THE NORTHERN ENGINEER

VOLUME 10, NUMBER 3

CRREL

The Cold Regions Research and Engineering Laboratory: recent work by CRREL staff

THE NORTHERN ENGINEER

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COVER and COMMENTS

Our front page for this special issue is a deliberate copy of a typical CRREL report cover. This imitation is truthful packaging, though, since all articles here are reports of some recent work by CRREL research personnel.

This issue honoring the Cold Regions Research and Engineering Laboratory would not have been possible without the help of many kind and skilled people. Among those especially deserving our thanks are Terry McFadden, who got the idea for this issue under way; Eb Rice, who kept nudging it along; CRREL Technical Publications Editor Edmund Wright and his staff, who saw to it that *TNE* received excellent copy in good time; and of course the authors who provided these articles. (The cover photograph of the flume in the Ice Engineering Facility at Hanover appears by courtesy of the CRREL Public Affairs Office.)

THE NORTHERN ENGINEER is a quarterly publication of the Geophysical Institute, University of Alaska - Dr. Juan G. Roederer, Director. It focuses on engineering practice and technological developments in cold regions, but in the broadest sense. We will consider articles stemming from the physical, biological and behavioral sciences, also views and comments having a social or political thrust, so long as the viewpoint relates to technical problems of northern habitation, commerce, development or the environment. Contributions from other polar nations are welcome. We are pleased to include book reviews on appropriate subjects, and announcements of forthcoming meetings of interest to northern communities. "Letters to the Editor" will be published if of general interest; these should not exceed 300 words. Subscription rates for *THE NORTHERN ENGINEER* are $10 for one year, $15 for two years, and $35 for five years. Some back issues are available for $2.50 each. Address all correspondence to THE EDITOR, THE NORTHERN ENGINEER, GEOPHYSICAL INSTITUTE, UNIVERSITY OF ALASKA, FAIRBANKS, ALASKA 99701, U.S.A.

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by Dean R. Freitag

The COLD REGIONS RESEARCH and ENGINEERING LABORATORY

CRREL, as the U. S. Army Cold Regions Research and Engineering Laboratory (Fig. 1) is known throughout the world, is a federal laboratory with a special mission. That mission is to understand the characteristics of the cold regions of the world and by application of that knowledge make it easier for man to work, live and pursue his interests there. Cold regions research was begun by the Army's Corps of Engineers at a time when the Corps was given major responsibilities for U. S. government construction and operation in the far north. The need for developing construction methods, operating techniques and design objectives that were more compatible with the realities of the cold regions was soon apparent.

CRREL was created in 1961 by combining two existing groups: the Arctic Construction and Frost Effects Laboratory of the New England Division of the Corps, and the Snow, Ice and Permafrost Research Establishment — a separate Corps research laboratory. Between them the two labs brought together at CRREL a galaxy of scientific and engineering talent ranging from expertise in such fundamentals as crystallography, optics and colloid chemistry through glaciology, earth sciences and meteorology to the engineering disciplines relating to design and construction of airfields, structures and complex mechanical systems.

CRREL is a Corps of Engineers lab and, as such, it has the advantages of the Corps' long-held concept of ser-

Figure 1. The Cold Regions Research and Engineering Laboratory (CRREL), October, 1978.

vice to the nation. CRREL research facilities and expertise are available to any federal, state or local agency that has need for them and has the funds to pay for the work. Indeed, work has been done for private interests when circumstances have permitted. This freedom helps to account for the diversity of research activity at CRREL at any particular time. It also helps account for the overall character of the laboratory.

The Corps of Engineers itself has a broad range of interests that demand the lion's share of CRREL's resources. The Corps is the prime constructor of barracks, airfields and all the other necessary components of military installations. It is also the proponent for the needs of the combat engineer, which involves expedient construction of roads, bridges, fortifications and defenses. The Corps also wears a hard hat as the constructor of federal works for the civil sector: dams, levees and water navigation facilities. All of these tasks require the ability to cope with low temperatures, winter conditions and unusual terrain. CRREL is counted on to respond to those needs.

Most of the remaining CRREL resources are devoted to projects for other federal agencies. They have recognized that cold regions problems require a specialist's approach and it is far better for them to employ the CRREL capability than develop their own. At present, the laboratory is working for such agencies as the Federal Highway Administration, Federal Aviation Administration, National Oceanic and Atmospheric Administration, National Science Foundation, United States Coast Guard and the U. S. Geological Survey.

Funding for all these projects comes from the sponsoring agency, whether the Corps of Engineers, FAA, NSF or whichever. Thus CRREL differs from most federal organizations; it does *not* get a yearly appropriation from Congress to do its mission. Instead each research or study project is justified and funded for the benefits that will accrue to its sponsor. Each project has a well-defined scope and objective, and a certain amount of funding is given the lab to conduct the research. CRREL then has the responsibility to do the work and produce the agreed-upon result within the amount of money allocated.

Since there are no directly authorized operating funds, an "overhead" charge must be made to pay indirect costs. All users of CRREL pay these costs, including the parent agency, the Corps of Engineers. Needless to say the magnitude of the overhead was, is, and will be the subject of discussion both within the lab and with CRREL customers. In general, though, the requirement that the laboratory earn its own keep has been a good thing. CRREL has to be cost-conscious and has to pay attention to the customer agency's objectives. This element of free enterprise makes for a better laboratory and a better technical output.

2-28-79

STAFF CAPABILITIES

RESEARCH ENGINEERS

Chemical	1
Civil (general)	15
Hydraulics	5
Soil Mechanics	7
Snow & Ice Mechanics	1
Pavements	6
Foundations	1
Electrical	5
General	3
Materials	1
Mechanical	10
Sanitary	4
	59

Figure 2. Capabilities of CRREL's research engineering staff.

2-28-79

STAFF CAPABILITIES

SCIENTISTS

Agronomist	1
Biologist	2
Chemist	4
Geodetic Science	1
Geographer	1
Geologist	6
Geophysicist	4
Meteorologist	2
Physicist	9
Physical Scientist	11
Soil Scientist	1
Glaciologist	3
Geochemist	1
	46

Figure 3. Capabilities of CRREL's scientific staff.

The ability to do work for various agencies has helped CRREL maintain a diverse yet reasonably balanced staff. Cold regions science and technology is a specialty that cuts across the traditional disciplinary lines. Ice crystals are a very special kind of crystal and frozen soil demands a very special kind of soil mechanics. Yet, both specialities may have application to certain cold regions problems.

The number of CRREL research engineers and scientists has remained relatively constant at about 100 in recent years. The current distribution and mix of disciplines is shown in Figures 2 and 3. Since no organization can possess all the specialties and resources that it might want, CRREL maintains a relation with a number of experts and consultants and part-time employees who can be called upon to fill a particular requirement. There are fifteen to twenty professional-level people in this category now and others can be added if needed. Also, CRREL has made it a policy to welcome visiting research specialists. College professors on sabbaticals and foreign scientists on extended visits often bring just the added dimension needed to augment the permanent staff. Frequently R & D contracts are let to universities or other organizations to accomplish specific tasks.

The overall personnel strength of the laboratory is, at the present time, restricted by directed manpower ceilings to 263 full-time positions. However, some flexibility is allowed for persons on temporary short-term appointments so that the number actually working on any given day may be greater.

The physical facilities that support the CRREL research effort really merit the description "unique." The main laboratory is located at Hanover, N. H. The research facilities are located in two buildings at this time and plans are underway for a third. The main lab building contains 24 cold-room laboratories, many capable of achieving temperatures in the -30°F range. Special provisions are available for lower temperatures but are seldom needed. Supporting the cold laboratories are more conventional chemistry, physics, soils and electronics labs. Among the specialized equipment available to researchers are mass spectrometers, atomic absorption spectrophotometers, an x-ray diffraction apparatus, scanning and transmission electron microscopes and a nuclear magnetic resonance device.

In 1973 a new building was completed that is devoted to the study of problems caused by ice in waterways. This lab, acclaimed as the finest in the world today, permits research that will relax the icy grip of winter on the nation's waterways. There is a refrigerated modeling area in which scaled-down rivers, harbors and lakes can be studied, a tilting refrigerated flume for frazil ice research and a large test basin in which ice force problems can be studied at near full-scale dimensions.

Another facility to be devoted to the study of frost effects, especially in relation to transportation systems, is in the planning stage.

Alaska represents a very important resource to CRREL. CRREL has an Alaskan Projects Office at Fairbanks with a small research and supporting staff. Test areas are maintained in the marginal permafrost terrain near Fairbanks and in the Caribou-Poker Creeks research watershed of the surrounding uplands. CRREL personnel excavated the tunnel in permafrost near Fox, Alaska, and in cooperation with the University of Alaska and the Bureau of Mines keep it available for research and observation. CRREL also monitors many construction projects being performed in Alaska by the Alaska District Corps of Engineers, the State of Alaska and private industry to observe current design and construction techniques. CRREL research is always aimed at improving the final product — bettering man's ability to live in and with the cold regions environment. Familiarity with actual work in the cold climates is an absolute must if the research is to be meaningful, and this Alaska gives to CRREL.

* * * *

Dean Freitag is Technical Director of the Cold Regions Research and Engineering Laboratory.

by Austin Kovacs

Recent Ice Observations

in the Alaskan Beaufort Sea Federal–State Lease Area

Ice conditions in the proposed Alaskan Beaufort Sea federal-state petroleum lease area have been actively researched since the winter of 1974-75 as part of the Bureau of Land Management/National Oceanic and Atmospheric Administration's (BLM/NOAA) Outer Continental Shelf Environmental Assessment Program (OCSEAP). The purpose of the program is to provide insight into one of the major environmental hazards to offshore hydrocarbon exploration and expected future development. At present the Alaskan Beaufort Sea lease sale is scheduled for December 1979. The lease area extends from the eastern side of Harrison Bay southeastward to Flaxman Island off the Canning River Delta. Inside the lease area is a chain of barrier islands which begins with Spy Island at the western end and extends to Flaxman Island at the eastern end. Inside the barrier islands the winter fast ice is protected from the forces active in the moving offshore pack ice. These forces, however, are active along the edge of the fast ice extending seaward of the barrier islands and on occasion cause major ice displacements and pressure ice ridge formations within this fast ice area as well as creating ice pile-up and ride-up on the barrier islands.

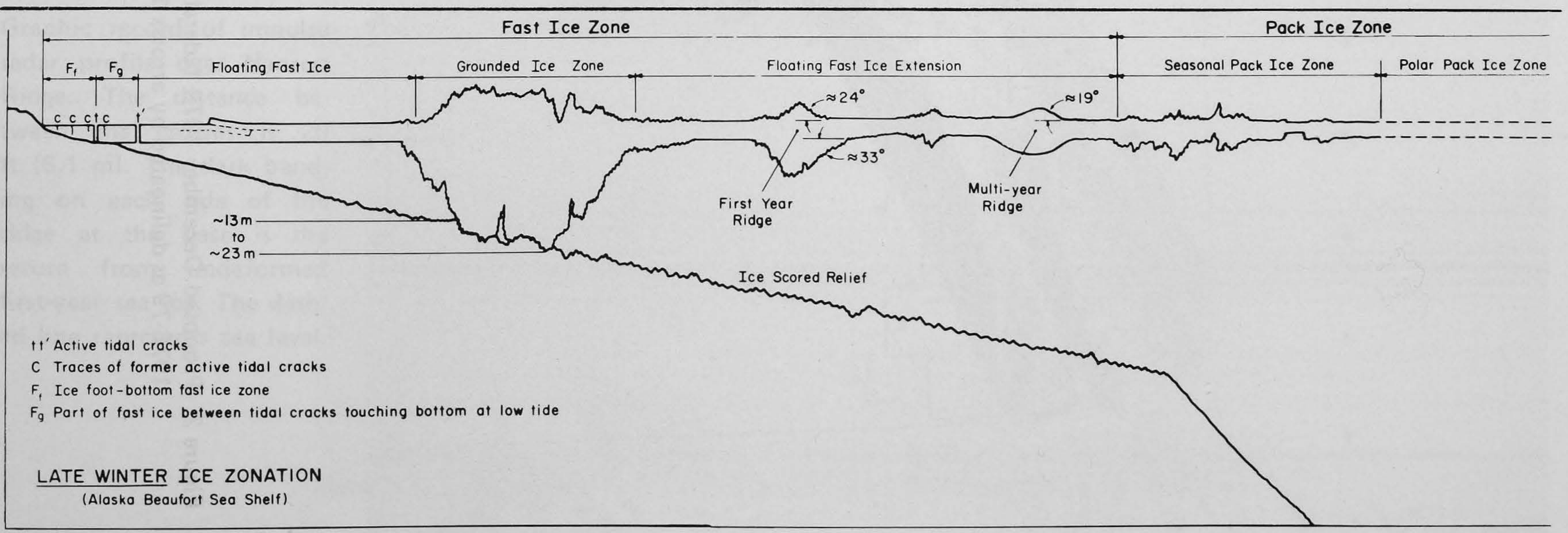
Since the winter of 1974-75 to the present, members of CRREL have been actively involved in various aspects of the OCSEAP program to gather information necessary to assess the potential environmental hazards of offshore petroleum development in the proposed lease area. As part of OCSEAP Research Unit 88, we have been involved with documenting sea ice morphology and deformation events. In March and April 1979 we performed on-site investigations of the fast ice regime in the lease area with NOAA helicopter support, and used side looking airborne radar (SLAR) imagery, collected as part of the OCSEAP, to expand and enhance our field study. A brief report of our recent observations is given in this article.

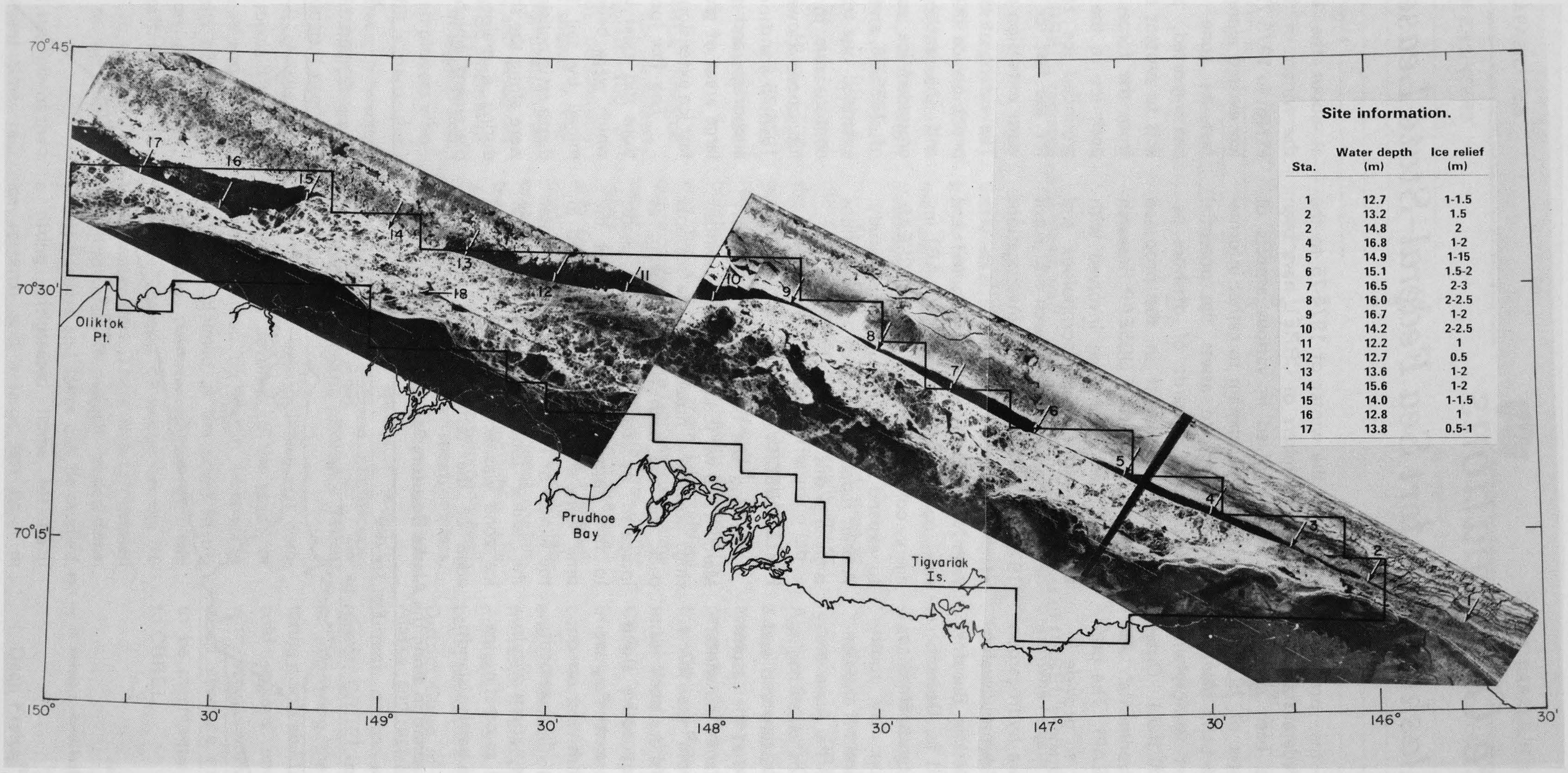
FIELD OBSERVATIONS

Beyond the barrier islands in early March 1979 we found very few grounded ridge areas and noted that the seasonal pack ice had been actively moving, as indicated by recently refrozen leads. In this respect, ice conditions at the time were similar to those observed in the winter of 1974-75. During this winter the "shear zone" of the seasonal pack ice zone was active along the seaward edge of the fast ice zone beginning at about the 15-m depth contour. In the winter of 1975-76 and to a lesser extent in 1976-77, large areas of grounded ice existed along the edge of the shorefast ice zone, and as Kovacs (1976) has reported, this grounded ice zone acts to protect the fast ice to the south from the forces induced by the moving pack ice to the north. In addition, the grounded ice zone provides anchorage for the fast ice and thus allows its seaward extension as depicted in Figure 1. The extent of this fast ice extension depends on ice thickness, pack ice motion and the anchorage provided by the grounded ice zone. During the winters of 1975-76 and 1976-77, the fast ice extended out to the 30- to 35-m depth contour due in part to this grounded ice zone. However, in the winter of 1974-75 and 1978-79, without the anchorage and protection provided by large areas of grounded ice, no "stable" fast ice extension developed.

The few locations where ice formations did exist in early March of 1979, which were believed grounded as determined by sail height and local water depth ratio considerations (Kovacs 1976), were along the shear boundary developed during a major seasonal pack ice displacement which occurred in November

Figure 1. Late winter ice zonation along the Alaska Beaufort Sea Coast.





Site information.

Sta.	Water depth (m)	Ice relief (m)
1	12.7	1-1.5
2	13.2	1.5
2	14.8	2
4	16.8	1-2
5	14.9	1-15
6	15.1	1.5-2
7	16.5	2-3
8	16.0	2-2.5
9	16.7	1-2
10	14.2	2-2.5
11	12.2	1
12	12.7	0.5
13	13.6	1-2
14	15.6	1-2
15	14.0	1-1.5
16	12.8	1
17	13.8	0.5-1

Figure 2. Proposed December 1979 federal-state Beaufort Sea lease area (inside irregular outlined area) and the seaward edge of the shore-fast ice during the winter of 1978-79 as delineated by arrows 1-17. Position 18 is the location of a 12-m-high pressure ridge grounded in 8 m of water.

Figure 3. Example of the shear ridge which formed at the shore fast ice/seasonal pack ice boundary during the fall of 1978.

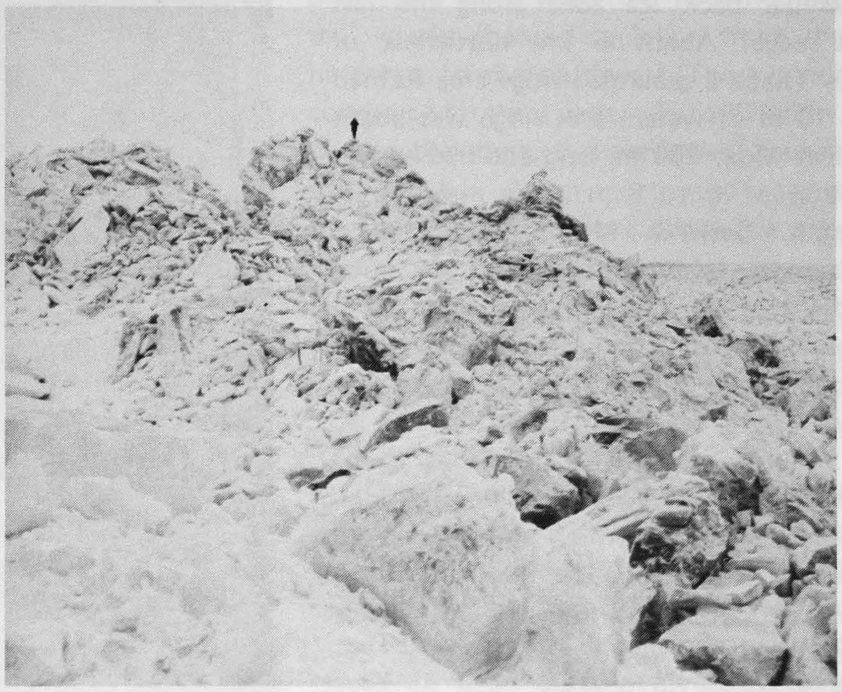


Figure 4. The Hanson Ridge. Note the dirt incorporated in many of the ice blocks.

1978. This boundary can be seen in the SLAR image of 28 November shown in Figure 2.

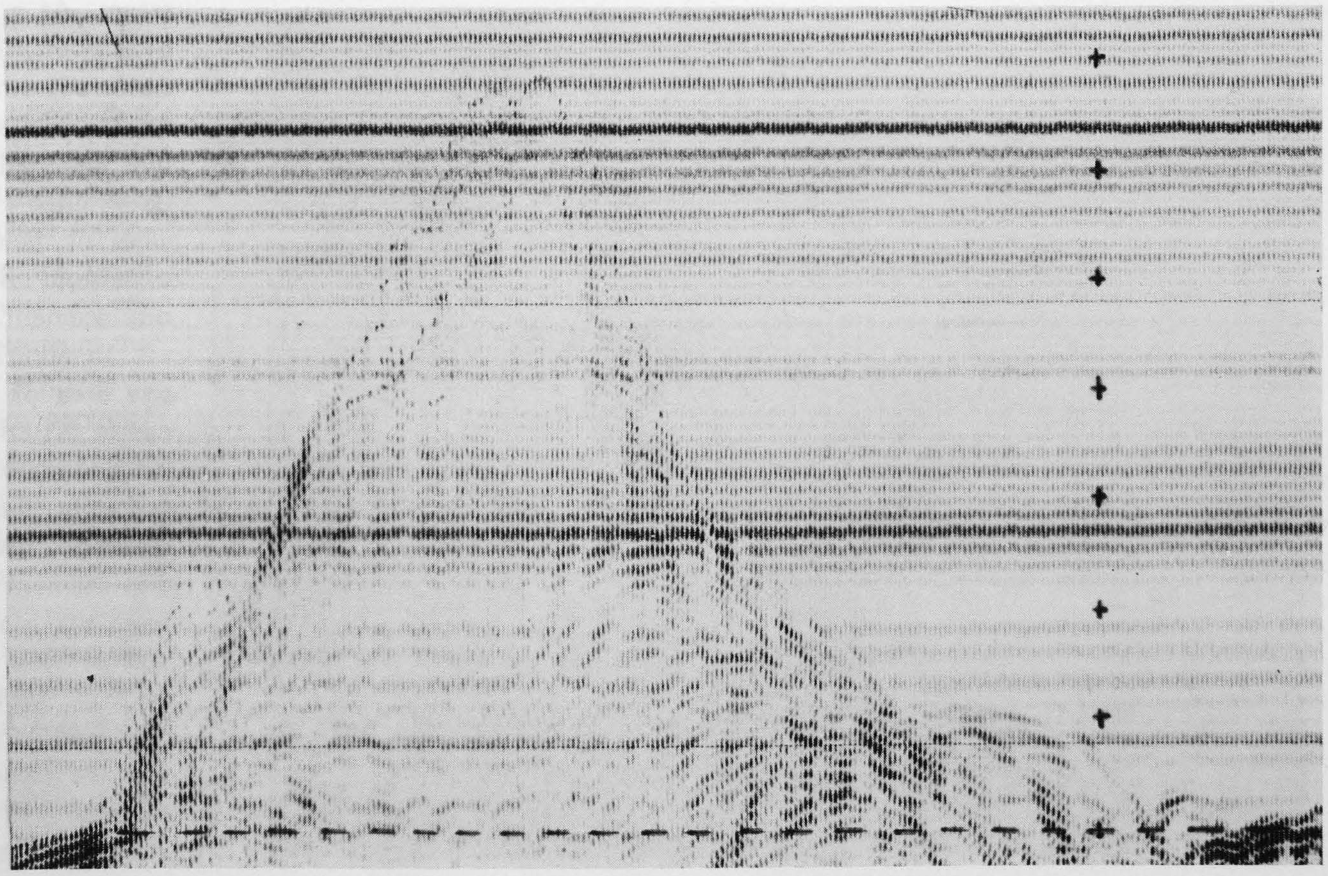
The water depth along the shore-fast ice zone, as clearly delineated by the long sinuous shear ridge (Fig. 3) that developed during the November ice movement displacement event, was measured at intervals of 15 minutes of longitude. The 17 measurement locations are shown in Figure 2 along with the tabulated water depth and local ice relief. As the table in Figure 2 shows, the water depth varied from about 13 to 17 m. Also shown in Figure 2 is the proposed 1979 Beaufort Sea federal-state lease area, which extends beyond the 1978-79 shore-fast ice zone.

The location of the shear boundary represents the outer extent of the shore-fast ice zone for years when there are few areas of grounded ice along the shore-fast ice edge, as in the winter of 1978-79. In other words, lack of grounded ice precluded a "stable" seaward extension of the fast ice zone as depicted in Figure 1.

A number of large grounded ridges did form within the lease area during a major storm which struck the Prudhoe Bay area during 16-18 March 1979. Storm winds were from the southwest at 32 to 50 km/hr on the 16th and 28 to 40 km/hr on the 17th. During this storm, temperatures hovered around -30°C. Ice displacements occurred in the

Figure 5.

Graphic record of impulse radar profile over Hanson Ridge. The distance between the crosses is 20 ft (6.1 m). The dark banding on each side of the ridge at the base is the return from undeformed first-year sea ice. The dashed line represents sea level.



seasonal pack ice zone along the fast ice edge. About 5 km northwest of Spy Island a grounded ridge area formed in 10 m of water. This ridge was about 30 m wide, 200 m long and had an elevation of 6 to 8 m along most of its length. Between Narwhal Island and Flaxman Island four large grounded ridge areas formed in waters 16 to 19 m deep. These large formations varied from about 150 to 400 m long and rose above sea level from 7 to 12 m.

North of Narwhal Island at about 70°26.2'N, 147°23.6'W, a very high grounded ridge formed in 18.5 m of water. This formation was first discovered by A. Hanson during an ice reconnaissance flight shortly after the 16-18 March 1979 storm (Fig. 4). This ridge, the Hanson Ridge, developed when the corner of a large ice floe impinged against the coastal ice. The resulting ice rubble pile was about 350 m long and up to 100 m wide. Five impulse radar profiles over the Hanson Ridge showed that the highest point on the ridge was 20.4 m above sea level (Fig. 5). An elevation survey of the ridge which included the top of the highest ice block revealed a maximum height of 21.3 m (K. Vaudrey, personal communication). However, neither of these elevations is representative of the surrounding relief, which was generally 14 to 17 m high over a length of about 100 m. Beyond this, the ridge's relief was progressively lower until it became 3 to 4 m high at the far ends.

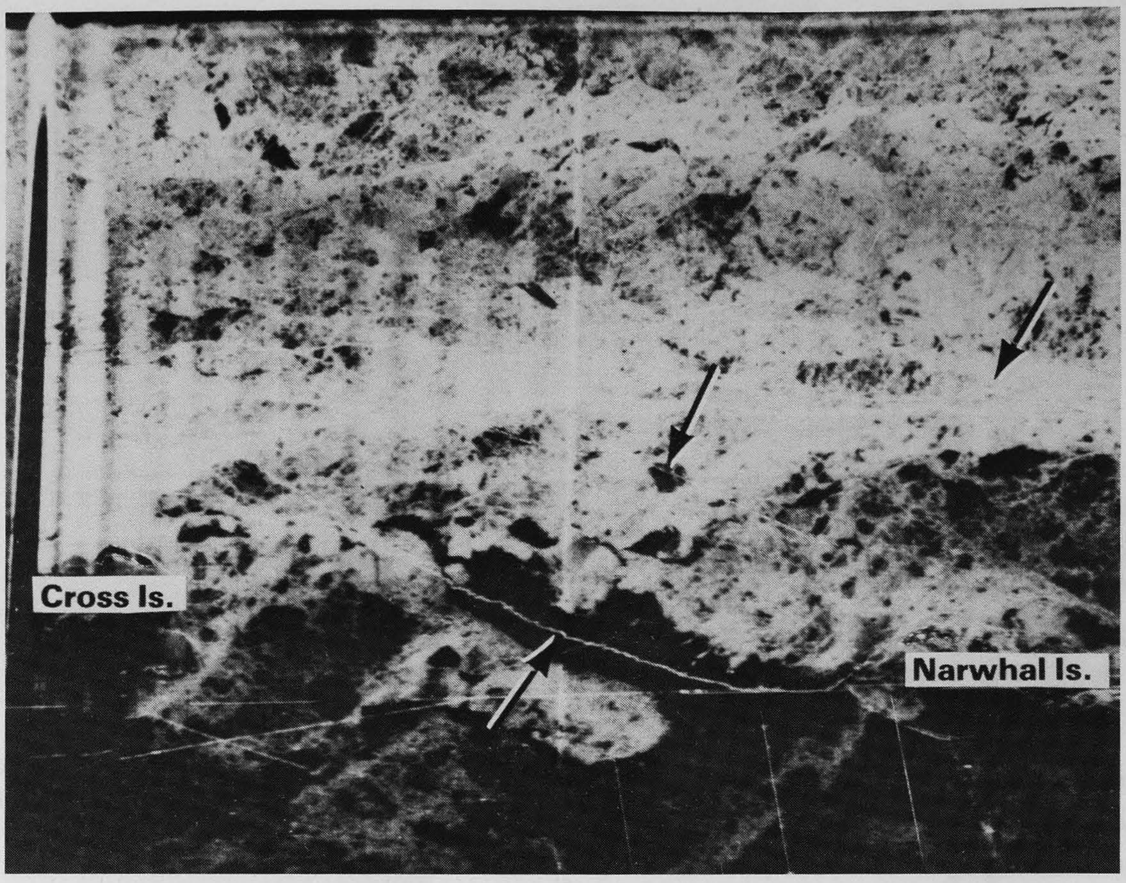


Figure 7. a) SLAR image of the Cross-Narwhal Island area. 17 April 1979. The two center arrows point to the edges of the large fast ice area which moved. The right arrow points to the site of Hanson Ridge.

Figure 6. Seismic line ice road displacement (center section) west of Narwhal Island in March 1979.

Major movements of the seasonal pack ice along the shore-fast ice edge were also noted after the 16-18 March storm. At a location 5 to 10 km west of Hanson Ridge, a movement of 1050 m occurred, which was clearly delineated by the lateral displacement of a seismic line ice road. The 1050-m distance was determined by the Geophysical Services Inc. field crew who lost this quantity of seismic line cable as a result of the ice displacement.

In addition to the above, an extensive area of the fast ice (1.65 m thick) nearly 20 km long, beginning at the fast ice boundary north of Cross Island, was suddenly displaced in a southwesterly direction toward Narwhal Island. This displacement stopped approximately 50 m from the island. Sections of north-south seismic line road which passed about 100 m west of Narwhal Island were displaced laterally up to 28 m during this ice movement event (Fig. 6). The boundary of the displacement is clearly visible in the SLAR image of 17 April,

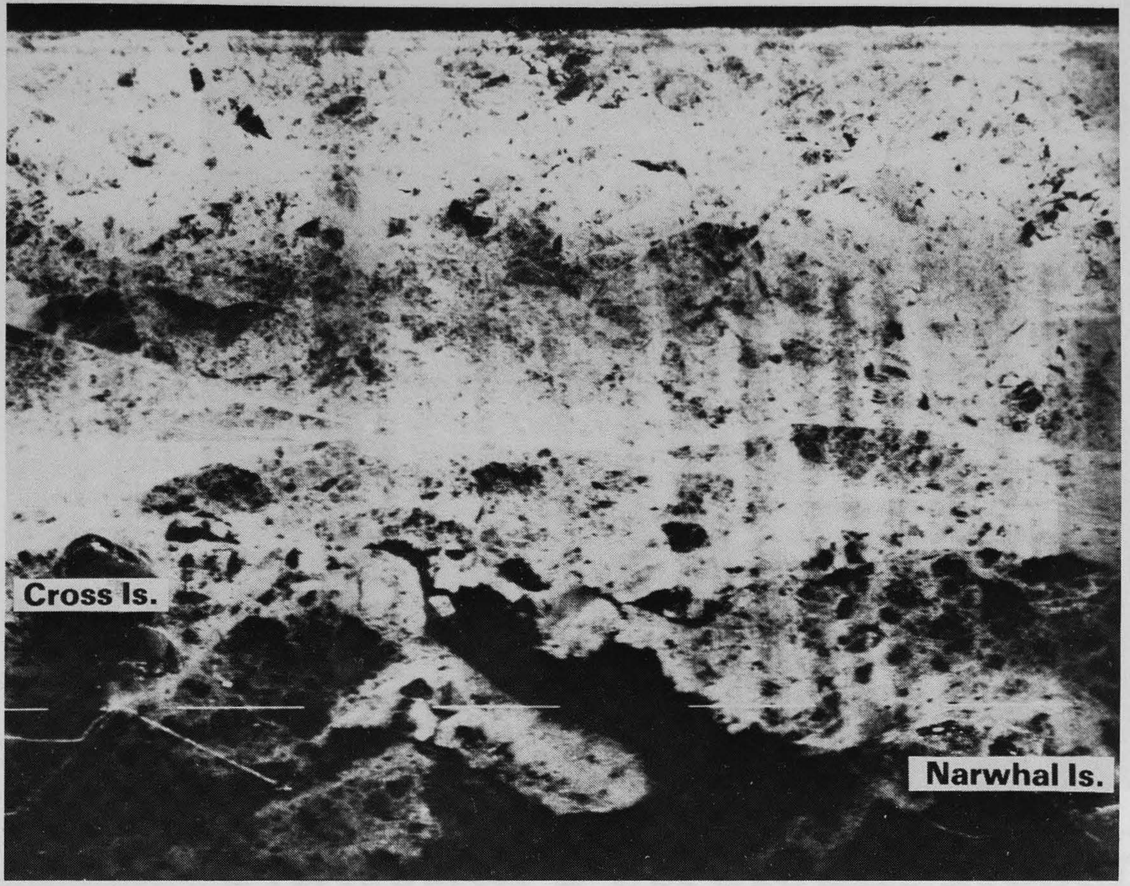


Figure 7. b) SLAR image of the Cross-Narwhal Island area. 9 March 1979.

whereas the 9 March image reveals that the displacement had not occurred prior to that date (Fig. 7).

In late May 1977 an area of the fast ice (1.70 m thick) midway between Cross and Narwhal Islands was also displaced in a southeasterly direction. This displacement was clearly outlined by the lateral movement suffered by another seismic line ice road (Fig. 8). Maximum road displacement was 126 m.

During March 1979 we noted that the fast ice inside the barrier islands from Reindeer Island eastward to Flaxman Island had significant surface roughness. The broken and ridged ice relief was a result of a 4-9 November northeast storm in which winds were from the northeast at 55 to 65 km/hr with gusts to 110 km/hr (J. Helmericks personal communication). Temperature at the time was -29°C. During this storm, the fast ice was broken and driven shoreward, forming pressure ridges, some as high as 4 m, on shoals where we have not seen such formations before. On Thetis Island, located on the eastern side of Harrison Bay, the ice was found to have either piled up or slid inland along approximately 400 m of coastline. The maximum inland movement was somewhat more than 60 m, and the ice came within 10 m of a cabin located on the island. The maximum height of the pile-up was on the order of 4 m. From J. Helmericks (personal communication) we learned that the ice pile-up was the largest to occur on Thetis Island in the last 10 to 15 years and that ice pile-ups on the island occur on the average of once every three years. On 10 November the winds changed quickly from the northeast to the southwest. These winds continued for three days at 25 to 40 km/hr. During this time, the previously broken fast ice was driven northward against the barrier islands where minor ice pile-up and ridge building occurred.

These observations revealed that even inside the barrier islands major ice displacements can occur during fall freeze-up.

Other interesting ice features noted were five floes about 30 m in diameter north of Argo Island, one 300- to 400-m diameter floe east of Argo Island and one floe to the south of Reindeer Island consisting of a surface layer of clear "freshwater" ice, 16 cm thick, underlain by 1.70 m of sea ice. The freshwater ice surface was very smooth and mostly snow-free, in contrast to the surrounding sea ice. Walking on this ice was difficult because of its slick mirror surface. The salinity of this ice was 0.2 parts per thousand, indicating that the melt would meet public health standards for potable water. Of the SLAR images taken during the winter of 1978-79 showing the Argo Island area, only the images of 28 November 78 and 3 January 79 (Fig. 9) could be used to locate the floes. The floes could be detected in the images because they ap-

Figure 8. Seismic line ice road displacement of May 1977.

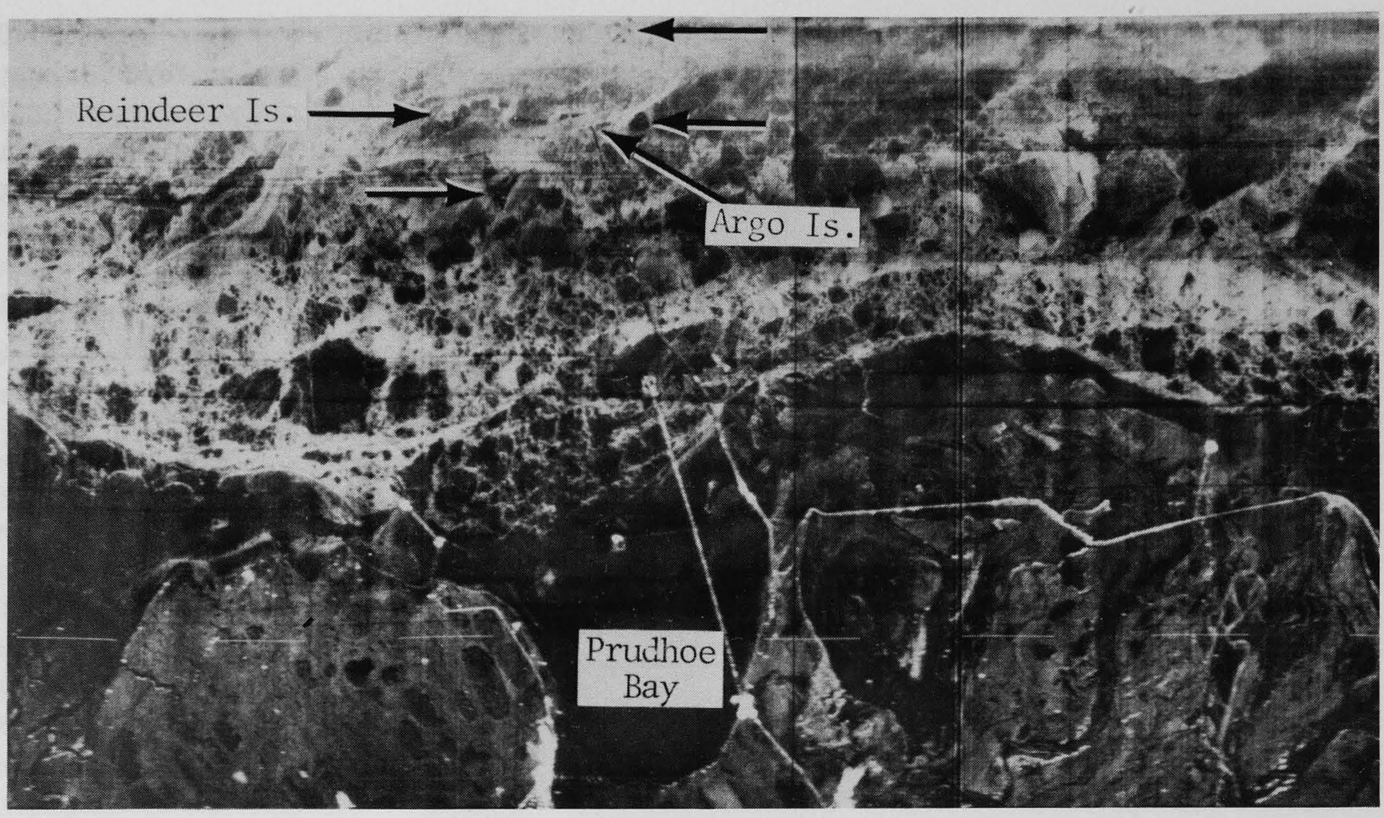


Figure 9. SLAR image of 3 January 1979 with arrows pointing to sites of "freshwater ice" floes.

peared darker than the surrounding sea ice.

The freshwater ice portion of these floes undoubtedly formed in one of the coastal river deltas and was subsequently broken free and driven offshore during the November storm referred to above. The most likely source area is off the Sagavanirktok River delta. In this area in April 1978 we found bottom fast ice composed of an upper layer of freshwater ice 35 cm thick underlain by 57 cm of saline ice.

DISCUSSION

There is a paucity of information on ice movement and deformation events in the Alaskan Beaufort Sea federal-state lease area. This is particularly true for early winter when limited daylight, cold weather and thin ice tend to restrict sea ice field studies. However, the observed location of the "freshwater ice floes" from the nearest river delta clearly indicates that fall storms can break up and displace ice for great distances inside the barrier islands. The importance of this finding is that structures placed in these waters not only must be designed to resist the forces associated with fast ice movement inside the barrier islands but also to withstand potential ice pile-up and override. In addition, the surprisingly large pressure ridges found inside the barrier islands, with their potential for gouging the sea bed or impinging against a bottom-founded structure, must now be considered in the design of these installations. The observations reported here show that fast ice over 1.6 m thick located seaward of the barrier islands can be suddenly displaced in excess of 100 m, that the seaward extent of the "stable" land-fast ice in the Alaskan Beaufort Sea federal-state lease area borders on the 13-m bathometric depth contour in years when there is a small amount of grounded ice in the grounded ice zone, and that major displacements of thick first-year ice and related pressure ridging can occur well within the proposed lease area.

As a result of our findings, we have recommended that the seaward extent of the proposed 1979 lease area be moved southward inside the shore-fast ice area. Here ice movements are less severe, and the possibility of ice pile-up or ride-up and the forces exerted by the pack ice on a manmade drilling structure would be greatly reduced. We feel that this recommendation should remain a condition of the lease until such time as a test structure has been built and evaluated for resistance to the dynamic ice conditions that exist in the seasonal pack ice zone.

ACKNOWLEDGMENTS

This study was supported by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration, under which a multi-year program responding to needs of petroleum development of the Alaska continental shelf is managed by the Outer Continental Shelf Environmental Assessment Program Office.

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* * * *

Austin Kovacs has specialized in cold regions engineering since 1961, when he was Arctic Engineer for Federal Electric Corporation of ITT. His work has ranged widely: a list of 90-plus papers of which he is author or co-author shows topics from mechanical properties of Greenland snow through road tests of Northwest Territories highways to brine infiltration in Antarctica. He has been a research engineer with CRREL since 1962.

by Frederick E. Crory

Design and Construction of Temporary Airfields in the National Petroleum Reserve–Alaska

BACKGROUND

While development work continues at a rapid pace at Prudhoe Bay, the search for more oil and gas on Alaska's North Slope is being carried out by both industry and government. In the National Petroleum Reserve-Alaska, formerly called Naval Petroleum Reserve No. 4, the seismic surveys and exploration programs of the Department of the Interior are a continuation and expansion of the work initially done by the U.S. Navy. The current program consists of drilling four to six shallow (<15,000-ft) depth wells each winter. Two deep wells to 19,000 ft or more are also scheduled each year.

Constructing new roads to these remote locations within the Reserve would be very costly and environmentally undesirable. The shallow explorations require less than 6 months to complete and can be drilled during the winter months. Equipment for the shallow drilling can be brought overland when the tundra and lakes are frozen and covered with snow. Nearby frozen lakes then can be used for temporary airstrips. All work at such shallow wells is completed before the spring breakup. The deep wells, however, require year-round support. In addition to the requirements for food, fuel, cement and other drilling equipment, a critical design constraint was the provision to move in an additional drill rig for drilling a relief well in the event of a blowout. To transport a large drilling rig by air requires about 100 trips in a C-130 type aircraft. Thus the need developed for an economical design for temporary airfields that could be built in winter and support both light and heavy aircraft for a period of 18 months or more.

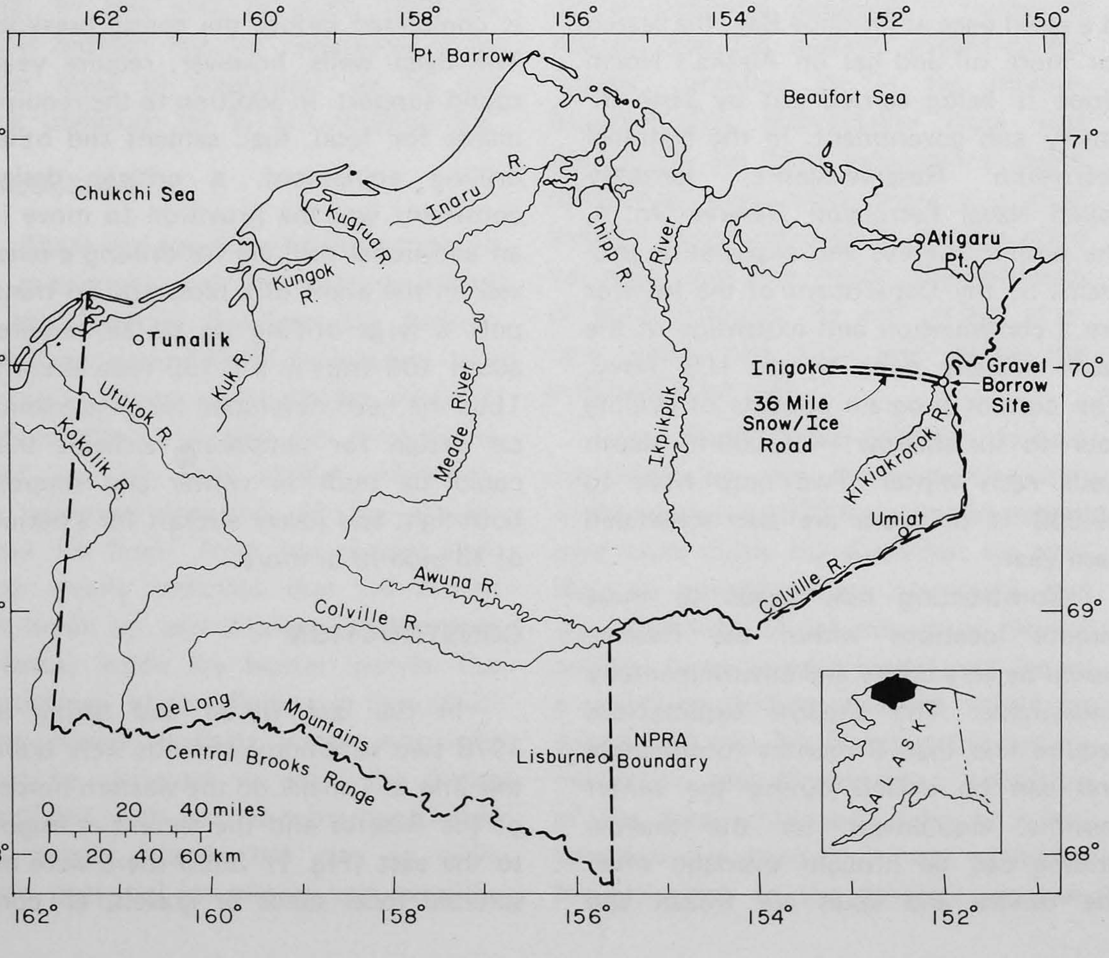
CONSTRUCTION

In the late winter and spring of 1978 two temporary airfields were built, the first at Tunalik on the western border of the Reserve and the second at Inigok to the east (Fig. 1). Since there were no suitable local sands or gravels, all construction material at Tunalik was trucked in over a snow/ice road from an ancient beach deposit some 6 miles to the west[1]. At Inigok the local sand could be used for fill and subgrade work; however, the gravel had to be trucked over a 36-mile snow/ice road, from the confluence of the Kikiakrorak and Colville rivers (see Figure 1). The frozen sand for the subgrade was placed in lifts directly on the tundra, and compacted using conventional methods employed with thawed soils. Special care was taken in compacting the top foot of the subgrade and achieving accurate grades. The careful grading permitted the quick placement of 60-psi expanded, extruded polystyrene insulation boards to keep the subgrade permanently frozen. The controlled compaction of the top of the subgrade was to minimize the amount of settlement, should the top of the subgrade thaw during construction or in the future. To prevent water from infiltrating the joints in the 2- x 8-ft insulation boards, all insulation was covered with a plastic membrane 4 mils thick. The plastic-covered insulation was then covered with 12 to 15 inches of gravel, placed by end dumping, as shown in Figure 2.

Figure 2. Tunalik airfield under construction in March 1978, showing single layer of 2 inches of insulation and plastic membrane over frozen subgrade.

Tunalik had only a single layer of insulation board, 2 inches thick, while Inigok had 3 inches of insulation placed in two layers with staggered joints. The thickness of insulation required was based on the warmer thawing index at Inigok[1]. To confirm the design objective that the insulation would keep the underlying subgrade frozen throughout the summer, thermocouple assemblies were installed at two different locations along the centerline of both airfields. Plots of the temperatures directly beneath the insulation are shown in Figure 3. At Tunalik the maximum temperature of the top of the subgrade reached 31° to 32°F, while at Inigok the maximum temperature was between 26° and 27°F. The maximum temperatures occurred in early August; the surface of the subgrade was cooled after that date by the cold sink at greater depths. This cooling trend occurred more than a month before the overlying gravel had refrozen. The warmer temperatures at Tunalik are believed to have been caused by both the thinner insulation and the placement of only a single layer, which is not as effective as two layers. The thermal performance observations of the airfields at Tunalik and Inigok have been continued throughout the winter of 1978-79 and will continue until at least the fall of 1979, when the drill sites are to be demobilized. An aerial view of the Inigok drill site and the all-season airfield is shown in Figure 4.

Figure 1. Map of National Petroleum Reserve-Alaska, showing location of insulated airfields.



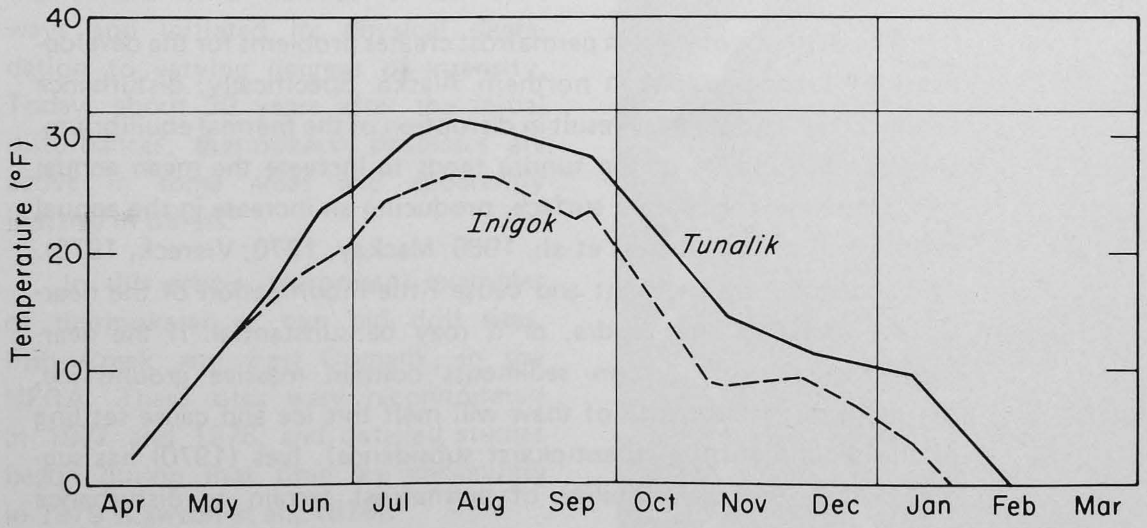
During the late winter and spring of 1979, another insulated airfield, similar in size to the Tunalik and Inigok airfields (150 x 5200 ft) was constructed at Lisburne, in the southeast corner of the Reserve (see Figure 1). This airfield was built using 2.5 inches of insulation, placed in two layers with staggered joints. The insulation was covered with a plastic membrane and covered with about 18 inches of crushed gravel, which was locally available.

While nothing is cheap or easy in such remote northern regions, these insulated airfields have provided the desired facilities while minimizing the disruption to the surrounding terrain. The airfields with adjoining parking aprons and short access roads to the drill pads were built with deep concern for avoiding any severe impacts to the surrounding tundra and will be revegetated or otherwise restored after the completion of the drilling program. The designs also provide for the potential upgrading of the airfields in the event they are to be reactivated in the future or required for permanent use. The insulation has avoided the use of large quantities of gravel and the attendant disruption of large areas to obtain borrow material. The small quantities of gravel used have also decreased the amount of ripping of frozen material required, with a decrease in construction time. While the great volume of insulation required places a large burden on logistics and transportation, this effort is not too difficult to accomplish in early spring. The insulation must be placed by hand, but this very labor-intensive effort can be accomplished in three weeks, normally in April when the air temperatures are not too severe.

Test areas were installed in a corner of the Inigok parking apron to investigate the effect of different thicknesses of insulation and for direct comparison with uninsulated areas. Test plots were also installed at Inigok last year to evaluate and optimize the best types of grasses and degree of fertilization required to revegetate both the exposed borrow areas, and the graveled runways, taxiways, parking apron and drill pad.

Figure 4. Aerial view of completed airfield and drill site at Inigok, July 1978.

Figure 3. Temperatures directly beneath insulation of Inigok and Tunalik airfields.



ACKNOWLEDGMENTS

The oil and gas exploration program in National Petroleum Reserve - Alaska is under the direction of Dr. George Gryc of the U.S. Geological Survey. Dr. Max Brewer is Chief of Operations. The exploration program including the engineering, construction and supervision of these airfields and drill sites is done by Husky Oil NPR Operations Inc., under contract to the U.S.G.S. Arctic Slope/Alaska General was the construction sub-contractor for the facilities described above.

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by Daniel E. Lawson and Jerry Brown

Human-Induced Thermokarst at Old Drill Sites in Northern Alaska

INTRODUCTION

The presence of ice-rich permafrost creates problems for the development of tundra regions in northern Alaska. Specifically, disturbance of the terrain surface may result in disruption of the thermal equilibrium. Usually, disturbance of the tundra tends to increase the mean annual temperature at the ground surface, producing an increase in the annual depth of thaw (e.g. Brown et al., 1969; Mackay, 1970; Viereck, 1973). This increase may be slight and cause little modification of the near-surface materials and tundra, or it may be substantial. If the near-surface, perennially frozen sediments contain massive ground ice, the increase in the depth of thaw will melt this ice and cause settling of the ground surface (thermokarst subsidence). Ives (1970) has suggested that the susceptibility of permafrost terrain to disturbance may be directly proportional to its ice content and inversely proportional to the mean annual ground temperature. Increased thaw may also induce a host of other thermokarst-related processes such as slope failure by slumping and flow, and gullying and removal of the near-surface materials by thermal and mechanical erosion (e.g. Mackay, 1970; French and Egglinton, 1973; French, 1974; McRoberts and Morgenstern, 1974a,b; Lawson, 1979). Brown and Grave (1979) have reviewed recent regional and site-specific studies of human-induced and natural permafrost terrain disturbance.

Although many short-term effects of human-induced disturbances on permafrost terrain have been documented, the long-term effects are poorly understood. Disturbance resulting from exploratory drilling in the Naval Petroleum Reserve Number 4, now designated the National Petroleum Reserve-Alaska (NPRA), during the late 1940's and early 1950's provides examples of these long-term effects and illustrates the rate of vegetation recovery to these initial and drastic impacts. As indicated in Lawson et al. (1978), vegetation recovery at one site has been remarkably complete and demonstrates the tundra's resiliency for recovery.

Thirty-six test wells were drilled in the NPRA during the period from 1944 to 1953 (Reed, 1958). These drill sites are located north of the Brooks Range in the Arctic Coastal Plain and Foothills Provinces of the Arctic Slope (Fig. 1). This entire region is underlain by permafrost, much of it ice-rich, and covered by tundra vegetation. Camp construction and drilling activities disturbed the tundra in a number of different ways and initiated its physical degradation to varying degrees of intensity. Today, about 30 years after the initial disturbances, thermokarst processes are active in some areas and apparently inactive in others.

In this article, we present examples of thermokarst at two old drill sites, Fish Creek and East Oumalik, in the NPRA. These sites were reconnoitered in 1977 and 1978, and detailed studies begun during that time are continuing in 1979 (Lawson et al., 1978).

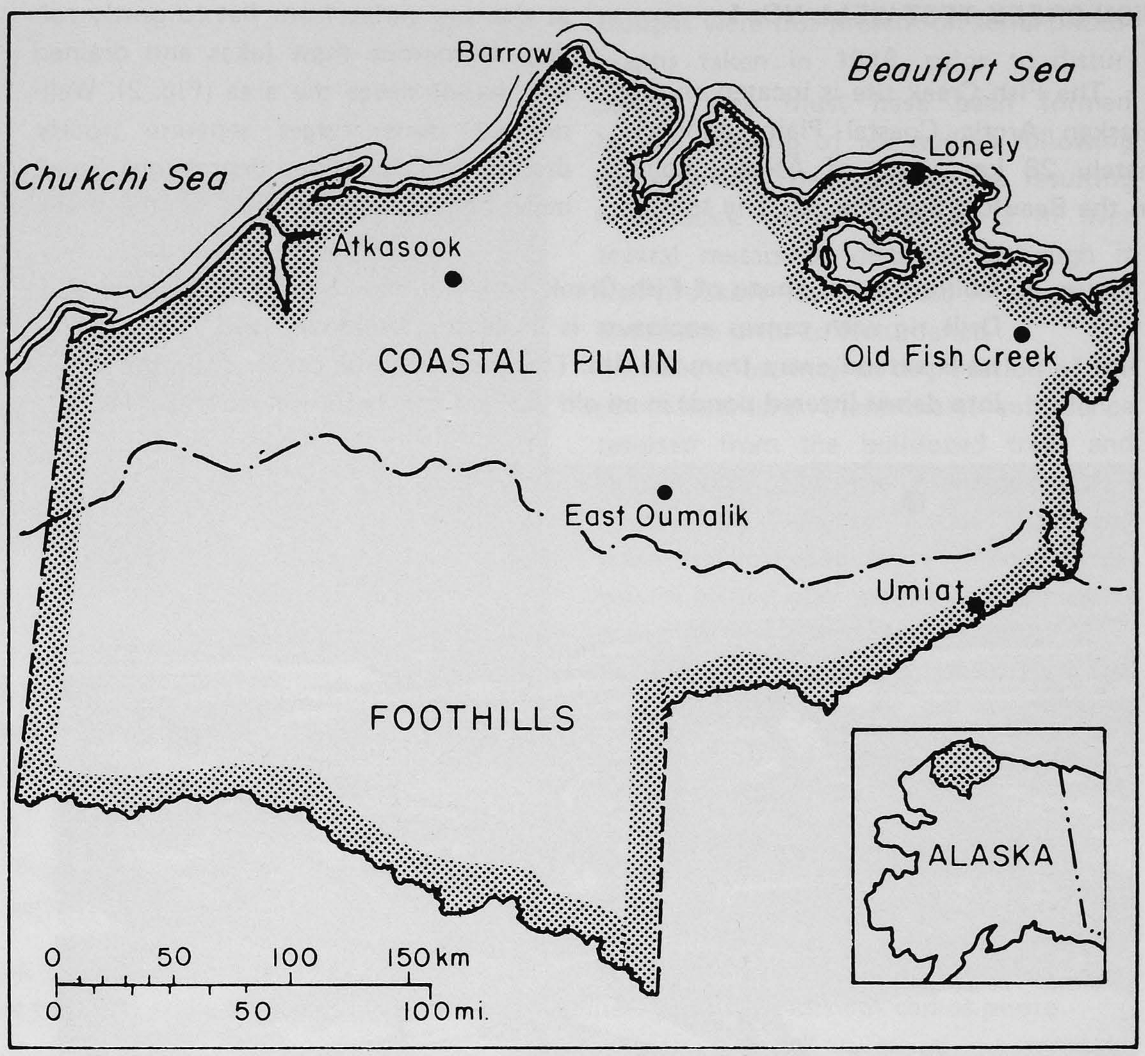


Figure 1. Location of East Oumalik and Fish Creek drill sites in NPRA and Alaska.

Figure 2. Aerial photo taken in 1948 showing the location of the Fish Creek drill site prior to disturbance. Polygonal ground on the drained lake basins and intervening upland surfaces indicate the presence of ice wedges. Rectangle marks approximate location of major drill site activities. North at top of photo. (Bar-74-029, 10 July 1948.)

FISH CREEK TEST WELL NO. 1

The Fish Creek site is located on the Alaskan Arctic Coastal Plain, approximately 28 km south of Atigaru Point on the Beaufort Sea (Fig. 1). The terrain at the site varies from flat to gently rolling. Numerous thaw lakes and drained lake basins cover the area (Fig. 2). Well-drained dune ridges separate poorly drained and undrained depressions. Small meandering streams, such as the creek at the Fish Creek site, flow in relatively narrow valleys that locally show relief of 5 to 10 m or so. The Fish Creek site lies mostly on a well-drained dune ridge adjacent to three drained lake basins.

Figure 3. Oblique aerial photo of Fish Creek Test Well No. 1 in 1949 (view east). Drill rig with canvas enclosure is in center. Bulldozed and "off road" trails extend away from the site. Two ditches in the center drain the area into debris-littered ponds in an old drained lake basin (photo U. S. Navy).

Figure 4. A bulldozed trail with berm at the Fish Creek drill site. A small thermokarst pond lies in the trail, near the center of the photo. View is northeast toward the drill site.

Tundra at this site overlies unconsolidated and well-sorted fine-to-coarse-grained sand of Quaternary age. Below a thin active layer, these sands are perennially frozen to a depth of about 180 m, and we estimate they have moisture contents of 30 to 75%. Polygonal ground is common on both the drained lake basins and upland surfaces (Fig. 2), indicating that ice wedges, one form of massive ground ice, underlie the site. Similarly, small pingos and incised beaded streams in the area indicate that massive ice in other forms may be present at the site. The precise distribution and volume of ice beneath the site are, however, not yet known.

Activities at the Fish Creek site began about 15 March 1949 and continued to 25 October 1949 (U. S. Navy 1949). Equipment weighing 2239 metric tons for camp construction and drilling was transported from Barrow between 31 January and 4 April 1949. Buildings of the camp, mainly Jamesway and Quonset huts, were set on piles and connected by boardwalks (Fig. 3). A National 50 rig set on wooden piles and a concrete pad was used to drill the test hole. During construction and camp occupation, snow and, in some places, the vegetation and upper soil horizons were bulldozed clear to provide vehicle access around the camp and to form trails for transporting water from the nearby creek and a small lake (Fig. 3). Three trenches were also excavated to drain water from the main camp area. Lawson et al. (1978) describe the site history in more detail.

The disturbances at Fish Creek vary in intensity and include off-road and bulldozed trails (Fig. 4), excavations (Fig. 3), individual and stacks of 55-gallon steel drums (Fig. 5), the camp structures, a winter runway, various types of solid waste such as wood, steel landing mats and bottles (Fig. 5), and hydrocarbon spills. Detailed descriptions and photographs of the disturbances are presented in Lawson et al. (1978). Under the present NPRA program, this site is being cleaned up in summer 1979.

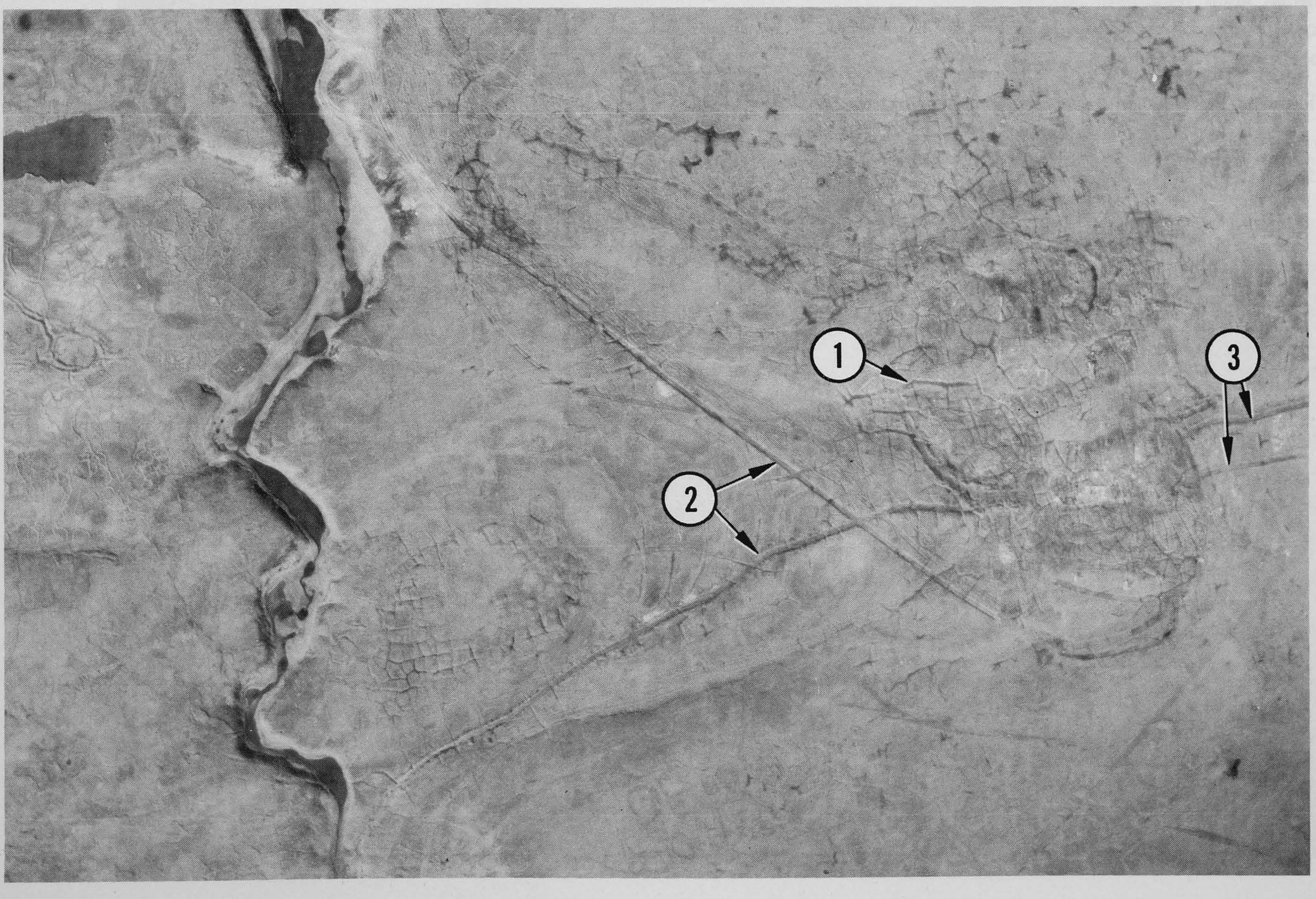
Figure 5. Wood, 55-gallon steel drums and other debris littering Fish Creek site. A large stack of steel drums lies near the horizon, left of center. Below it, short wooden piles protrude above the vegetation.

These disturbances resulted in the thaw degradation of the permafrost and subsidence of the ground surface.

A 1977 aerial photograph of the site (Fig. 6) shows a well-defined polygonal pattern of troughs on it. Since these troughs were not present on aerial photographs taken in 1948, prior to disturbance, they must have been formed by the melting of ice wedges following disturbance. The relief of the resulting hummocky surface may be 2 m over several meters of distance, although it was probably less than 0.5 m across the entire site prior to disturbance.

The most intense degradation of the permafrost and thermokarst subsidence resulted from the bulldozed trails and excavations, and the movement of a number of vehicles across bulldozed trails and off-road areas. These disturbances caused compaction and damage or complete destruction of the vegetation and soil cover. Today these locations are generally covered by thermokarst ponds of width comparable to the disturbance and with subsidence generally 0.5 m or more. Along one of the bulldozed trails, thermokarst subsidence led to thermal and hydraulic erosion and

Figure 6. Aerial photograph of the Fish Creek site on 21 August 1977. Thermokarst subsidence above ice wedges forms the polygonal pattern (1), while thermokarst trails (2) and excavations (3) form mostly linear features. North at top of photo.

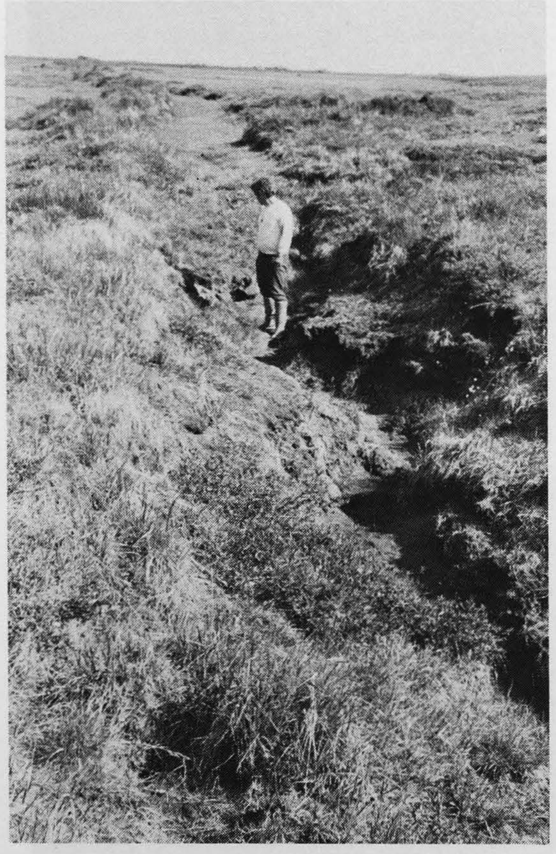


relief across parts of it in excess of 2.0 m (Fig. 7).

The intensity of the disturbance determined the extent of thermokarsting and appears to be reflected in the thaw depths measured in disturbed and undisturbed areas of the site. Areas of intense disturbance, such as those of bulldozed trails or repeated vehicle passage, were thawed to a mean depth of 53 cm in late July 1977, whereas lightly disturbed or undisturbed areas, such as those beneath solid waste or off-road areas over which vehicles passed only once were thawed to a mean depth of about 32 cm.

We are uncertain whether thermokarst subsidence is continuing over most of the site today; however, the water-filled thermokarst troughs and ponds and the sporadic occurrence of blocks of soil and vegetation in them suggest that some ice wedges are still melting. An ice wedge with only about 18 to 30 cm of covering soil is adjacent to an active thermokarst pond and is apparently melting today. The similarity of thaw depths in lightly disturbed and undisturbed areas may indicate that thermal equilibrium has been reached at some locations.

Figure 7. Gully formed by thermal and hydraulic erosion along a thermokarsted, bulldozed trail at the Fish Creek drill site.



EAST OUMALIK TEST WELL NO. 1

The East Oumalik site is located about 8 km north of the boundary of the Arctic Coastal Plain and the Foothills Provinces (69° 47′ 29″ N, 155° 32′ 39″ W, Fig. 1). The site itself lies on an upland surface that is surrounded on three sides by two small meandering streams (Fig. 8). The upland surface has little relief but slopes gently to the north. These streams have cut valleys with bottoms that often lie 15 to 30 m below this surface. Lakes, often deeply incised, are common in this region (Livingstone et al., 1958). Drained lake basins occur less often. Near the site, they lie in the valleys.

Ice-rich, perennially frozen sediment of Quaternary age forms the upland. It generally consists of silt to fine sandy silt that shows no sedimentary structure except for horizontal laminations in some instances. Moisture contents measured in sediment samples within 2 m of the surface ranged from 50 to 150%. Drilling to 1- to 2-m depths at 10 locations revealed massive segregated, pore and wedge ice in these sediments. Fluvial erosion of the western edge of the upland also exposed an ice wedge extending 11 m below its surface. Polygonal ground indicative of wedge ice was, however, not apparent on the undisturbed upland surface (Fig. 8). Pingos and beaded streams also occur near the site. We do not know, however, the overall distribution and volume of ice beneath this site.

Drilling at East Oumalik began on 23 October 1950 and was completed 30 December 1950 (U. S. Navy, 1951). Camp construction apparently began in April 1950, after completion of the Oumalik Test Well No. 1, located about 19 km west-northwest of East Oumalik. The drill rig and camp structures used here originated from the Oumalik drill site. Six Quonset and Jamesway huts and 11 wanigans were used for housing and shops. A Wilson Super Titan Rig set on a foundation of 12 in. (30.5 cm) x 12 in. timbers was used to drill the test hole. Some areas in the camp were bulldozed clear of vegetation and soil to provide vehicle access. Two ditches were also excavated to drain the upland surface across the northeast facing valley slope. This site was partially cleaned up in summer 1978 and is scheduled for completed clean-up in 1979.

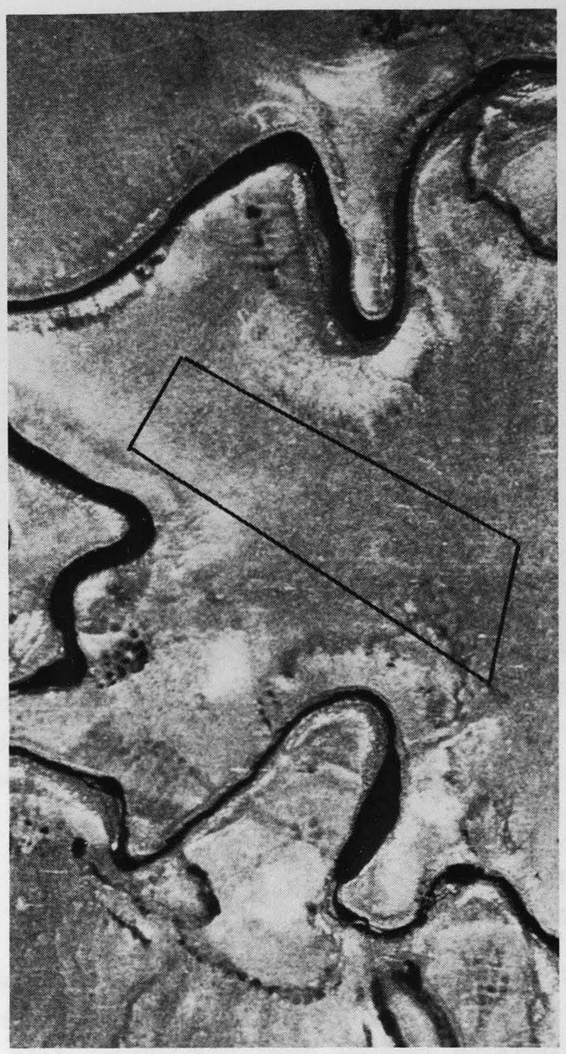


Figure 8. Enlargement of part of aerial photo of East Oumalik drill site in 1948 prior to disturbance. Boxed area shows location of major camp activities. Upland surface has little relief and lacks a polygonal pattern or other features indicative of ground ice. North at top of photo. (Bar-124-147).

The disturbances at East Oumalik are similar in type to those at the Fish Creek site, but the resulting degradation far exceeds that of Fish Creek. A hummocky topography with variations in relief of 1 to 8 m over several meters distance and numerous water-filled depressions cover the entire area upon which camp construction and activities took place (Fig. 9). Prior to disturbance, relief over several meters was probably less than 0.2 m and only 2 to 3 m across the entire upland site. Disturbances have resulted in deep thermokarst subsidence that has been accompanied by thermal

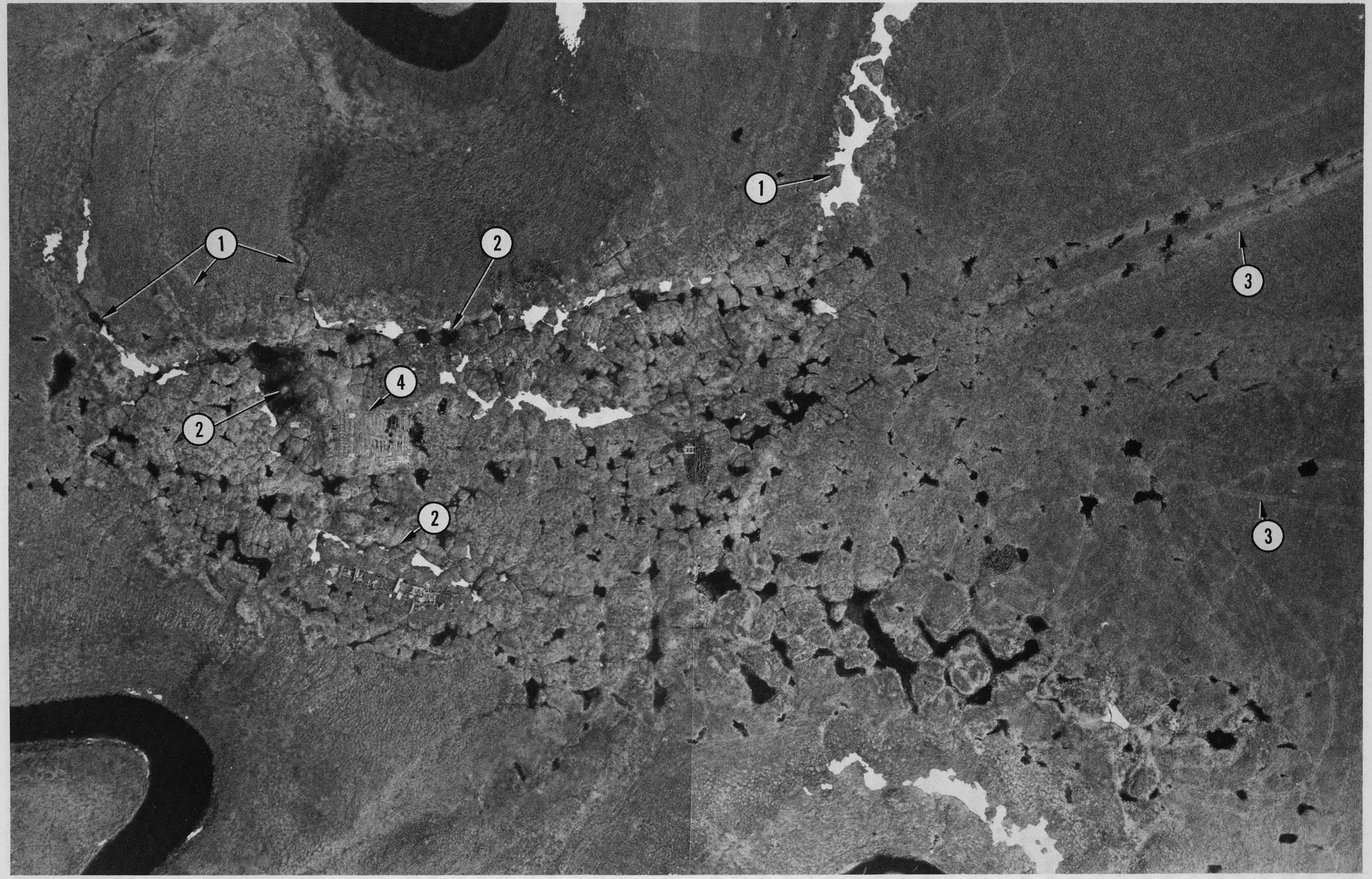


Figure 9. Aerial photographic mosaic of the East Oumalik drill site in June 1978. The hummocky topography and thermokarst ponds and troughs clearly demarcate the extent of the drill site activities. Locations of drainage ditches (1), bulldozed trails (2), "off-road" trails (3), and structures (4) all exhibit varying degrees of thermokarst degradation. North is approximately to the upper left corner of the photo.

and hydraulic erosion and by slumping and collapse of the slopes adjacent to the thermokarst ponds and troughs.

As with the Fish Creek site, the most intense degradation of the permafrost resulted from the removal and destruction of the vegetation and soil by bulldozing, and the multiple passages of vehicles over off-road "trails." Unlike Fish Creek, however, these disturbances have produced thermokarst depressions with dimensions that far exceed those of the original trail or excavation. Thermokarst troughs developed along former trails may exceed 4 m in depth and 15 m in width (Fig. 10).

The historical development of the hummocky topography at the East Oumalik site apparently reflects the high ice content of the supersaturated silts and their inherent instability upon thawing. Initially, increased thaw due to disturbance caused thermokarst subsidence and the formation of thermokarst ponds. Ditches were excavated to drain these areas, but these ditches also promoted thermal and hydraulic erosion along their lengths. These areas underwent headward erosion into the upland surface and, concurrently, sloping trails suffered the same processes. At the same time, thermokarst subsidence increased the depth of thaw in the sediments of the trough and pond slopes. This initiated marginal slope collapse and slump. Because they are readily entrained by flowing water, meltwater probably removed at least some of these mass wasted silts.

Today large thermokarst depressions are found over much of the site in response to these processes. These depressions are small valleys that may be relatively flat-bottomed or covered by polygonal troughs or ponds developed over melting ice wedges. Frequently, they are enclosed by high angled slopes, some of which are undergoing collapse and slump (Fig. 11). Such slumping and collapsing slopes, as well as an ice wedge exposed in a bank adjacent to a thermokarst pond (Fig. 12), indicate that thaw is still active some 28 years after the initial disturbance.

Thaw depths may reflect this fact. The depth of thaw in the center of the deepest thermokarst troughs exceeded 2 m, while across the site it typically ranged from 0.4 to 1.0 m in late July 1978. In contrast, undisturbed areas of the upland surface typically were thawed to 0.2 to 0.5 m.

CONCLUSION

The two examples of impact and recovery at old drill sites on permafrost terrain indicate the need for detailed investigation of the characteristics of permafrost, particularly its ice content and distribution, prior to final site selection for construction or other activities, and minimization of surface terrain disturbance during any activity in permafrost regions.

The degree of thermokarst degradation is related to ice content. The East Oumalik site with its high ice content in fine silts has undergone significantly more thermokarst development than the Fish Creek site where ground ice is less extensive in the sandy materials. East Oumalik shows active thermokarsting and few stabilized areas, whereas Fish Creek is essentially stabilized with vegetation recovery well advanced and few unstable areas present. We expect that our continuing studies of thermokarst and related vegetation studies by our biological colleagues across northern Alaska will permit prediction of the consequences of disturbance and the subsequent recovery rates under varying subsurface and climatic conditions.

ACKNOWLEDGMENTS

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Figure 10. Thermokarst ponds in irregular depression developed beneath the location of a trail on the East Oumalik drill site. Depth of the ponds exceeds 1 m and of the depression 2 to 3 m. The depression is about 12 m wide here.

Figure 11. Large thermokarst "valley" where bulldozed trail, estimated to have been 6 m wide, was located in 1950. In places, the depression exceeds 4 m in depth and 15 m in width. Polygonal troughs and a pond by the man indicate thawing of ice wedges to this depth. Bare spots and collapsed blocks of sediment and vegetation lie on the "valley" slope behind him.

Figure 12. Thermokarst pond and an ice wedge exposed on its bank (below man). Collapsed blocks of soil and vegetation lie in and next to the pond.

We thank Dr. Max Brewer and Dr. George Gryc of the U. S. G. S. for their continuing encouragement and valuable assistance throughout this study, and Larry Gatto and Richard Haugen of CRREL for technical review of this paper.

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by Edwin Chamberlain

Overconsolidated Sediments in the Beaufort Sea

INTRODUCTION

In recent years considerable information has been obtained on the engineering, chemical, thermal and geological properties of submarine sediments in the Alaskan Beaufort Sea. This information, obtained under the sponsorship of the Bureau of Land Management/National Oceanic and Atmospheric Administration Outer Continental Shelf Environmental Assessment Program (OCSEAP), will be used to provide a technical basis for evaluating the hazards related to the development and production of offshore petroleum resources in the Alaskan Beaufort Sea.

Figure 1. Reported locations of dense overconsolidated sediments in the Alaskan Beaufort Sea.

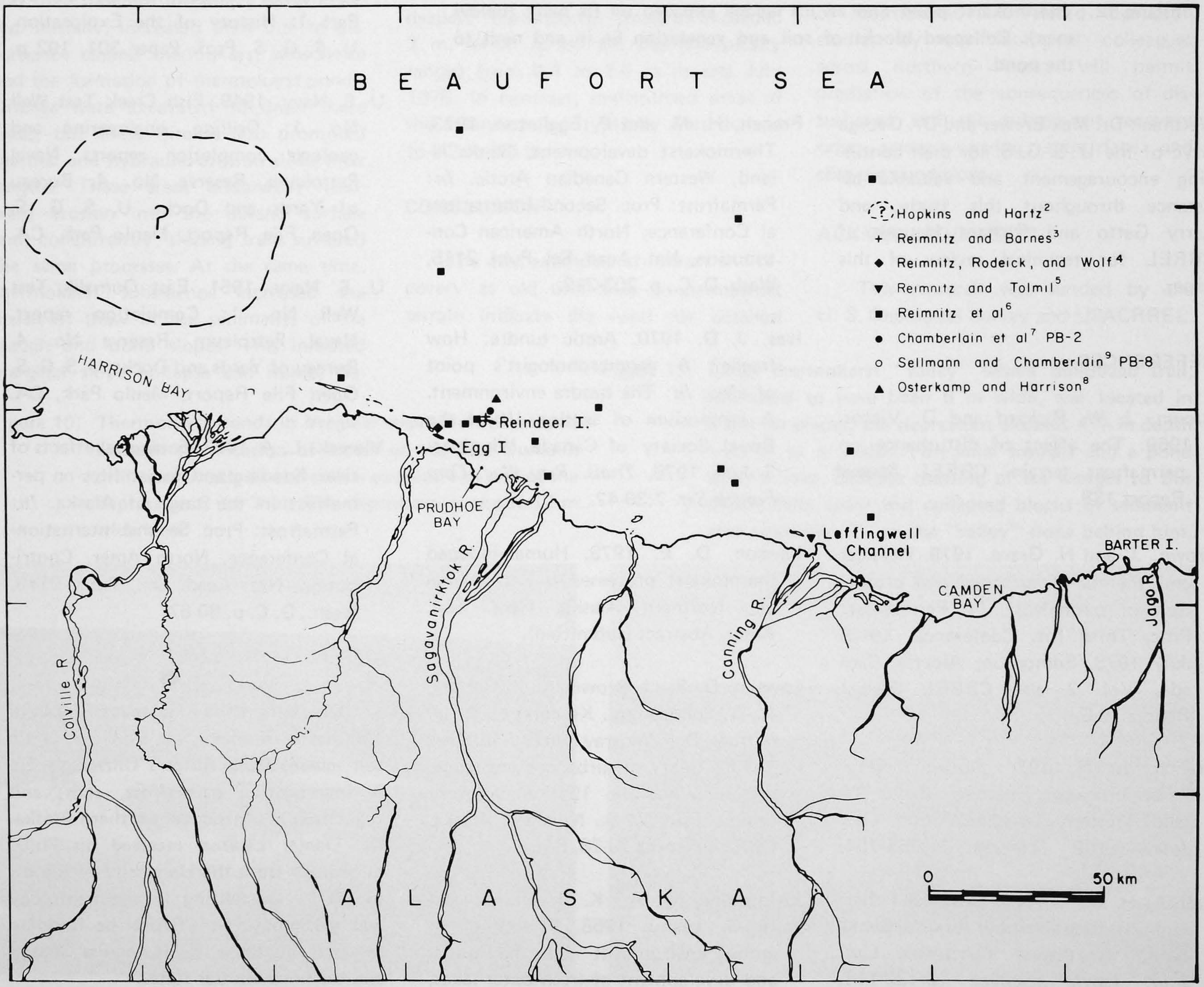
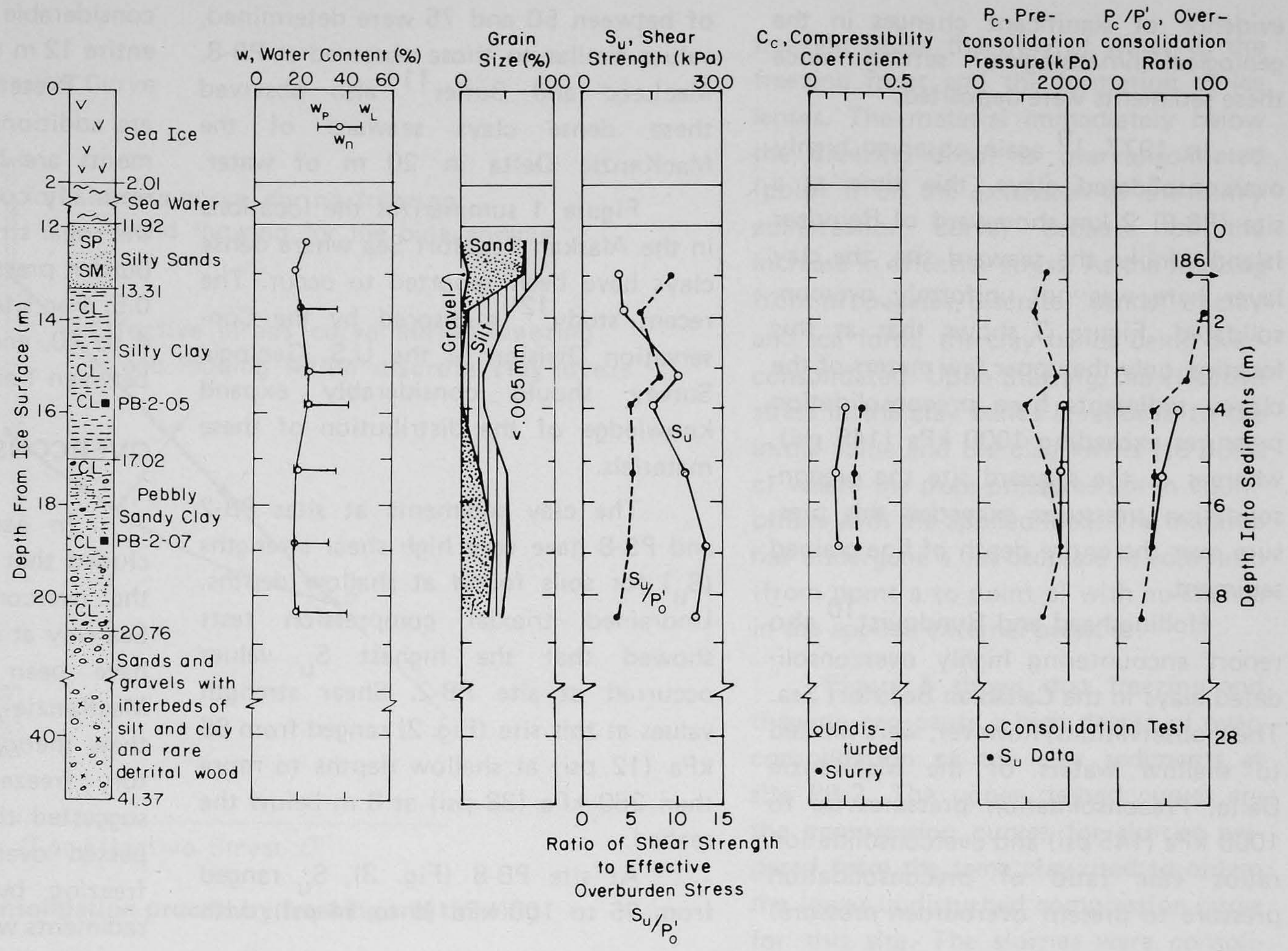


Figure 2.

Drill hole log and engineering properties of sediments at site PB-8.



Subsea ice-bonded permafrost was observed to occur widely in this region. The presence of ice in the submarine sediments, of course, presents thaw subsidence and thaw weakening problems similar to those encountered on land. But the problems are complicated by the ocean setting where ice forces and site access present additional obstacles to be overcome.

Another important feature of the Beaufort Sea sediments and the subject of this paper is the presence of highly overconsolidated clays. These dense clays have been observed by numerous investigators to occur over a wide region. Mostly shallow deposits less than 10 m (33 ft) thick have been reported; however, there is reason to believe[1] that much deeper deposits occur.

These overconsolidated clays can have a significant influence on offshore operations. On the positive side, they provide high strength and bearing capacity sites for artificial islands or gravity structures. They may also provide stable foundations for undersea pipelines. On the negative side, these clays make access difficult to underlying sands and gravels for use as fill materials for offshore island construction. In addition, where these clays occur on the inner part of the continental shelf, it appears that the top of ice-bonded permafrost is much nearer to the sea bed than in regions where the clays are absent. Thaw instability problems may occur in these areas.

I will discuss in this report some properties of the overconsolidated clays, their distribution, their probable overconsolidation mechanism, and some implications for the design of offshore structures.

DISTRIBUTION AND PROPERTIES

Hopkins and Hartz[2] report that much of the sea floor to the north of the Colville River is underlain by a *compact stony mud* of the Flaxman Formation. These same sediments were observed on the outer coastal plain. Reimnitz and Barnes[3] observed *stiff, cohesive materials* seaward of Reindeer Island (Fig. 1) and they suggested that these sediments occupy extensive areas of the inner shelf and some areas of the central and outer shelf. Reimnitz, Rodeick and Wolf[4] report *very stiff silty clay* underlying a scour feature about half a kilometer seaward of Egg Island near Simpson Lagoon. More recently, Reimnitz and Toimil[5] report *dense clays* in the deepest part of Leffingwell Channel.

Perhaps the largest number of observations of these stiff clays was made by Reimnitz et al.[6] They report that these clays occur widely in the upper 15 cm of sediment eastward from the Colville River to the Canning River, extending from shallow nearshore waters to more than 100 km offshore in 1062 m of water.

I first observed these very stiff overconsolidated clays in 1976 in a core taken from a drill hole at site 3 km seaward of Reindeer Island (PB-2) in the same region studied by Reimnitz and Barnes.[3] For the first time in the Alaskan Beaufort Sea the vertical extent of the overconsolidated clay was determined. Figure 2 shows that this clay is capped by approximately 1.4 m of silty sand and is more than 7 m thick. Osterkamp and Harrison[8] also observed these dense clays 4 km farther offshore of Reindeer Island.

Laboratory one-dimensional consolidation tests showed that these clays had been compressed sometime in the past, under pressures exceeding 1800 kPa (260 psi), considerably higher than the maximum overburden pressure of 50 kPa (7 psi) currently on the deepest part of the clay section at site PB-2. These very high preconsolidation pressures are direct evidence of significant changes in the geological/climatological setting since these sediments were deposited.

In 1977, I[9] again observed highly overconsolidated clays, this time at a site (PB-8) 2 km shoreward of Reindeer Island. Unlike the seaward site, the clay layer here was not uniformly overconsolidated. Figure 3 shows that at this location only the upper few meters of the clayey sediments have preconsolidation pressures exceeding 1000 kPa (145 psi), whereas at the seaward site the preconsolidation pressures exceeded this pressure over the entire depth of fine grained sediment.

Hollingshead and Rundquist[10] also report encountering highly overconsolidated clays in the Canadian Beaufort Sea. Their observations, however, were limited to shallow waters of the MacKenzie Delta. Preconsolidation pressures up to 1000 kPa (145 psi) and overconsolidation ratios (the ratio of preconsolidation pressure to present overburden pressure) of between 50 and 75 were determined, values similar to those observed at PB-8. MacLeod and Butler[11] also observed these dense clays seaward of the MacKenzie Delta in 20 m of water.

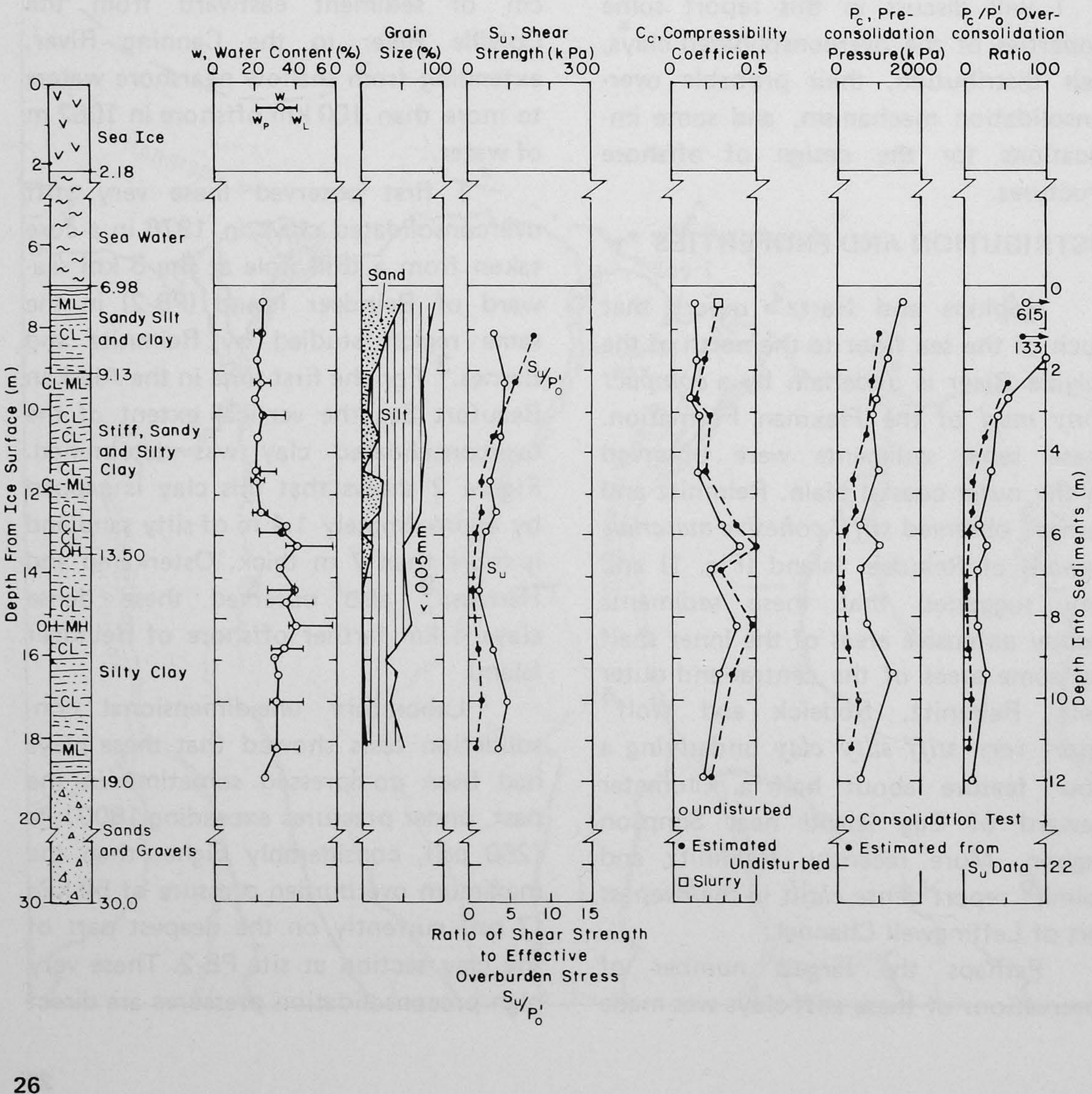
Figure 1 summarizes the locations in the Alaskan Beaufort Sea where dense clays have been reported to occur. The recent study[12] sponsored by the Conservation Division of the U.S. Geologic Survey should considerably expand knowledge of the distribution of these materials.

The clay sediments at sites PB-2 and PB-8 have very high shear strengths (S_u) for soils found at shallow depths. Undrained triaxial compression tests showed that the highest S_u values occurred at site PB-2. Shear strength values at this site (Fig. 2) ranged from 85 kPa (12 psi) at shallow depths to more than 260 kPa (38 psi) at 8 m below the seabed.

At site PB-8 (Fig. 3), S_u ranged from 25 to 100 kPa (4 to 14 psi), with considerable variation occurring over the entire 12 m thick section.

These high shear strength values are additional indicators that these sediments are highly overconsolidated. For normally consolidated clays the ratio of the shear strength (S_u) to the in-situ overburden pressure (P_o) is generally less than 0.5. For site PB-2 this ratio ranged from 4 to 10, and at site PB-8, S_u/P_o ranged between 1 and 8.

Figure 3. Drill hole log and engineering properties of sediments at site PB-8.



OVERCONSOLIDATION MECHANISM

In earlier reports[7,9] it was concluded that freezing and thawing caused the overconsolidation of the Beaufort Sea clay at site PB-2. Similar conclusions have been reached for clays in the MacKenzie River Delta.[10] The freeze-thaw theory was supported with laboratory freeze-thaw consolidation tests. I suggested that a transient barrier island passed over this site and induced the freezing by thermally connecting the sediments with the atmosphere.

Recently additional information has prompted a reconsideration of the overconsolidation process. The earlier conclusions were based principally on preliminary evaluations of stratigraphic, paleontologic, geochronologic, and sea level data which suggested that these sediments ranged in age from contemporary to perhaps 10,000 years old. Results of recent analysis of carbon and pollen[13,14] sampled from cores indicate that the overconsolidated sediments at PB-2 are much older, perhaps dating as much as 50,000 years BP.

Also, reevaluation of the data for all the other sites that I have investigated revealed that most of the fine-grained sediments were overconsolidated.[10] The degree of overconsolidation and magnitude of the preconsolidation pressures varied considerably, the dense highly overconsolidated clays occurring only at sites PB-2 and PB-8.

Furthermore, it appears that dessication erosion, changes in chemistry, secondary consolidation and shallow seasonal freezing of the bed sediments may also be factors affecting the consolidation properties.

Because some of this information is conflicting and controversial, evaluation of the precise mechanism will be

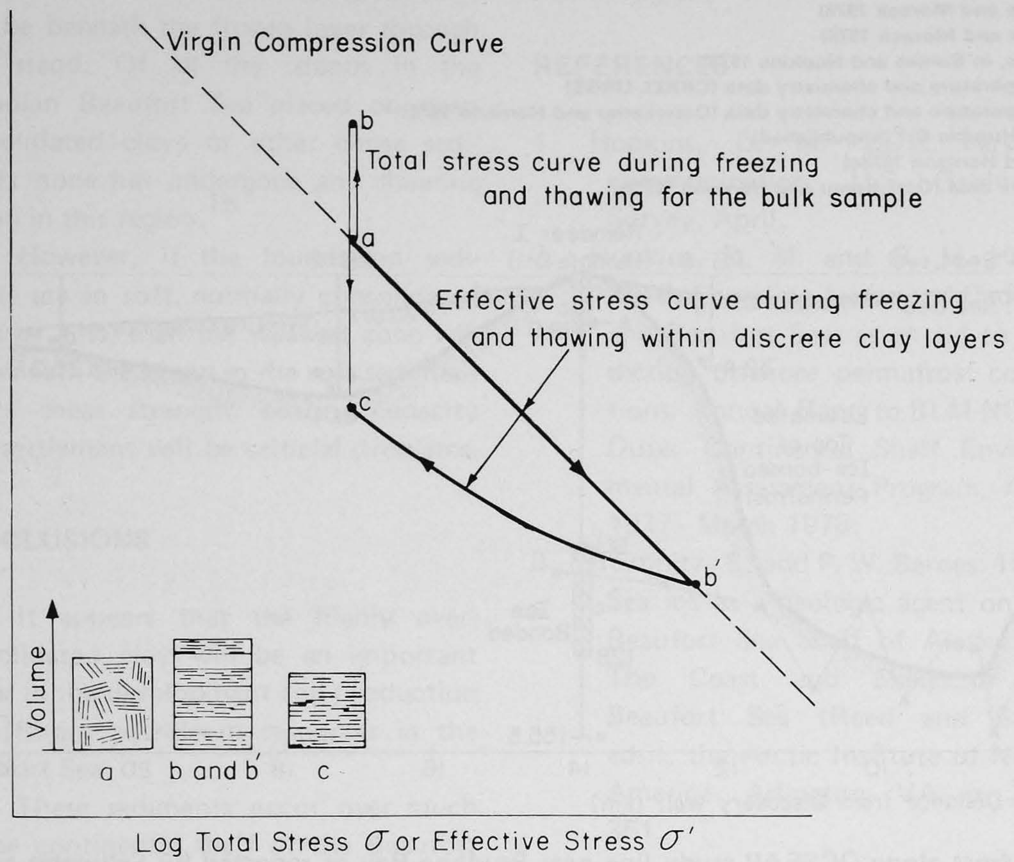


Figure 4. Theorized overconsolidation process by freezing and thawing.

deferred except to conclude that freeze/thaw was probably the dominant factor in preconsolidating these clays. None of the other factors can account for the magnitude of the overconsolidation. The large differences between the overconsolidation pressures and ratios at sites PB-2 and PB-8 are probably due to the more recent freezing and thawing of the sediments at PB-2 as Reindeer Island migrated shoreward over this site, as it is doing today under the influence of wave, ice, and current forces.

FREEZE-THAW CONSOLIDATION

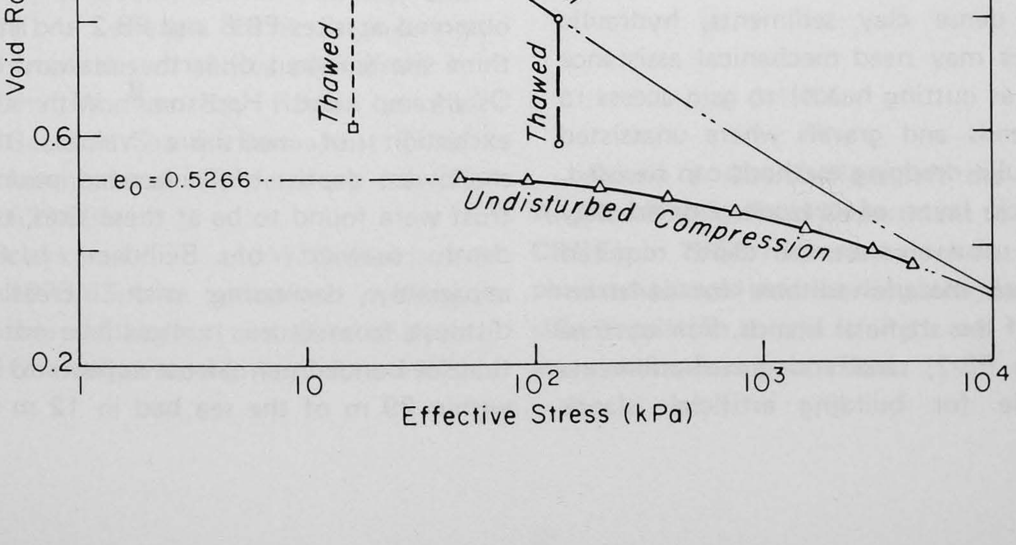
The phenomenon of overconsolidation by freezing and thawing has been observed by numerous researchers studying the consolidation properties of thawing soils. Generally, the overconsolidation has been attributed to the negative pore water pressures generated at the freezing front, which cause an increase in the effective stress on the material immediately below. As a result, the clay particles are reoriented into a more compact structure.

The process is best depicted in terms of effective stress, i.e. the difference between the total applied stress and the pore water stress. Figure 4 illustrates the process.

A clay slurry is normally consolidated (point a) and frozen unidirectionally with water free to flow to and from the unfrozen part. The large negative pore water pressures that develop during freezing cause the flow of water to the freezing front and the formation of ice lenses. The material immediately below the freezing front is overconsolidated (point b on the extension of the slurry compression curve) because of the increase in effective stress. As the freezing front propagates, discrete "bands" of clay and ice form, the clay bands being overconsolidated. Upon thawing, the effective stress in the clay bands is reduced to the initial value and the clay swells (to point c) where the pore pressures are in equilibrium with the applied load. The material has undergone a net decrease in void ratio (from point a to point c) with no change in the applied external pressure.

Figure 5 shows that freezing and thawing can cause a high degree of overconsolidation of the clay sediments at site PB-2. The upper dashed curves are the compression curves for slurries prepared from the same clay used to obtain the lower undisturbed compression curve for this site. The slurries were consolidated unidirectionally by doubling pressure increments, much like the undisturbed material. One slurry test was consolidated to 16 kPa (2.3 psi) effective stress and the other 128 kPa (18.6 psi) prior to freezing. At 16 kPa, freeze and thawing accounted for 85% of the difference between the slurry and undis-

Figure 5. Comparison of freeze-thaw and undisturbed consolidation curves.



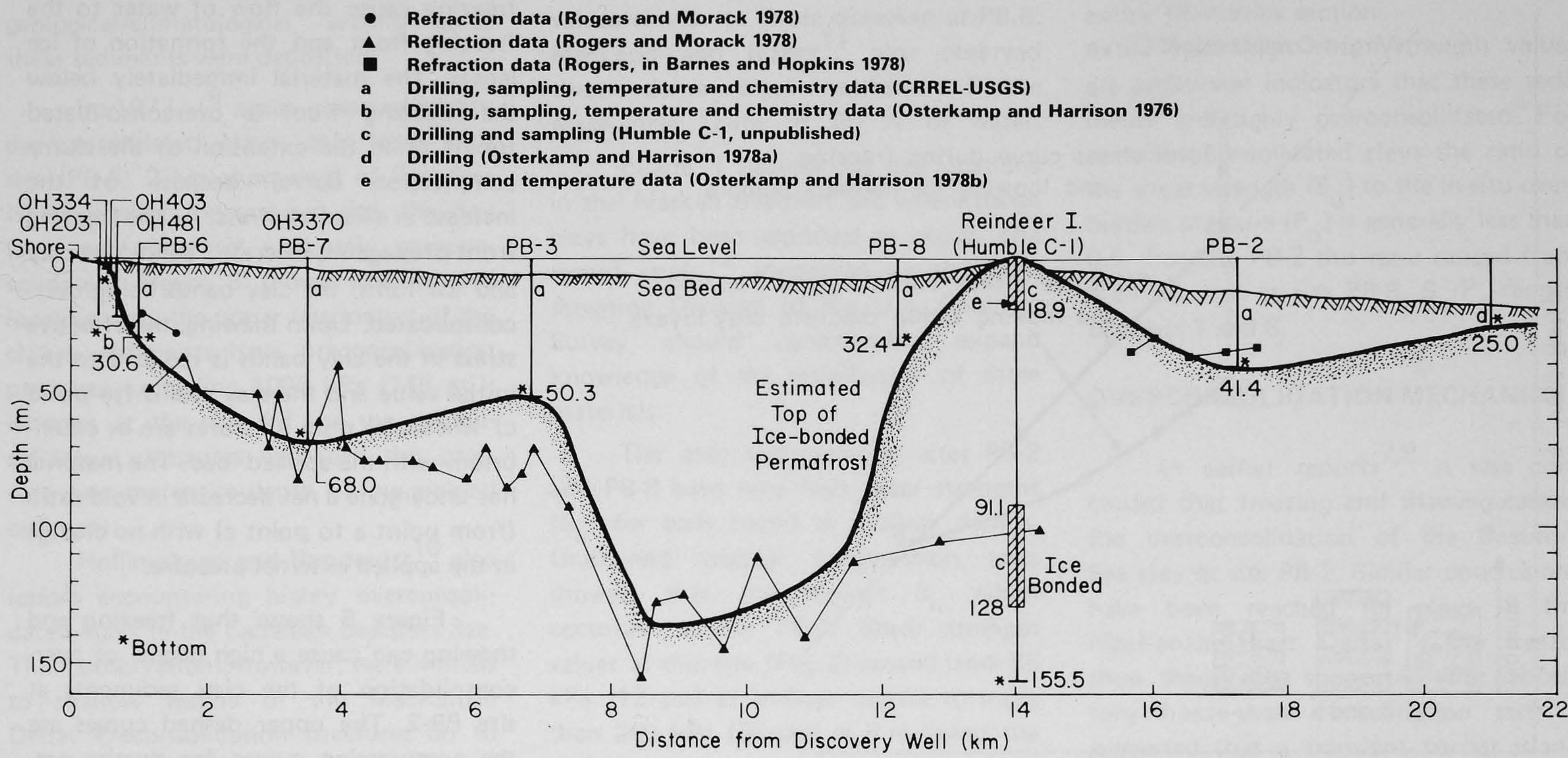


Figure 6. Summary of depth to ice-bonded permafrost along OCSEAP study line near Prudhoe Bay as reported by Sellmann and Chamberlain[9]. Locations at which the dense overconsolidated clays were observed are PB-8, PB-2, and d. Note the rise in top of ice-bonded permafrost seaward of PB-2.

turbed curves while at 128 kPa, 75% of the difference was accounted for.

This is a very good agreement, considering the uncertainty of the influence of freezing rate and number of freeze-thaw cycles or the effects of drying and wetting on these materials when reconstituted for testing purposes.

IMPLICATIONS

As previously mentioned, the overconsolidated fine-grained sediments restrict access to sands and gravels for use as construction materials. This is especially critical because large quantities of sands and gravels will be required to build the artificial islands needed for drilling platforms.

Because of the high strength of these dense clay sediments, hydraulic dredges may need mechanical assistance (such as cutting heads) to gain access to the sands and gravels where unassisted hydraulic dredging methods can be used. A thick layer of overconsolidated clay would also increase the depth required to reach material suitable for construction of the artificial islands. For instance at site PB-2, sand and gravel sediments suitable for building artificial islands lie at a depth of 20.8 m below sea level. Since the maximum depth to which existing dredges can operate is approximately 45 m,[11] 46% of the maximum reach of the dredge would thus be used to gain access to the sands and gravels. And nearly half of that reach would be through the dense clay which would greatly reduce the dredging rate. Such a site would be avoided in preference for a site with more easily dredged materials.

The other potentially more serious handicap is the apparent shallow depth of ice-bonded permafrost beneath these clays. Figure 6 shows the estimated position of the top of ice-bonded permafrost along the study line investigated during the OCSEAP investigation. The dense highly overconsolidated clays were observed at sites PB-8 and PB-2 and at a third site (marked d) farther seaward by Osterkamp and Harrison.[8] With the exception of nearshore values, the shallowest depths of ice-bonded permafrost were found to be at these sites, the depth seaward of Reindeer Island apparently decreasing with increasing distance from shore. It should be noted that ice-bonded permafrost appears to be within 29 m of the sea bed in 12 m of water at site PB-2 and within 8 m of sea bed at the Osterkamp-Harrison site in 17 m of water.

Results of the USGS 1979 drilling program[12] should provide more information on this relationship. If this apparent correlation of shallow ice-bonded permafrost with the overconsolidated sediments is confirmed, then it is certain that dredging in regions where these dense sediments occur will be avoided because of the extreme difficulty in excavating frozen materials. If this correlation is not found to occur, locations with dense clays should make excellent sites for placing artificial islands because of the high shear strength of the overconsolidated clays.

Artificial islands, especially those placed outside the fast ice zone, will be subject to very large horizontal ice forces. Failure can occur through a slope, through the island itself or through the sediments on which it is founded.

Assuming that a frozen crust will form on such an island to resist a slope failure before the maximum ice forces are developed (mid to late winter), my calculations show that the weakest zone will be either through the island or its foundation. If the foundation sediments are highly overconsolidated, as they are at site PB-2, then the critical shear zone will be beneath the frozen layer through the island. Of all the islands in the Canadian Beaufort Sea placed on overconsolidated clays or other dense sediments none has undergone any shearing action in this region.[15]

However, if the foundation sediments are in soft, normally consolidated clays or silts, then the weakest zone will be beneath the island in the soft sediment where shear strength, bearing capacity and settlement will be criticial problems.

CONCLUSIONS

It appears that the highly overconsolidated clay will be an important factor in the development and production of offshore petroleum resources in the Beaufort Sea.

These sediments occur over much of the continental shelf of the Beaufort Sea. In developing borrow sites for offshore island construction, regions where these sediments are thick may need to be avoided in preference for sites where unfrozen sands and gravels are readily available near the sea floor.

All of the fine-grained sediments appear to be overconsolidated, with the overconsolidation probably being caused by freezing and thawing. The thickest, densest and most uniform and highly overconsolidated sediments observed to date occur seaward of Reindeer Island. These clays have very high shear strengths and bearing capacities. If sands and gravels are readily available nearby, these clays will make good sites for placing artificial islands. If ice-bonded permafrost is found in or immediately beneath these clays, these sites may have to be avoided because of thaw instability problems.

ACKNOWLEDGMENTS

I wish to acknowledge the many helpful discussions with my co-workers, P. V. Sellmann of CRREL and D. M. Hopkins of the U.S. Geological Survey. This work was supported by the Bureau of Land Management and managed by the National Oceanic and Atmospheric Administration as part of their Outer Continental Shelf Environmental Assessment Program.

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Edwin J. Chamberlain left the Los Angeles County Road Department to join CRREL in 1962. His recent work has emphasized thawed and thawing soils, especially in relation to soil strength and resilience, and subsea permafrost.

by Gary Phetteplace

Waste Heat Recovery for Heating Purposes

INTRODUCTION

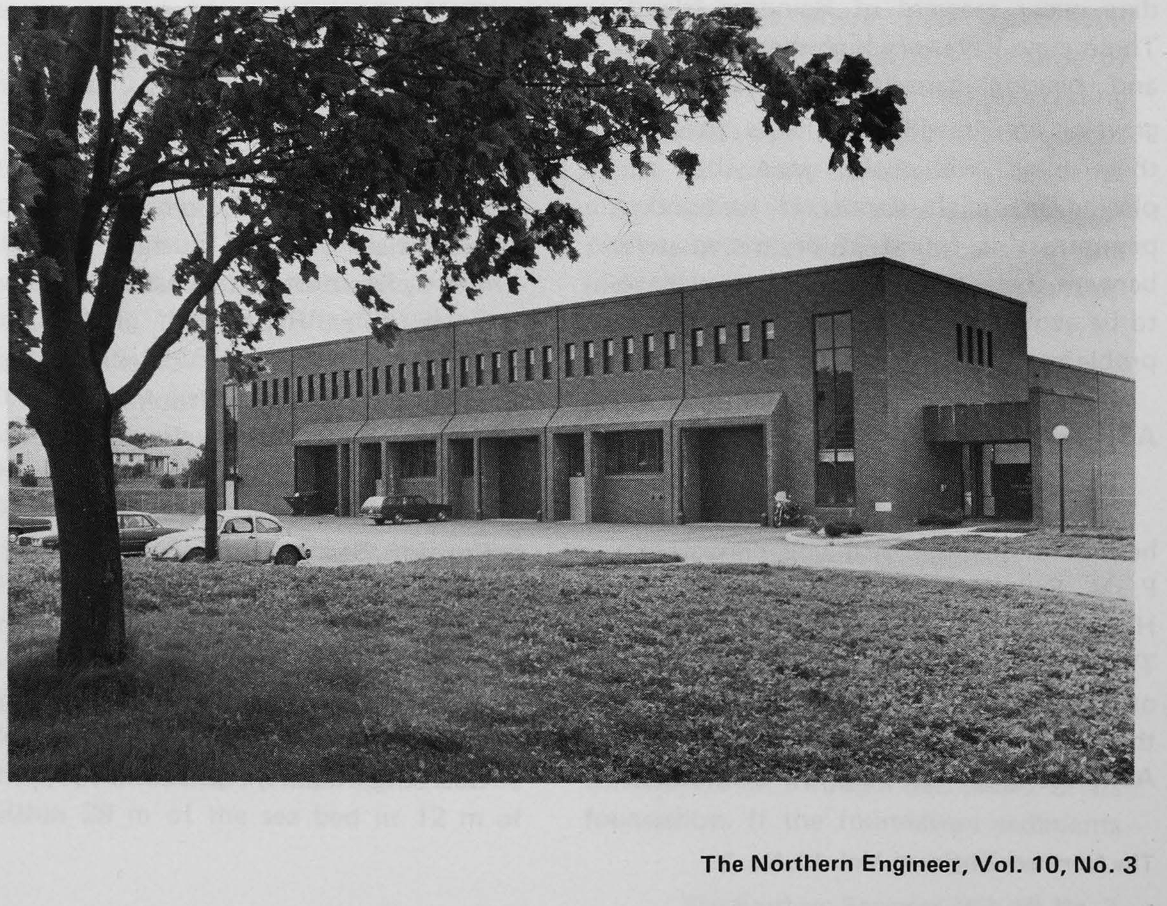
In Hanover, New Hampshire, the United States Army Cold Regions Research and Engineering Laboratory (CRREL) has recently completed construction of an Ice Engineering Facility. The offices of this building are heated by heat pumps whose heat source is waste heat. Using heat pumps rather than an oil-fired heating system saved $10,000 initially and also reduced operating costs. This article will first discuss the building itself and the aspects which make waste heat recovery favorable, and then will review the principles of heat pumps and examine how they are used in the new Ice Engineering Facility.

The Ice Engineering Facility is a special purpose building designed to study the problems caused by ice and its effects. One large room, refrigerated to -10°F, is an 80 ft x 120 ft clear span research area. The floor in this room is capable of withstanding loads of 400 $\mathrm{lbf/ft^2}$. In another room is a test basin 30 ft wide x 8 ft deep x 120 ft long. This room is also refrigerated to -10°F. A third large room, which can be refrigerated to -20°F, contains a flume with a refrigerated bottom. The total for these and other smaller refrigeration tasks in the building requires a refrigerating plant with a capacity of 200 tons. In order to cool this refrigeration system, more than 2.4 MBtu/hr of waste heat must be rejected in the refrigeration condensers. This waste heat is used to heat the building both directly and with the aid of heat pumps. Waste heat is also used directly for ice melting. Before discussing the Ice Engineering Facility system, let's examine what a heat pump is and how it can help recover waste heat.

HEAT PUMP BASICS

A heat pump is a cyclic device which transfers heat from a lower tem-

CRREL's Ice Engineering Facility.



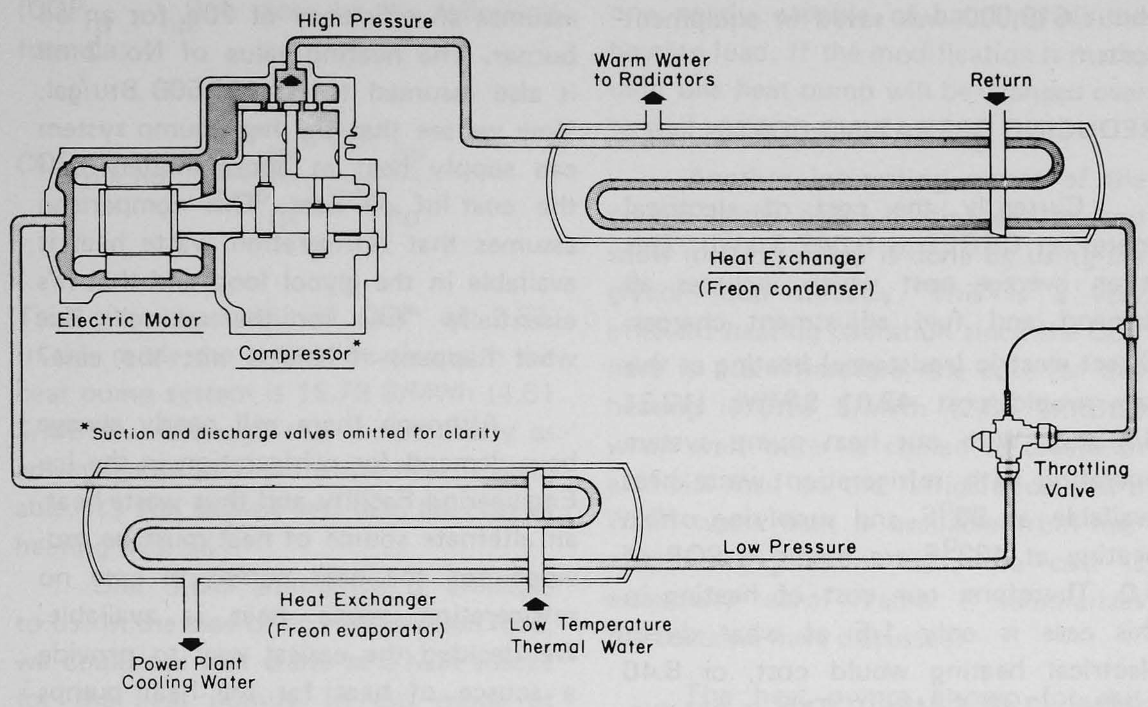


Figure 1. The major components of a heat pump.

perature source to a higher temperature sink. Heat normally flows in the opposite direction, that is, from "hot" to "cold". Therefore for a heat pump to work we need to add energy, usually in the form of electricity. The most common example of a heat pump is a refrigerator. It removes heat from the low temperature of its interior and rejects that heat to the higher temperature on its exterior. Thus, it "pumps" heat back into its surroundings, where the heat originated.

With the aid of Figure 1 it is possible to trace the thermodynamic cycle of a heat pump. Since this is a cyclic device, there is no true starting or finishing point for the cycle: arbitrarily, we shall begin where the refrigerant is mostly liquid and is at low temperature and pressure. This is its state after it leaves the throttling valve as shown in Figure 1. The refrigerant then enters the evaporator where it takes on sufficient heat from the heat source to be evaporated from the liquid state to the gaseous state at nearly constant temperature and pressure. The refrigerant is usually slightly superheated after leaving the evaporator in order to prevent problems in compression.

The refrigerant next enters the compressor where its pressure is increased. In the process of compression the temperature of the refrigerant also increases.

From here the gaseous refrigerant flows on to the condenser. At nearly constant pressure, heat is now extracted from the refrigerant. This is the latent heat of vaporization of the refrigerant as it condenses from its gaseous state to its liquid state. The liquid refrigerant now enters the throttling valve and has its pressure reduced. Upon exit from the throttling valve, the refrigerant is now ready again to complete the cycle just described.

Many other factors require consideration when designing an actual heat pump. However, the basics of an actual cycle are well represented by our simplified cycle.

Since the condensing process occurs at higher pressure than the evaporation process, the condensing temperature is also higher. Thus, heat is "pumped" from a low temperature source to a higher temperature sink. The price paid for this process is the energy input to the compressor.

The performance of a heat pump is measured by the ratio of the useful heat output to the energy input. This parameter is called the coefficient of performance (COP) and is given by the following formula:

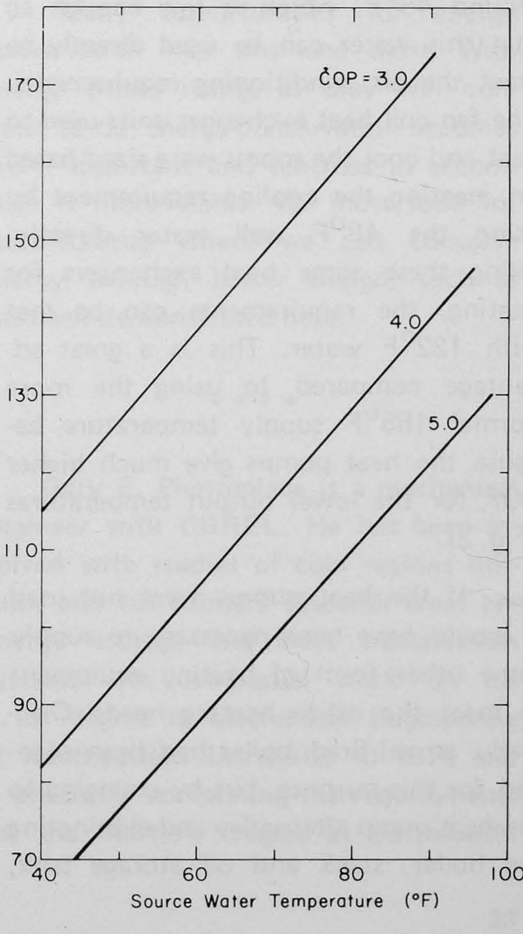
$$\text{COP} = \frac{\text{Useful heat output}}{\text{Energy input to compressor}}$$

(The units used in this expression must be consistent.) The COP is only a measure of the thermodynamic performance of a heat pump. Economic performance must consider other factors which we shall discuss later.

The COP of a heat pump is a function of the difference between the temperature of its source and sink. The smaller this temperature difference, the higher the COP we can obtain. Figure 2 gives values of the COP which could be expected for a water source heat pump. These results assume a cycle efficiency of 85% of that obtainable from the corresponding Carnot cycle. The combined efficiency of the motor/compressor is assumed to be 65%. The approach temperature in the heat exchangers is assumed to be 15°F and the temperature drop across the evaporator is assumed to be 5°F. These are all reasonable assumptions.

As can be seen from Figure 2, when using heat pumps it is always advantageous to utilize the output heat at the lowest temperature possible. Since the source of heat is usually waste heat or a natural heat source, its temperature is nearly always fixed.

Figure 2. Typical COP values for water source heat pumps.



THE OPPORTUNITY AT CRREL

As stated earlier, the Ice Engineering Facility requires about 200 tons of refrigeration capacity for its mission activities. This is done with a mechanical refrigerating plant which uses ammonia as the refrigerant. Liquid ammonia is circulated to the areas where refrigeration is required. The ammonia is cooled in condensers by a mixture of glycol and water. This glycol mixture enters the condensers at approximately 79^{O}F and exits at about 90^{O}F. A water-cooled condenser is also provided. A schematic diagram of the entire system is shown in Figure 3.

With the exit temperature of the glycol mixture this high, it can be used directly for some heating applications. This is done for laboratory heating, basement and shop heating, and ice and snow melting. Normal design practice for hot water heating systems for offices uses water temperatures around 185^{O}F. For this reason, direct use of the waste heat was not possible and so heat pumps were chosen to supply the office heating. The glycol loop is a good source of heat for the heat pumps.

A nearly unique opportunity existed with respect to air conditioning for the office areas. Well water is available in large quantities at temperatures around 48^{O}F, which is low enough so that this water can be used directly to meet the air conditioning requirements. The fan coil heat exchanger units used to heat and cool the rooms were sized based on meeting the cooling requirement by using the 48^{O}F well water directly. Using these same heat exchangers for heating, the requirements can be met with 122^{O}F water. This is a great advantage compared to using the more normal 185^{O}F supply temperature because the heat pumps give much higher COP for the lower output temperatures (Fig. 2).

If the heat pumps were not used it would have been necessary to supply some other form of heating equipment to meet the office heating needs. Originally an oil-fired boiler had been planned for this purpose, but by changing to the heat pump alternative and eliminating the boiler, stack and oil storage tank, about $10,000 was saved in equipment costs.

REDUCING OPERATING COSTS

Currently the cost of electrical energy at CRREL is 0.042 $/kWh. This is an average cost which includes all demand and fuel adjustment charges. Direct electric (resistance) heating at this rate would cost 42.01 $/MWh (12.31 $/MBtu). With our heat pump system operating with refrigeration waste heat available at 90^{O}F and supplying office heating at 122^{O}F we obtain a COP of 5.0. Therefore, our cost of heating in this case is only 1/5 of what direct electrical heating would cost, or 8.40 $/MWh (2.46 $/MBtu). This is not surprising since direct electric heating is seldom the best choice and a heat pump is nearly always advantageous because it usually has a COP greater than unity. This, remember, is only the operating cost—capital cost must also be considered. Oil heating is usually the best economic alternative; with the current price of No. 2 fuel oil at CRREL being 0.47 $/gal, the cost of heating with oil is 16.55 $/MWh (4.85 $/MBtu). This assumes an efficiency of 70% for an oil burner. The heating value of No. 2 oil is also assumed to be 138,500 Btu/gal. Now we see that the heat pump system can supply heat at approximately half the cost of oil heat. This comparison assumes that refrigeration waste heat is available in the glycol loop and that it's essentially "free for the asking". But what happens if this is not the case?

Although there will nearly always be a demand for refrigeration in the Ice Engineering Facility and thus waste heat, an alternate source of heat must be provided for the heat pumps in case no refrigeration waste heat is available. We decided the easiest way to provide a source of heat for the heat pumps would be to provide an artificial demand for refrigeration at times of little or no actual demand.

This artificial load on the refrigeration system is created by chilling well water from 48^{O}F to 39^{O}F. In this case we must also consider the COP of the refrigeration plant in the calculation of our COP for the system. The COP of the refrigeration plant is 4.6 as a heat pump. The combined COP of the re-

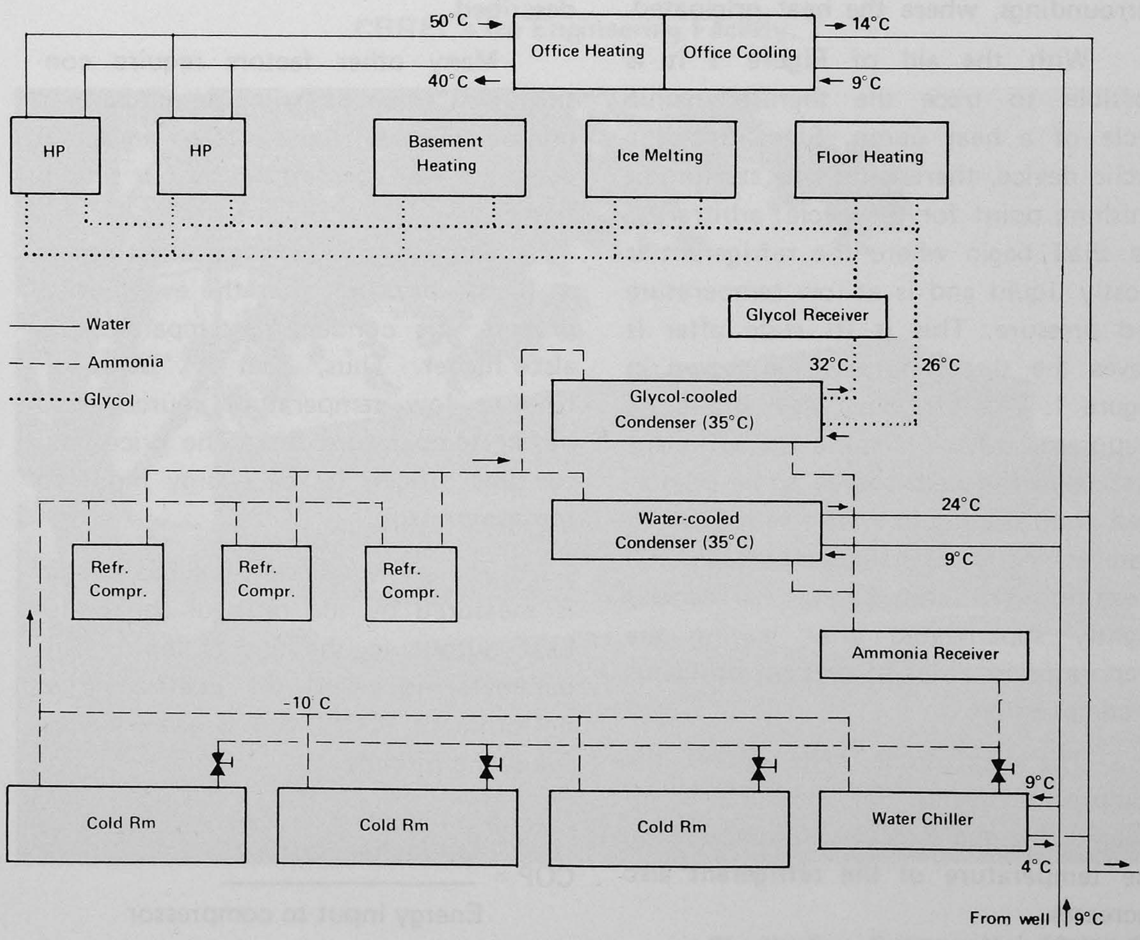


Figure 3. Ice Engineering Facility heating and refrigerating systems.

frigerating plant and the heat pumps (COP_{rp+hp}) is given by the following formula:

$$COP_{rp+hp} = \frac{COP_{rp} \times COP_{hp}}{COP_{rp} + COP_{hp} - 1}$$

This gives a combined COP of 2.67. In this mode the cost of heating with the heat pump system is 15.73 $/MWh (4.61 $/MBtu). Although this is not nearly as advantageous as when waste heat is available, it's still slightly less than the cost of heating with oil.

One other alternative is available to us: In the case of no refrigeration load, we could use well water as a heat source for the heat pumps. In this mode of operation we would get a COP of 3.5. The cost of heating in this case would be 12.00 $/MWh (3.53 $/MBtu). This would require modifications to the system, however. If we find that we operate in the combined mode with the COP at 2.67 for a significant amount of time, we will make this modification. Two heat pumps are installed in the building with either one nearly capable of handling all the heating load. If the modification is made, only one heat pump will be changed over to well water as a heat source.

Another interesting aspect of the system is the direct heating and ice and snow melting which is done by using the glycol loop directly. This is a very efficient heating operation since the COP here is 4.6. Therefore, the cost for this heating is 9.13 $/MWh (2.68 $/MBtu) when well water is chilled to create an artificial load on the refrigeration plant. When waste heat is available from necessary refrigeration load, the cost is essentially zero! Table 1 summarizes the costs we have discussed.

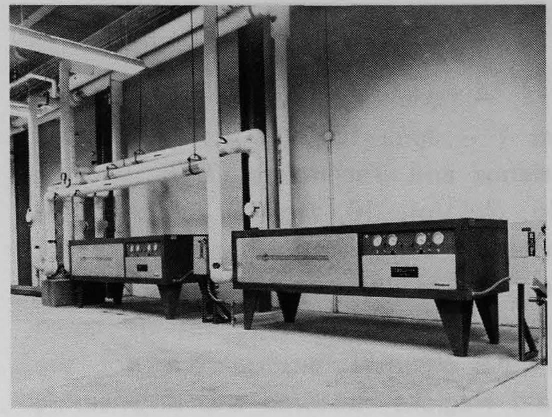


Figure 4. Westinghouse Templifier heat pumps as installed.

The heat pumps chosen for this application were Westinghouse Templifier units; Figure 4 shows them as installed. Two units are used, each having a heating capacity of 440 kW (1.5 MBtu/h). The working fluid for the heat pumps is Freon 22. They were designed to supply output temperatures between 104°F and 140°F. This variable supply temperature is possible by varying the condensing temperature, which is accomplished by using reciprocating compressors with variable discharge pressure. Partial load conditions can also be handled with these heat pumps by unloading one or two of the four cylinders of either compressor. Both of these features, variable output temperature and variable capacity, make it possible for the heat pumps to conform closely to the load and to meet the requirements with high efficiency. We expect the seasonal COP of the system, including all modes of operation, to be greater than 3.4.

TABLE 1

Costs for the Various Modes of Heating in the Ice Engineering Facility

Method	Task	Efficiency or COP	Cost ($/MWh)	Cost ($/MBtu)
Direct electric heating	Comparison	1.0	42.01	12.31
Oil heating	Comparison	0.70	16.55	4.85
Heat pumps (refrigeration waste heat available)	Office heating	5.0	8.40	2.46
Refrigeration plant and heat pumps (refrigeration waste heat not available or insufficient)	Office heating	2.67	15.73	4.61
Heat pumps (well water heat source)	Office heating	3.5	12.00	3.52
Refrigeration Plant (well water artificial load)	Basement heating Lab heating, and ice and snow melting	4.6	9.13	2.68

Although actual measurements have not yet been made, we expect this system to reduce heating costs by about 25% compared to oil heating. Increased reliability and reduced maintenance costs are also expected.

Many opportunities for energy conservation like this one exist. With energy prices rising, as they will continue to do, energy conservation becomes more important and schemes to accomplish it more viable. We must look for opportunities where we can conserve energy through better design, such as has been demonstrated here.

* * * *

Gary E. Phetteplace is a mechanical engineer with CRREL. He has been involved with studies of cold regions utilities, and his primary research areas are energy storage and heat transmission systems. He completed work on his B. S. degree in Mechanical Engineering at Northeastern University in 1975 and is presently completing the requirements for the Master's Degree at Dartmouth.

PUBLICATIONS

A review copy of Volume 1, Number 1 – June 1979 – of **Cold Regions Science and Technology** (*TNE* Vol. 9, No. 3; Vol. 10, No. 1) reached here recently; the timing is appropriate for mention in our special CRREL issue, since Editor Malcolm Mellor is based at the Hanover headquarters for the Cold Regions Research and Engineering Laboratory and four of the seven articles in this inaugural issue were contributed by CRREL personnel.

The journal is an elegant production cleanly and readably printed on high-quality paper, copiously illustrated with maps, diagrams, graphs, charts, tables, and a few sharp black and white photographs. The quality of the contents matches that of the presentation. Titles in this issue are: *Determining subsea permafrost characteristics with a core penetrometer – Prudhoe Bay, Alaska; Relationships between January temperatures and the winter regime in Germany; Application of the Andrade equation to creep data for ice and frozen soil; Water flow through heterogeneous snow; Snowpack albedo and snow density; Freezing and thawing tests of liquid deicing chemicals on selected pavement materials;* and *On icebergs and their uses. A report to the Australian Academy of Science.* In addition, there are detailed reviews of a meeting (*First International Symposium on Ground Freezing*) and two books (*Geotechnical Engineering for Cold Regions* and *Polar Regions Atlas*, a CIA publication) as well as a Calendar of Events.

In less graceful hands, this technically excellent and densely informative journal conceivably could have been an exercise in sterile specialization. Many scientific specialty journals are, since they can be understood only by researchers immersed in the particular field, but **Cold Regions Science and Technology** is written and edited to communicate with readers in many fields. Judging by this issue, Mellor has held to the aims set forth in his opening editorial: "(1) fostering two-way communication between the research practitioners and the users of applied science (especially users in industry), and (2) easing information retrieval by drawing together some of the material that tends to get lost in obscure reports and limited-circulation conference proceedings."

Vol 1 (1979) will consist of four issues. The subscription price is US $75.50/Dfl. 155, including postage. A *free sample copy* is available on request from *Elsevier Scientific Publishing Company, P. O. Box 211, 1000 AE Amsterdam, The Netherlands.*

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TNE's neighbor down the hall at this Institute, *Dr. Syun Akasofu*, is the author of a new book in the *Alaska Geographic* series: **Aurora Borealis – The Amazing Northern Lights.** (Granted, the book has very little to do with engineering, but we're assuming that most people interested in the north are likely to appreciate an abundantly illustrated, readable, and technically informative treatment of this beautiful polar phenomenon.) Akasofu reviews the legends and lore of the northern lights as well as the scientific efforts to understand them, a review he can bring well up to date since he works in the forefront of that field.

The soft-cover volume costs $7.95 and is available wherever *Alaska Geographic* is sold. Since Akasofu is donating his author's copies and discount to the Travel Fund for Geophysical Institute graduate students, however, books purchased through this Institute will help send struggling young scientists to professional meetings and symposia. Therefore you might wish to order your copy from *Kate Barr, Business Office, Geophysical Institute, University of Alaska, Fairbanks, AK 99701.*

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For readers interested in alternate/appropriate technology, we recommend most highly the newspaper-style **Masonry Stove Guild Newsletter.** Note, please, that the recommendation is not limited to people whose interest lies in Russian or Finnish fireplaces, kachelofen, brick cookstoves or tile room heaters, although Editor Albie Barden seems determined to make his newsletter the Western hemisphere's state-of-the-art source on such devices.

The Newsletter exemplifies a sensible approach and attitude toward a small-scale appropriate technology. The Guild's underlying assumption is that masonry stoves constitute an established technology, since they have been used for centuries in Europe, and a good one whose time has returned. Past that starting point, the Newsletter attempts to gather and pass on available information in practical fashion. Editor Barden holds workshops for stove builders in which stoves are actually built; he prints details and difficulties, critiques plans, exposes problems, scolds unresponsive dealers, and warns that measurements, tests, and time are all needed before contemporary stove masons can claim to have come up to their European antecedents, much less surpassed them. The whole effort seems to temper the typical alternate energy group's enthusiasm with Yankee level-headedness and patience.

The **Masonry Stove Guild Newsletter** is mailed at several-month intervals to Guild members; membership is $5 per year. Write to the Guild at *R.F.D. 1 - Box 38, Norridgewock, Maine 04957.*

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The American Society of Civil Engineers has asked *TNE* to publish the following announcement:

There is a growing, interdisciplinary interest in cold regions practice. The **Proceedings of the May 1978 Specialty Conference (in Anchorage, Alaska) of the American Society of Civil Engineers** emphasize the broad range of engineering problems and solutions in the cold regions of the world. The two volumes contain 73 papers, the keynote and luncheon addresses, state of the art reviews, panel discussions, and summary statements. The papers are divided into the following areas: Land, Coastal, and Resource Development; Materials, Manpower, Equipment, and Methods; and Commercial, Institutional and Industrial Facilities Support Systems. You may purchase this publication by sending an order and a check for $40.00 to *ASCE Publication Sales Department, 345 East 47th Street, New York, New York 10017.*

THE **NORTHERN ENGINEER**

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