*Frost Problems and Photo Interpretation of Patterned Ground**†

RAGNAR THORÉN,
Captain, Royal Swedish Navy

ABSTRACT: *Frost conditions of both the seasonal and permanent type are of considerable importance in agriculture, road building, and building construction in Arctic areas. Photographic interpretation offers great possibilities in the analysis of frost conditions. This is because the various types of frost conditions may be identified by a number of tone and texture patterns which they create on the ground, and which are readily visible in aerial photography.*

(*Jahreszeitliche sowie fortwaehrende Frostzustaende ueben betraechtlichen Einfluss aus in der Landwirtschaft, Strassenbau und Bau-Konstruktion in arktischen Gebieten. Luftbild Interpretation ist von groesstem Wert in der Analyse der Frostzustaende. Das ist der Fall, da verschiedene Arten von Frostzustaenden identifiziert werden koennen durch die Zahl der Schattierungen und Gewebemuster, die dieselben auf der Oberflaeche verursachen, und die leicht zu erkennen sind in Luftbildaufnahmen.*)

WHEN the water in the ground freezes, ground frost forms. If frozen a part of the year only, this frozen condition may be called *seasonal frost*. Perennial frozen ground, on the other hand, is called *permafrost*. The thin surface layer of permanently frozen ground, that thaws in summer and freezes in winter, is called the *active layer*.

SEASONAL FROST PROBLEMS

Seasonal frost is a normal condition of the ground in northern countries during wintertime. For agriculture it is even of special importance, and actually favorable for the wintering of rye, while snowfall on nonfrozen ground is dangerous for such wintering.

For roads, on the other hand, severe ground frost may end with a catastrophe. The process of water freezing in soils will often be accompanied by expansion resulting in lifting the ground; this is called *frost-heaving*. Heaving of the ground surface caused solely by the crystallization of the original water contents in the freezing soil, independent of any water supply, is always very slight and usually of no practical importance. All frost-heaving of any practical significance depends upon the water suction to the freezing layers, mainly from a ground water supply. This suction is of capillary nature and varies with the mechanical composition of the soil. Frost-heavings of about 8 inches (20 cm.) are quite common in Scandinavia, especially in the northern parts. The silt and loam sediments show a normal heave of about 6–8 in. (15–20 cm.), and at places where frost-boil appears during thawing (see below), the heave can be 12–16 in. (30–40 cm.) or more. Moraine-ground usually shows a less amount of heave, about half of that for silt; 8 inches, however, is not unusual (Beskow).

Frozen soil often shows a special structure with layers or lenses of pure ice within the soil; this is called ice-stratified soil. These ice layers may show very different structural pictures, depending on the type of soil. In general the ice layers are parallel to the ground surface, i.e. mostly horizontal. The finer the soil, the coarser the structural elements.

When the ice in the ground melts there will be an excess of water, thereby lowering the supporting capacity of the roads. If traffic then is allowed, the road surface will most likely break down. The melting process may be accompanied by a soil-heaving phenomena, called *frost-boil*. Among the processes of soil freezing and thawing, frost-boil is the most damaging one to the highways.

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† See also the other report of this Working Group 3 which is in this issue and also the Group Report in PHOTOGRAMMETRIC ENGINEERING, Vol. XXV, (1) 121.

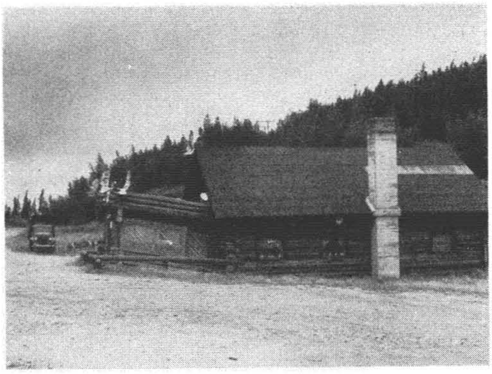

FIG. 1. A typical example showing what may happen if the builder is not familiar with the permafrost conditions: Bert and Mary's nice little inn at Richardson Highway between Fairbanks and Big Delta, Alaska, originally built with a veranda as a coffee-room. Ten months later, however, useful as a steep-sloping entrance only, to the settled main building. (Photo by the author August 24, 1955.)

Permafrost Problems

The seasonal frost is no doubt a problem for the constructor. It is a small one, however, compared to the controlling influence of permafrost on certain engineering projects; examples are transportation, surface and underground exploration, construction and durability of structures in or on permafrost, water supply, sewage disposal, etc.

Permanently frozen ground is common not only in the Arctic but in several subarctic areas. To ignore permafrost in construction is to invite delays, expensive repairs, or later failures (Black).

If proper location and construction methods are not used, permanently frozen ground can cause collapse of both roads and buildings. Heaving, settling in the thawed ground, and poor drainage are the main problems. Figure 1 illustrates what may happen if an architect is not familiar with permafrost problems. Neither the landlord nor the builder had any idea of the presence of permafrost in this area of the subarctic region of Alaska. There was, however, permanently frozen ground. When the insulating surface was removed, the ground thawed and the main building, which was constructed with a heavy concrete footing, settled. If by chance the result had been heaving instead of settling, an ice wedge could have broken the floor and appeared in the kitchen!

Permafrost, however, presents not only many special engineering problems but agricultural problems as well. The less disturbance of the natural insulating vegetation and soil cover, the better. Farming activities quite naturally include clearing the surface with the object of cultivating new fields, which may be undermined by large ice masses. Then, when the soil cover is disturbed and the surface is cleared, the ice melts and thermokarst mounds and pits are formed. Thus the new fields may eventually become difficult or impossible to cultivate (Pévé).

FIG. 2. *Sorted circles* and *polygons* (center) in stony terrain, the polygons up to 15 feet (4.5 m.) across, on North East Land, Svalbard, at 650–800 feet (abt. 200–240 m.) above sea level. (Ground photo by the author July 30, 1957.)

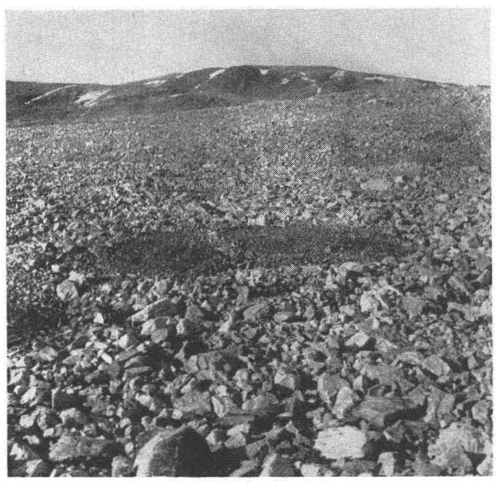

FIG. 3. A vast area closely covered with blocks crumbled through frost action. In this Devils Acre *sorted polygons* and *sorted circles* appeared everywhere. Ground photo from North East Land, between Mt. Celsius at Murchison Bay and the West Ice at abt. 850 feet (250 m.) above sea level. (Taken by the author July 30, 1957).

When settlers use winter-roads across bogs, the higher conductivity of cold of the hard-pressed snow or ice cover on the tracks, causes an increase in the thickness of the permafrost there. In summer, when the snow has melted and the top level of the frost sinks, it will drop less beneath the road than in the surrounding terrain. This higher level of the road will increase in height next year, as well as the following year, and soon the road will have to be abandoned (Bergström, Fries and Lundqvist).

Another serious problem facing the settler in arctic regions is the distribution and quality of ground water. In vast areas of permafrost zones the ground water is shallow and of poor quality on permanently frozen ground. In the greater part of eastern Siberia, as example, ground water cannot even properly develop, because of the permafrost (Zaborski).

In Sweden systematic research and laboratory experiments as regards soil freezing and frost-heaving was started in 1925 when "The Swedish State Road Institute" and "Geological Survey of Sweden" in co-operation included these questions in their program work. Beskow (1935) presented an important paper dealing with "Mechanics of Soil Freezing," "The Frost-heaving Process," "Hydrodynamic Postulates of Frost-heaving" and "Temperature Conditions in Freezing Ground."

Further, the Royal Swedish Institute of Technology, Stockholm, has a complete Ice laboratory with equipment for freezing experiments at −22° Fahr. (−30°C.) of soil and water masses, e.g. ground frost experiments, damming experiments with ice flows, etc.

In the Soviet Union, where vast areas are undermined by permafrost, all government organizations, municipalities, and co-operative societies are required to make a thorough survey of the permafrost conditions according to a prescribed plan, before any structure may be erected in the permafrost region.

FIG. 4. A close-up photo of a *sorted circle* (debris island), about 4 feet across, in the same terrain as shown in Fig. 3, taken by the author July 30, 1957.

FIG. 5. Close-up view of a *non-sorted circle*, 4 to 5 feet across, in stony terrain not far from the West Ice, North East Land, at abt. 920 feet (280 m.) above sea level. (Photo by the author July 30, 1957.)

Photo Interpretation of Patterned Ground

Thus, a true knowledge of the problems concerning frozen ground and the occurrence of permafrost in different areas is of great im-

FIG. 6. *Sorted polygons* at Murchison Bay, North East Land, 26 feet (abt. 8 m.) above sea level. Depth of active layer abt. 24 in. (60 cm.) and thickness of permafrost not far from 1,000 feet (abt. 300 m.). (Photo by the author July 28, 1957.)

FIG. 7. Close-up photo of a *sorted polygon*, abt. 4 feet (1.1–1.2 m.) across, in the same area and at the same level as in Fig. 6. (Taken by the author July 28, 1957).

portance. Similarly to photo interpretation having been proven of great value for discovering archaeological secrets, e.g. traces of ancient settlements, interpretation of photographs, showing terrain features, may be useful for revealing areas or patches of permanently frozen ground. Especially at high latitudes many geomorphic features stand out in beautiful relief as patterned ground (see below). If air photos are taken on suitable days with favorable light conditions in spring or perhaps early summer, when the snow coverage has been melted and foliage does not conceal the features of the terrain, quite a good result of a careful analysis of the pictures may be expected.

Vertical air photos as well as obliques ought to be taken in both color and black-and-white. Actually, color photos are often preferable, especially as obliques. In either case, the photos must be taken at a scale which is large enough for studying the ground details.

The interpretation of air photos should be supported by field observations and checked, if possible, by analyzing ground photos, taken at the same season and which show important details that are easily recognizable in the air photos. This is a common experience: the analyzing of both air and ground photos will offer the interpreter the best chances of a good result.

Classification of Patterned Ground

As regards classification of patterned ground there are several fine papers published in different languages, among others by the pioneer Bertil Högbom, Sweden (1914) in his scientific work (for the degree of Doctor of Philosophy, Uppsala 1914) on the geological importance of the ground frost, entitled "Über die Geologische Bedeutung des Frostes." Thirty years later another excellent work was presented in German by Carl Troll, Bonn (1944), see below.

In English there is an excellent review presented by Washburn in 1956 (*see references*), entitled "Classification of Patterned Ground and Review of Suggested Origins." The term *Patterned Ground* is introduced by Washburn as a group term for the more or less symmetrical forms, such as circles, polygons, nets, steps, and stripes, that are characteristic of, but not necessarily confined to, mantle subject to intensive frost action (Washburn).

The arrangement by the Washburn-classification of commonly obvious characteristics of patterned ground is in the direction of the increasing gradient. Most circles, nets and polygons occur on essentially horizontal ground. Steps and stripes, on the other hand, are limited to slopes. Further, within these two main groups of characteristics, patterned ground can be ascertained by the presence or absence of obvious sorting between stones and fines. According to this, Washburn classifies *Circles* in (a) Sorted (including debris islands) and (b) Non-sorted (including peat rings, tussock rings), *Nets* in (a) Sorted and (b) Non-sorted (including earth hummocks),

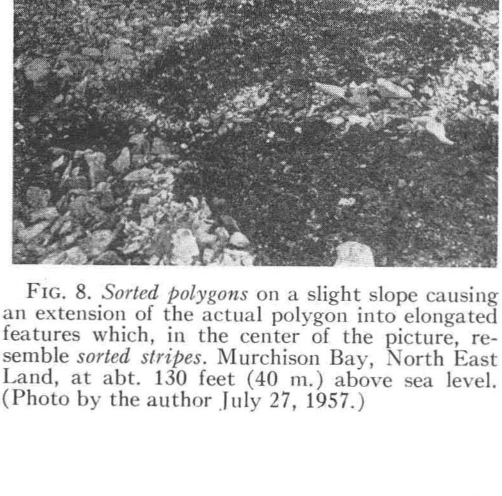

FIG. 8. *Sorted polygons* on a slight slope causing an extension of the actual polygon into elongated features which, in the center of the picture, resemble *sorted stripes*. Murchison Bay, North East Land, at abt. 130 feet (40 m.) above sea level. (Photo by the author July 27, 1957.)

Polygons in (a) Sorted and (b) Non-sorted (including frostcrack polygons, ice-wedge polygons, tussock-birch-heath polygons, desiccation polygons), *Steps* in (a) Sorted and (b) Non-sorted and, finally, *Stripes* in (a) Sorted and (b) Non-sorted.

Washburn defines *Sorted circles* as patterned ground whose unit component, the *mesh*, is dominantly circular and has a sorted appearance commonly due to a border of stones surrounding finer material. Debris islands are sorted circles occurring amid blocks or boulders. *Non-sorted circles* are patterned ground whose mesh is dominantly circular and which has a non-sorted appearance due to the absence of a border of stones, such as that characterizing sorted circles. *Sorted nets* are patterned ground whose mesh is intermediate between that of a sorted circle and a sorted polygon and has a sorted appearance commonly due to a border of stones surrounding finer material. *Non-sorted nets* are patterned ground whose mesh is intermediate between that of a non-sorted circle and a non-sorted polygon and has a non-sorted appearance due to the absence of a border of stones such as that characterizing a sorted net. *Sorted polygons* are patterned ground whose mesh is dominantly polygonal and has a sorted appearance commonly due to a border of stones surrounding finer material. *Non-sorted polygons* are patterned ground whose mesh is dominantly polygonal and has a non-sorted appearance due to the absence of a border of stones such as that characterizing sorted polygons.

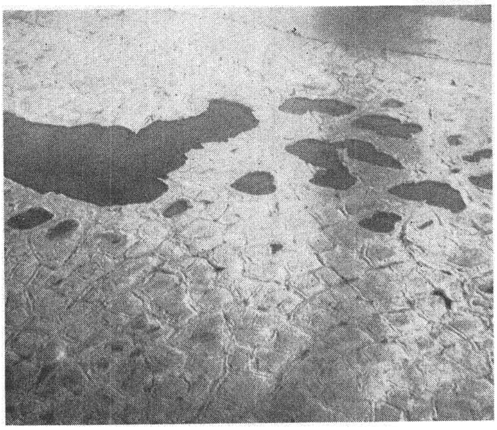

FIG. 10. Low-oblique of *non-sorted polygons* (ice-wedge polygons) on Arctic coastal plain near Point Barrow, in the continuous-permafrost zone, Alaska. Flat tundra surface. Part of a great thaw lake at top, angled thaw ponds (high center). Most of the polygons are high-centered, separated by shallow troughs. In left foreground and right center there are several low-center polygons with ponds developing in their center. (Photo by the author.)

FIG. 9. Low-oblique of *non-sorted polygons* (ice-wedge polygons) on the coastal plain, Arctic Slope, Alaska, southeast of Point Barrow, in the continuous-permafrost zone. Part of thaw lakes top right and left foreground, a rounded thaw pond left center. Most of the raised polygons are high-centered with low ridges around the margin of the flat-topped polygon. They are confined to relatively well drained areas between lake basins. The troughs around them are rather wide and sometimes deep as well. Be careful to avoid false relief with the troughs standing out as ridges. (From a color photo taken by the author August 15, 1955.

Depending on usage, synonymous terms may include fissure-polygons, mud-polygons, contractional polygons, and others. Ice-wedge polygons, tussock-birch-heath polygons, vegetation polygons and desiccation polygons are special varieties of non-sorted polygons. The ice-wedge polygons are characterized by bordering ice wedges. Synonymous terms are tundra polygons and Taymyr polygons. *Sorted steps* are patterned ground with a steplike form and a sorted appearance due to a downslope border of stones embanking an area of finer material upslope. *Non-sorted steps* are patterned ground with a steplike form and a non-sorted appearance due to a downslope border of vegetation embanking an area of relatively bare ground upslope. *Sorted stripes* are patterned ground with a striped pattern and a sorted appearance due to parallel lines of stones and intervening strips of dominantly finer material oriented down the steepest available slope. *Non-sorted stripes* are patterned ground with a striped pattern and a non-sorted appearance due to parallel lines of vegetation-covered ground and intervening strips of relatively bare ground oriented down the steepest available slope. A synonymous term is solifluction stripes (Washburn).

Britton's excellent paper on "Vegetation of the Arctic Tundra" (1957), *see references*, also

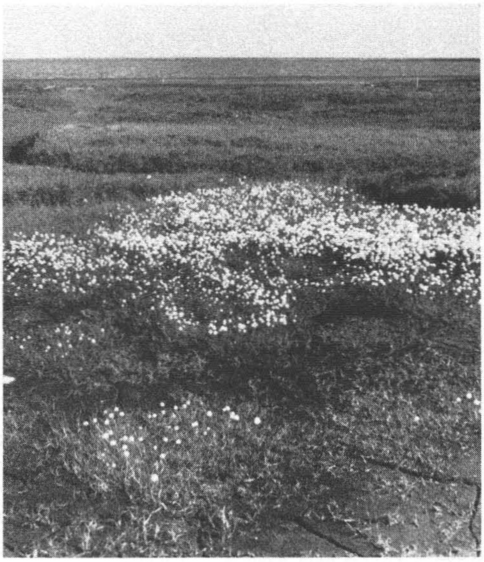

FIG. 11. Ground photo of *non-sorted polygons* (ice-wedge polygons) in the continuous-permafrost zone near Barrow, Arctic coastal plain of Alaska. Flat to high-centered polygons with shallow troughs (upper center); "Alaska Cotton" (Eriophorum Scheuchzeri), center; Mud cracks (foreground). (Photo by the author August 19, 1955.)

deals with the conspicuous ground patterns on the Coastal Plain, the ice-wedge polygons. Depending especially on differences in distribution and permanency of standing waters and the distribution of vegetation types, the surface of the polygons may vary in many respects. According to the origin, growth and decay of the polygons, i.e. their gradational forms, the features will change from flat surface with cracks to low-centered polygons, and, finally, to high-centered polygons. Low-center polygons are characteristic of the wettest terrain and high-center ones of the best drained slopes. Ridged polygons are ice-wedge polygons with low ridges around the margin of the polygon.

In the Swedish Arctic region, especially on permanently frozen peat-bogs, there are dome-shaped hillocks generally 10–13 feet high (observed maximum 23 feet) composed of a core of massive ice or ice-impregnated peat covered by about 3 feet of insulating peat and moss species. They are called "palsar" and may be compared with the Alaskan isolated, steep-sided, symmetrically rounded mounts or hillocks called *pingos*. These may attain a height of 10 to 100 feet or more, and are prominent features on the Arctic plain.

DISTRIBUTION OF PATTERNED GROUND

Patterned ground occurs not only in polar, subpolar, and alpine regions, but even in many other areas of the world, where climate and terrain favor frost action. A typical example of a more or less unexpected area of patterned ground is the low-leveled island Öland in the southern Baltic Sea at the east coast of Sweden. Öland is known for its silurian-ordovician limestone layers, its mild climate in summer and fall but with relatively cold winters. There occur perfect developed patterned ground with sorted as well as non-sorted nets and polygons, well worth a careful study (Rydquist, 1957). Troll, too, *see references*, has described these features and shown some good photos from this fascinating island in his well known work "Strukturböden, Solifluktion und Frostklimate der Erde," 1944. Troll chose most of the pictures in this work from high alpine regions, e.g. *Hohe Tauern* at about 8,860 feet (2,700 m.) and *Lechtal Alps* at about 7,540 feet (2,300 m.), both in Austria, *Jedigöl*, Ala Dag in Turkey (north of Cyprus) at 9,840 feet (3,300 m.), *Ethiopia* at 9,840–10,820 feet (3,000–3,300 m.), *Mount Kenya*, East Africa, at abt. 13,120–14,100 feet (4,000–4,300 m.), *Drakbergen* (the Dragon Mountains), South Africa, at 6,560–8,200 feet (2,000–2,500 m.) and 10,160–10,500 feet (3,100–3,200 m.) and Cordillera Real, *Bolivia*, at about 15,740–16,730 feet (4,800–5,100 m.). Further, there are striking photos from the Arctic, showing characteristic ground patterns in *West Spitsbergen* and *Alaska*, the *Taymyr Peninsula*, Central Siberia, and others.

Washburn has chosen excellent photos of patterned ground for his above mentioned "Classification" from *Alaska, Canada, East Greenland, West Spitsbergen, Northern* and *Middle Sweden* (Dalecarlia), and *Mendoza-Argentina* (Cordillera de Los Andes).

In his earlier paper on "Patterned Ground"

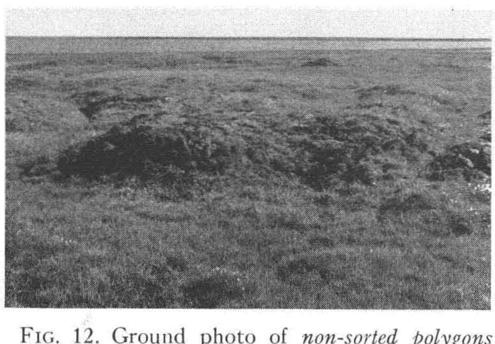

FIG. 12. Ground photo of *non-sorted polygons* (ice-wedge polygons) in the continuous-permafrost zone near Barrow, Arctic coastal plain, Alaska. High-centered, partly cracked, polygons (center), a great thaw lake in background. (Photo by the author August 19, 1955.)

(1950), Washburn has shown photos from *Canada* (Banks Island and Victoria Island), *East Greenland*, *Svalbard* (West Spitsbergen), *Sweden* (Öland and Dalecarlia) and *Faeroe Islands.*

An excellent low-oblique from Randböldalen, Central-East Greenland, of a volcano-like "Pingo," taken by Lauge Kochs exp:s, is shown in a paper by Hoppe (1957), *see references.*

Högbom (1914) preferably used photos of patterned ground from Spitsbergen-tundras, but from Dovre, *Norway*, at 3,940–5,250 feet (1,200–1,600 m.) and northern *Lappland*, Sweden, at 3,600 feet (1,100 m.) as well. Lundqvist (1948) shows photos of conspicuous patterned ground from *Sweden* northeast of Helagsfjället at Lat. about 62.8° North and 3,660 feet above sea level, etc.

Sako (1958) and others use in their paper, *see references*, photos from the central highland of *Hokkaido*, the northernmost island of *Japan*, where well-sorted polygons occur at 6,000 feet (abt. 1,840 m.) and sorted stripes at 4,900 feet (1,500 m.). On the main island *Honshu* the same patterns occur at 10,200 feet (3,100 m.) and 8,000 feet (abt. 2,450 m.) respectively.

Of all other observations concerning patterned ground, I will here mention only Roscoe's report (1952) on *Antarctic* surface features studied by photo-geographical methods, *see references.* When analyzing air photos of nonglaciated areas there, Roscoe found patterned ground with perfectly developed large non-sorted polygons on really steep slopes. This interesting statement is worth closer study in large-scale stereograms, and, if possible, checking by field observations.

Finally, may be mentioned that traces of periglacial ground frost with reminiscences of patterned ground, e.g. polygons and ice-wedges etc., occur in many areas of earlier glaciated regions in different parts of the world (Johnsson).

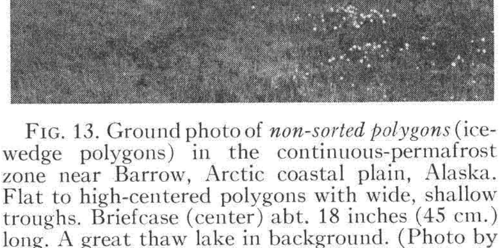

FIG. 13. Ground photo of *non-sorted polygons* (ice-wedge polygons) in the continuous-permafrost zone near Barrow, Arctic coastal plain, Alaska. Flat to high-centered polygons with wide, shallow troughs. Briefcase (center) abt. 18 inches (45 cm.) long. A great thaw lake in background. (Photo by the author August 19, 1955.)

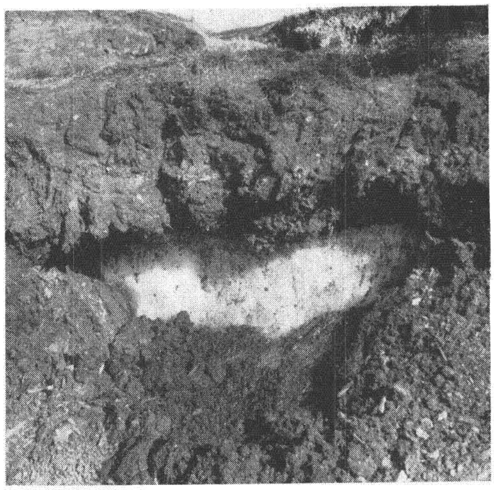

FIG. 14. Ground view of an *ice-wedge* in the permafrost zone west of Barrow, Alaska. The cut clearly shows the position of the wedge beneath the trough between two raised polygons. (Photo by the author August 20, 1955.)

My own contribution to the collection of patterned ground pictures are the photos shown in this paper. In color, however, they are more striking. Some of them are from the Arctic coastal plain of *Alaska*, taken in August 1955, while others are from the *North East Land*, Svalbard, taken by the author in July 1957.

CONCLUSION

The development of improved photographic technique, as regards camera equipment, photographic emulsions, and photo processing equipment as well, favor photo interpretation. Thanks to the new electronic printers, the pictures show up a wealth of the finest details even in seemingly hopeless parts of a negative. Photos with measuring accuracy and perfect sharpness always favor interpretation. On the basis of these facts, it may be stated that the great possibilities which photo interpretation of to-day offer to the researcher will be of special importance also in areas with ground frost problems. For the progress of engineering and agriculture in such areas, as well as for the fascinating scientific research of patterned ground, photo interpretation as a science will no doubt be of great help and value, and therefore cannot be overlooked.

Selected References

Bergström, Erik and Thore Fries. "Några iakttagelser över palsar och deras förekomst i nordligaste Sverige." *Geol. Fören. Förhandl.* Bd 32. Häft. 1. Stockholm 1910.

Beskow, Gunnar. "Tjälbildningen och Tjällyftningen," med särskild hänsyn till vägar och järnvägar (Soil Freezing and Frost Heaving). *Sveriges geologiska undersökning* Ser. C, N:o 375. Statens Väginstitut, Stockholm, Medd. 48. 1935.

Beskow, Gunnar. "Praktiska metoder att bedöma markens t jälfarlighetsgrad." *Tidskriften Vägmästaren* N:r 2, 1933.

Black, Robert F. "Some problems in Engineering Geology caused by Permafrost in the Arctic Coastal Plain, Northern Alaska." *Arctic*, Vol. 10, Nr 4. 1957.

Black, Robert F. "Polygonal patterns and ground conditions from aerial photographs." PHOTOGRAMMETRIC ENGINEERING, 18:123–134. 1952.

Britton, Max E. Arctic Biology, "Vegetation of the Arctic Tundra." *Biology Colloquim Proceedings*, 1957.

Britton, Max E. "A Tundra Landscape." *Research Reviews*. Office of Naval Research, Washington, D.C. 1958.

Hamberg, Axel. "Zur Kenntnis der Vorgänge im Erdboden beim Gefrieren und Auftauen sowie Bemerkungen über die erste Kristallisation des Eises in Wasser." *Geol. Fören. Förhandl.* Bd 37, pp. 583–619. Stockholm 1915.

Hopkins, David M., Thor N. V. Karlström, and others. "Permafrost and Ground Water in Alaska," a shorter contribution to General Geology. *Geological Survey Professional Paper* 264-F. Washington 1955.

Hoppe, Gunnar. "Frostfenomen och glacialmorfologi i södra Sverige." Ymer. häfte 1, 1957.

Högbom, Bertil. "Uber die Geologische Bedeutung des Frostes." Inaugural-Dissertation, Uppsala University, 1914.

Johnsson, Gunnar. "Glacialmorfologiska Studier i Södra Sverige" (Glacial Morphology in Southern Sweden). Medd. från Lunds Universitets Geogr. Inst. Avhandl. 30, 1956.

Lundqvist, G. "De Svenska Fjällens Natur." STF:s publ. nr 1045. Stockholm 1948.

Péwé, Troy L. "Effect of Permafrost on Cultivated Fields, Fairbanks Area, Alaska," a contribution to Alaskan Geology. *Geological Survey Bulletin* 989-F. Washington 1954.

Roscoe, John H. "Contributions to the Study of Antarctic Surface Features by Photogeographical Methods." (Parts of a dissertation for the degree of Doctor of Philosophy, University of Maryland, 1952.)

Rydquist, Folke. "Studier av polygonmark på Stora Alvaret, Öland." Geografiska proseminariet, Stockholms Högskola, Dec. 6, 1957.

Sako, Sumitoshi, Shimpei Kawachi, Tadaharu Fujiki, Kunio Kobayashi, Masuji Inagaki and Mitsuyoshi Chino. "Notes on the splendid sorted polygons on Mt. Tomuraushi." *Earth Science* (Chikyu Kagaku), No. 36, Feb. 1958.

Thorén, R. "Med Svenska Örlogsmän i Arktis." *Tidskrift i Sjöväsendet*, Kungl. Örlogsmannasällskapet, Nov. 1957.

Troll, Carl. "Strukturböden, Solifluktion und Frostklimate der Erde." Diluvial-Geologie und Klima, Geologische Rundschau, Band 34, pp. 545–694, Stuttgart 1944.

Vilborg, L. "The Uplift of Stones by Frost." *Geografiska Annaler*, Årg. XXXVII, pp. 165–169, 1955.

Washburn, A. L. "Classification of Patterned Ground and Review of Suggested Origins." Bulletin of the Geological Society of America. Vol. 67, pp. 823–866, 1956.

Washburn, A. L. "Patterned Ground." Revue Canadienne de Géographie. Vol. IV, Nr 3–4, pp. 5–54. 1950.

Zaborski, Bogdan. "U.S.S.R." Geography of the Northlands, American Geographical Society Special Publication No. 32, 1955.