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GEOLOGICAL SURVEY CIRCULAR 275

OCCURRENCE AND DEVELOPMENT OF GROUND WATER IN PERMAFROST REGIONS

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OCCURRENCE AND DEVELOPMENT OF GROUND WATER IN PERMAFROST REGIONS

By D. J. Cederstrom, P. M. Johnston, and Seymour Subitzky

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INTRODUCTION

The project upon which this report is based was undertaken at the request of the Corps of Engineers, U. S. Army. Its purpose was to collect and summarize the information available on the location and development of ground-water supplies in regions of permanently frozen ground.

Although surface water or water from existing wells will continue to supply a large part of the requirements for tactical purposes as well as for many temporary or permanent military installations, in some parts of the world these supplies are seriously limited, contaminated, or even nonexistent. In the Arctic, an area of increasing strategic importance, freezing of both surface and subsurface water creates additional problems.

Ground water, admittedly all-important in regions of inadequate surface supplies, also has certain inherent qualities which make its utilization distinctly advantageous in many other respects. Where sufficient quantities are available, ground-water supply is generally the least expensive as the construction of dams and long pipelines is unnecessary, filtration is generally not required, its temperature remains constant, it commonly is safe bacteriologically, its source is not readily affected by military operations, and it is less vulnerable to sabotage including pollution by chemical or biological poisoning agents (Research and Development Board, 1949).

Field maneuvers in the Arctic by the Armed Forces and data presented by the Panel on Hydrology of the Committee on Geophysics and Geography, of the Research and Development Board, Department of Defense, clearly indicate a serious deficiency in programs of research and development of the water supply, especially in relation to the presence of permanently frozen ground.

It is realized that the scope of this subject is broad, with many ramifications, and that the present report can do no more than summarize the most important source matter and indicate those areas in which additional research, both of the literature and in the field, should be continued in order to provide satisfactory solutions to the many complex problems.

The request from the Corps of Engineers set forth the following objectives to be accomplished by the Survey during the fiscal year 1952:

1. Make a search of foreign and domestic literature regarding the development of ground water in the Arctic.

2. Collect all available information regarding drilling and winterization of equipment in Alaska and Canada from well drillers, mining companies, and other individuals.

3. Make studies of certain representative regions in Alaska regarding recognition of permafrost areas by reconnaissance and by study of aerial photographs.

4. Make a study of geophysical methods of prospecting for ground water in the Arctic.

5. Prepare reports summarizing and evaluating the results of the studies enumerated above, and make recommendations regarding the additional work necessary to reach the general objective.

This report, prepared by the Ground Water Branch of the Geological Survey, covers items 1 and 2. The work was done under the supervision of A. N. Sayre, chief, Ground Water Branch.

Previous Work

Although considerable basic data relating to construction projects in permafrost areas are already available, there is a marked lack of information regarding the occurrence and development of ground water in these regions. Among the sources of information on the occurrence and development of ground water in permafrost areas are two reports by the Armed Forces of the United States as listed and described below.

1. Permafrost or permanently frozen ground and related engineering problems (Muller, 1947). This report is a comprehensive summary of both United States and Russian literature on the subject before 1945. Much of the report is devoted to ground water and its relation to permafrost, and brief mention is made of water-distribution systems. No information is included on well drilling.

2. Exploratory well drilling in permafrost: Engineer Research and Development Laboratories, Rept. 1045, April 1948. Among other conclusions

reached, this report recommends further drilling in permafrost areas to determine--

(1) What additional modifications are necessary on standard drilling equipment to be used in arctic work.

(2) What additional supplementary equipment is needed to support water-well drilling and development in permafrost areas.

(3) What additional drilling techniques are necessary to help in the development of ground-water sources in permafrost areas.

The report recommends further that the percussion drilling machine be used in preference to the rotary drilling machine for water-well drilling in permafrost areas.

Acknowledgments

The authors wish to acknowledge the cooperation received from the personnel of the Engineer Research and Development Laboratories, especially from Charles R. Keatley, Harry N. Lowe, Jr., and Arthur L. Donahew. A large number of background data were assembled at Fort Belvoir under the direction of Kirk D. du Nann.

Thanks are due also the Geophysics Branch, the Military Geology Branch, and the Navy Oil Unit of the Survey and the many drillers, contractors, and engineers in Alaska and Canada, all of whom cooperated to the fullest extent.

OCCURRENCE OF GROUND WATER

As a basis for a discussion of the occurrence of ground water in permanently frozen ground, a generalized summary of the manner in which ground water is present in the earth is given here.

General Conditions

Ground water occurs in the openings--cavities, fissures, and pore spaces--of rocks and saturates them to a variable height. The upper boundary of the zone of saturation is known as the water table. (See fig. 1.)

Between the water table and the earth's surface is the zone of aeration, which contains water held by molecular attraction within the interstices of the earth materials. This water has been called vadose water and is not available to wells or springs. The zone of aeration may be divided into three parts--the zone of soil water, the intermediate zone, and the capillary fringe.

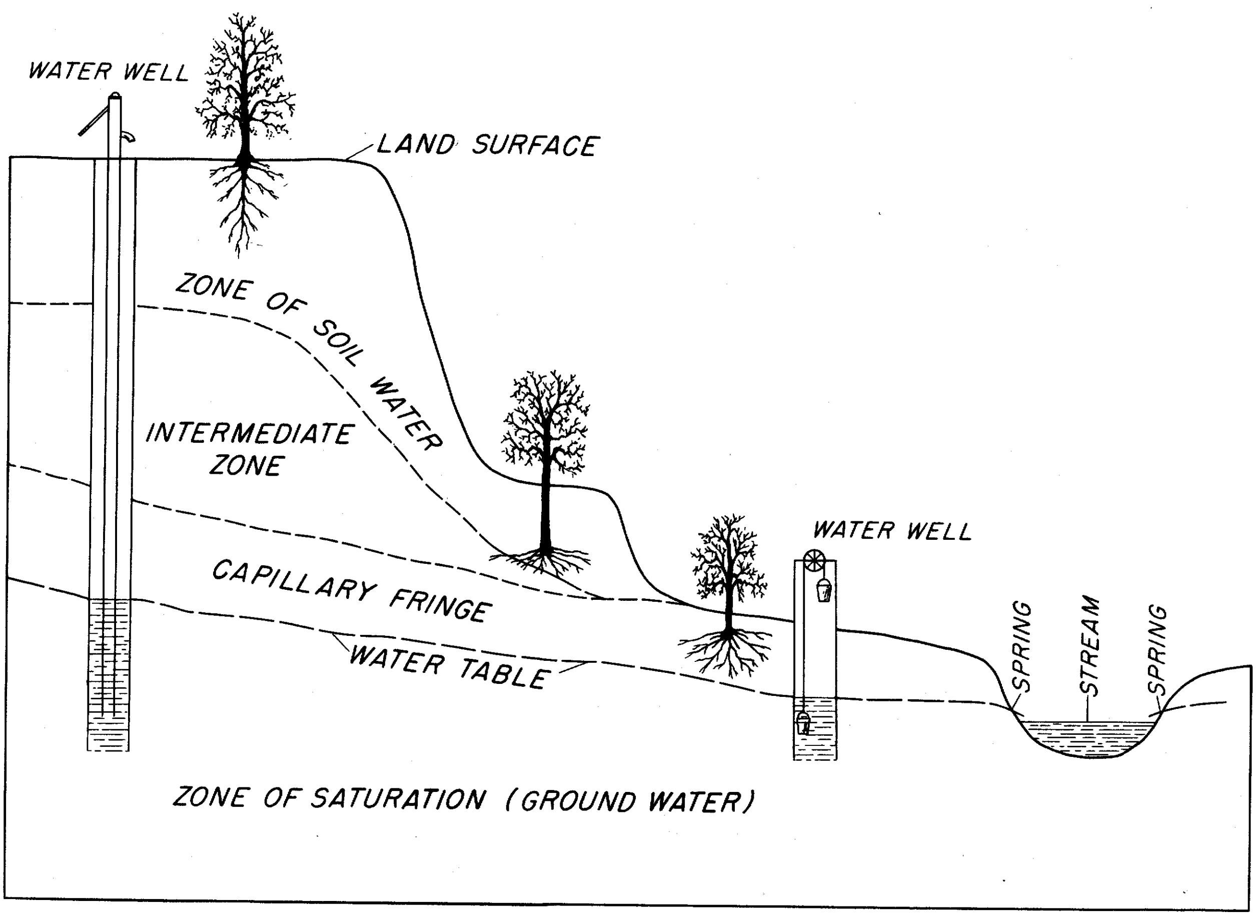

Figure 1. --Zones of subsurface water.

The zone of soil water, which lies nearest the surface, discharges water to the atmosphere by evaporation and by transpiration from plants.

Between the capillary fringe and the zone of soil water is the intermediate zone, which may be thought of as the residual part of the zone of aeration. Through the intermediate zone, water not retained by the zone of soil water seeps downward to the water table. However, some of this water is held in the intermediate zone by molecular attraction. Where the zone of saturation lies close to the surface, the intermediate zone may be absent.

Just above the water table is the capillary fringe. The water in it is held above the zone of saturation by capillary forces, and, although the lower part of the fringe may be completely saturated, the water will not flow into a well. The height of the capillary fringe depends on the texture of the material in which it lies; the height is greatest in fine-grained materials and least in coarse-grained or cavernous material.

Some of the water falling upon the earth in the form of rain or snow percolates into the ground; a part of this precipitation may move down to the zone of saturation, where it becomes ground water. Ground water tends to move toward lower elevations; it may continue to move underground until it reaches the sea, or it may discharge as springs at the surface and thus contribute to the flow of streams, evaporate, or be transpired by vegetation. When, in periods of drought, the water table falls below the level of the springs and streams, these become dry.

Under artesian conditions water occurs in strata overlain by beds of impermeable material, such as clay. The water-bearing stratum is generally filled with water back to its outcrop or intake area on higher ground and hence is under pressure. In wells that penetrate this saturated stratum below the intake area, water will rise above the base of the impermeable material.

Water-Bearing Characteristics of Rock Types

Water is present in the zone of saturation in all types of rock, both consolidated and unconsolidated, but the ease with which these formations yield water differs greatly and is dependent upon the number and size of open spaces in the rock material, the degree to which they are interconnected, and other factors.

Consolidated Rocks

The igneous and metamorphic rocks with certain exceptions contain little or no water. Granitic rocks, dense basalt, rhyolite, gneiss, schist, and slate generally yield no water themselves, but fractures, fissures, and shattered zones within them may yield water. The fractures in the more brittle rocks--certain granites and gneisses, rhyolites, and some basalts--remain open and may yield large quantities of water, whereas those in the more plastic rocks--schists and slates--do not remain open and generally yield only small quantities of water. Some basalts contain interconnected vesicles and even large tunnels and transmit large quantities of water.

In some places the weathered bedrock overlain by alluvial material may yield small amounts of water.

Few wells obtaining water from homogeneous hard rocks are known in Alaska. This does not indicate, however, that wells of this type might not be productive in many arctic or subarctic hard-rock areas.

The consolidated sedimentary rocks are generally bedded and may contain water in the interstices between the rock grains, in fissures and fractures (as in igneous and metamorphic rocks noted above), along the bedding planes, or in solution cavities in the rock itself (as in limestone). Sandstone and conglomerate that have not been tightly cemented and limestone that has solution cavities or channels may yield large quantities of water, whereas tightly cemented sandstones, massive limestones, and shales may yield very little water.

Fine-grained deposits, such as shales or clays, usually are relatively impermeable and may prevent water from seeping down to the regional zone of saturation, thus creating a perched water body.

Structural features, such as anticlines, synclines, monoclines, faults, joints, crushed zones, and volcanic dikes, have a bearing on the occurrence of ground water; but, because these are largely confined to hard-rock areas and are not commonly significant in a water-development program in arctic areas, they will not be discussed here.

Unconsolidated Rocks

Unconsolidated rocks are the most abundant and widespread of all important water-bearing formations; and in most places in the Arctic, and throughout the world for that matter, well-water supplies are sought in this type of formation. Two main types of unconsolidated deposits predominate--stream-laid deposits and glacial deposits, both of which cover large areas in Alaska, Canada, and the U. S. S. R. Unconsolidated marine deposits are areally much smaller and are unimportant.

Alluvium

Alluvium (a stream-laid deposit) results from the erosion of older rock masses and is moved toward the sea by both large and small streams. During this movement downstream, certain textures and topographic forms are characteristic of the deposit at various stages.

Alluvium in narrow valleys.--Flat-floored gently sloping narrow valleys occur in the headwater areas of large streams and in tributaries to large, broad valleys in downstream areas. The deposits are generally thin and poorly sorted, though coarse in texture, and therefore are inferior water-bearing formations. However, it has been found that many such narrow valleys contain a relatively deep fill of alluvium, including some well-sorted material, such as coarse sand or gravel, which may yield large water supplies. In the upper Tanana Valley and in tributaries to the Tanana just north and northwest of Fairbanks, Alaska, such narrow valleys commonly contain fill ranging in thickness from a few feet to 300 feet, and much of the material is permeable gravel. In other places much of the material may have been derived from preexisting fine-grained unconsolidated deposits, such as glacial till, or from consolidated rocks that break down into fine-textured material, and in such places permeable beds of coarse material are scarce. Hence it may not be assumed that deep, narrow valley fills will everywhere contain highly permeable water-bearing beds. Along the valley floor the water table will generally be high, and in some places water may be within the limits of suction lift.

Alluvium in wide valleys.--Much of interior Alaska is characterized by very broad, almost level valleys lying between prominent mountain ranges. Downstream from the headwater areas of high relief and upstream from the delta discharge areas the valleys, such as the Tanana in the vicinity of Fairbanks, the Yukon between Tanana and Holy Cross, and the lower Koyukuk, are a few to many miles wide and are filled with an unknown thickness of well-sorted material, predominantly sandy so far as is known. The rivers draining these valleys are braided meandering streams, which swing back and forth across the valley floors depositing sediment and gradually building up the levels of the valleys. Hence these valley floors are distinguished by prominent meanders, old meander scars, and abandoned channels, many of which are now dry. Coarse well-sorted sands and gravels are commonly present, the water table is high, and large supplies of ground water have been obtained from these deposits. In places bedrock "islands" project through the "sea of alluvium," and bedrock may lie close to the surface, particularly near the valley sides, where favorable thicknesses of water-bearing material may be absent. Much of the water from the broad alluvial valleys is of poor quality because it is high in iron or organic content, or both.

Delta areas.--Near the mouths of some large rivers, particularly the Yukon River below Marshall and the Kuskokwim River below Aniak, vast delta deposits were laid down. These deposits are of unknown thickness and, so far as is known, are predominantly fine grained. The water table is high and ground water is generally available, but the use of standard well screens is necessary to develop wells successfully.

Alluvial terraces.--Extending outward from the low slopes of many prominent mountain ranges, and of considerable areal extent in places, are alluvial terraces. These terraces are a few feet to several hundred feet higher than the dominant stream in the adjacent flat-floored valley.

The terrace deposits lie close to the source of material from which they were derived and commonly contain coarse gravel and even large boulders. The water table may be as much as several hundred feet below the surface. Fairly large streams, their beds sealed by glacial flour, flow across some of these terraces. These are "perched" streams, and the height of water in such streams is not indicative of the height of the regional water table.

Alluvial slopes.--Certain low mountain ranges in the interior of Alaska are mantled to a greater or lesser extent with a silty deposit containing some vegetal material. Where the vegetal content is high, the material is called muck. The fine silt is, at best, a poor water-bearing formation, but in places thin beds of coarse material may be present near the bedrock surface. In other places the muck may conceal buried valleys, which have only slight topographic expression. Such buried valleys may contain excellent water-bearing beds beneath the silt cover. The water level ranges widely; in a few places artesian conditions prevail and the water pressure surface is above the land surface, whereas elsewhere the water table may be 50 to 100 feet, or more, below the land surface.

Glacial Deposits

Within the area of permanently frozen ground in Alaska (see p. 5), glacial deposits are present west of the Alaska Range, in the vicinity of the Kilbuck Mountains, and in local areas on the Noatak and Chandalar Rivers, which are in the immediate vicinity of the Brooks Range. In Canada glacial deposits occur on the Canadian shield where they are generally thin, except locally in depressions. In the U. S. S. R. glacial deposits cover large areas in the western Siberian tundra.

Glacial deposits as water-bearing formations range from very poor to very good. Glacial till, a mixture of unsorted boulders, silt, and clay, may be recognized in the field by its generally hummocky surface. Most wells ending in glacial till yield little or no water; they are successful only when an occasional sandy bed is penetrated. Glacial gravel and sand make up the outwash plain formed downstream from melting glacial ice; in places these are excellent water-bearing materials. Glacial silt, however, which is widespread and very thick in places, is not water-bearing.

Occurrence of Saline or Brackish Waters

In some locations near the sea, as on sand spits, barrier beaches, and peninsulas, heavy pumping of wells and consequent lowering of the water table result in the intrusion of sea water or raising of the contact between fresh and salt water at the well site, and the water obtained is brackish or salty. In such localities, wells should be located where danger of salt-water contamination is at a minimum and where fresh-water recharge is at an optimum. Such wells should be pumped lightly. In some instances it may be practical to make frequent chloride analyses of the water to determine when to cease or reduce pumping in order to avoid salt contamination.

Possibly more important, insofar as the purpose of this study is concerned, is the occurrence of salty water in sediments many miles from the sea. Great areas were once covered by sea water, and, because of poor circulation of ground water in the sediments thus saturated, the saline water has not been flushed out. Thus, in the Copper River basin of Alaska, saline water is found in several wells about 300 feet deep, although in shallower wells nearby, there is fresh water of good quality. It is suspected that fossil salt water may be found at depth in the Yukon - Kuskokwim delta. Salt water, saltier than the present water in Kotzebue Sound, was obtained from a bed within the permafrost and in the thawed ground beneath the permafrost at Kotzebue. In Nome, along the Snake River and about a mile inland, a well drilled into bedrock yielded salty water although fresh water is obtained nearby from wells in thawed alluvium-filled stream channels where seaward circulation is at an optimum.

OCCURRENCE OF GROUND WATER IN AREAS OF PERMANENTLY FROZEN GROUND

The occurrence of ground water in large areas of the Arctic and subarctic differs somewhat from its occurrence in warm climates, because of the presence in greater or lesser amounts of permanently frozen, impermeable ground underlying or interbedded with unfrozen deposits of varying degrees of permeability. However, in the subarctic the ground is not everywhere frozen to great depths, and ground-water supplies are not everywhere difficult to obtain. Rather, ground water may be obtained in thawed areas between permafrost masses in many places. Moreover, there are many places where the permafrost does not extend down to the bottom of alluvial basins, and ground water is available beneath the frozen material. However, in northern Siberia, northern Canada, the southern flank of the Brooks Range, and certainly on the Arctic slope of Alaska, the difficulties of finding thawed ground, either as vertical discontinuities in the permafrost mass or beneath a considerable thickness of permafrost, are greater; and in some of these places development of ground-water supplies will be impractical if not impossible.

The presence of permafrost in any area may be indicated by fissure polygons, thawed lakes, or other signs of melting of underlying frozen ground, by certain types of vegetation, or, less commonly, by frost mounds. Within the frozen ground clear ice masses are common.

Geographical Distribution of Permafrost

Nearly 50 percent of the area of the Soviet Union is underlain by permafrost (fig. 2). The area of continuous permafrost lies north of a line beginning at latitude 72° N. on the Yamal Peninsula, passing to latitude 65° N. at longitude 100° E. and latitude 61° N. at longitude 140° E., thence to Cape Novarin on the Bering Sea. A zone of discontinuous permafrost lies south of this area, the southwestern boundary of which follows the Arctic Circle from the White Sea to longitude 60° E., thence southeastward to the Mongolian border near longitude 90° E. Discontinuous permafrost covers most of Asiatic Russia east of this line except for small portions east of the Amur River and south of Uka on the Kamchatka Peninsula.

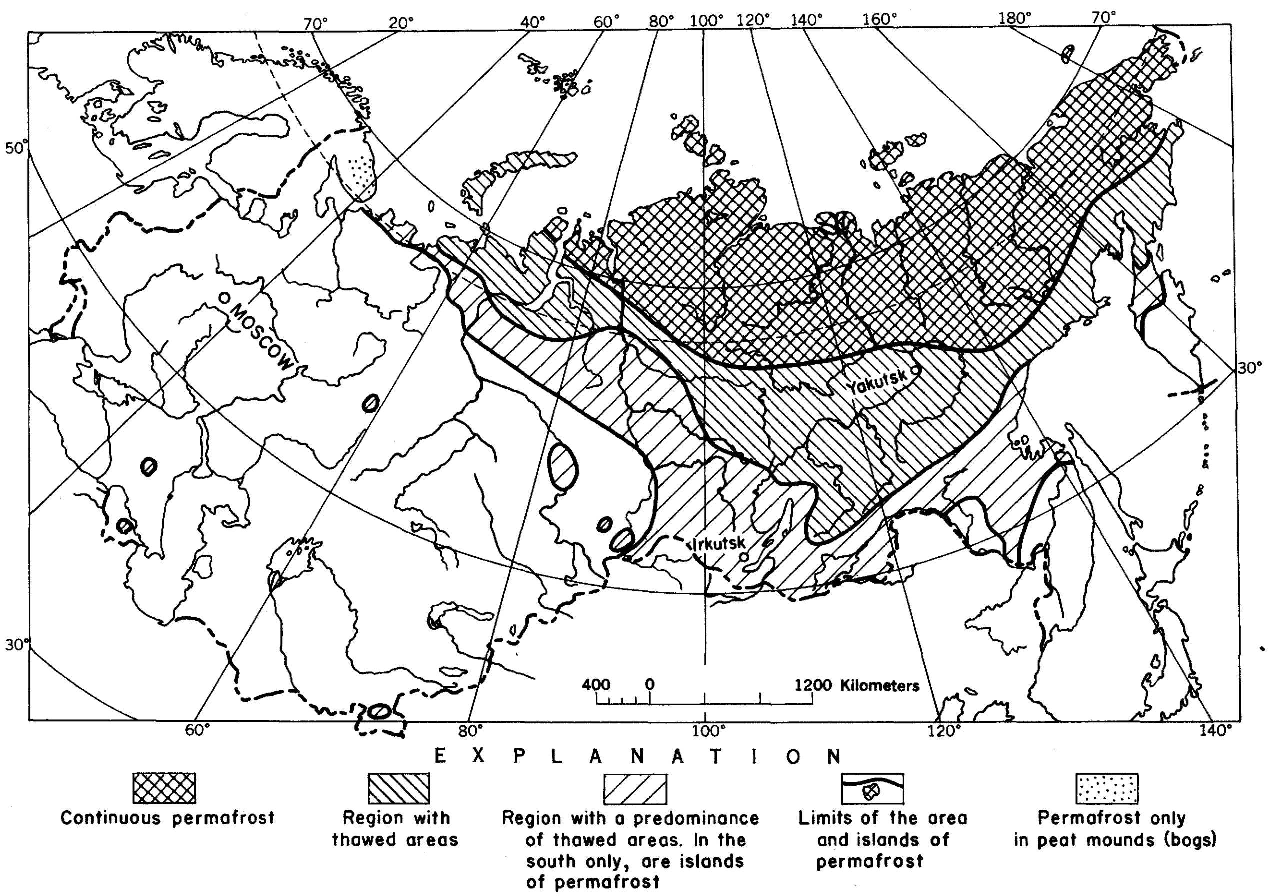

Figure 2. --Map showing geographical distribution of permafrost in the U. S. S. R.

In Canada the permafrost boundary roughly follows the 60th parallel from the Alaskan border to the 110th meridian, thence to the south end of Hudson Bay where it extends northeastward to the east coast of Greenland near the Arctic Circle (fig. 3).

In Alaska permanently frozen ground occurs, speaking in broad terms, nearly everywhere except in the Pacific coastal region. In this wide area permanently frozen ground does not occur continuously except north of the Brooks Range, and even there some

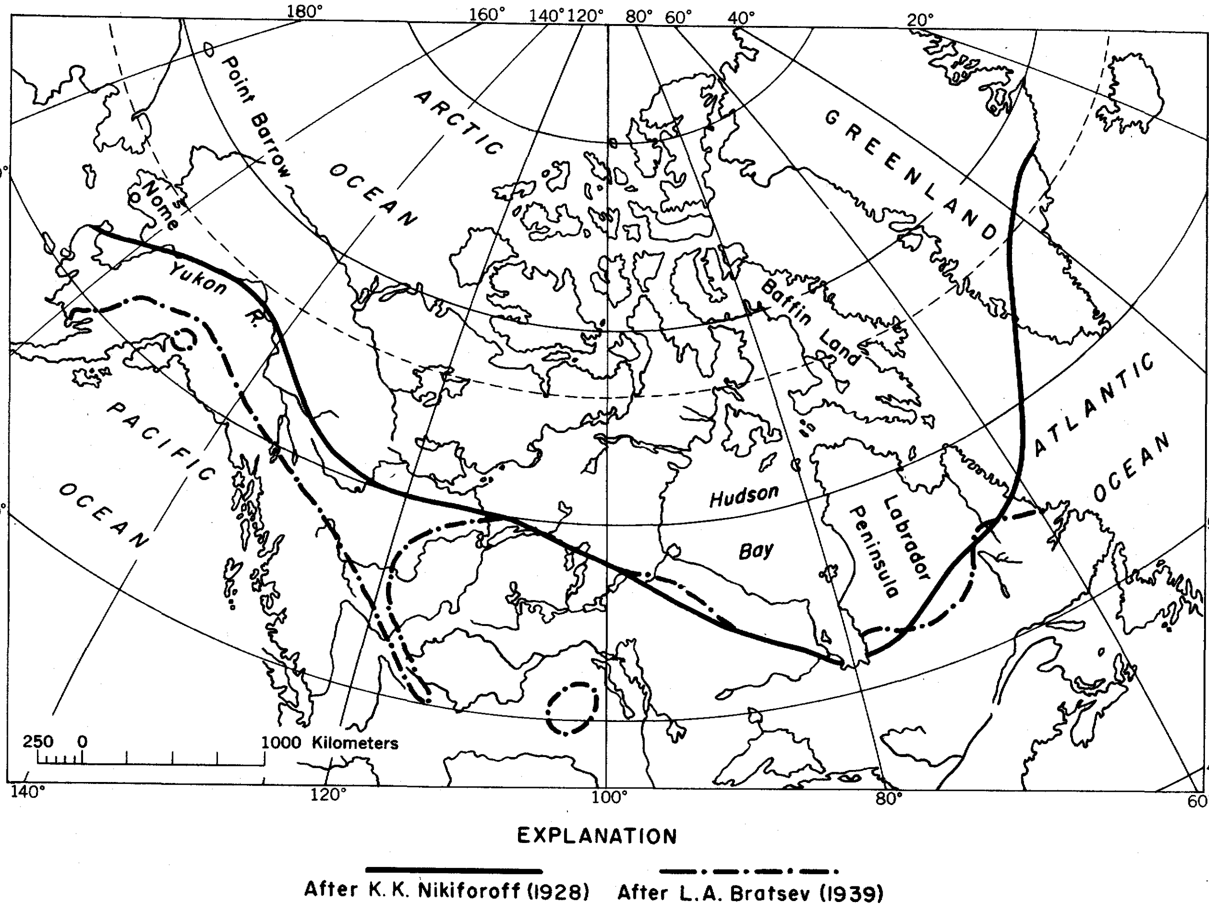

Figure 3. --The southern border of permafrost distribution and permafrost islands in North America.

discontinuities are probable. Near the southern limits of the permafrost area, permanently frozen ground occurs only in scattered masses where the insulating ground cover or other conditions are very favorable. Farther north and in the interior of Alaska the masses of frozen ground are larger and thicker. In the upper Yukon drainage system, wide areas of continuous permafrost several hundred feet thick may be found, and on the southern flanks of the Brooks Range the permafrost thickens and the thawed areas between the permafrost masses are much fewer. On the Arctic slope in Alaska the ground is known to be frozen to a depth of as much as 1,100 feet. Permafrost to depths of 1,800 feet has been reported in the U. S. S. R. Vertical discontinuities in this thick mass may occur only along major rivers.

Types of Occurrences

Ground water may occur as (1) suprapermafrost water, (2) subpermafrost water, and (3) intrapermafrost water in thawed zones between masses of frozen ground (fig. 4).

Suprapermafrost Water

Nearly everywhere in the Arctic and subarctic regions the upper surface of the ground is thawed to some extent during the summer months, and in many places the thawing may extend deep enough (generally less than 8 feet) to create an appreciable reservoir of ground water, which is known as suprapermafrost water. During the warm months this water may be available to shallow wells and pits. In many places, however, winter frost extends downward to the permanently frozen ground, and the zone of suprapermafrost water disappears entirely until the following season. A shallow well, dependent upon such conditions is found on the beach at Point Hope, Alaska (68°10' N. - 166°30' W.).

During the winter, water saturating the ground above the permafrost level may become completely frozen. When freezing of such saturated ground progresses downward, there is in many places suprapermafrost water under pressure, trapped between the active winter layer and the impermeable permafrost basement. Presumably the freezing point of such

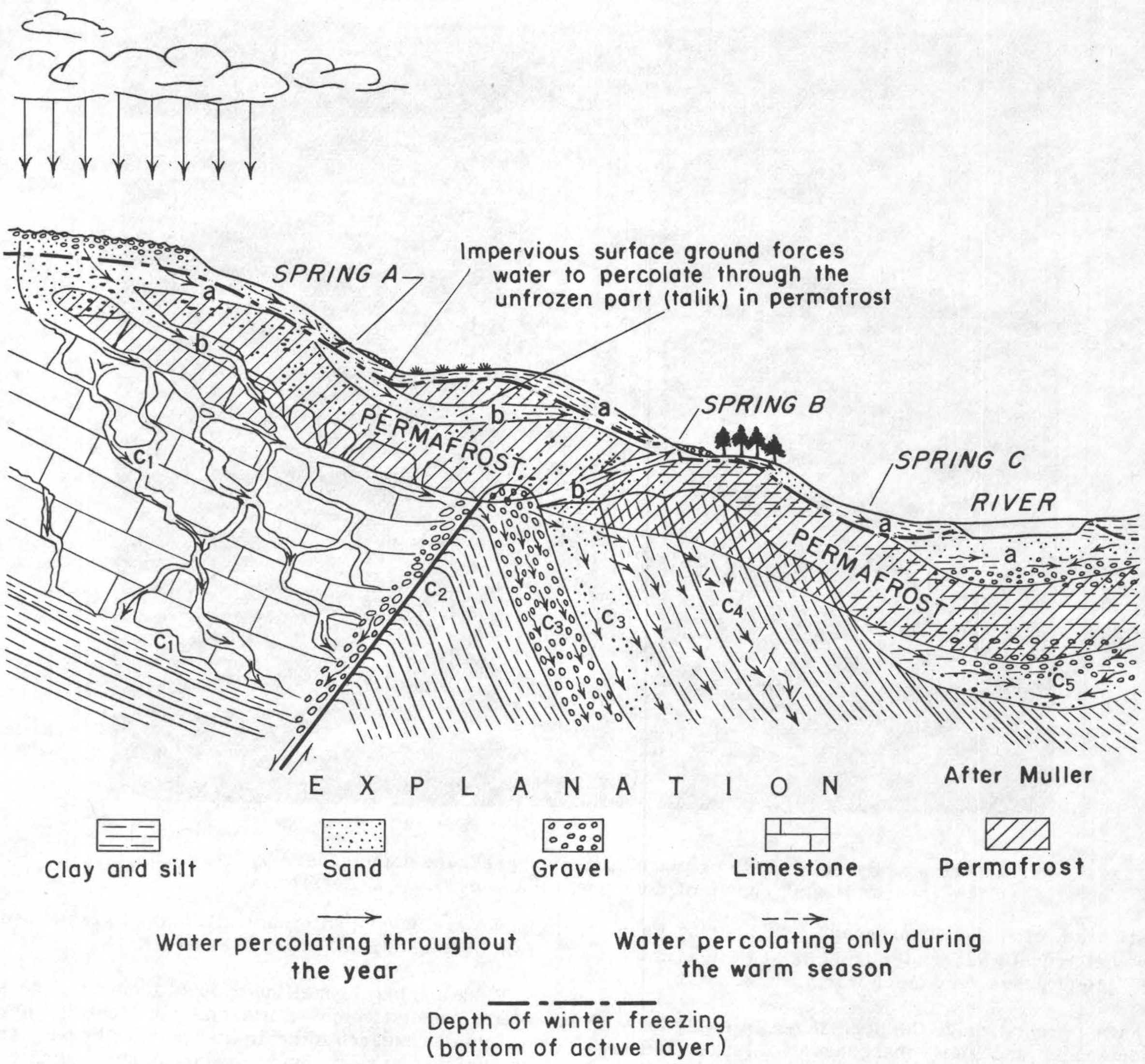

Figure 4. --Diagram showing occurrence of ground water in permafrost regions.
a - Ground water above the permafrost (suprapermafrost water).
b - Ground water within the permafrost (intrapermafrost water).
c - Ground water below the permafrost (subpermafrost water).
c_1 - Water in solution channels (karst water).
c_2 - Water along a fault fissure (fissure water).
c_3 - Water in a porous layer in bedrock (aquifer).
c_4 - Water in bedrock joints (fissures) - (fissure water).
c_5 - Water in alluvial deposits (alluvial water).

Springs A and C will cease flowing in the winter.
Spring B will probably flow the year round.

water is somewhat lower where it is under pressure. Such water may, in effect, be squeezed laterally and at some weak point bulge up to form hydrolaccoliths, or spill out to form frost mounds. Hydrolaccoliths, which probably originated in this manner, are present in the lower Noatak River valley near Noatak and just east of Kivalina, Alaska (fig. 5). At Kotzebue the presence of such water was demonstrated when a small Eskimo dwelling, built on the frozen muskeg, thawed a conduit to the trapped water below with the result that water rose, flooded the dwelling, and forced the family to vacate. Similar examples are given in the Russian literature. In some places this trapped water may provide useful supplies of water in areas where prospects of obtaining ground water otherwise seem to be negligible. In many places these supplies may be small, however, and may become depleted in a few days.

Much remains to be learned about the occurrence of trapped suprapermafrost water in the Arctic; it is suggested that the development of extremely light mobile or portable equipment for investigating the possibilities of such water might be considered. A field

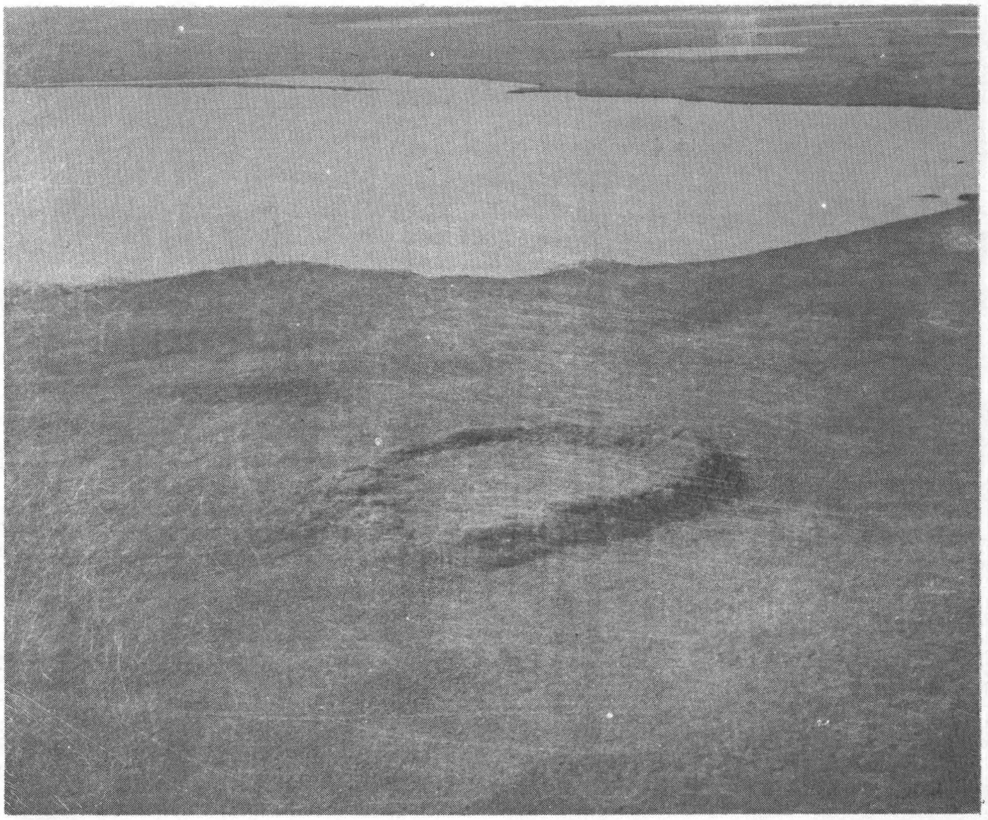

Figure 5. --Hydrolaccolith or pingo, artesian-pressure dome caused by freezing, near Noatak, north of Kotzebue. Photo by D. J. Cederstrom.

investigation of such occurrences, made during February and March when winter frost is at its maximum depth, might prove very much worth while.

Thawed ground above the permafrost is likely to be present under and along the courses of large rivers, in lakes of all kinds except the very small or shallow lakes, and on flood plains and lower terraces of large rivers. Water absorbs heat relatively rapidly in the summer and loses it more slowly in the winter. Hence, the ground temperature under standing or flowing water tends to increase during the warm months, and in time the frozen ground beneath or immediately adjacent to the body of water is partly or totally thawed. Dry land, where the insulating moss cover is broken or removed, receives a heat increment from warm precipitation in the summer; during the winter, protected by a snow cover, it retains some of this heat. The thawing process may be greatly accelerated locally where heated buildings transmit heat downward. The increased movement of ground water above the permafrost is also effective in promoting thawing of the upper portion of the permafrost mass.

Wells yield suprapermafrost water in the Fairbanks area where the frost level has receded primarily because of the breaking of the vegetative cover. At Kotzebue several wells are developed in thawed areas beneath heated buildings. In the vicinity of streams or abandoned meander channels some wells near Fairbanks are developed in naturally thawed ground underlain by permafrost.

Considering the melting brought about by breaking of the vegetative cover it seems apparent that here is a field of research hitherto disregarded by workers in permafrost areas. Such research may indicate that areas near which small semipermanent and permanent installations are contemplated may be prepared in order to make available small supplies of suprapermafrost water. It is possible that by stripping the vegetative cover, flooding the ground to absorb maximum heat during the summer, lowering the water level at least a foot or two below the land surface during the winter to inhibit heat loss in the cold months, such areas being protected by the snow covering during the winter, a significant thawed area might be created within a year or two sufficient to provide a suprapermafrost ground-water supply. Free water would be available from the zone between the winter frost and the now-lowered permafrost; and, further, this free-water zone would, in places, receive accretions from adjacent undisturbed areas, where normally some trapped pressure-type suprapermafrost water would occur. Whether this trapped water would, upon draining out laterally, allow winter frost to progress rapidly to the permafrost level, and thus shut off further accretions, remains to be seen.

In accidental or planned permafrost-recession areas, the frost recession is caused by activities of human beings. Hence, both organic and inorganic contamination of the ground-water supply becomes a problem.

Subpermafrost Water

In a great many areas subpermafrost water in the thawed zone beneath permanently frozen ground is a source of ground-water supply. Large quantities are available in places and the supply is generally of the highest sanitary quality.

The great alluvial areas in the permafrost zone south of the Brooks Range offer good possibilities of developing subpermafrost water in many places. To the north all the shallow alluvial fill in the valleys may be frozen and free water may not occur in the alluvium; but in the subarctic areas of frozen ground, it is likely that the alluvial fill in even the small valleys is not frozen to bedrock, and consequently subpermafrost water should generally be available.

Many wells have penetrated 40 to 200 feet of permafrost in the Fairbanks area and have developed excellent permanent supplies of water beneath the frozen zone. In Nome the alluvial apron lying between the mountains and the sea is completely frozen down to bedrock, and subpermafrost water is therefore not available from the alluvium.

The thickness of the permafrost in alluvial areas, particularly the relation of the lower boundary of permafrost to bedrock, can be estimated in some places, but accurate determination can be made only by test drilling or by geophysical methods.

Although attention is generally given in Alaska to the desirability of developing subpermafrost water from alluvium, it should be borne in mind that subpermafrost water may occur in bedrock areas beneath the alluvium or in bedrock areas with no alluvial cover, from fissures, joints, solution channels, or other openings in the rock mass.

In a few places permafrost will act as an impermeable cap rock, and, where frozen ground laps up against higher ground, the impermeable permafrost may act as a confining layer to water migrating downward from the higher ground, and artesian conditions will exist. Flowing wells due to these geological conditions have been drilled at Dawson, Yukon Territory, and at Fairbanks.

Intrapermafrost Water

Intrapermafrost water is water that occurs within the thawed zones of permanently frozen ground. It commonly occurs in alluvium near rivers or in abandoned river channels. Intrapermafrost water may occur in a thawed gravel bed in an otherwise frozen mass of fine clayey sediments. However, free water available from vertical thawed fissures or through natural "pipes" in the ground within the permafrost mass is also included in the definition; hence, for the purpose of this report, all water in small thawed areas lying between masses of permafrost will be considered as intrapermafrost water (fig. 6). Although water occurring in fissure zones in rocks, along deep-seated faults, along veins or dikes, near large springs fed from depth, and in tilted beds in alluvial fans is also considered to be intrapermafrost water, these

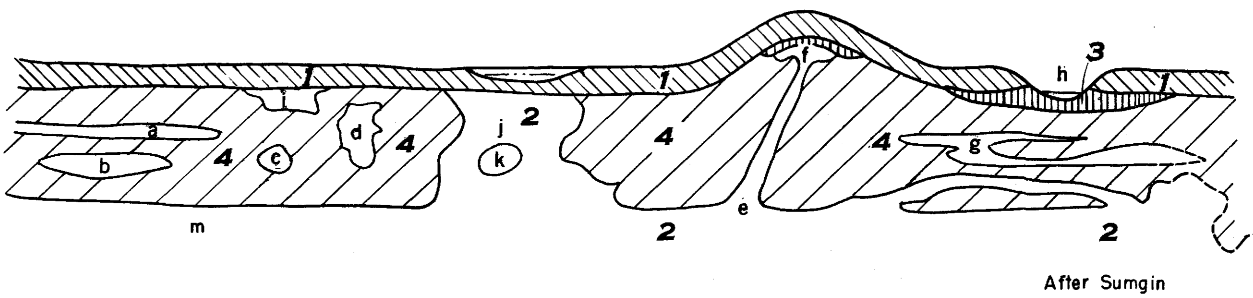

Figure 6.--Section showing intrapermafrost waters.

a - Layer type.
b - Lenses, ribbons.
c - Veins, pipes.
d - Block.
e - Crevice-vein type.
f - Hydrolaccolith.
g - Multilayer type.
h - Lake produced by thawing.
i - "Window" of the suprapermafrost thawed layer.
j - "Window" of the completely thawed layer.
k - Island of permafrost.
m - Subpermafrost thawed layer.
1 - Active layer.
2 - "Talik" (thawed) layer.
3 - Ice.
4 - Permafrost.

occurrences are possibly of more academic than practical interest. In this report, therefore, attention will be given to the occurrence of water in thawed ground that occurs between continuous masses of frozen ground above and below and that are, in some places, of considerable extent. As the southern limits of the permafrost areas are approached, the areas of thawed ground are considerably more extensive than are areas of frozen ground.

Summary

Ground water in permafrost areas occurs mainly in thawed ground.

In general, thawed ground is sought (1) under large rivers and adjacent to large rivers; (2) in or near the smaller streams; (3) in or near standing bodies of water, such as lakes formed in abandoned meander channels or muskeg lakes originating in differentially thawing frozen ground; (4) in "new" ground formed in the concave side of present river meanders not necessarily immediately adjacent to the stream; (5) in dry abandoned meander scars or dry lakes; (6) in places where the insulating cover has been stripped and thawing has been rather profound; (7) on south-facing hillsides.

It will be realized that in many places ground water in the intrapermafrost zone is connected hydrologically with water in the supra and subpermafrost zones and the one type of environment in effect grades into the other. For example, where a frost mass has a wedge shape, suprapermafrost water grades laterally into the completely thawed area containing intrapermafrost water, and the thawed area under the frost wedge will contain subpermafrost water. In the most northerly locations it is more likely that "pockets" of water, distributed either laterally or vertically, are small and are depleted rapidly. In the middle and southerly latitude in the permafrost zone, it may be assumed, most thawed areas are interconnected, and total depletion of free water is improbable.

METHODS OF GROUND-WATER INVESTIGATIONS IN THE ARCTIC

General Conditions

In any part of the world, whether or not it is underlain by permafrost, the occurrence of ground water is directly related to the subsurface geology. Therefore in determining the ground-water potential of any area, a knowledge of the local geology is essential. Vegetation in some places is of value as an indicator of ground water and of permanently frozen ground. The presence of permafrost greatly affects the occurrence, movement, and accessibility of ground water; means are therefore being developed for the recognition of permafrost bodies from surface features. In most areas the science of geophysics when coupled with geologic studies is of great value in locating subsurface features, including ground water and permafrost.

As geologic studies are essential to ground-water investigations, surface features of the areas involved, both topographic and geologic, should be mapped. Bedrock outcrops should be mapped and determinations made of their nature, including the location and altitude of stratigraphic units, geologic structures, degree of weathering, and probable water-bearing characteristics.

Geologic studies in the Arctic follow in general the pattern used in more temperate climates. However, geologic mapping under the rigorous conditions of the far North becomes a rather arduous undertaking (English, 1949?). Stereoscopic study of aerial photographs and direct reconnaissance of the ground by airplane, or even with field glasses from the higher parts of the terrain, provide valuable preliminary information. This preliminary work must be followed by actual examination of the area on foot. The geologist must make an examination of the outcrops, recording all pertinent information and taking necessary rock and water samples. This work must be carried out in the summer months, as the snow cover conceals the surface in the winter.

Rock outcrops are generally less numerous in the Arctic than in other parts of the world. Much of the terrain is moss covered and only the more resistant rocks reveal their presence, and these in many places only by a scattering of their fragments on the surface of the moss. However, the underlying rock may be only a foot or so below the land surface and in most places can be uncovered by digging. Even though chemical weathering is at a minimum, it is difficult because of the frozen ground to dig deep enough with a pick to get a satisfactory rock sample. Where transport facilities permit, a small rotary drill for obtaining cores to a depth of about 10 feet would be very useful in sampling (English, 1949?).

If aerial photographs are available for stereoscopic study, they may be used in locating outcrops, in planning routes of travel, and as a base for the geologic map.

In places where outcrops are few or lacking, as in alluviated areas, and where well logs are not available, exploratory holes must be drilled to provide subsurface information. Complete logs should be recorded so that a geologic cross section can be constructed.

Survey of Ground-Water Resources

[Adapted from Muller, 1947]

When making an appraisal of the ground-water resources of a permafrost area, three types of investigations may be required:

1. Reconnaissance survey. This survey may be completed in a few hours or a few days and will include a brief trip through the area to observe the major topographic and geologic features and the characteristics of typical wells, and to interview local engineers and others.

2. General survey. A general survey may require from a few days to a few months and should include geologic mapping, recording water levels in wells, and making pumping tests and water analyses.

3. Field techniques and special problems. This study generally will require several months or more and will include drilling, longtime pumping tests, and study of freezing problems.

Along with these surveys it will be necessary to obtain available climatological data, which should be summarized, as shown in figure 7.

Essential field equipment for ground-water surveys will include a tape, stop watch, thermometers, current meter, collecting bottles for water sampling, or possibly equipment for making a partial analysis of water. A geologic map of the area, if available, is used as a source of basic data, and such additional features as are necessary should be added. If the area has not been mapped geologically, which is the usual situation, it will be necessary to make a suitable map.

In examining outcrops various phenomena peculiar to Arctic geology may be noted:

SUMMARY OF CLIMATOLOGICAL DATA

Geographic position: ________________________________
(or name of meteorol. station)

Longitude: ____________ Latitude: ____________ Altitude: ____________

Name of nearest town: ________________ Distance to it: ____________

Name of drainage basin: ________________________________

	Mean Monthly												Mean Annual
	J	F	M	A	M	J	J	A	S	O	N	D	
Barometric pressure													
Winds: direction													
velocity													
Temp. of the air													
Minimum temp. of the air													
Maximum " " " "													
Absolute minimum													
Absolute maximum													
Days with freezing t^o													
Precipitation													
Minimum precipit.													
Daily precipitation													
Mean minimum													
Mean maximum													
Days with precipit.													
Humidity of the air													
Mean minimum													
Mean maximum													
Evaporation													
Mean minimum													
Mean maximum													
Dew point													
Thickness of snow-cover													
Beginning of " "													
Disappearance " "													
Cloudiness													
Sunshine													
Solar radiation													
Soil temp.: at surface													
at ____ ft.													
at ____ ft.													
at ____ ft.													
at ____ ft.													
at ____ ft.													
________ at ____ ft.													

(Muller, 1945)

Figure 7. --Summary of climatological data.

1. The amount of jointing and whether joints are open or sealed. Material that fills the joints should be determined--whether it is mud, ice, or mineral deposit. The size of joints, their orientation, and their relation to bedding and to relief should be observed and recorded. Joints opened by frost action should also be noted. Frost-filled joints may extend several feet below the surface of the ground and may be traced along the surface for hundreds of feet; in the summer they are usually closed and can easily be overlooked; the best time to observe them is in the autumn (September to November) and early in the spring (February to April). The presence of polygonal frost cracks has great hydrologic significance as they permit the rain and surface water to seep down into the water-bearing horizons above the permafrost. They also permit lateral circulation of water, which upon freezing forms ice veins or ice wedges.

2. Porosity of the ground and incidence of caves. Large caverns should be thoroughly explored -- their size, orientation, relation to relief, to jointing, and to the composition of the rock, and their position with reference to their present and past base levels of erosion. In large caverns containing flowing water the temperature of the air and of the wall rock should be measured. The presence of ice masses should be noted and their origin should be ascertained.

3. Constancy of stratigraphic horizons. This includes the study of lateral changes in the character of the rocks, particularly with regard to porosity or permeability.

4. The presence of various spring deposits, such as iron, lime, and ice.

5. Bleaching, traces of encrustation, and other indications of the presence of moisture.

6. Products of weathering--their character, extent, and composition.

7. Pleistocene and Recent deposits. These should be thoroughly investigated, particularly in relation to the extent of permafrost.

The following observations should be made regarding the plant and animal life:

1. Trees growing on a slope may have curved trunks indicating the creep, or solifluction, of the ground along the permafrost table. Orientation and areal distribution of curved trunks should be noted, and the age of straight and curved trees should be determined.

2. A "drunken forest," a group of irregularly inclined trees, normally indicates the presence of frost mounds of swelling ground.

3. Willow groves point to the presence of ground water that freezes for only a short time.

4. Trees on pingos (large frost mounds) may indicate the age of the mounds.

5. The depth of tree roots in the permafrost province approximately corresponds to the thickness of the active layer, which makes it possible to estimate the thickness of the water-bearing zone above the permafrost.

a. Peat and moss usually indicate a relatively thin water-bearing zone above permafrost.

b. Pine and fir commonly grow where permafrost is either absent or lies at considerable depth.

c. Larch and birch, especially dwarfed and stunted individuals, indicate the presence of permafrost close to the surface.

6. Holes of burrowing animals should be examined carefully as they usually occur where the water above the permafrost begins at some depth below the surface of the ground. The material that is thrown out of the hole by the animal may furnish information as to the composition of the active layer.

The study of relief of the area has a direct bearing on the solution of certain ground-water problems. The following features of relief should be examined:

1. The character of terraces, slopes, and valley floors.

2. Positive elements of relief that are produced by frost action, such as frost mounds, pingos, and pseudoterraces. These features should be shown on a map.

3. Cave-in lakes, funnels, sinkholes, and related structures caused by permafrost phenomena. These features should be mapped.

4. Landslides, slumps, solifluction, karst phenomena (in either ice or limestone), and frost cracks in the soil.

Other features to be studied in connection with the survey of water resources of an area include--

1. Icings. (A mass of surface ice formed during the winter by the successive freezing of sheets of water that may seep from the ground or from the frozen surface of a river.)

2. Springs and polyn'yas. (A polyn'ya is a hole or window in river ice, which remains unfrozen during all or part of the winter because of a local inflow of warmer water, as from a deep-seated spring or from a warm tributary.)

3. Wells and drill holes.

4. Test pits, ditches, and other excavations.

5. Water bodies, such as rivers, lakes, and swamps.

The amount of detail with which each of the above items should be studied will be determined by the purpose of the survey or by the nature of the assignment.

RECOVERY OF GROUND WATER IN PERMAFROST REGIONS

Purpose and Scope

The purpose of this section is to review drilling methods and techniques being used in regions of permanently frozen ground to determine how the best results can be achieved with the greatest economy of effort. In compiling this information two general sources have been used: (1) the literature on the subject of drilling, mostly of United States, Canadian, and Russian origin, and (2) personal interviews with those who have had experience in drilling in permafrost.

Sources of Information

In the literature, information dealing directly with the problems involved in drilling permafrost is not plentiful, and that which does exist is scattered throughout the mass of material that has been written on the Arctic and subarctic regions. Where drilling is mentioned, few detailed data on actual operations are included. This is particularly true of the Russian literature so far obtained. It would seem that the Russians may not know a great deal about such drilling, or, if they do, they have not yet reported on it. However, a large amount of material is yet to be translated and reviewed.

In the literature of the United States only a few publications are of any material benefit. Report 1045 of the Engineer Research and Development Laboratories, U. S. Army (Crumlish, 1948), contains detailed descriptions of actual operations, and it has been helpful in forming the nucleus of the present discussion. Reports of the U. S. Navy Petroleum Reserve No. 4, Point Barrow, Alaska (U. S. Geological Survey, unpub.) furnish information on equipment and techniques in oil-well drilling, some of which are applicable to water-well problems. "Discussion of winterization activities, Hq. AAF" (Air Force Tech. Comm. Rept. 4) contains useful information. Most of the other data available on the subject have been gleaned from miscellaneous sources, comprising technical and trade publications and government reports, including those of the armed services.

The most readily usable and dependable information has been gained from the field work of ground-water geologists of the U. S. Geological Survey in Alaska and Canada and from personal interviews with representatives of other government agencies, both in the United States and Canada; and with miners, drillers, contractors, and engineers engaged in drilling in permafrost regions.

Problems Involved

The problems of drilling in areas of permafrost are caused and aggravated by the low temperature of this type of ground and of the atmosphere. Because of these negative temperatures and the resulting ice cementation of the ground, normal drilling methods used in temperate climates are not effective. The method of wet drilling practiced in temperate climates, which uses water-base drilling fluids, will cause solid freezing of the tools in the drill hole in regions of permafrost. When using the completely dry methods of boring with auger tools, drive pipes, and well points, sufficient penetration into the permafrost is not possible. Characteristically, permafrost converts loose and incoherent materials, such as alluvium, into an ice-cemented material of granitelike hardness.

Thus, the negative surface and subsurface temperatures cause operational difficulties which necessitate modifications of presently used drilling techniques and equipment, including, for example, mud pumps, mud pits, and water-carrying equipment. Further, the climate and limitations imposed by the terrain are additional factors to be considered in any drilling operation.

Drilling Equipment and Methods

Various types of drilling equipment have been used in the permafrost areas of Alaska and northern Canada, mainly for mineral exploration. Rotary drilling is employed for deep drilling at the Naval Petroleum Reserve No. 4 in Alaska. Diamond drilling is carried on in mineral exploration in bedrock at many places in Canada. Cable-tool or percussion drilling is used extensively for shallow holes in the placer-gold explorations as well as in water-well drilling.

Naval Petroleum Reserve No. 4, Alaska

Many detailed operational records and well logs are available from the Navy Petroleum Reserve No. 4 (U. S. Geological Survey). A few representative examples are given herewith.

North Simpson test well 1 (approx. lat. 71°03'N., long. 157°58' W.) near Point Barrow was drilled to a depth of 3,774 feet by using a rotary rig. The drilling fluid was a brine solution, 50 pounds of salt to a barrel (53 gallons) of water. The salinity was later reduced to 35 pounds of salt to a barrel of water. A 100-pound bag of rock salt was used for each 15 to 20 feet of hole drilled. As the materials being penetrated were clays or shales, the hole made its own mud, and it was necessary to add only water and "aquagel" from time to time. The viscosity rose occasionally and was controlled by the addition of "pyro" and "quebracho." The temperature of the mud was kept as low as possible to prevent excess thawing of the permafrost; the temperature varied from 51 F at the top of the hole to 74 F at the bottom. A total of 13 drilling bits were used, in 5 sizes ranging in diameter from 9 5/8 inches to 22 inches. Drilling was begun May 6, 1950, and the hole was completed June 2, 1950.

Three holes (Ruby 1, 2, and 3) were drilled at the Umiat Field (approx. lat. 69° - 23'N., long. -152°0'W.) with cable tools. These wells were drilled to depths of 840, 1075, and 825 feet, respectively. A brine solution of 35 to 50 pounds of salt to a barrel of water was used to prevent freezing. At all 3 wells only enough drilling fluid was used to operate efficiently and to keep the hydrostatic head from forcing the brine into the sands.

At many locations in Petroleum Reserve No. 4, thermistor cables have been set in the wells to determine the thermal gradient. These studies which are being carried on by the U. S. Geological Survey will furnish information on the location and thickness of the permafrost.

Fort Churchill, Canada

At Fort Churchill, Manitoba, on Hudson Bay, the Engineer Research and Development Laboratories (Crumlish, 1948), carried on experimental drilling during July-November 1947. Both rotary and percussion methods were used. The rotary rig was equipped with a 6-cylinder gasoline engine and a 4 by 5 duplex mud pump. The percussion equipment was powered by a 4-cylinder gasoline engine. Five wells were drilled, 3 by percussion method, ranging in depth from 35 to 194 feet.

As a result of this drilling it was concluded, among other things, that permafrost drilling with either type of drilling machine is possible but that the percussion type is more adaptable to drilling in permafrost, and the modification of both machines would result in more efficient operation. Crumlish (1948, p. vi.) recommended that:

1. Further drilling be conducted in permafrost areas to determine--

   a. What additional modifications are necessary to standard drilling equipment.

   b. What additional supplementary equipment is needed to continue water-well drilling and development in permafrost areas.

   c. What additional drilling techniques are necessary to develop ground-water resources in permafrost areas.

2. The percussion drilling machine be used in preference to the rotary drilling machine for water-well drilling in permafrost areas.

3. Drilling teams be organized for 24-hour operation.

4. The modification suggested in the report be made on both the rotary and percussion drilling machines. On the rotary rig (1) the sandline drive should have a separate clutch and should not operate off the master clutch, (2) grease nipples should be installed on the masthead for lubricating the sheaves, and (3) removable backup posts should be placed on the spider plate to be used in conjunction with the chain tongs when running drilling tools or casing. On the percussion rig (1) the lever throttle should be replaced with a wheel-type throttle, and (2) the coal-fired forge of the percussion rig should be adapted for oil firing. Fuel oil or gasoline will be available more readily than coal in the Arctic.

5. Additional tools and equipment be provided for the rotary and percussion drilling machines.

6. Suitable shelters be designed for each type of drilling machine for arctic operations.

7. The development of a combination percussion and rotary-drilling machine be investigated further.

U. S. Geological Survey Drilling Procedure in Alaska

In the course of exploration for ground water in the Fairbanks area 5 holes were drilled that penetrated 50 to 100 feet of permafrost, and 1 hole was drilled at Kotzebue where frost extended from the surface to a depth of 239 feet.

Drilling in the permafrost zone at Fairbanks presented no unusual problems. Drilling progressed by open hole although it was found that surface casing was necessary to keep out warm surface water. Holes stood open very well but muck tended to slough badly after 4 or 5 days. In 1 hole where much medium sand was penetrated, the bit wore rapidly and had to be dressed frequently. In a 164-foot hole it was impossible to pull the casing with the light rig used, and it is thought that the casing had frozen to the walls of the hole.

At Kotzebue, where permafrost is thought to be considerably colder than at Fairbanks, saline water in the hole froze overnight, and it was desirable to bail all the water from the hole at the end of the day if possible. It was not possible to do this in the zone between 80 and 100 feet, where saline water ran into the hole and tended to fill it. During the course of drilling, hot water from a barrel was introduced into the bottom of the well by a bailer. This was sufficient to produce enough melting to clear the hole of slush ice.

The hole was cased as drilling proceeded, and there was no difficulty in driving the upper portion of the hole. As it was deepened, however, driving became more difficult, and the upper part of the hole was steamed out with a prospector's steam boiler. This was only partly successful, for steam could not be introduced below a depth of about 100 feet because of pressure involved. A better plan would have been to connect several drums with pipe, heat the water quickly by introducing steam into the drums, and pump this hot water to the bottom of the hole, salvaging overflow from the well to refill the drums.

It was found later that the introduction of heat is not necessary; a much better method is to drill and drive as rapidly as possible with as short a time interval between operations as practical. During periods of idleness the casing will tend to freeze to the walls, but, if not solidly frozen, it will break loose when hammered. Because the couplings tend to create an annular space around the pipe, the pipe will not adhere to the walls if it is kept in constant downward motion. Thus it seems obvious that to penetrate more than 150 feet of permafrost, drilling should be done on a 24 - hour basis if possible, and only enough heat should be introduced into the well to form a sludge at the bottom of the hole and increase the hole diameter slightly beyond bit size.

If casing were driven into the permafrost and left for further driving or pulling at a future date, it probably would be necessary first to thaw the walls in order to free the casing and then to move the casing as continuously as possible, without adding more heat.

Most of the information presented in the remainder of this section, except where noted, was obtained by personal interviews with miners, drillers, contractors, and engineers experienced in drilling in permafrost regions.

Drilling an open hole entirely through the permafrost and into thawed ground beneath is not recommended because water will run into the hole from the thawed ground and will freeze solid or make slush and hinder driving of casing. According to Mr. E. Erickson, of the Beaver Mining Co., Fairbanks, there is also the danger of sand rushing in, almost completely filling the hole. The best procedure might be to drill an open hole in the permafrost to a depth known to be above thawed ground and then to set the casing and drive it down, after which casing should follow as the hole is deepened. If there is danger of sanding the hole, it can be kept filled with water, possibly saline water, as thawed ground is approached. This water should be removed during periods of idleness.

Prospect drilling at Fairbanks, Dawson City, and Nome

In the exploration and evaluation of gold-bearing ground in Nome and Fairbanks, Alaska, and in Dawson City, Yukon Territory, mining companies have drilled millions of feet of 6-inch-diameter hole by the cable-tool method. The depths range from a few feet to more that 300 feet; the average depth is estimated to be 80 to 100 feet. The holes are drilled largely in permanently frozen ground and these are generally uncased. It may be assumed that the drilling operations represent the ultimate in economy and efficiency in this type of ground. As these holes were drilled for gold exploration, most of them did not reach thawed ground and did not encounter water.

The three areas mentioned are underlain by unconsolidated deposits, mostly medium gravel, and overlain by a variable thickness of silt mixed with decayed vegetation. Inasmuch as the silt is removed by thawing and hydraulic stripping, the drilling is largely confined to the medium gravel and a few feet of the underlying bedrock, which is generally weathered schist.

Fairbanks Exploration Co.

Mr. R. B. Earling, general manager of the Fairbanks Exploration Co., characterizes the cable-tool method of drilling in the Fairbanks area as an easy and simple method requiring a few simple precautions and no special equipment. With continuous drilling there are no freezing problems.

The general technique is to drill a hole and to set casing when the full thickness of permafrost has been penetrated if it is desired to retain the hole for a period of time. Any freezing of the casing to the wall is simply dealt with by introducing warm water. It is to be noted here, however, that in the Fairbanks area the temperature of the frozen ground is rarely below 31 F. In drilling an open hole the ordinary procedure is to keep the drilling water cold rather than warm. No salt is added.

Dry frost is uncommon, but, when it is penetrated, gravel tends to run into the hole. To remedy this condition, ice or snow is introduced into the hole and the mud wall is frozen. Dry frost above the zone of permafrost, as commonly referred to, is dry gravel that has a temperature below 32 F but contains no ice as a cementing substance.

The bit used in prospect drilling is of a plain chisel type known as a placer bit. It is much thinner and has a greater cutting quality and a less blunt impact than the conventional bit. The shape of the bit tends to reduce the sludge wash, thus keeping the hole narrower and minimizing sloughing.

Bits are dressed by forging rather than welding. According to Mr. Earling, the wearing of a bit below gage is not a serious problem. The forging method is not particularly less expensive than welding but it produces a better shaped bit.

Considerable winter drilling has been done at Fairbanks although ordinarily no drilling is done in the two or three coldest months. The only special equipment necessary is a steam boiler or source of hot water for cleaning the tools at regular intervals and, occasionally, to clean off accumulated ice on the rig. No weather precautions are necessary for the operator other than protection from the wind which is rare in Fairbanks. A canvas rig parka such as is used at Nome was tried out at Fairbanks and found to be a nuisance. A small heated portable shed, known as a dog house, is desirable during winter operations for efficient panning of gold. Such a shed would facilitate the examination of cuttings from wells.

A common type of hot-water heater is an elongate boilerlike structure consisting of a firebox extending through the stove to a chimney at the far end. A water jacket extends around this boiler from which water may be taken through top ports. The desirable feature of this simple device is that whole logs may be burned without being cut.

Mr. Ted Loftus, of the Fairbanks Exploration Co., stated that drilling in permafrost is easier than in thawed ground, although somewhat harder on the bits. At peak efficiency a crew will make from 90 to 100 feet of open hole per 8-hour shift, but a bit will need to be dressed after only 30 feet. Bits are forge dressed because, according to Mr. Loftus, stellite is not sufficiently durable or as economical. At the Fairbanks operations a 5-bit furnace is used, and 2 men can dress 40 bits in 8 hours.

Although open-hole drilling is the common practice, it has been found that frozen muck will melt, squeeze, and slough after standing open a week; such holes must be cased if further drilling is to be done, even though frozen ground may lie beneath.

Drilling operations with no special weather protection have been quite successful down to atmospheric temperatures of -35 and -40 F. Occasionally, a small windbreak is put up, which consists of 2 canvas walls 6 feet high and 4½ feet wide set at right angles, braced and placed at a position to deflect the gentle breeze.

Mr. Maurice Butler, of Fairbanks, prospect driller for the Fairbanks Exploration Co., before going into private practice drilled water wells in a number of places in Fairbanks. According to Mr. Butler, on one operation 25 dressings were required for 6 drills in 3 shifts. This would average about 1 1/3 bits per shift, or, if 90 feet per shift is considered as the average hole drilled, a bit dressing about every 60 feet.

Mr. Butler reported that the worst problem found in drilling frozen ground is the rounding of the lower outer edge of the bit. This produces a progressively smaller hole and the bit has a distinct tendency to stick. Mr. Butler welds his bit points, building them up with mild steel, covering them with studite, and then grinding. He believes the forge method is better but more difficult to use.

This driller favors the placer bits for water-well drilling in frozen ground in Fairbanks. When the casing freezes to the walls of the hole, the use of warm water is recommended before an attempt is made to remove the casing.

U. S. Smelting, Refining & Mining Co., Nome

According to Mr. Carl Glavinovich, assistant superintendent, drilling in frozen ground is much less costly than in thawed ground, and better footage is obtained per hour. An open hole is drilled ordinarily except in areas of dry frost where casing must be used. Mr. Glavinovich défines dry frost as well-sorted gravels cemented with clear ice veins, which tend to melt rapidly with attendant slumping. According to Mr. Glavinovich, the average footage obtained is 65 to 90 feet per 8-hour shift. In Nome, 30 or 60 feet can be drilled before it is necessary to change bits. Some years ago bits were dressed by welding hard-surface material, but this method was abandoned in favor of forge dressing.

The placer bit has been used here, as in Fairbanks and Dawson City; it is superior to the conventional bit in gravel and sand but has a tendency to stick in soft bedrock, such as weathered schist.

Open-hole drilling is practiced even in the summer, although a length or two of casing may be set at the surface to prevent caving at the machine site and wetting of the hole by surficial water.

Because of high winds, rigs at Nome are invariably winterized by a cover of 18-pound canvas (figs. 8, 9). Considerable cold-weather drilling has been done in Nome and in the interior of the Seward Peninsula. However, drilling at more than 25 F below zero is inefficient because of the difficulty in starting a cold machine and because tools tend to break. There is also much accumulation of frost rime at low temperatures.

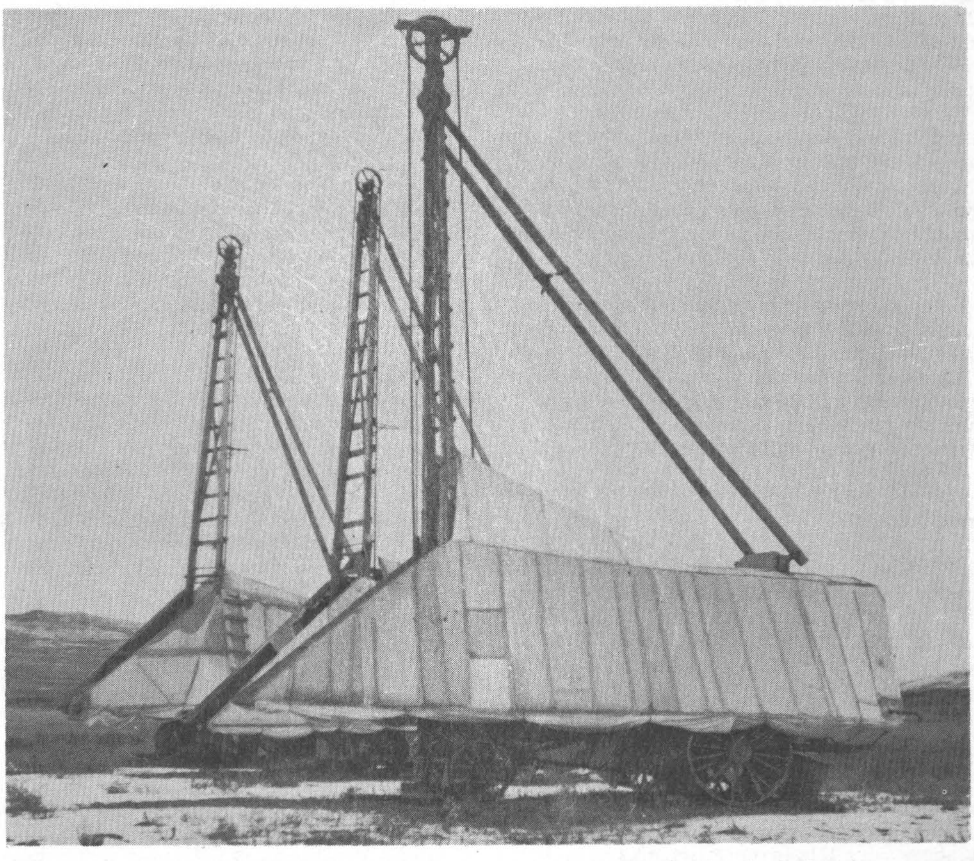

Figure 8.--Percussion rigs with parkas, Nome. Photo by D. J. Cederstrom.

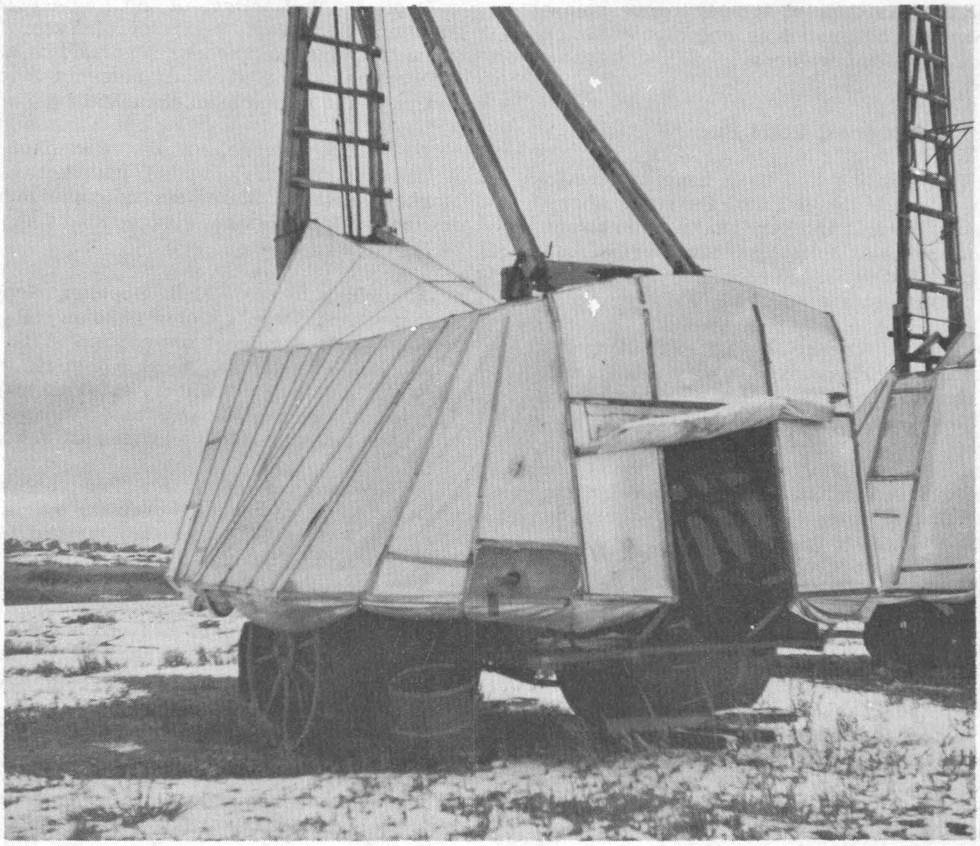

Figure 9.--Closeup of parka, percussion rig, Nome. Photo by D. J. Cederstrom.

According to Mr. Jack Macumber, driller, dry frost causes the main difficulty in cable-tool drilling in permafrost. Openhole is always used. No particular difficulty is noted in the icing of tools, and they require very little heat.

Winter drilling is done inside the canvas parka of the rig, but no heat is provided for the operator and drilling is continued in temperatures as low as -25 F without personal discomfort. An orchard heater is used if heat is necessary.

Warm water facilitates starting of motors on cold mornings, and starting fluid is used regularly in the combustion chambers.

Mr. Macumber points out that winter drilling has one advantage: It is possible to move out anywhere on the soggy tundra and to level off and hold the machine with ease.

Mr. Walter Taylor, former driller for the U. S. Smelting, Refining & Mining Co., at Nome, also reports no particular difficulty in drilling in permafrost, except that the edges of the bit tend to wear down rapidly; in one operation as much as 3 hours out of 10 may be used in dressing bits.

Mr. Taylor favors warm water to slush out the sides of the hole before bailing. It is necessary to have warm water to wash down the tools and to free them of ice accumulation.

The parka-covered rig ordinarily is ample protection against the weather.

Yukon Consolidated Gold Corp.,
Dawson City, Canada

According to Mr. Arnold N. Nordale, resident manager, Yukon Consolidated Gold Corp., it is easier to drill by the cable-tool method in frozen ground than in thawed ground, with the slight difference that it takes somewhat longer to make a sludge in frozen ground. No casing is ordinarily used, and the placer bit is always used where the ground is frozen. Where the ground is thawed, casing is driven ahead of the hole. Mr. Nordale states that bits used in drilling frozen ground need sharpening only a little more frequently than those used in thawed ground. The bits are sharpened by forging.

The ground at Dawson is frozen down into bedrock, which lies as much as 350 feet below the land surface. Where the vegetative cover has been broken, however, permafrost has thawed down to as much as 40 or 50 feet below the surface.

At ordinary temperatures, down to about -20 F, no protection is needed for the drill operator, and generally no drilling is done at temperatures below -20 F. Mr. Nordale has noted no significant metal failure of tools at low temperatures.

Arctic Contractors, Point Barrow

Much cable-tool drilling has been done by Arctic Contractors in the vicinity of Point Barrow, where permafrost is considerably thicker than in other areas previously discussed. At Point Barrow permafrost extends to a depth of about 1,150 feet, and the lowest temperatures in the frost are about 14 F.

Another notable difference between drilling at Barrow and drilling at Fairbanks is that the material penetrated at Point Barrow is consolidated sedimentary beds, such as limestone, shale, and sandstone.

Mr. Eugene Davis, project manager of Arctic Contractors at Fairbanks, states that cable-tool drilling proceeds by making an open hole, but that a brine is used to produce a sludge in the cold drilling environment. The 8- to 12-percent (by weight) sodium chloride solution remains liquid at temperatures as low as about 14 F. Not only does the brine permit formation of sludge in the cold medium, but it assures better penetration of the bit. A greater rate of penetration is claimed by building up the bit with hard-surface material, and as much as 100 feet per day is not rare. On August 1, 1951, there was drilled 120 feet of frozen shale and sandstone.

A maximum of 1,600 feet of open hole has been drilled at Barrow, although, as noted above, the lower portion of the hole is in thawed ground.

Practically no slumping of deep open holes is noted except near the top.

Drilling at Wiseman and Rampart

Mr. Earl Young, of Anchorage, has drilled wells in the Fairbanks area as well as on the Yukon River and in the vicinity of Wiseman. He states that drilling is easier in permafrost than in thawed ground, but, although better footage is made through the permafrost, it is necessary to sharpen tools more frequently. No caving of an open hole ordinarily results except in dry frost. Where such a condition is found, ice or snow is introduced to freeze the walls of the hole.

Casing is generally set at the surface to keep out warm surface water.

Mr. Young has drilled 180 feet of open hole in frozen ground (soft consolidated rock) in the Rampart area, northwest of Fairbanks, and about 175 feet in frozen gravel at Chatanika, near Fairbanks.

Miscellaneous Cable-tool (Percussion) Drilling

According to Mr. O. Kelley, district airways engineer, Canadian Department of Transport, Edmonton, a well at Aishihik that was drilled to a total depth of 60 feet penetrated 50 feet of permafrost. No special difficulty was noted.

Capt. R. V. Darling, of the Engineer Maintenance Division, Northwest Territory of Yukon Detachment, Royal Canadian Engineers, reports that no well drilling has been done at establishments under his jurisdiction in the entire Mackenzie Valley.

Mr. Jack Grange, of the Canadian Division of Health and Welfare, whose jurisdiction covers the Mackenzie Basin, states that no community there has drilled wells; to his knowledge, no cable-tool drilling has even been tried.

According to Col. J. S. Beeman, Senior Highway Engineer and Deputy Commissioner, R. C. E., and Major R. C. Paris, commanding 17th Work Co., R. C. E., Whitehorse, a cable-tool rig was used to a very slight extent at military establishments in Yukon Territory, but capable personnel to operate the machine were not available and very little work was done.

Mr. Maury, of the Tower Construction Co., Montreal, states that about 10 years ago 67 shallow holes were drilled by the cable-tool method for foundation testing at Fort Churchill. Permafrost was penetrated at 3 feet and the average depth of the holes was about 13 feet. Permafrost as such caused no difficulty, although in places the presence of boulders was troublesome. Wear on the bits was fairly great, and, when about 40 feet of frozen ground was drilled, it was necessary to resharpen the bit.

Mr. Taylor Walker, of the Imperial Oil Co., at Toronto, reports that the only difficulty in drilling permanently frozen ground by either cable-tool or rotary method was sloughing of the walls in the upper portion of the holes when too-warm fluid was introduced. Cementing of the casing to the soft walls was not possible in a few holes because of the sloughing.

Rotary Drilling

According to Mr. Eugene Davis, Arctic Contractors, rotary drilling at Point Barrow has been entirely successful. The formations penetrated at Point Barrow are consolidated sedimentary rocks; their characteristics are entirely different from those of the frozen and unfrozen unconsolidated sands and gravels of the broad valley fills, which are typical of the more habitable land in interior Alaska.

Rigs used in the Point Barrow area are completely housed and maintain a comfortable working temperature at all times. The mud used in rotary operations enters the drill stem at a temperature of 35 or 40 F, and the rig is operated continuously.

Mr. Carl Glavinovich, of the U. S. Smelting, Refining and Mining Co., reports that a few years ago the rotary method of drilling was tried in the Nome area and was unsuccessful. Drilling bits were snapped off in the gravelly ground and much caving resulted from the introduction of head and drilling fluid. Difficulty was also caused from time to time by the loss of circulation.

Rotary drilling was carried out to a small extent at Ladd Field, Fairbanks, in 1948, and much difficulty was caused by the loss of drilling fluid where permeable gravels were encountered in thawed ground.

Mr. Ernest G. Stoeckeler, of the U. S. Corps of Engineers, Permafrost Section, St. Paul, Minn., points out that, because rotary drilling of frozen sand and silt is more rapid than cable-tool drilling in the same material, it may be practical to use a combination rotary-cable tool rig where (1) the permafrost to be penetrated is thick, (2) where a number of holes are to be drilled and the total footage will be great, and (3) where moving the necessarily heavier drill rig load (including drilling clay) to the site will not impose a particular hardship. In such places, the permanently frozen ground would be drilled by the rotary method and the thawed ground beneath by the cable-tool method.

Jet-drive Drilling

A considerable amount of drilling for domestic-well supplies is done by the jet-drive method in Fairbanks. The wells are 2 inches in diameter and have penetrated as much as 200 feet of frozen ground.

The equipment is simple and light and consists of a small derrick and a small engine with a cathead (fig. 10). Pipe is pushed down into the ground and advanced by manually dropping on it a small weight fastened to a line running over a sheave on the derrick to the cathead. The jet point (fig. 11) is made from a reducer, which is ground into a bullet shape and attached to the end of the 2-inch pipe. Above the jet point a number of quarter-inch holes are drilled for a distance of 1 to 2 feet. Through the head of the drive point a $\frac{1}{2}$-inch thaw-line pipe projects a maximum of 2 feet. The $\frac{1}{2}$-inch pipe enlarges to a $\frac{3}{4}$-inch pipe about 2 feet above the jet point inside the 2-inch pipe.

A jet of water is pumped through the small thaw line during the drilling operation. This line is hung on a simple chain hoist and is slowly moved up and down, which allows it to penetrate the sediments ahead of the jet point. When the thaw pipe is about 2 feet ahead of the jet point, it is retracted, the casing is driven as far as it will go with ease, and the process is then repeated.

Cold water is used in this process and, according to Mr. Ortho Stevens, of Fairbanks, a temperature of about 40 F is the optimum. Jet-drive drilling proceeds about three times as fast in permafrost as in thawed ground; one man operating a rig alone will average about 28 feet a day if the holes are 100 feet or less in depth. The maximum Mr. Stevens has drilled alone is 49 feet a day, whereas in early spring drilling, where conditions were not entirely satisfactory, the footage was as little as 16 feet a day.

This method of drilling obviously has considerable merit as it is inexpensive, quick, requires very light equipment, and, where permeable gravels are present, produces moderate quantities of water. As much as 40 gpm has been obtained from 2-inch wells equipped

Figure 10.--Jet-drive rig in operation at Fairbanks. Photo by D. J. Cederstrom.

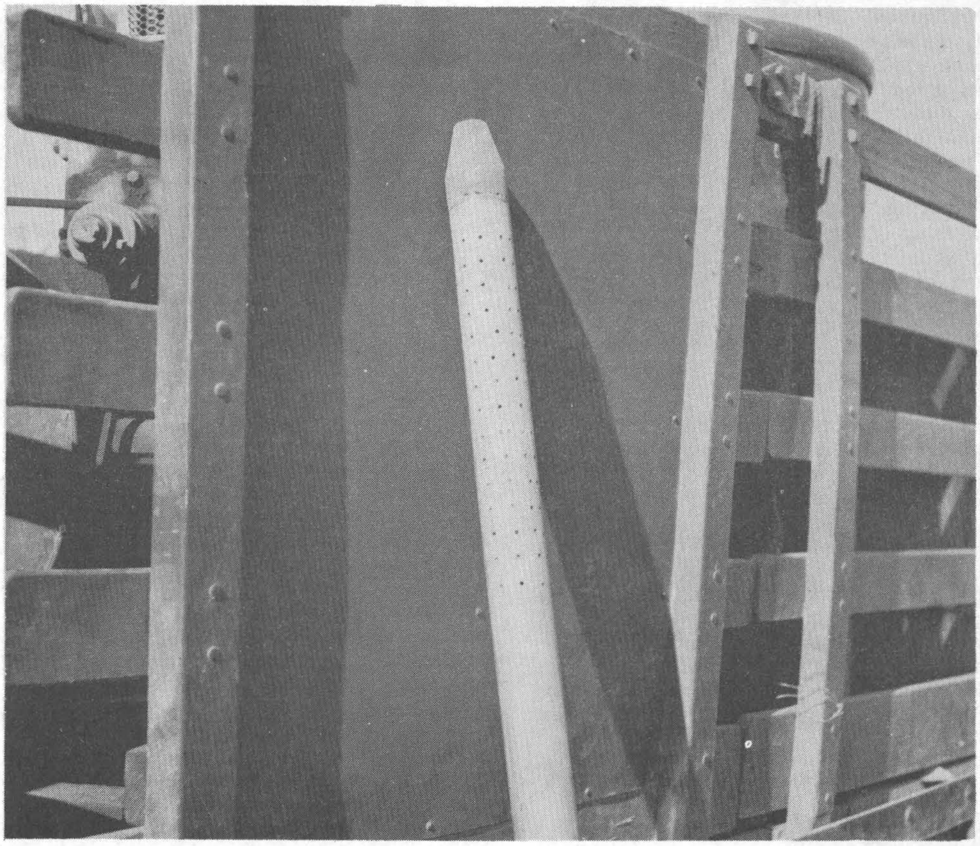

Figure 11.--Jet point, used in jet-drive drilling at Fairbanks.
Photo by D. J. Cederstrom.

with a suction pump, with less than 20 feet of draw-down.

The disadvantages are that it requires at least 10 or 15 gallons of water a minute, and the drilling becomes rather slow and difficult below a depth of 100 feet, particularly through thawed ground. Well construction by this method in other than highly permeable formations such as those found in Fairbanks, might be quite difficult, although not necessarily much more so than that of the larger diameter open-end wells commonly constructed. The large pebbles common in the Fairbanks area cause only minor difficulties in this type of drilling, for they are probably pushed aside as room is made for them by removal of fine-grained material. In many places, however, immovable boulders can be a serious obstacle to this method of well construction. Where water levels are low and well diameters are small, only small quantities of water can be pumped; the freezing of such wells as they pass through permafrost would be a serious problem.

Jetting

So far as can be learned, the jetting method has never been used in permanently frozen ground, but in many places it might be successful. If the casing followed the hole rather closely, little difficulty from slumping or freezing would be experienced where the permafrost was not particularly cold.

As with the rotary method, however, there would be a tendency to lose circulation in very permeable beds, in which situations the casing would have to be driven ahead and the sediments literally drilled out of the pipe. Likewise, large boulders would cause considerable difficulty. The principal disadvantage of this method is the requirement of a large supply of water for drilling and the difficulty of working with this method in other than the warmer months. The desirability of this method remains to be demonstrated.

Diamond Drilling

Diamond drilling has been practiced successfully at a number of places in the Arctic, mainly for the exploration of mineral deposits. Although diamond-drill equipment is light and easily transportable, the small-diameter holes commonly drilled must be kept filled with fluid, which has a tendency to freeze rapidly even while drilling is in progress.

According to Mr. Jack McTague, manager of Boyles Bros. Drilling Co., Edmonton Branch, "chrome-treated" calcium chloride was added to the drilling water to forestall freezing during operations at Rankin

Inlet, Hudson Bay. It was found that half a pound per gallon would prevent freezing for 20 minutes in an open hole between the surface and a depth of 225 feet. Between 300 and 345 feet, $1\frac{1}{2}$ pounds per gallon kept the hole open 1 hour. At Rankin Inlet, drilling reached a maximum depth of 800 feet and was still in permafrost.

Fuel oil was found unsatisfactory as a drilling fluid, as it picked up too much moisture.

At Pine Point on the southern shore of Great Slave Lake, an area of spotty permafrost, diamond-drill holes were used as wells to supply drilling water for subsequent holes.

A prefabricated shack was built around the drill for protection against the weather. The shack was open at the top, allowing the derrick to project above it. With heat in the shack it was possible to work at temperatures of -60 F. While working at these lower temperatures it was necessary to heat the drilling fluid, and an oil-fired water heater was used. This heater is capable of raising by 50 F the temperature of water flowing through it at 5 gpm. It consumes $\frac{3}{4}$ to $1\frac{1}{2}$ gallons of oil per hour.

At Fort Churchill, Mr. John Johnson, driller for the Foundation Co., Montreal, reported that diamond drilling was successful and warm water was used to prevent freezing. However, this warm water caused some caving in the upper unconsolidated material. The following spring, cold muskeg water was used in diamond drilling and was found to be more desirable; the hole would stay open for about an hour after drilling had ceased.

Dr. J. A. Retty, of Montreal, stated that the Ungava iron deposits were extensively explored by diamond drilling, and, until other excavations were made, it was not apparent that permafrost was present, insofar as drilling techniques were affected.

According to Mr. J. C. Nicholls, of the International Nickel Co., Toronto, diamond drilling on the west coast of James Bay penetrated 200 feet of frozen rock. Here a homemade boiler consisting of copper coils in an oil drum was constructed, which heated the drilling water satisfactorily.

Wing Commander R. B. Whitey, Director of Construction, Engineering, and Design, Air Force Headquarters, Ottawa, states that diamond drilling in frozen ground to a maximum depth of 60 feet was accomplished at northern Air Force installations with a very light drill furnishing a $\frac{3}{4}$-inch core. Although very light in weight and relatively easy to transport, this drill was too small to use at depths greater than 50 feet. Boulders in frozen glacial till would tend to deflect the drill and cause jamming.

Dr. Duncan Derry, of the Frobisher Co., Montreal, reports that diamond drilling was carried out in the summer of 1950 at Blyklippen, Mistersweg, Greenland. Excessive core loss was caused largely by the antiquated equipment that was used, but later drilling of frozen ground with a modern diamond drill, using warm water, was accomplished with no difficulty.

Dr. Stuart Dodson, of the Frobisher Co., Toronto, has been closely associated with considerable drilling at Yellowknife. There, he says, the ground is frozen to a depth of 200 feet where protected by muskeg, but in bare-rock areas permafrost is not present. At Yellowknife drilling was done withoug heat or salt, and there were no special difficulties so long as the operation was maintained continuously. About 400 holes were drilled, of which only 4 were unsuccessful.

In places at Yellowknife as much as 80 feet of overburden has been cored, but generally a casing with a cutting edge is jetted down through the overburden and seated in the rock. After the casing is seated, coring proceeds in the conventional manner.

Mr. Don Cameron, consulting engineer, Toronto, stated that the first diamond drilling in permafrost took place at Rankin Inlet in 1931. The string of tools froze in the hole and was lost. Later a homemade outfit was used to heat water for drilling. When shutdowns took place, the drilling water was replaced by sea water to prevent freezing of the hole.

Mr. Cameron pointed out also that at Yellowknife warm water was used successfully, but that he prefers using a saline solution. In drilling with warm water in fractured rock, the frost boundary at first is driven back from the hole and subsequently advances again, exerting a heaving action that pushes rock fragments into the hole and tends to cause jamming of the string of tools.

In the use of a saline solution Mr. Cameron favors calcium chloride, which is less expensive than sodium chloride. He believes that salt of any type is preferable to heat because the transportation cost of salt is less than that of oil.

Dr. Bell, of Noranda Mines, Toronto, noted that much diamond drilling, in which a sodium chloride solution was used, had been done successfully in the Mayo Landing district, Yukon Territory.

Mr. A. W. Johnston, of Johnston and Powellson, consulting geologists, Toronto, considers that diamond drilling in fractured and weathered rock is undesirable. Any thawing action in the wall produces loose cavings, which tend to fill the hole and jam the tools. Mr. Johnston is of the opinion also that throughout the Canadian shield area diamond drilling is a satisfactory method of making a hole but that in the entire Cordilleran region diamond drilling should be avoided if possible. Mr. Johnston notes that 50 feet of overburden can be penetrated with the diamond drill with relative ease by casing off with 2-inch pipe, but, where the overburden is thicker than 50 feet, drilling is difficult.

Mr. Bremner, under Dr. C. S. Beale, of the Dominion Observatory, Ottawa, Canada, was in charge of a drilling project at Resolute Bay and succeeded in having a hole drilled to 450 feet in permanently frozen rock. He reports that initially considerable trouble was experienced because of poorly trained personnel and inadequate heating arrangements, but that finally these inadequacies were corrected and progress was made with comparatively little difficulty. According to Mr. Bremner, the temperature of the permafrost was 8 F at a depth of 100 feet.

A great many diamond-drill holes have been put down in nearly all Arctic and subarctic Canada for the purpose of exploring mineral deposits. The diamond drill, being light in weight, has proved desirable and even necessary in many places where holes drilled at an angle have been needed to explore steeply dipping veins. Permafrost has been a real problem in that the fluid-filled hole tends to freeze shortly after drilling has stopped and, in places, will freeze even while drilling is in progress.

Two schools of thought exist regarding the way to overcome the freezing action of permafrost. One school recommends the use of heated water and the other, the use of a saline solution. The advocates of the saline solution maintain that fractured rock will tend to stand if the wells are not thawed and that the use of a saline solution is less expensive than the use of heat.

In only one place was a diamond-drill hole used as a source of water supply and that was in unfrozen ground in an area of sporadic permafrost. The rapid freezing of the usual small-diameter diamond-drill holes, even of some containing saline solutions, is a strong argument against using this equipment for the construction of water wells in areas of frozen rock; also, diamond drills are particularly difficult to use in areas of unfrozen unconsolidated material. The holes are small and freeze rapidly; the data available indidate that it would be almost impossible to develop these as a source of supply of water from below permafrost. Further, the diameters of diamond-drill holes commonly are so small that a pump large enough to produce more than a minimum quantity of water could not be installed.

On the other hand, a large-diameter hole, cased or uncased, could be easily and thoroughly steamed out to drive the frost back from the hole initially, and subsequently a large pump could be installed to pump a quantity of warmer subpermafrost water sufficient to maintain the well without freezing. If frozen, a hole of larger diameter can generally be thawed out without too much difficulty, whereas a diamond-drill hole of small diameter makes such thawing very difficult or impossible.

It has been found that diamond drilling through the overburden, either thawed or frozen, and in fractured bedrock, as in west and northwest Canada, is accomplished with difficulty owing to rock fragments falling into the hole.

Drilling Fluids

Drilling fluid used in drilling permafrost for ground water must meet two requirements: (1) it must remain in a liquid state during the drilling operation, and (2) it must not contaminate any possible sources of water. However, the latter effect may be eliminated by pumping.

When using mud as a drilling fluid, the use of a small hand-operated prospect boiler to keep the mud from freezing proved satisfactory at the Umiat core test 1 of the Naval Petroleum Reserve, Alaska. Various heavy drilling muds were used in drilling. The weight of the fluid was increased by the addition of various chemical agents, such as aquagel, gel-flake, baroid, fibrotex, smentox, micatex, and impermex. During the rotary drilling at Fort Churchill the drilling mud was kept at temperatures below 40 F so that the permafrost was not thawed excessively. It is possible for mud to be formed in the holes while drilling through clayey formations.

The technique of using hot water as a drilling fluid was practiced at Resolute Bay, Cornwallis Island, in drilling permafrost by diamond drill to install thermometers. In this operation it was found satisfactory to use a 1,000-gallon tank for water storage, and two pumps were needed to circulate the water. One pump was used to force the water through a coil heater into a 50-gallon reservoir. The second pump circulated the hot water through the drill rods into the drill hole. A system of valves was used to allow circulation of the water from the tank through the heater and back into the tank if the drilling operation was stopped and the reservoir was full. The water supplied at the drill rods was 90 to 100 F, but it was found later that still higher temperatures were more satisfactory.

To summarize briefly the practice of hot-water circulation: (1) The water system should be so arranged that water is supplied at the rate of 400-500 gallons per hour, 24 hours a day, for as long as drilling is required. (2) Water is supplied to the drill rods at a temperature of approximately 180 F. (3) The operation should be continuous. (4) A combination of at least two heaters should be used, one at the source of the water and the other at the reservoir containing the water. A third heater, at the point of injection into the drill rods, is recommended.

Brine as a drilling fluid is ideal for permafrost areas except for the possibility of contamination. In water-well drilling the practice of developing the well by pumping after drilling or allowing the well to flow clears out the brine. Brine was used successfully at the Navy Petroleum Reserve No. 4, Alaska, in drilling with percussion tools. A suitable solution was prepared by mixing 35 pounds of rock salt (NaCl) with a barrel of water (53 gallons).

Russian literature makes reference to the use of brine as a drilling fluid for exploratory bore holes.

The Air-cleaned Drill

An article entitled "Seismic oil prospecting with an air-cleaned drill," (World Petroleum, 1951) deals with the use of air as a drilling fluid to raise cuttings out of the drill hole. The method is used primarily in drilling and shot holes for seismic exploration. Tricone rock bits, $4\frac{3}{4}$ inches in diameter, have been used successfully, and this would indicate a possible application to water-well drilling. The greatest depth reached before March 1951 was 500 feet; it may be possible to reach a depth of 2,000 feet. A volume of air of 200 to 500 cubic feet per minute is required, operation being satisfactory at about 319 cubic feet per minute. In relation to its application to permafrost drilling the following is quoted from the article:

"Tests in dry areas having proved that compressed air can be substituted for water as a lifting power, Shell (Shell Oil Co.) is experimenting with the method as a possible solution of troubles often found in Canadian operations, where winter temperatures go down to forty degrees below zero, and all exposed water is subject to freezing. Experience so far with this type shot hole drilling in Canada has given promising results."

This process is in early stages of development. Many functions remain to be smoothed over, mainly regarding the amount of air to be injected and the number and size of air outlets at the bit. Further information will be obtained when available.

Cementing and Grouting

Cementing operations in permafrost areas must be modified to accommodate the low temperatures encountered. The use of cement fulfills the purposes of (1) firmly seating surface casing and preventing the loss of drilling fluid between the annular space of the casing and the side walls of the drill hole and (2) sealing off undesired ground water and preventing slumping of unconsolidated formations before the casing is set. In permafrost drilling a liquid slurry of cement is sometimes used to keep the drill hole free from ice when drilling is stopped for a period of time. Ice forming in a drill hole tends to cause freezeup of the drill rods, a difficulty that would not be encountered in drilling out a cement plug.

The low temperatures extend the normal time required for construction-type cement to set. To overcome the extended-time factor, the following methods were practiced: At the U. S. Navy Petroleum Reserve No. 4, Alaska, in South Barrow test well 1, an early set of cement was achieved by preheating the cement powder for 24 hours before mixing it with warm water. At Simpson Seeps core test, standard construction cement mixed with warm water and a solution of calcium chloride($CaCl_2$) set up in 36 hours. At South Barrow test well 4, standard construction cement was used with an admix of a 4-percent solution of calcium chloride. This method yielded a satisfactory cement job. The endothermic reaction produced by the admixture of calcium chloride enabled sufficient heat to be supplied to the cement to overcome the retarding of setup time produced by the low temperature of the permafrost. Steam may also be applied to heat the concrete in place during the curing period; this was practiced at Fort Churchill, Canada (Crumlish, 1948, p. 22).

The use of regular oil-well-type cement, as used at the South Barrow test well 2, Navy Petroleum Reserve No. 4, Alaska, proved more satisfactory than standard construction-type cement treated with calcium chloride solution. Calseal cement was used with favorable results at the North Simpson well 1, Navy Petroleum Reserve No. 4.

Pumping

When pumping wells in permafrost, several precautions should be followed. Pumping should be regular and, if not continuous, at least for a part of every day, to prevent water from freezing in the permafrost zone. The highest possible water level should be maintained to prevent the infiltration of salt water in coastal areas or on islands. At regular intervals wells should be backpumped to clear away fine silts and sands which may be clogging the screens (Navy Department, 1948-49).

Freezing of Water Wells

Very little freezing takes place in large-diameter wells that are in constant or nearly constant use in the Fairbanks area. In this area the permafrost temperature is only slightly below freezing.

Considerable difficulty has been experienced, however, by users of 2-inch-diameter domestic wells unless the wells are put to constant use. A few wells in active use have also shown a tendency to freeze even in July, and special measures must be taken to thaw these out.

The city of Fairbanks maintains two large steam boilers for thawing out sewer lines and wells that freeze. Generally such a well is steamed for a day or more, the frost boundary thus being driven back from the well and the possibility of freezing in the future being greatly reduced.

Some wells can be thawed out by simply introducing a brine.

Many households have an arrangement whereby excess hot water from the domestic hot-water tank can be led directly into the well. Where a well passes through more than 100 feet of permafrost, the hot water is drained into the well several times a year (generally in the winter when more hot water is available) to forestall possible freezing of the well at times of limited use or idleness.

Protection of pumps and the upper portion of well casings by resistance wires is practical and is illustrated in an article by A. J. Alter (1950b, p. 519-532).

Summary and Conclusions

Considerable drilling in permanently frozen ground has been accomplished in Alaska and Canada. The drilling has been largely by the cable-tool method in Alaska, but rotary drilling has been done at Point Barrow and jet-drive drilling at Fairbanks. In arctic and subarctic Canada, diamond drilling has been the general practice, except for some rotary and cable-tool work at Norman Wells and Fort Churchill and cable-tool drilling at Dawson City.

Each type of drilling has been done successfully, considering the objectives in mind. Diamond drilling has furnished cores of material penetrated and commonly is used to drill inclined holes for exploration of mineral deposits. Rotary drilling provides deep holes in a minimum of time. Cable-tool drilling provides holes of moderate depth, utilizes a minimum of heavy equipment, and requires few special techniques. The jet-drive method provides economical small-diameter holes.

Each method has certain objectionable features. In diamond drilling the fluid circulated tends to freeze, the hole diameter commonly is smaller than is desirable for well development, and unconsolidated ground is difficult to drill. Rotary drilling has similar disadvantages, except that large-diameter holes can be drilled. The jet-drive method is limited to a depth of about 200 feet, furnishes only small-diameter holes, and is used with difficulty in bouldery ground. The cable-tool method is somewhat slow where holes several hundred feet deep are to be drilled.

It is therefore concluded that in drilling holes 50 to 500 feet deep in permanently frozen ground in the Arctic and subarctic, the cable-tool method is the most practical one for water-well exploration, for the following reasons: (1) All types of ground, either frozen or unfrozen, may be drilled, though some types are drilled with difficulty; (2) a minimum of heavy equipment is required; (3) good cable-tool drillers should be more readily available than good rotary drillers; (4) fewer special techniques are required and fewer special problems arise, particularly as (5) cable-tool drilling requires a minimum of fluid, and freezing of tools during drilling is an almost nonexistent problem; (6) samples obtained during drilling of most aquifers are excellent, thus simplifying the determination of proper sediments for water-supply development; (7) a reasonably large-diameter hole can be made which, when cased, can be readily thawed out or drilled out if necessary.

DISTRIBUTION OF WATER IN ARCTIC COMMUNITIES

A number of methods of distributing water have been used in the Arctic. The most common method is by tank truck, but some pipe distribution systems are in use. They employ three alternate schemes to avoid freezing: (1) the water is preheated, (2) the water is recirculated, or (3) the pipes are enclosed in heated conduits called utilidors. Combinations of preheated water and recirculated water are used in some places. Some typical examples are given below.

Fairbanks

Little effort is made to distribute water throughout the city of Fairbanks in the winter. During the summer water is available through small-diameter pipe laid on the surface, but in the winter it is available only from the Northern Commercial Co., which distributes both water and steam for heat.

At Ladd Field the water lines are laid with other service lines in huge concrete utilidors. This method of distribution is excellent but is either impractical or too expensive for most communities or for small installations.

Nome

In Nome summer lines are laid throughout the town, but in winter water is hauled by wagon. However, Carl Glavinovich makes the important observation that between Moonlight Springs and the site of dredging operations near Nome a 15-inch wooden pipeline reduced to an 11-inch steel pipe with a 30-foot fall carried water a total distance of 2,000 feet intermittently all winter long. The temperature of the water entering the pipe was 34 F, and the pipe was partly buried in the earth and partly covered by snow drifts. The pipe was drained after each period of use. No freezing or formation of ice was experienced.

Dawson City

By observing a number of precautions, water in Dawson City, according to Arnold N. Nordale, is distributed all year round without difficulty. The water is pumped continuously from a well adjacent to the Yukon River and brought up to a temperature of 37 F by steam points discharging in the well. The formation of ice in the lines is thus prevented by maintaining the temperature at certain critical spots in town (determined by trial and error) at about 33 F.

The mains are buried only a foot or two beneath the surface and are kept above the permafrost, but no insulation is placed around the pipes. The critical factor is to keep water in motion, particularly at the discharge terminals where taps are only three-eighths to one-half inch in diameter and discharge only a few gallons a minute. The system requires a great deal of water; about 1,000 gpm is pumped to supply 160 homes and business houses. This average of about 5 gpm per outlet is the result of practically every tap in town being kept open constantly through the cold season. The cost of water service is about $10 a month per outlet, which may be inexpensive considering the remote location and the long severe winters.

The importance of having running water available at any price must be considered also in relation to other sanitary facilities. With a running-water system, a sewage system and indoor modern plumbing are possible. Where an ample supply of water for household use is not available, this facility cannot be installed.

A sidelight on the distribution of water in Dawson City is the behavior of the canal feeding the hydroelectric plant. During freezeup some trouble is experienced with floating ice fragments, but, after the canal freezes over, no further difficulties occur, and water continues to flow uninterruptedly beneath the ice to the plant. Here also, the amount of water used is relatively large and the motion of the water is continuous.

Yellowknife

Mr. Kellett, of the Department of Public Works of the Canadian Government, Department of Resources and Development, was responsible for the installation and initial operation of the water-distribution system at Yellowknife, on the northern shore of Great Slave Lake, Northwest Territory. At Yellowknife about 4 miles of pipeline forms a water distribution system which was constructed at a cost of about one and a quarter million dollars. At present there are only 100 service connections, but the system is designed for 500 connections.

The area is underlain largely by unconsolidated material and only about 15 percent of the pipe is laid in rock material. The pipe is buried at a depth of 6 feet and covered with 6 inches of moss with sand on top. A sewer line is laid at a depth of $8\frac{1}{2}$ feet.

The water mains are 8 inches in diameter and the return lines are 6 inches in diameter. The branches from the main line are 6 and 4 inches in diameter. Throughout the system a number of valves operate to permit a return flow to the pumping plant from even the smallest service lines.

Water from Great Slave Lake is heated to 36 F at the intake by steam jets into the pipe before being circulated. The system costs about $25, 000 or $30, 000 a year to operate but could serve at its full capacity at only a little higher cost.

Whitehorse

According to Major R. C. Paris, the officer commanding 17th Work Company, R. C. E., Whitehorse uses about $1\frac{1}{2}$ million gallons of water a day. This water is distributed through 8- and 6-inch mains with 2-inch feeders. The feeders run directly under the homes that are served in the upper end of town and connect with the main on the opposite side of the service connection. This method of connection is designed to permit flow back and forth from one main to another; heat is picked up from water passing through the service line under the individual home, eliminating freezing of the service connections. In the lower downtown area the old existing system is kept from freezing by opening the terminals during the colder weather, as at Dawson City.

About 2, 500 people are supplied with water.

Donjek River

At the Donjek River on the Alaska Highway about 100 miles south of the Canada-Alaska boundary, the small military establishment is served by a 2-inch pipeline which leads from the well to a storage tank and returns to the well in a $\frac{3}{4}$-inch line. Constant circulation is maintained. Both pipes are enclosed in a simple wooden utilidor about a foot square and packed with insulating material. The utilidor is about a foot above the ground. Heat is added at the pumphouse in order to maintain open lines at all times.

Kluane Lake

At operation Eager Beaver, at mile 1056 on the Alaska Highway, a distribution system has been built similar to that installed at the Donjek River. Major Peter Taylor, R.C.E., has taken steps to check temperatures on the system in winter.

Fort Chemo, Hudson Strait

According to Mr. G. Jacobson, of Tower Construction Co., Montreal, water at this installation is distributed in 2-inch pipe inside 4- or 6-inch pipe. A counterflow system is used, the water in the feed line flowing in an opposite direction to that in the outer warm line. Twenty-four people are served by this installation, which has 210 feet of line. Air temperatures in winter are as low as -20 F. The counterflow is pumped at a rate of 36 gpm and is heated by diesel exhaust.

CONCLUSIONS

As a result of these studies it is concluded that ground water is present in most permafrost areas and that its recovery is practicable where the permafrost thickness is not too great. The advantages of using ground-water supplies for military installations in the Arctic are very great and efforts to determine the most efficient methods of location, recovery, and distribution should be continued.

A large volume of material has been written on the subject of permafrost in this country, in Canada, and in the U. S. S. R. Scattered throughout this literature are many references dealing with associated ground water. The Russian literature is especially voluminous, and much of it is as yet untranslated. The report, Permafrost or permanently frozen ground and related engineering problems (Muller, 1947) contains a summary of all available information of Russian origin until 1945. However, all matters pertaining to water sources in the U. S. S. R. have been classified since the 1930's, as a matter of security, and have not been made available outside the country. Progress in locating and developing ground water in the permafrost regions behind the Iron Curtain is therefore a matter of conjecture. It is probable, however, that Yakutsk, a city of 100, 000 population, was still without public water-distribution or sewerage systems in 1946. Most of the Russian literature so far reviewed has dealt, mainly, with the basic research and academic aspects of the problem, much of which is already known in other countries. It is possible that continued search may yield more tangible information.

Obviously, the first step in the acquisition of a ground-water supply, is the location of a satisfactory source. This will involve a complete assessment of the ground-water resources of the area, and it should be made by a geologist experienced in ground-water work and familiar with the phenomenon of permafrost and its occurrence.

Aerial photos are useful in the study of areal geology, permafrost, and related ground-water occurrences. Successful forecasting of permafrost conditions by the study of aerial photos alone, however, is a highly complex procedure capable of yielding consistent results only in the hands of specialists familiar with the geologic, geomorphic, botanic, and climatic factors involved. Even then, the reliability of the interpretation is greatly enhanced by ground studies at representative sites within the area. It is therefore believed that, in their present state of development, the techniques of aerial-photo interpretation of permafrost conditions should be applied only by qualified personnel and that wherever possible supplemental ground studies should be made.

Three basic methods of geophysical exploration are resistivity, refraction seismic, and electromagnetic. Of the three, resistivity is the most useful single method of prospecting for ground water. However, in the winter months, when the ground surface is frozen, seismic refraction may have some advantages over the resistivity method. Theoretical considerations indicate that the electromagnetic method also has important advantages for winter use, but at present no experimental data are available regarding its value for ground-water prospecting.

Once the ground-water body has been outlined it must be drilled and developed. Regarding the selection of proper drilling equipment and methods, it seems that the percussion (cable-tool) drill, using a minimum amount of drilling fluid, is most satisfactory because of the simplicity of its construction, ease of operation, and minimum logistic support required. Presently available cable-tool equipment seems to be adequate and reasonably economical. The difficulty of transporting such equipment, as it is now built, is moderate, but thought might be given to construction of rigs in such a manner as to permit disassembly into smaller units readily transportable by planes smaller than a DC-3.

The greatest need is additional practical knowledge of conditions in the arctic areas. At Fairbanks a mass of data is available; we know that wells may be constructed there with relative ease, either in thawed ground between permafrost masses or by going through the permafrost to thawed ground below. Maintenance of wells is not a difficult problem. In Fairbanks, however, the permafrost is not excessively thick or very cold.

It is felt that the most important single problem at present is lack of knowledge of the characteristic occurrence of ground water in areas where the permafrost is thicker, colder, and areally more continuous than at Fairbanks. The mechanical difficulties attendant upon drilling thicker and colder frost, the subsequent maintenance of producing wells in such ground, and the areal distribution and thickness of frozen ground along the Arctic Circle in interior Alaska are significant factors about which little is known. At present it seems more important that these factors be studied than that an investigation of new drilling techniques or equipment be undertaken.

Along the Arctic Circle in interior Alaska the frost is thicker, colder, and more continuous than in coastal or southerly regions. Questions such as the following must be answered: Does permafrost extend down to bedrock? Will the colder mass significantly change the drilling techniques used so successfully at Dawson City, Nome, and Fairbanks? Can wells be maintained by being pumped at intervals or must they be operated continuously, as at Yakutsk? Will steaming out of wells drive the frost back from the casing walls or is the cold reserve so great that the results of such action will be shortlived?

These questions can be answered only by drilling wells and making pumping tests. Geophysical investigations will be profitably carried on during reconnaissance surveys and simultaneously with the drilling, to interpolate data between wells, to project data from other wells, and to prove the extent to which geophysical study can be substituted for exploratory drilling.

It is acknowledged that the present report does not supply the answer to many problems calling for solution. It is therefore urged that a program including geological and geophysical prospecting and water-well drilling in northern Alaska be started and carried forward to completion.

From the studies so far completed, it is concluded that the greatest benefits will be derived by making further studies along three principal lines of action:

1. Continue the search of the literature, both domestic and foreign (including the Russian). A file of pertinent abstracts should be prepared. Close liaison should be maintained with other Government agencies, including the Library of Congress, Snow Ice and Permafrost Research Establishment, Army Map Service, Air Force, Office of Naval Research, and Bureau of Yards and Docks.

2. In the field, establish a research project in some suitable locality in Alaska north of the Arctic Circle. This area is suggested because it is in the zone of continuous permafrost and the data to be obtained will extend northward the practical knowledge now available in the zones of discontinuous and sporadic permafrost.

With a standard percussion (cable-tool) drill, several holes should be put down at selected sites within the area. Records should be made of all operational details and complete geologic logs prepared. Water samples should be collected for analysis, and, at the conclusion of the drilling, pumping tests should be made. Thermistor cables should be placed in certain drill holes so that temperature gradients may be recorded.

Before actual drilling can begin, it will be necessary to make a reconnaissance of the selected region so that an assessment of the ground-water potential can be formulated and drilling sites selected.

Drilling equipment should include a cable-tool rig, capable of drilling a 6-inch hole to a maximum depth of 1,200 feet, with all appurtenant equipment and supplies. Before the rig is shipped to the selected area, a test well should be drilled to insure that the equipment is in good working condition and accessories are in proper sizes and quantities.

3. Conduct additional geophysical field surveys in the Fairbanks, Big Delta, Tanacross, lower Koyukuk, and other districts where geologic and drilling control are available to (1) determine the practicable methods of locating aquifers and thawed and frozen ground in a variety of permafrost environments, (2) test and evaluate geophysical equipment under winter conditions, and (3) train additional professional personnel in conducting geophysical ground-water surveys under arctic and subarctic conditions.

Geophysical surveys, under this proposal, would be made in areas drilled by the Geological Survey, the Department of Defense, the city of Fairbanks, and the U. S. Smelting, Refining & Mining Co., and other localities where geologic and drilling control are available or can be obtained. Thermal, seismic, and electrical logs should be obtained in all drill holes that are still accessible; additional holes should be drilled to test geophysical interpretations. Thermal, seismic, and electrical logs should be obtained in these holes also, to permit correlating the various factors affecting water supply, such as lithologic character of the formation, porosity, permeability, and permafrost conditions, with physical measurements, such as electrical resistivity and potential seismic velocity, and temperature. The information gained from study of these relationships would aid both in the interpretation of geophysical results in this area and in establishing general basic principles that would increase the effectiveness of geophysical surveys in other permafrost areas.

In the immediate future the greatest attention should be given to the application of resistivity and seismic methods, but preliminary tests of electromagnetic methods should be undertaken also, insofar as time and funds are available.

Geophysical field work should be started early in July and continued through September. Additional field work should be done during the early winter after freezeup, and during the late winter about 2 months before breakup. The winter work would determine the effects of the frozen surface layer, as well as of low temperatures, on equipment.

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