Mackay, 1963; Pihlainen et al, 1956).

A typical stereo pair (A11941-199 and 200) in this subdivision is shown in Figure 5, located at Arctic Red River, N.W.T., on the Mackenzie River. Two main patterns are evident:

(A) Medium grey tone with closely spaced black flecks and some light grey blotches in the northeast and west-central sections of the photographs. This is stunted spruce growth up to about 20 ft high with moss and lichen ground cover, similar to the forested areas in photograph No. 7. The active layer is 2 to 3 ft thick and the permafrost is probably 200 to 300 ft thick.

(B) Closely spaced, irregularly shaped light grey to white smooth-textured areas, with irregularly shaped black areas. These are low, flat, wet grass- and sedge-covered depressions with shallow pools of water up to 100 ft in diameter. The pools are of thermokarst origin, indicating the presence of large masses of ground ice in the underlying permafrost. Similar thaw ponds and polygonal cracks are also evident in the foreground of photograph No. 7.

A very good example of a beaded stream is shown in the other stereo pair (A21015-203 and 204) in Figure 5. The enlargements or "beads" in the stream are caused by the melting of large masses of ground ice in the underlying permafrost. This aerial photograph is from Fort Good Hope, N.W.T., on the Mackenzie River and is actually located in the northern portion of the discontinuous permafrost zone. This feature occurs frequently in the continuous zone and can be observed in the other stereo pair in Figure 5 extending diagonally from southeast to northwest.

2. Tundra

Tundra covers approximately the southern half of the continuous permafrost zone, including all the land area of mainland Canada west of Hudson Bay and north of the treeline plus the southern parts of three large islands - Baffin, Victoria and Banks - in the southern part of the Arctic Archipelago. A surface peat layer is well developed, generally a few inches to several feet thick; the active layer is usually less than 3 ft. Surface features associated with permafrost are well developed and clearly visible on airphotos. As a result, most of the papers about aerial photographs in the permafrost region describe features occurring most frequently in this subdivision (Bird, 1967; Fletcher, 1964; Hussey, 1962; Mackay, 1962; Mackay, 1963; Pressman, 1963; Ray, 1960; Stager, 1956; Svensson, 1964).

Several typical surface features associated with permafrost conditions are clearly shown in the stereo triplet in Figure 6. These aerial photographs are also shown and described by Mackay (1963, p. 75).

(A) The circular hill, with cracks radiating from the summit, is a pingo. It is about 400 ft in diameter and probably 100 ft high, similar to the pingo in photograph No. 8. Raised-centre tundra polygons up to 100 ft in diameter are visible in the lake bed depression in which the pingo is situated.

(B) The white rippled area on the east shore of the lake is a slumped hillside caused by the melting of ground ice in the underlying permafrost (photograph No. 9).

3. Polar Desert

This comprises the northern half of the continuous permafrost zone and is confined to the Arctic Archipelago. Vegetation is sparse or non-existent and is a minor factor in the permafrost environment. Coupled with frigid climatic conditions that are the most severe in Canada, this results in a wide assortment of surface features associated with permafrost occurring over extensive areas. They show up on the aerial photographs more clearly than in any other subdivision.

A typical stereo pair is shown in Figure 7. The high-centred polygons in the southeast section of the aerial photographs (Pattern A) are about 100 ft in diameter (photograph No. 10). The black irregularly shaped areas are water-filled polygonal trenches. The scalloped edge of Pattern A is caused by the melting of ground ice in the polygonal trenches at the edge of the low escarpment. The active layer is less than 3 ft and the permafrost is probably 2,000 ft thick. Polygonal cracks such as the one in Photograph No. 11 are also prevalent in this subdivision.

CONCLUSIONS

The interpretation of permafrost conditions by the use of black and white aerial photographs has been actively pursued by many investigators for more than 20 years. Most notable of these workers are Mollard and Sproule in Canada, Frost and his colleagues in the United States, and Protas'eva in the U.S.S.R. Great advances have been made and a considerable degree of accuracy attained in assessing permafrost conditions. With the steady increase in mineral resource exploration and production activities, and with accompanying community (townsite) development, these investigations have proved to be particularly valuable in Northern Canada where large-scale map coverage is sparse.

There is, however, still a considerable degree of imprecision and uncertainty connected with this aspect of airphoto interpretation because it does not exist at the ground surface and thus is never directly exposed to the aerial camera or the airphoto interpreter. The actual nature of the subsurface conditions has to be inferred from surface features. This is particularly difficult in the discontinuous zone. As more information is obtained from the field and related to patterns on airphotos, this situation should improve.

Accompanying this steady development in the use of black and white airphotos is the increasing use of colour and testing of other forms of remote sensing imagery. High cost has so far curtailed the extensive use of colour photographs. Their main advantage in the interpretation of permafrost conditions is the greater ease of identifying vegetation and soil types, thus improving the inferences concerning subsurface conditions. Tests have been carried out on remote sensing imagery such as infra-red thermal scanning, radio phase and apparent resistivity, but they are not developed to the point where they can be used to detect and delineate such features as bodies of permafrost, thickness of active layer, thickness of permafrost, and occurrence of ground ice. Infra-red thermal scanning can only delineate ground surface thermal patterns and little is known of the relation of these to subsurface permafrost conditions. Radio phase and apparent resistivity penetrate the permafrost, but they do not appear to be sufficiently sensitive to distinguish frozen ground from unfrozen ground in all situations.

It is the main purpose of this paper to illustrate some of the techniques of interpreting surface features that are or may be related to permafrost conditions, but it is not a final authoritative statement on the subject. Many of the papers in the field are cited as references and should be consulted for a more complete appreciation of the present situation. Black and white airphotos have been used for more than two decades in the interpretation of permafrost conditions. Despite the advent of other more sophisticated methods their relatively low cost and availability ensure their continued use for the foreseeable future.

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AERIAL PHOTOGRAPHS

	Permafrost Subdivision	Airphoto Number	Taken by	Date	Altitude ft, a.s.l.	lens focal length in.	Approx. Scale	Location
1.	Southern fringe -peatlands	A14961-127,128	RCAF	Sept. 3, 1955	30,000	6	5,000':1"	30 mi. N.W. of Attawapiskat, Ont.
2.	Widespread discontinuous -peatlands	A14188-119,120	RCAF	June 30, 1954	20,400	6	3,400':1"	10 mi. E. of Gillam, Man
3.	Widespread discontinuous -mineral terrain	A11551-41,42	RCAF	Aug. 25, 1948	17,340	6	2,890':1"	15 mi. N.W. of Schefferville, P.Q.
4.	Continuous -forested	(a) A19941-199,200	Spartan	June 13, 1967	6,100	6	1,000':1"	Arctic Red River N.W.T.
		(b) A21015-203,204	Spartan	June 20, 1969	6,100	6	1,000':1"	Fort Good Hope, N.W.T.
5.	Continuous -tundra	A12902-118, 119 120	RCAF	Aug. 23, 1950	20,000	6	3,333':1"	20 mi. NE. of Tuktoyaktuk, N.W.T.
6.	Continuous -polar desert	A12725-70,71	RCAF	July 18, 1950	9,000	6	1,500':1"	4 mi. E. of Isachsen, N.W.T.

Copies of these aerial photographs may be purchased from the National Air Photo Library, 615 Booth Street, Ottawa, Canada.

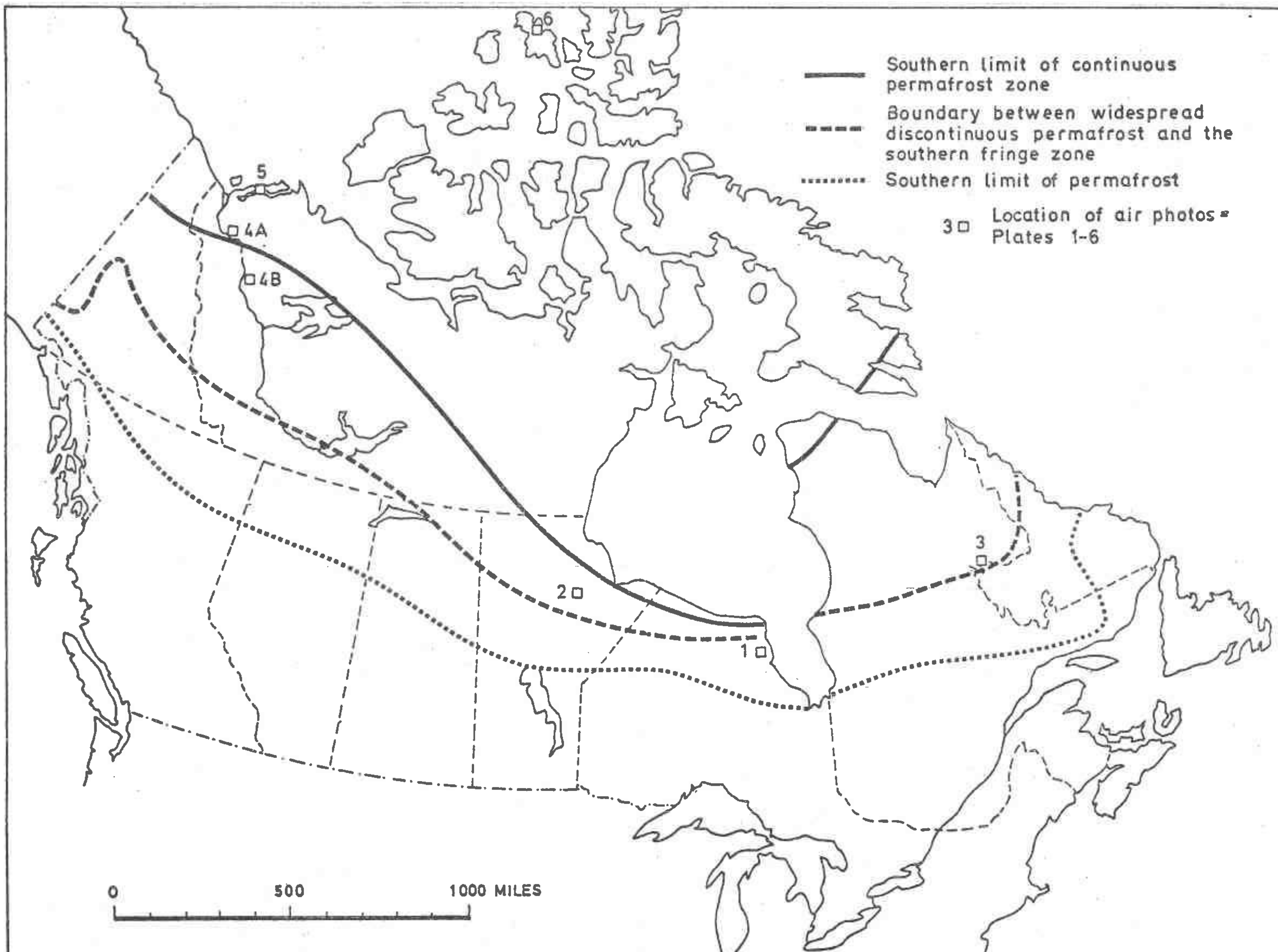


FIGURE 1 PERMAFROST DISTRIBUTION

FIGURE 2 TYPICAL AERIAL AND GROUND PHOTOGRAPHS OF PEATLANDS IN SOUTHERN FRINGE OF DISCONTINUOUS ZONE IN NORTHERN ONTARIO

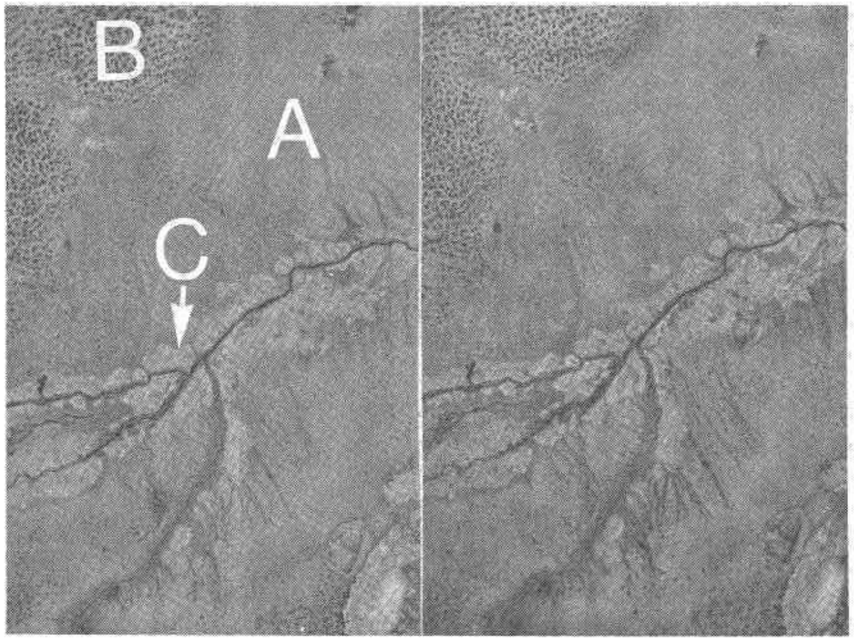
Airphotos: A14961-127 and A14961-128 (scale 5,000 ft:1 in.) (Courtesy National Air Photo Library, Ottawa.)

Photograph No. 1

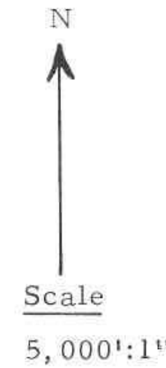
Small, youthful palsas consisting of sedge peat with virtually no living vegetation. The active layer is $1\frac{1}{2}$ ft and the permafrost is 5 ft thick. There is no permafrost in the surrounding wet peatland. The location is at the southern limit of the discontinuous zone near the south end of James Bay about 5 miles west of Moosonee, Ontario (September 1965).

Photograph No. 2

Mature peat plateau 15 ft high formed from coalesced palsas containing permafrost (airphoto Pattern C). Note dense coverage of burned spruce trees, dense Labrador tea and hummocky lichen and Sphagnum-covered peat surface. No permafrost exists in sedge-covered depression in foreground (September 1965).



A14961-127 A14961-128



Photograph No. 1

Photograph No. 2

FIGURE 2

FIGURE 3 TYPICAL AERIAL AND GROUND PHOTOGRAPHS OF PEATLANDS FROM NORTHERN HALF OF DISCONTINUOUS ZONE IN NORTHERN MANITOBA.

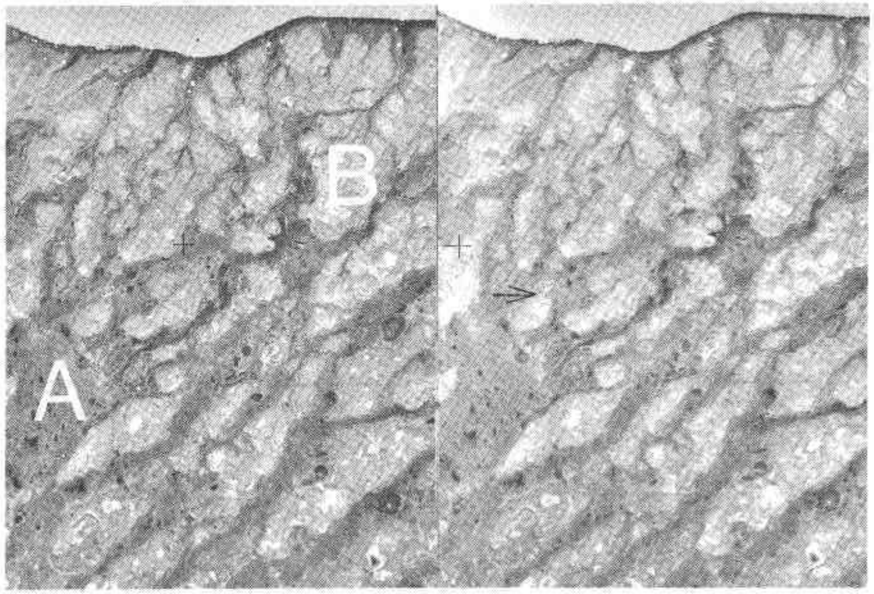
Airphotos: A14188-119 and A14188-120 (scale 3,400 ft:1 in.) (Courtesy National Air Photo Library, Ottawa.)

Photograph No. 3

Aerial view from altitude of about 500 ft of terrain in aerial photograph showing low wet treeless areas with no permafrost (Pattern A) and forested peat plateaux with permafrost (Pattern B) (October 1963)

Photograph No. 4

Ground view of terrain in aerial photograph showing low, wet, treeless areas with no permafrost (Pattern A) and forested peat plateaux with permafrost (Pattern B) (October 1963).

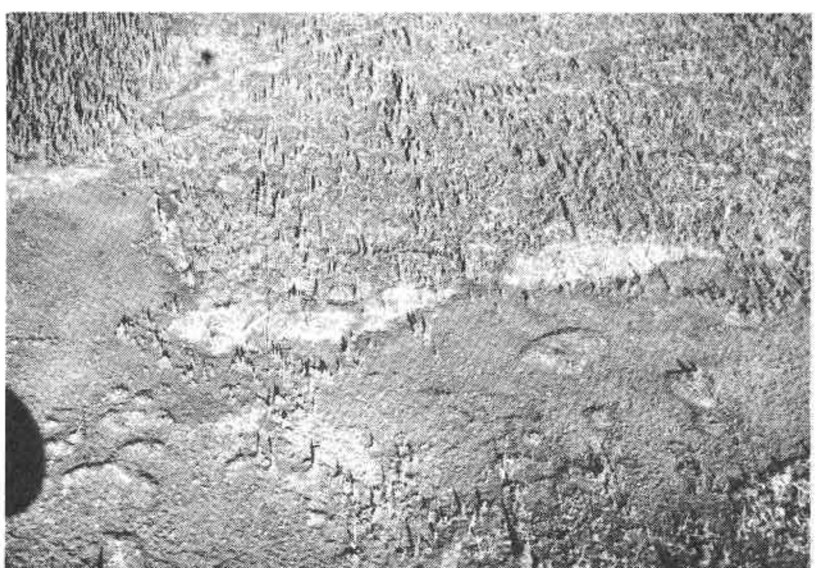


A14188-119

A14188-120

Scale

3,400':1"



Photograph No. 3

Photograph No. 4

FIGURE 3

FIGURE 4 TYPICAL AERIAL AND GROUND PHOTOGRAPHS OF MINERAL TERRAIN IN NORTHERN HALF OF DISCONTINUOUS ZONE IN NORTHERN QUEBEC NEAR SCHEFFERVILLE.

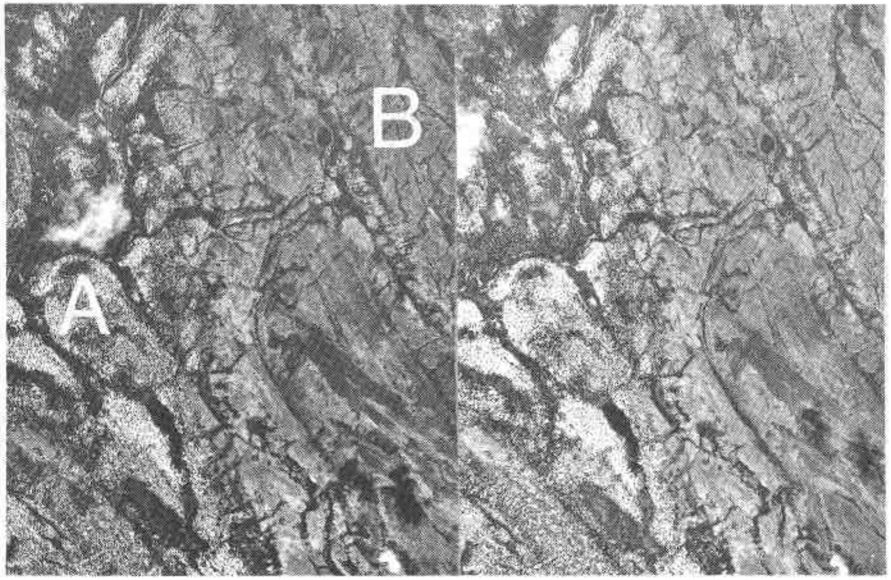
Airphotos: A11551-41 and A11551-42 (scale 2,890 ft:1 in.) (Courtesy National Air Photo Library, Ottawa.)

Photograph No. 5

Lichen-spruce woodland in valleys (Pattern A) (June 1959).

Photograph No. 6

Lichen-heath tundra on upland surfaces (Pattern B) (June 1959).



A11551-41 A11551-42

N

Scale

2,890':1"

Photograph No. 5

Photograph No. 6

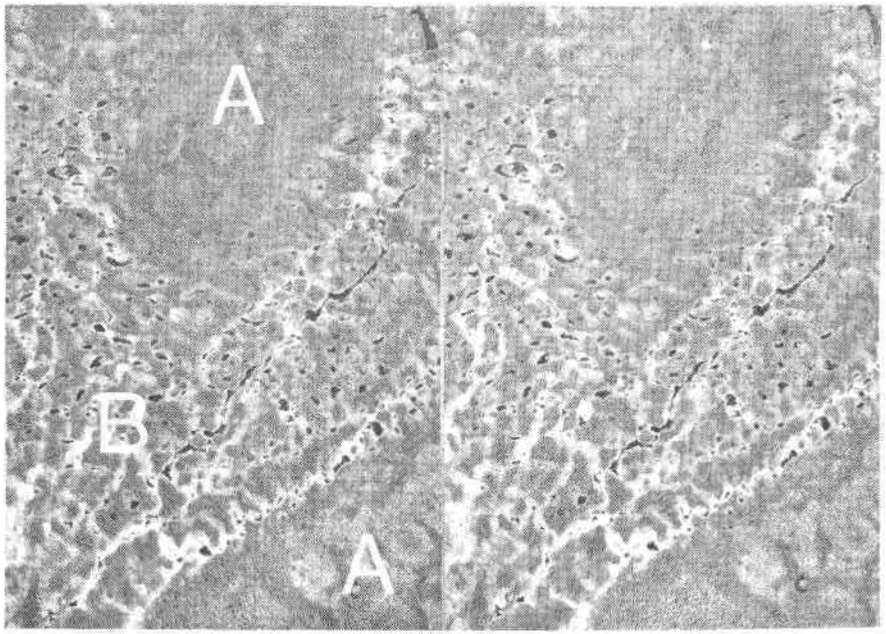
FIGURE 4

FIGURE 5 TYPICAL AERIAL AND GROUND PHOTOGRAPHS OF FORESTED BAND OF CONTINUOUS ZONE, NORTHERN MACKENZIE WATERWAY.

Airphotos: A19941-199 and A19941-200 (scale 1,000 ft:1 in.); A21015-203 and A21015-204 (scale 1,000 ft:1 in.) (Courtesy National Air Photo Library, Ottawa.)

Photograph No. 7

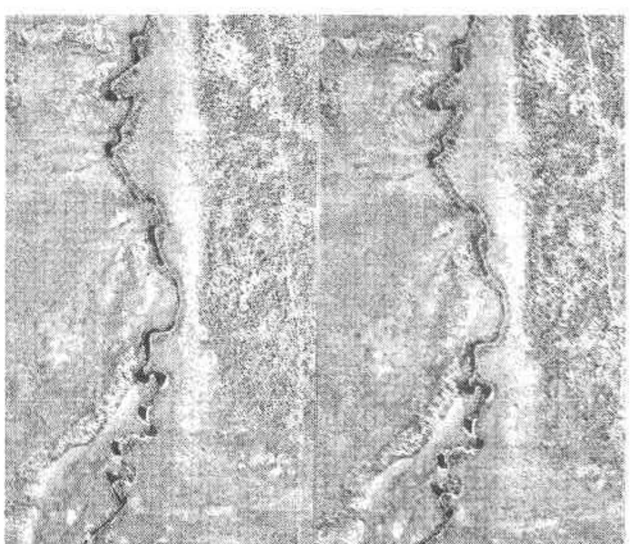
Aerial view from altitude of about 800 ft of thaw lakes up to 500 ft in diameter and polygonal cracks in forested band along southern edge of continuous permafrost zone. Location is at Benjamin Lake, about 140 miles northeast of Yellowknife, N.W.T. This is shown as the northern part of the widespread discontinuous permafrost on the Permafrost Map of Canada (Brown 1967a), but conditions are similar to those in the forested continuous zone (Purdue University photograph, August 1951).



A 19941-199 A19941-200

Scale

1,000':1"



A21015-203 A21015-204

Scale

1,000':1"

Photograph No. 7

FIGURE 5

FIGURE 6 TYPICAL AERIAL AND GROUND PHOTOGRAPHS OF TUNDRA IN CONTINUOUS ZONE NEAR TUKTOYAKTUK, N.W.T.

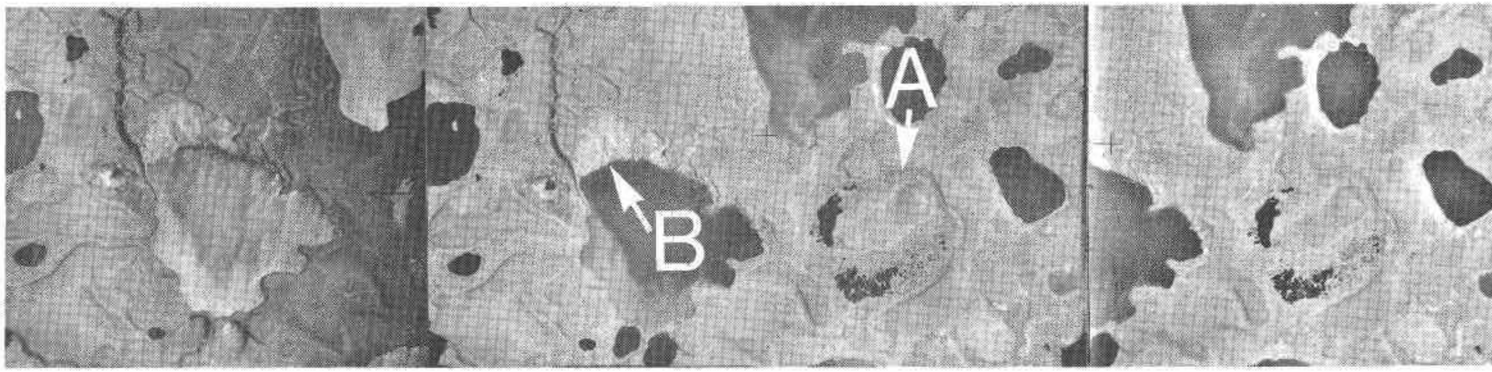
Airphotos: A12902-120, A12902-119 and A12902-118 (scale 3,333 ft:1 in.) (Courtesy National Air Photo Library, Ottawa.)

Photograph No. 8

Aerial view from about 800 ft of a pingo (Pattern A). It is located in a lake bed, is about 130 ft high, and has a core of massive ice (August 1951).

Photograph No. 9

Aerial view from an altitude of about 500 ft of hillside slumps caused by thawing of ice-rich permafrost (Pattern B) in same area as pingo. (National Film Board Photograph, June 1960).



A12902-120 A12902-119 A12902-118

N

Scale

3,333':1"

Photograph No. 8

Photograph No. 9

FIGURE 6

FIGURE 7 TYPICAL AERIAL AND GROUND PHOTOGRAPHS OF POLAR DESERT IN THE CONTINUOUS ZONE OF THE HIGH ARCTIC.

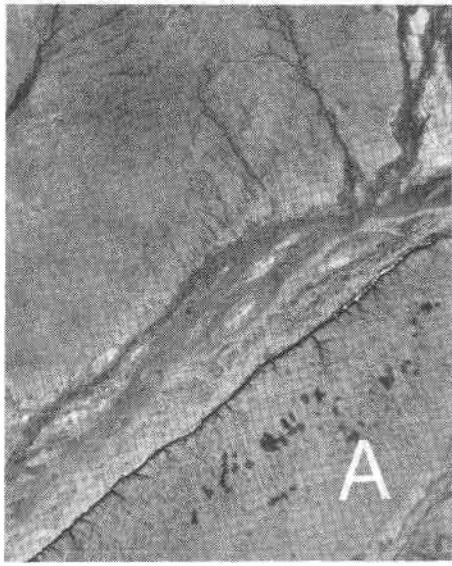
Airphotos: A12725-71 and A12725-70 (scale 1,500 ft:1 in.) (Courtesy National Air Photo Library, Ottawa.)

Photograph No. 10

Aerial view from an altitude of 500 ft of ice wedge polygons 50 to 100 ft in diameter on Ellef Ringnes Island near Isachsen, N.W.T., and similar to those on aerial photograph. Grey patches at bottom of photograph are thermokarst ponds. Polygonal trenches toward the top of the photograph are wet but not water-filled. (Photograph courtesy of the Geological Survey of Canada, August 1967).

Photograph No. 11

Sand wedge containing organic layers beneath polygonal trench in glaciofluvial deposit at Mary River, northern Baffin Island. Active layer is 5 ft thick. Blocks of massive ice 80 ft thick occur in these deposits (July 1965).



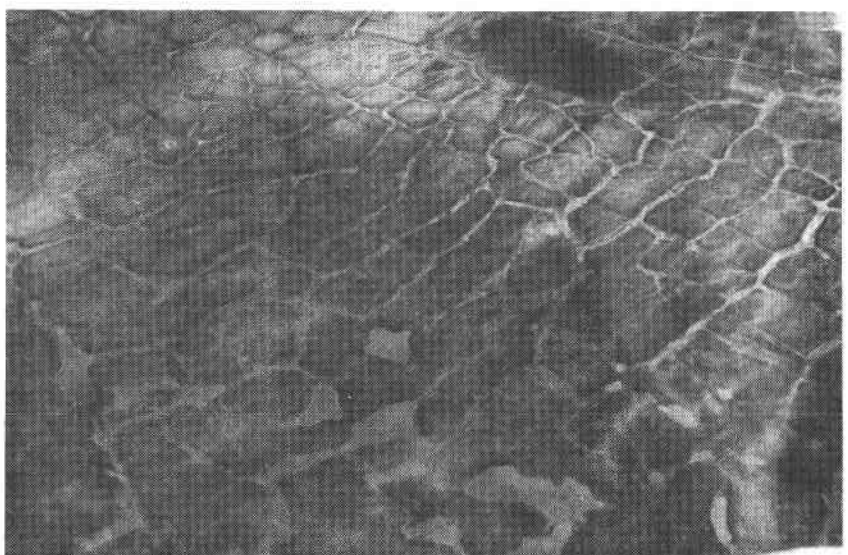
A12725-71

A12725-70

N

Scale

1, 500':1"



Photograph No. 10

Photograph No. 11

FIGURE 7